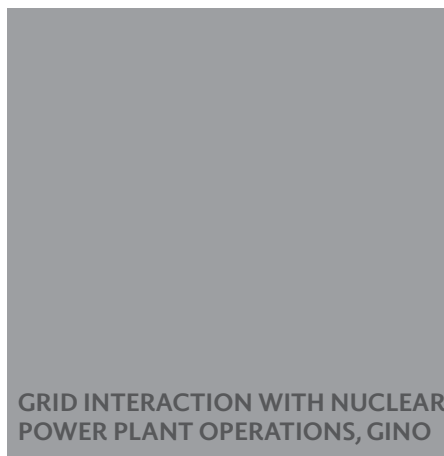
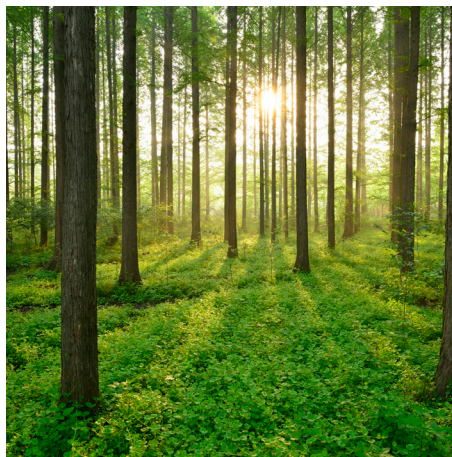
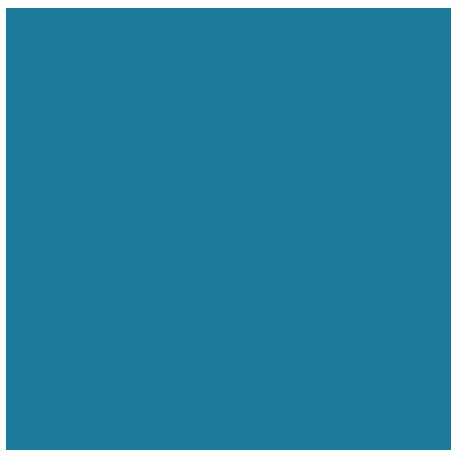


VOLTAGE DIP TRANSIENTS AND AUXILIARY EQUIPMENT IN NUCLEAR POWER STATIONS

REPORT 2025:1090



GRID INTERACTION WITH NUCLEAR
POWER PLANT OPERATIONS, GINO



VOLTAGE DIP TRANSIENTS AND AUXILIARY EQUIPMENT IN NUCLEAR POWER STATIONS

**MATH BOLLEN, ABDALLAH AMMAR HOSENY UOSEF
LULEÅ UNIVERSITY OF TECHNOLOGY, SKELLEFTEÅ, SWEDEN**

ISBN 978-91-89919-90-7 | © Energiforsk February 2025

Energiforsk AB | Phone: 08-677 25 30 | E-mail: kontakt@energiforsk.se | www.energiforsk.se

Foreword

This report forms the results of a project performed withing the Energiforsk Energiforsk Grid Interaction with Nuclear power plant Operations (GINO) Program. The GINO Program aims to increase the knowledge of aspects of the interactions between the external grid and the Nordic nuclear power plants. Part of this is to investigate technical issues.

Voltage dip transients, caused by faults in transmission systems, can adversely affect auxiliary equipment in nuclear power stations. Understanding these transients is crucial for maintaining equipment reliability.

In nuclear power plants, voltage dip transients can lead to severe operational disruptions. Ensuring the stability and immunity of auxiliary equipment against these transients is vital for safe plant operations.

This study investigates the origin, propagation, and impact of voltage dip transients on auxiliary equipment in nuclear power stations. It aims to provide insights and recommendations for mitigating these effects.

The results highlight the significant impact of voltage dip transients on equipment performance. The study concludes with recommendations for further research and measures to enhance equipment immunity.

The study was carried out by Math Bollen and Abdallah Ammar Hoseny Uosef, Luleå University of Technology. The study was performed within the Energiforsk GINO Program, which is financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft, Karlstads Energi, the Swedish Radiation Safety Authority and Svenska Kraftnät.

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

This report addresses transients that occur at the beginning and ending of voltage dips, so-called “voltage-dip transients”. Such transients occur for example due to faults in transmissions systems and propagate to the terminals of auxiliary equipment in nuclear power stations, where they may appear with higher amplitude; such transients may adversely affect auxiliary equipment. The report further discusses other voltage-quality disturbances and includes a set of recommendations on further work.

Voltage dips are short-duration reductions in rms voltage, with earth faults and short circuits a major cause of severe voltage dips. Voltage dips are in most cases characterized by their residual voltage and their duration. Other voltage-dip characteristics may also impact the performance of equipment but are often not included in studies. This includes voltage-dip transients: oscillations that occur at the beginning and ending of voltage dips due to faults. There is a serious lack of knowledge on the origin, propagation, and impact of voltage-dip transients, despite their potential major impact on equipment performance.

Simulations have been performed of the origin of voltage-dip transients due to faults at transmission level and their propagation to the terminals of auxiliary equipment in a nuclear power station. Different fault types are shown to result in voltage-dip transients with different characteristics. Different fault locations result in voltage-dip transients with different characteristics. Changes in the transmission grid result in voltage-dip transients with different characteristics. An important observation from the simulations is that the magnitude of the oscillations may be larger at the equipment terminals than in the transmission grid.

The impact of voltage-dip transients is studied for induction motors, synchronous motors, and power-electronic converters. It is shown that the presence of voltage-dip transients, next to the actual voltage dip, will result in more severe impact on equipment. The main concern is with the impact on power-electronic converters and the way in which the protection of such converters will react to voltage-dip transients.

Important recommendations from the work include: detailed simulations of origin and propagation of voltage-dip transients; permanent measurements in the transmission grid and in the auxiliary grid; detailed studies of the impact of voltage-dip transients on equipment and methods to ensure equipment immunity; design of internal and external grid; considering other voltage disturbances; and further research by different stakeholders.

An important conclusion from this work is that voltage-dip transients deserve much more attention than they have received before.

Keywords

Electric power transmission, nuclear power stations, power quality, voltage dips, power-system transients

Sammanfattning

Rapporten behandlar transienter som uppstår i början och slutet av spänningsdippar, så kallade "spänningsdiptransienter". Sådana transienter uppstår bland annat på grund av fel i transmissionsnätet; de sprider sig till klämmorna av hjälputrustning i kärnkraftverk, där de kan uppträda med högre amplitud; och de kan påverka hjälputrustning negativt. Rapporten även diskuterar andra spänningskvalitetsstörningar och innehåller detaljerade rekommendationer för fortsatt arbete.

Spänningsdippar är kortvariga sänkningar av spänningens effektivvärde, med jordfel och kortslutningar huvudkällor till allvarliga dippar. Spänningsdippar karakteriseras oftast genom sin kvarstående spänning och varaktighet. Andra karakteristiker av dippar kan också påverka utrustningen men ingår ofta inte i studierna. Detta inkluderar spänningsdiptransienter: oscillationer som uppstår i början och slutet av spänningsdippar på grund av fel. Det finns en allvarlig brist på kunskap om ursprung, utbredning och påverkan av spänningsdiptransienter, trots deras potentiella stora inverkan på utrustning.

Simuleringar har utförts av ursprung av spänningsdiptransienter på grund av fel i transmissionsnätet och deras spridning till klämmorna av hjälputrustning i ett kärnkraftverk. Olika typer av fel har visat sig resultera i spänningsdiptransienter med olika egenskaper. Olika felplatser resulterar i spänningsdiptransienter med olika egenskaper. Förändringar i transmissionsnätet resulterar i spänningsdiptransienter med olika egenskaper. En viktig observation från simuleringarna är att storleken på oscillationerna kan vara större vid klämmorna av utrustning än i transmissionsnätet.

Effekten av spänningsdiptransienter har studerats för asynkronmotorer, synkronmotorer och kraftelektroniska omvandlare. Det har visat sig att förekomsten av spänningsdiptransienter, bredvid det faktiska spänningsfallet, kommer att resultera i mer allvarlig påverkan på utrustningen. Det främsta potentiella problemet är inverkan på kraftelektroniska omvandlare och hur skyddet av sådana omvandlare kommer att reagera på spänningsdiptransienter.

Viktiga rekommendationer från arbetet inkluderar: detaljerade simuleringar av ursprung och spridning av spänningsdiptransienter; permanenta mätningar i transmissionsnätet och i kärnkraftverkets interna nät; detaljerade studier av påverkan av spänningsdiptransienter på utrustning och metoder för att säkerställa utrustningens immunitet; design av interna och externa nät; beakta andra spänningsstörningar; och ytterligare forskning gjort av olika intressenter.

En viktig slutsats från detta arbete är att spänningsdiptransienter förtjänar mycket mer uppmärksamhet än de har fått tidigare.

List of content

1	Introduction	10
1.1	Voltage dips	10
1.2	Voltage-dip characteristics	10
1.3	Equipment immunity: voltage tolerance	11
1.4	Fault-ride through	11
1.5	Voltage-dips and nuclear power plants	12
1.6	Organisation of this report	13
2	Voltage dips, transients, and their characteristics	14
2.1	Voltage dips	14
2.2	Voltage-dip characteristics	14
2.2.1	Phase-angle jump	14
2.2.2	Waveform distortion	14
2.2.3	Voltage-dip transients	15
2.2.4	Point-on-wave	15
2.2.5	Voltage unbalance; voltage-dip type	15
2.3	Checklist for equipment design	16
2.3.1	Pre-event segment	16
2.3.2	During-event segments	16
2.3.3	Transition segments	17
2.3.4	Voltage-recovery segment	18
2.3.5	Multiple dip events and composite dip events	18
2.4	Transients	19
2.5	Voltage dip statistics	20
2.5.1	Magnitude and duration	20
2.5.2	Statistics for transmission systems	21
2.5.3	Interpretation and applicability of voltage-dip statistics	24
3	Measured voltage dips	26
3.1	Propagation from 130 kV to 10 kV and 400 V	26
3.2	Measurements at 130 kV	28
3.3	Measurements of Voltage dips in nuclear power plants	30
3.4	Voltage-dip transients at lower voltage levels	32
3.5	Fault types for all and for severe dips	33
4	Simulation of voltage dips and voltage-dip transients	34
4.1	Models, cases, and results presented	34
4.1.1	Model of the transmission system	34
4.1.2	Model of the nuclear power station	34
4.1.3	Cases studied	35
4.1.4	Results presented	36
4.2	transmission system – Generator on	36

4.2.1	Single-phase-to-ground fault	37
4.2.2	Phase-to-phase faults	39
4.2.3	Two-phase-to-ground faults	41
4.2.4	Three-phase faults	43
4.3	Transmission system – generator off	45
4.3.1	Single-phase-to-ground fault	46
4.3.2	Phase-to-phase faults	47
4.3.3	Two-phase-to-ground faults	49
4.3.4	Three-phase faults	51
4.4	Nuclear power station – generator off	53
4.4.1	Single-phase-to-ground faults	54
4.4.2	Phase-to-phase faults	56
4.4.3	Two-phase-to-ground faults	58
4.4.4	Three-phase faults	61
4.5	Nuclear power station – generator ON	63
4.5.1	Single-phase-to-ground fault	64
4.5.2	Phase-to-phase faults	65
4.5.3	Two-phase-to-ground faults	67
4.5.4	Three-phase faults	69
4.6	Comparison of the voltage-dip transients	71
4.6.1	Beginning of the voltage dip at 22-kV	72
4.6.2	Beginning of the voltage dip at 6 kV	72
4.6.3	Beginning of the voltage dip at 525 V	73
4.6.4	Ending of the voltage dip at 22 kV	73
4.6.5	Ending of the voltage dip at 6 kV	74
4.6.6	Ending of the voltage dip at 525 V	74
4.7	sensitivity analysis	75
4.7.1	Different fault locations	75
4.7.2	Cable fault versus line fault	76
4.7.3	Add line to the system	77
4.7.4	Transformer saturation	77
4.8	impedance-earthed systems	80
4.9	Discussion of the results	83
5	Impact of voltage dips and voltage-dip transients on equipment	84
5.1	Induction motors	84
5.2	Synchronous motors	86
5.3	Diode rectifiers for three-phase adjustable-speed drives	88
5.4	Rectifiers with active front end	89
5.5	Protection relays	91
5.6	Observations	93
6	Other voltage disturbances	94
6.1	high levels of even harmonics due to geomagnetically induced currents	94

6.2	Harmonics	96
6.3	supraharmonics	96
6.4	Interharmonics	97
6.5	Transients due to capacitor-bank energizing	98
6.6	Transients due to cable energizing	99
6.7	Abnormal switching transients	100
6.8	Voltage dips due to transformer energizing	100
6.9	Transformer saturation upon fault clearing	100
6.10	large voltage unbalance	101
6.11	Temporary overvoltages upon fault-clearing	101
6.12	Other characteristics of voltage dips due to faults	101
7	Findings and recommendations	103
7.1	Simulations of voltage dips and voltage dip transients	103
7.1.1	The need for simulations	103
7.1.2	Propagation in the transmission grid	103
7.1.3	Operational states of the transmission system	105
7.1.4	Impact of fault position	106
7.1.5	Propagation in the nuclear power station	107
7.1.6	Propagation in frequency domain	107
7.2	Permanent measurements	108
7.2.1	Events: voltage dips and transients	108
7.2.2	Variations: harmonics	110
7.2.3	Interharmonics and supraharmonics	110
7.2.4	Post-interference analysis	111
7.3	Immunity tests and requirements	111
7.3.1	Immunity requirements	111
7.3.2	Verification and immunity testing	112
7.3.3	Primary tests	113
7.4	Design of internal and external grid	113
7.4.1	Moving the point-of-common coupling	113
7.4.2	Detuning the supply paths	114
7.4.3	Diversifying equipment	114
7.5	Other voltage disturbances	114
7.6	Further research	115
7.6.1	Extent of the geographical area	115
7.6.2	Harmonic filters	115
7.6.3	Grid-connected equipment	116
7.6.4	Error made because of approximations	116
7.6.5	Characteristics of voltage-dip transients	116
7.6.6	Data analysis	117
7.6.7	Post-interference analysis	117
7.6.8	Impact on equipment	117

	7.6.9 Other voltage disturbances	118
	7.6.10 Spreading the knowledge	118
8	Concluding remarks	120
9	References	121

1 Introduction

The auxiliary equipment in nuclear power stations, like any grid-connected equipment, may be adversely impacted by voltage disturbances at its terminals. Voltage disturbances (or, voltage quality disturbances) come in two forms: voltage-quality variations and voltage-quality events. Voltage-quality variations are present continuously, for example harmonic distortion in the voltage waveform. Voltage-quality events only occur occasionally, for example voltage dips and voltage transients.

This report addresses one specific type of event, voltage dips; the emphasis is on the voltage-dip transients at beginning and ending of the dip.

1.1 VOLTAGE DIPS

A voltage dip (also known as “voltage sag”) is a short-duration reduction in voltage magnitude. Voltage dips are almost exclusively due to a short-duration high current, typically somewhere else in the power system. Most common causes of voltage dips are short-circuit faults, earth faults, motor starting, and transformer energizing. Typical durations of voltage dips are from less than 100 ms up to several seconds. The interest in voltage dips is mainly due to their impact on industrial installations. Already a voltage dip of 100 ms duration can result in a production stoppage with several hours or even a few days of production loss as a result.

Energizing of capacitor banks, AC cables, and equipment with a grid-size capacitor results in a reduction in voltage with a duration of a millisecond or less. The resulting voltage disturbances are referred to as voltage transients or switching transients and typically treated separately from voltage dips, despite there being arguments for treating them together with voltage dips.

Researchers and engineers have been aware of voltage dips for many years, where voltage dips due to motor starting were of major importance in the design of industrial installations. During the 1990’s, voltage dips due to faults reached the forefront of power-quality research and in discussions between the public network operators and their industrial customers. One of the reasons for this was the shift to adjustable-speed drives, which showed to be very sensitive to voltage dips due to faults. This resulted in a range of publications, where [1]-[5] are some of the classical ones.

1.2 VOLTAGE-DIP CHARACTERISTICS

Characterization of voltage dips came on the agenda at about the same time (i.e. during the 1990s); dip duration and residual voltage or voltage drop were from the beginning the two main characteristics. These characteristics were assumed to be the ones that had most impact on the performance of equipment exposed to voltage dips. Other characteristics that were studied include phase-angle jump, point-on-wave, and three-phase unbalance. Important contributions to the standardization of voltage dip characteristics were IEEE 1346 [6]-[7], IEEE 493 [8]-

[9], IEC 61000-4-30 [10], and IEEE 1564 [11]-[12]. The IEC power-quality monitoring standard, IEC 61000-4-30, has made a huge contribution to the power quality field by defining strict and reproduceable measurement definitions for a range of power-quality disturbances, including voltage dips. The standard, however, only defines residual voltage and dip duration as characteristics. A list of other characteristics, without definition, was given in an informative annex with the first edition of the standard but was removed in subsequent editions. The IEEE equivalent for voltage dips, IEEE 1564 [11], also includes a definition for “characteristic voltage”, therewith partly including three-phase unbalance.

A comprehensive overview of the knowledge on voltage dips, as relevant for practical applications, was gathered by an international working group resulting in a technical brochure published in 2010 [13]. The technical brochure resulted in several recommendations to different stakeholders, including a checklist with voltage-dip characteristics to be considered in the design of grid-connected equipment. This checklist is reproduced in Section 2.3 of this report.

1.3 EQUIPMENT IMMUNITY: VOLTAGE TOLERANCE

The potential negative impacts of voltage dips made that, from several sides, requirements were established for the immunity (known as “voltage tolerance”) of grid-connected equipment and installations. This immunity was also a major part of the above-mentioned technical brochure [13]. The earliest voltage-tolerance curves came from the manufacturers of computing and communication equipment. The Information and Telecommunication Industry Council (ITIC), a branch organization of equipment manufacturers, recommended their members to ensure a certain level of voltage tolerance of their equipment [5, Section 5.2.4]. A stricter voltage tolerance requirement was recommended by SEMI, a branch organization for manufacturers of semiconductors [14], to be used by their members in the specification of equipment in manufacturing installations. The document [15] came with a detailed testing procedure to verify compliance. A set of voltage tolerance tests, for specific combinations of residual voltage and duration, are part of two IEC standards: IEC 61000-4-11 [16] and IEC 61000-4-34 [17]. Both documents include two types of unbalanced voltage dips, but apart from that only residual voltage and duration are used for the voltage-tolerance requirements. A more recent document, IEEE 1668 [18], includes tests for balanced voltage dips and two types of unbalanced voltage dips. The document does however not include a method for identifying voltage-dip type from measurements. Recent work has started for the revision of IEEE 1564 [11] to include measurement-based definitions of three-phase unbalance [19] and phase-angle jump [20]. The status of that work is not known to the authors of this report.

1.4 FAULT-RIDE THROUGH

Another development on immunity of equipment against voltage dips was initiated by the transmission-system operators. To ensure operational security after a severe transmission-system fault, requirements were placed on the voltage tolerance of large production units, including nuclear power plants. The term “fault-ride through” is often used instead in voltage tolerance or immunity, but the

phenomenon is the same: equipment or installations connected to the grid do not behave as intended because of voltage dips at their terminals. An early version of these fault-ride-through requirements, for thermal power units, was in place in the Nordic interconnected system (Nordel) already in 1982 [21]; the dimensioning case, according to [21] was the voltage dip due to a two-phase to ground fault cleared by the back-up protection. The subject became high on the agenda with the introduction of large amounts of wind power in countries like Denmark, Spain and Germany. The requirements were generally based on the one for the Nordic interconnected system [21], but different for each country [22]. More recently, several grid codes have been issued by the European commission, including voltage-tolerance requirements for small and large production units, with the aim of harmonizing the requirements between different countries [23]. The dimensioning case, in modern grid codes, is often the voltage dip due to a three-phase fault.

Most of the standards and requirements only use residual voltage and dip duration as characteristics of voltage dips. Unfortunately, three-phase unbalance never made it into the IEC power-quality monitoring standard. Three-phase unbalance was relevant already for the kind of three-phase equipment that was in use in industrial installations during the 1990s [24]. Several more recent studies have also shown the impact of other dip characteristics on the performance of equipment. Studies have especially been directed towards the impact of three-phase unbalance and phase-angle jumps on wind-power installations [25]-[27].

1.5 VOLTAGE-DIPS AND NUCLEAR POWER PLANTS

Voltage dips due to faults can potentially impact the stability of the synchronous generator in a nuclear power plant. This issue is rather well understood and beyond the scope of this project. However, the impact of voltage dips originating in the transmission grid on auxiliary equipment in the nuclear power plants is not so well discussed in the literature. This report concentrates on one specific characteristic of voltage dips, transients at the beginning and end of the voltage dip, and how that impacts the auxiliary equipment. These transients are not part of the common characterization of voltage dips and not included in the fault-ride-through requirements for generator units as for example part of the grid codes. The emphasis on voltage-dip transients in this report does however not imply that other characteristics are not of importance for the performance of the auxiliary equipment. Some of the other characteristics of voltage dips and some other voltage-quality disturbances will be briefly discussed in Chapter 2 and Chapter 6.

Previous studies performed by Luleå University of Technology on wind power installations and electric vehicle charging have shown that the simplified voltage-dip model (residual voltage and duration) is no longer sufficient to study voltage-dip immunity and fault-ride-through [28]-[34]. These studies showed, among others, that dip characteristics at transmission level can be different for faults occurring at different times of the day or year, that amplification of transients needs to be considered in the propagation to lower voltage levels, that events due to cable and transformer energizing should be included, and that there is a risk of unwanted tripping of wind turbines and protection relays in wind parks. A

phenomenon that, according to these studies, should receive specific attention is the presence of oscillations at the beginning and ending of a voltage dip due to a fault [28]. There is no existing terminology for this phenomenon. However, in this report, we will use the term “voltage-dip transients”. Its characteristics and behavior are similar to those of switching transients. Like the oscillations with switching transients [35, Section 6.3.3.3], oscillations at beginning and ending of voltage dips are in some cases amplified while propagating from the transmission system to grid-connected equipment at lower voltage levels.

The impact of events in the power grid on equipment in nuclear power stations has received attention after a few serious incidents. Studies that were initiated because of this [36]-[39] concentrated on lighting transients, temporary overvoltages, and open-phase conditions. Voltage dips are addressed in some studies, but only considering rms voltage and duration. None of the studies includes phase-to-phase faults, two-phase-to-ground faults, phase-angle jumps due to cable faults, wide-scale transformer saturation due to voltage recovery, or voltage-dip transients (oscillations at beginning or ending of a voltage dip).

The non-consideration of the detailed characteristics of the voltage dips and their propagation from the transmission to the lower voltage levels might underestimate the impact of voltage dips on auxiliary equipment in nuclear power plants. The main emphasis in this report is on voltage-dip transients.

1.6 ORGANISATION OF THIS REPORT

This report is organized as follows:

- Chapter 2 summarizes the knowledge on characteristics of voltage dips and transients. The chapter also includes a checklist to be used in the design of grid-connected equipment for which voltage-dip immunity is important.
- Chapter 3 presents measurements of voltage dips and voltage dip transients. The faults causing these dips originated, for most of the dips, at transmission level. However, the measurements were obtained at different voltage levels.
- Chapter 4 presents the results of faults simulations on a simplified version of the south-west Swedish transmission system. The voltage dips and voltage dip transients are shown in the transmission grid and at different locations in the auxiliary grid.
- Chapter 5 discusses how voltage dips and voltage-dip transients potentially impact the auxiliary equipment in a nuclear power plant.
- Chapter 6 lists and describes other power grid events apart from voltage dips and transients that can potentially impact the auxiliary equipment in nuclear power plants.
- Chapter 7 presents the findings and recommendations from the study presented in this report.
- Chapter 8 contains some concluding remarks.

2 Voltage dips, transients, and their characteristics

2.1 VOLTAGE DIPS

A voltage dip is a short-duration reduction in voltage magnitude, in most cases due to an increase in current magnitude. That increase in current magnitude can be far away from the location in the grid where the reduction in voltage magnitude, i.e., the voltage dip, is measured or experienced by grid-connected equipment. The most severe dips are due to the largest increase in current magnitude, which occurs during a fault. Other important causes of voltage dips are transformer energizing and motor starting. The latter is mainly an issue in low-voltage networks and in some medium-voltage industrial networks. Transformer energizing is mainly an issue in public grids of higher voltage levels. Voltage dips due to faults attract most attention in the literature and, for example, in discussions between public network operators and their customers.

The basic characteristics of voltage dips are well-defined in standards. According to the IEC standard on power-quality monitoring, IEC 61000-4-30 [10], a voltage dip is detected by a power-quality monitor when the one-cycle rms voltage drops below a threshold, typically equal to 90% of the nominal or pre-event voltage. Once the dip is detected, its “single-event characteristics” can be calculated, where “residual voltage” and “dip duration” are defined in IEC 61000-4-30. The definitions in IEEE 1564 [11] are equivalent to the ones in IEC 61000-4-30.

2.2 VOLTAGE-DIP CHARACTERISTICS

Several additional single-event characteristics (next to residual voltage and dip duration) are proposed in the literature, where dip type and phase-angle jump are most developed. For more details, the reader is referred to the cited references below and other literature on voltage-dip characteristics. Overviews are given in, among others, [5], [13], [25], and [35].

2.2.1 Phase-angle jump

Together with the drop in voltage magnitude, at the beginning of a voltage dip, the voltage also shows a change in phase angle: the voltage zero crossings during the voltage dip are shifted in time compared to the ones before the voltage dip. This phenomenon is referred to as “phase shift” or “phase-angle jump” [20]. The phase-angle jump is generally small (just a few degrees) for dips originating in the transmission system, but larger (up to some tens of degrees) for dips originating in the distribution system. Faults near transmission cables could also result in larger phase-angle jumps.

2.2.2 Waveform distortion

For dips due to faults, transformer saturation may occur upon fault clearing because of the sudden rise in voltage magnitude. If the fault originates at

transmission level, transformers over a large geographical area may saturate. Due to the transformer saturation, the voltage after the recovery (i.e. after fault clearing) will exhibit similar waveform distortion as during a transformer-energising dip, with substantial levels of both odd and even harmonics. The saturation, and therefore the waveform distortion, may be especially severe when the transformer is lightly loaded, for example at night.

2.2.3 Voltage-dip transients

Oscillatory transients can be associated with the beginning and ending of voltage dips (fault initiation and fault clearing, respectively). The magnitude and duration of this transient are related to the damping time constant of the grid, which normally is less than one-cycle. The amplitude of this transient has its maximum value at the maximum of the system voltage, and it may change during the propagation of the dip to the terminals of equipment connected to the grid.

For multi-phase faults (two-phase-to-ground and three-phase) the fault clearing takes place in two or three stages, resulting in a more complicated transient at the ending of the dip [43].

2.2.4 Point-on-wave

The beginning of a voltage dip (for example, the occurrence of a fault) may happen anywhere on the (50 Hz) voltage waveform. To quantify this, the term “point-on-wave” has been introduced. Fault-clearing occurs, with very few exceptions, at the current zero crossing, corresponding to a specific point-on-wave for the voltage. This point-on-wave is different for different fault locations and thus for different voltage dips. Point-on-wave of dip ending (or, point-on-wave of fault clearing) is thus also a relevant characteristic.

The point-on-wave may be defined as the phase angle of the fundamental instantaneous voltage corresponding to the instant at which the dip begins or ends. There is however no standard or commonly used definition of point-on-wave.

2.2.5 Voltage unbalance; voltage-dip type

Voltage dips due to faults can be classified in types from A to G. Type A is related to balanced (also called symmetric) dips, which means that all the phases experience the same reduction in voltage magnitude. When caused by electrical faults, type A is related to three-phase and three-phase-to-ground faults. Types B to F represent unbalanced (also called asymmetric) dips with different reduction in voltage magnitude in the different phases [5]. Although the classification into Types A to G is commonly used in the scientific literature, other terminology is used in standardization, for example Type I, II and III refer to the major voltage drop being in one, two or three phases, respectively, in IEEE 1668 [18]. Unbalanced voltage dips are caused by asymmetrical faults, such as phase-to-ground, phase-to-phase, and two-phase-to ground faults. Balanced dips do not change their type when propagating from high to low voltage levels. Unbalanced dips can change type during such a propagation according to the transformer windings connection.

2.3 CHECKLIST FOR EQUIPMENT DESIGN

A summary of voltage dip characteristics was created by an international group of experts (CIGRE/CIREN/UIE Joint Working Group C4.110) to assist equipment developers and manufacturers in making equipment less susceptible to voltage dips. As indicated in the technical brochure by the working group [13], the summary “can be used as a checklist for a fast and transparent assessment of equipment and process sensitivity to voltage dips during all stages of equipment and process design”. The checklist was created in 2010 but is sufficiently general to still be valid today.

The text below is largely based on the above-mentioned technical brochure, but adapted where needed, for example to make it more relevant for transmission systems. In the text below, reference is several times made to “phases”, this may be the phase-to-neutral, phase-to-ground, or phase-to-phase voltages. There is an obvious difference between these voltages, but the general reasoning about characteristics remains the same. In the original checklist, the term “voltage channel” is used, based on the use of that term in the IEC power-quality monitoring standard, IEC 61000-4-30 [10].

2.3.1 Pre-event segment

The pre-event segment concerns the voltage waveform and characteristics before the start of the actual dip, i.e. before the fault, motor starting, or transformer energization. The following characteristics should be considered:

- The actual or expected values of the pre-event voltage magnitudes, voltage phase angles, harmonics and other waveform distortion, voltage magnitude/phase angle unbalance and frequency.

2.3.2 During-event segments

The during-event segments cover the actual event, in case of a fault this would be from the first fault initiation to the last fault-clearing. There may be multiple during-event segments, depending also on the definition of segment.

The following characteristics should be considered during the actual dip, i.e. for each during event segment:

- **Dip magnitude.** Quantifies the reduction in voltage magnitude, usually expressed as a root mean square (rms) value of the instantaneous voltage in any of the affected phases. In IEC standardization, the term “residual voltage” is used.
- **Dip duration.** The time during which a reduction in voltage magnitude is present for each phase, or in at least one of the phases. For dips due to transformer energizing, the voltage recovers gradually, and it is not possible to uniquely define a dip duration.
- **Dip shape.** Dips with the constant during-event rms voltage magnitude are referred to as “rectangular dips”, while non-rectangular dips have variable rms voltage magnitude. Non-rectangular dips may be due to impact of generation

or consumption on the voltage during the fault or due to post-fault transformer saturation.

- **Dip voltage magnitude unbalance.** In case of unsymmetrical faults (single-phase and two-phase faults) and in case of transformer energizing, voltage magnitudes in different phases are different.
- **Phase-angle jump.** The change in voltage magnitudes during a dip is often associated with a change in the corresponding voltage phase angles. This is referred to as the phase-angle jump. In case of unsymmetrical faults, phases with different voltage magnitudes will typically have different changes in phase angle. Events have been reported where a significant phase-angle jump occurred without a noticeable change in voltage magnitude. These could be due to the loss of a major transmission line or a major generation unit.
- **Phase angle unbalance.** For dips with different voltage magnitudes in the different phases, the during-dip voltages will also experience unbalance in phase angle.
- **Waveform distortion and transients.** Dips due to transformer energising are associated with a high level of harmonic distortion, while some dips have high-frequency transients imposed on the fundamental component of the during-dip instantaneous voltage. Transformer energizing results in both odd and even harmonics; their impact is however most noticeable for even harmonics as those levels are normally very low.

2.3.3 Transition segments

The term “transition segment” refers to the transition between two different levels of the voltage magnitude and/or voltage phase angle. The most common examples of transition segments are the ones associated with fault initiation and fault clearing. The term was originally introduced as part of automatic analysis of voltage dips [40]-[41]. Additional transition segments occur for developing faults and for faults that are cleared by circuit breakers at different locations [42].

The following characteristics should be considered for transition segments:

- **Dip initiation.** The first transition segment marks the instant of dip initiation (i.e. the transition from pre-dip voltage to during-dip voltage), manifested as a sudden drop in voltage magnitude at the start of the dip.
- **Point-on-wave of dip initiation.** Phase angle of the instantaneous pre-dip voltage waveform at which the transition from pre-dip voltage to during-dip voltage occurs.
- **Multistage dip initiation.** At the dip initiation, the drop in voltage magnitude in a phase may take place in several steps due to e.g. developing faults. The corresponding multiple stages may occur at a sub-cycle time scale, or at time scales up to seconds.
- **Dip ending.** The last transition segment marks the instant at which the underlying cause of the dip is cleared, manifested as a sudden voltage rise. It is followed by a voltage recovery segment. For dips due to transformer energizing, there is no such dip-ending transition segment; instead, the voltage recovers gradually.

- **Point-on-wave of dip ending.** Phase angle of the post-dip instantaneous voltage waveform at which the transition from during-dip voltage to post-dip voltage occurs.
- **Multistage dip ending.** The voltage magnitude rise at the ending of a dip due to a fault may take place in several steps due to e.g. difference in circuit breaker opening instants in different phases [43], or at different network locations. The corresponding multiple stages may occur at a sub-cycle time scale, or at a time scale of up to one second.
- **Damped oscillations.** Transition segments are often associated with damped oscillations, whose frequency of oscillation and damping time constant depend on the location/type of the fault and characteristics of system load and generation.

2.3.4 Voltage-recovery segment

The voltage-recovery segment starts with the last transition segment and does not have a defined ending. With dips due to faults, the voltage-recovery segment starts with the last fault clearing; with dips due to transformer energizing, the voltage-recovery segment normally starts with the energizing instant; voltage dips due to transformer energizing do normally not have any event segments.

The following characteristics should be considered during the voltage-recovery segment:

- **Voltage recovery.** During the voltage recovery segment after a fault, the voltages are usually balanced and with close to nominal magnitude, but they may show a gradual trend towards their new steady state values.
- **Post-fault dip (prolonged voltage recovery).** After the initial cause of the dip (e.g. short circuit fault) has been cleared and after the affected voltages already experienced main rise in magnitudes, the voltage magnitudes in some phases may still be significantly below their pre-event values. This part of the voltage recovery segment is sometimes referred to as a post-fault dip.
- **Post-dip phase shift.** Phase angle difference between the steady state pre-dip and post-dip voltages. Typically occurs when a (faulted) part of the network is disconnected to clear the underlying cause of the dip, resulting in a change in system impedances.

2.3.5 Multiple dip events and composite dip events

As mentioned already a few times in the previous subsections, voltage dips due to faults can contain multiple event segments; next to that, even more complicated events may occur. The two types of such events are briefly discussed below.

Multiple dip events occur within a short period of time, ranging from less than one second up to one minute. Examples include successive dips due to adverse weather (e.g. lightning storms), or dips due to automatic reclosing actions after the occurrence of a short circuit fault.

In case of polyphase events, voltage dips in some of the phases are accompanied by interruptions and/or swells in the other phases.

Multiple dip events and polyphase events may impact equipment in a different way than the individual events.

2.4 TRANSIENTS

Transients, either voltage or current transients, are short-duration power-quality events. They occur only occasionally and are a major deviation from the ideal or normal voltage waveform. There is no standard upper limit for the maximum duration of a transient, but typically either half a cycle (10 ms) or one cycle (20 ms) is used.

The main sources of transients are lightning strokes and switching actions. Different types of switching actions cause different types of voltage transients. The most common severe switching transients are due to switching of capacitances, either capacitor banks or long AC cables. Such transients show a damped oscillation where the oscillation frequency depends on the size of the capacitance and the inductance of the grid at the location of the switched capacitance.

The length at which an AC cable should be considered a long cable, in this context, depends on the voltage level, on the short-circuit capacity, and on the number of cable circuits in parallel. For transmission voltages, any cable longer than a few kilometres should be considered as long and a potential source of switching transients. This is further discussed in Section 6.6.

Non-synchronized energizing of capacitor banks or cables results in more severe transients than synchronized energizing. Non-synchronized energizing of a capacitor bank at transmission-level results in an oscillation with a frequency in the range 300 to 1000 Hz [44]-[45]. For synchronized switching, the magnitude of the transient is significantly lower, but resonances may still result in serious magnitudes of the oscillations at lower voltage levels or elsewhere in the transmission grid.

Switching of long AC cables can result in lower oscillation frequencies [46]-[48], where values as low as 100 Hz have been reported as part of expansion planning [49]-[50]. Like with capacitor banks, synchronized switching can be used for energizing of long AC cables; this will significantly reduce the magnitude of the oscillations in the switching transients. However, synchronization errors and amplification at lower voltage levels or elsewhere in the transmission grid may still result in amplitudes that could cause unwanted equipment tripping. Synchronization is not possible with fault clearing, which always occurs at the voltage zero crossing. Resonances close to low-order harmonics, together with transformer saturation upon fault clearing, can result in increased levels of harmonic distortion and so-called “temporary overvoltages” [51, 52].

The switching of a cable and/or a capacitor bank, when other cables are located nearby will result in a back-to-back energizing transient. During such a transient, high overvoltage can occur, which can be further amplified by resonances [53, 54].

An important distinction is made by Allan Greenwood [55] between “normal switching transients” and “abnormal switching transients”. The latter are less common and are often associated with higher instantaneous voltage levels. The

distinction originated from the study of circuit breakers and switches but is of importance for power quality (i.e. at the terminals of grid-connected equipment) as well. Examples of abnormal switching transients are “current chopping”, “restrike during capacitor deenergizing”, “restrike during inductor deenergizing”, and ferroresonance [35, Section 6.3.4].

There is no standard or commonly used method for the detection or characterization of voltage or current transients, although many power-quality monitors include such a function. Attempts were made to start a discussion on such characteristics within an IEEE working group, but they have not resulted in a proposal for a standard method.

An early work on switching transients is the book by Reinhold Rüdenberg [56, 57]. A more modern classical work on switching transients is the one by Allan Greenwood [55], which was written strongly from a circuit-breaker perspective; knowledge on switching transients was important for the dimensioning of circuit breakers. More recent books include [58], [59] and [60], all of them still very much written from the perspective of the circuit breaking.

There is limited literature on the propagation of switching transients, on the way they impact grid-connected equipment, on characterization of switching transients, or on any of the measurement issues related to transients. The impact of capacitor energizing transients on electrical drives was briefly on the agenda around 1990 [61]-[66].

An important phenomenon, also reported in some of the publications referred to in the previous paragraph, is the amplification of the oscillation’s magnitude at lower voltage levels. If the resonant frequency at the higher voltage level (where the capacitor or cable is being energized) is similar to the one at the lower voltage level (where equipment is connected to the grid), the relative magnitude of the oscillations at the lower voltage level can be higher than at the higher voltage level [67]-[69].

2.5 VOLTAGE DIP STATISTICS

2.5.1 Magnitude and duration

The magnitude of a voltage dip due to a fault is influenced by the fault type, fault resistance, distance from the sensitive installation, short circuit power, and grid topology. The duration is determined by the operation time of the protection. For instance, if a fault is in the first protection zone, the voltage dips typically last less than 100 ms. The duration will be longer if the backup protection or other protection zones are activated.

When the dip propagates to lower voltage levels, the dip type and magnitude can be influenced by the transformer winding connection. Also, the residual voltage generally increases when the dip propagates to lower voltage levels.

The number of voltage dips also depends on the system earthing and on whether the phase-to-neutral or the phase-to-phase voltages are used.

Information on the number of voltage dips, as a function of magnitude (residual voltage) and duration, can be obtained from measurement campaigns (statistical methods) and from calculations together with information on fault statistics (stochastic methods) [5, Chapter 6; 35, Chapter 5]. Most of the available information has been obtained from measurement campaigns, where one of the overall conclusions is that the number of voltage dips is very strongly location dependent.

2.5.2 Statistics for transmission systems

One way of presenting voltage-dip statistics is through a scatter diagram, where each dot represents the residual voltage and duration of a voltage dip. An example is shown in Figure 1 ([35], Section 10.4); the scatter plot in the figure shows the results from four years of monitoring at six different 400-kV substations within a distance of a few hundred kilometres from each other, somewhere in Europe. Most of the voltage dips have durations below 200 ms and the number of dips increases with increasing residual voltage; voltage dips with residual voltage above 90% were not recorded by the monitoring system.

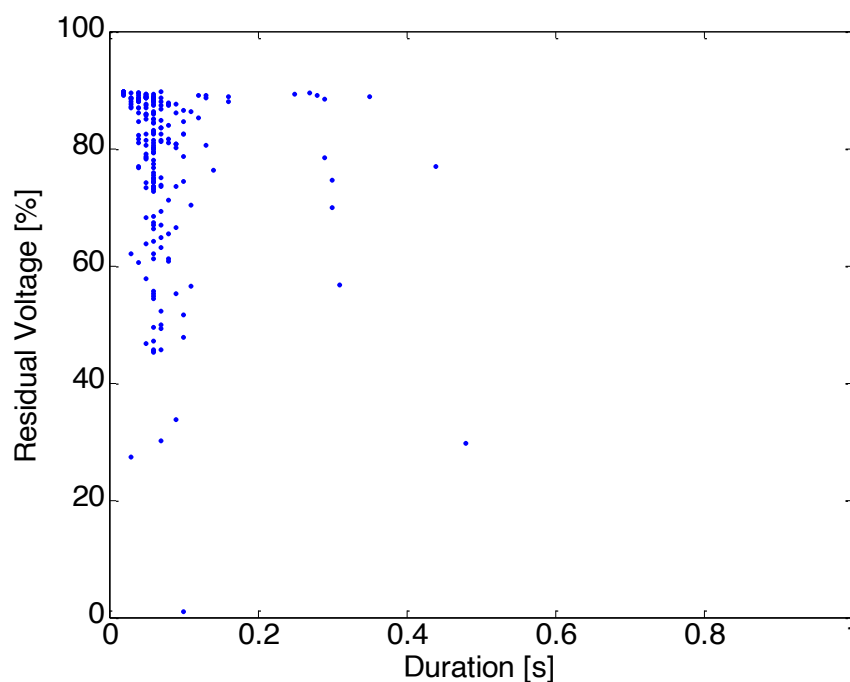


Figure 1. Scatter plot for four measurement locations, at 400 kV, during six years of measurements [35].

Of relevance for important equipment, like the auxiliary equipment in nuclear power stations, are not so much the statistics but the extreme events. Extreme events in this example include the voltage dip with residual voltage close to zero and the one with duration around 450 ms and residual voltage around 30%.

Statistics on voltage dips in the Finnish 110-kV grid are presented in [70]; measurements were performed of the phase-to-neutral voltages. The relatively high number of long and shallow dips may be related to the system earthing in the Finnish 110-kV grid.

Table 1. Annual average number of voltage dips measured in the Finnish 110 kV grid for different residual voltage and duration [70]

Residual voltage	Dip duration				
	<20 ms	20 – 100 ms	0.1 – 0.5 s	0.5 – 1 s	1 – 5 s
85 – 90 %	30	15	5	5	1
70 – 85%	20	20	5	5	1
40 – 70%	10	10	5	2	1
1 – 40%	5	5	1	1	0

Voltage dips statistics for the Finnish 110-kV grid were obtained by calculation of residual voltage from fault statistics over the period 1980 through 2000, the dip duration was obtained from protection settings [71]. The results are shown in Table 2 for the 95%-site and in Table 3 for the 50%-site.

Table 2. Average number of voltage dips for the 95%-site in the Finnish 110-kV grid, obtained from fault statistics over the period 1980 through 2000 [71].

Residual voltage	Dip duration							
	<20 ms	20 – 100 ms	0.1 – 0.5 s	0.5 – 1 s	1 – 3 s	3 – 20 s	20 – 60 s	60 – 180 s
85 – 90 %								
70 – 85%								
40 – 70%			2					
20 – 40%			8					
10 – 20%			18	9				

Table 3. Average number of voltage dips for the 50%-site in the Finnish 110-kV grid, obtained from fault statistics over the period 1980 through 2000 [71].

Residual voltage	Dip duration							
	<20 ms	20 – 100 ms	0.1 – 0.5 s	0.5 – 1 s	1 – 3 s	3 – 20 s	20 – 60 s	60 – 180 s
85 – 90 %								
70 – 85%								
40 – 70%			1					
20 – 40%			4					
10 – 20%			16	8				

The results from monitoring at transmission level (EHV, extra high voltage, i.e. 200 kV and above) are presented in a CIGRE report from 2004 [72]. Some of the data presented in that report are reproduced below. The results in Table 4 are obtained by monitoring six locations at 400 kV for one year each.

Table 4. Average number of voltage dips, during one year of measurement, for six locations at 400 kV [72].

Residual voltage	Dip duration							
	<20 ms	20 – 100 ms	0.1 – 0.5 s	0.5 – 1 s	1 – 3 s	3 – 20 s	20 – 60 s	60 – 180 s
85 – 90 %	6	30	3	1				
70 – 85%	1	36	6					
40 – 70%		12	3					
10 – 40%		1.5			0.7			
<10%					0.5			

The results shown in Table 5 are obtained from 28 locations at 110 kV, 220 kV and 400 kV, during about two years of monitoring per location. The data shown is for the 95th percentile, most likely the site with the highest number of voltage dips. Statistics for the median (50th percentile) location are shown in Table 6.

Table 5. Number of voltage dips per year, for the worst among 28 locations [72].

Residual voltage	Dip duration							
	<20 ms	20 – 100 ms	0.1 – 0.5 s	0.5 – 1 s	1 – 3 s	3 – 20 s	20 – 60 s	60 – 180 s
85 – 90 %		10	6					
70 – 85%		7	16	1				
40 – 70%		7	5	1				
10 – 40%			1					
<10%								

Table 6. Number of voltage dips per year, for the median among 28 locations [72].

Residual voltage	Dip duration							
	<20 ms	20 – 100 ms	0.1 – 0.5 s	0.5 – 1 s	1 – 3 s	3 – 20 s	20 – 60 s	60 – 180 s
85 – 90 %		3	1	1				
70 – 85%		4	8					
40 – 70%		3	2					
10 – 40%			1					
<10%		1						

The results in Table 7 and Table 8 are obtained from nine locations at 275 kV during one year of monitoring.

Table 7. Number of voltage dips per year, 95th percentile per bin over 9 locations [72].

Residual voltage	Dip duration							
	<20 ms	20 – 100 ms	0.1 – 0.5 s	0.5 – 1 s	1 – 3 s	3 – 20 s	20 – 60 s	60 – 180 s
85 – 90 %		46	9	1	2			
70 – 85%		93	9	3				
40 – 70%		33	3					
10 – 40%		9		4	1			
<10%		6	5		1			

Table 8. Number of voltage dips per year, 50th percentile per bin over 9 locations [72].

Residual voltage	Dip duration							
	<20 ms	20 – 100 ms	0.1 – 0.5 s	0.5 – 1 s	1 – 3 s	3 – 20 s	20 – 60 s	60 – 180 s
85 – 90 %		10	1					
70 – 85%		32	3	1				
40 – 70%		13						
10 – 40%		1						
<10%								

Voltage-dip statistics for a few European countries are presented in the 7th benchmarking report by the Council for European Energy Regulators [73]. Most of the data is for public distribution networks or merged over all voltage levels. Some data is however specific for transmission networks; this data is reproduced below.

Data for the Irish transmission system is shown in Table 9; no dips were reported with residual voltage below 80% or with duration longer than 500 ms.

Table 9. Voltage-dip statistics for the transmission network in Ireland [73].

	80 – 90%; 10 – 200 ms	80 – 90%; 200 – 500 ms
2018	35	3
2017	55	0
2016	31	3
2015	35	3

Average number of voltage dips per location per year, for Kosovo over 2018, are shown in Table 10. Statistics for Portugal are shown in Table 11.

Table 10. Voltage-dip statistics for Kosovo over 2018 [73].

Residual voltage	Dip duration				
	10 – 200 ms	0.2 – 0.5 s	0.5 – 1 s	1 – 5 s	5 – 60 s
80 – 90 %	2				
70 – 80%	1				
40 – 70%					
5 – 40%					
< 5%					

Table 11. Voltage-dip statistics for Portugal over 2015 through 2018 [73].

Residual voltage	Dip duration				
	10 – 200 ms	0.2 – 0.5 s	0.5 – 1 s	1 – 5 s	5 – 60 s
80 – 90 %	45.1	1.6	0.8	0.3	0.02
70 – 80%	16.3	0.3	0.1	0.1	0
40 – 70%	18.4	0.3	0.1	0.06	0.02
5 – 40%	2.3	0.1	0.02	0.04	0.003
< 5%	0.1	0.01	0.05	0.01	0

2.5.3 Interpretation and applicability of voltage-dip statistics

The previous section (Section 2.5.2) showed statistics on the number of voltage dips for locations in transmission systems. There is limited publicly-available information on voltage-dip statistics in transmission systems. Many transmission system operators have power-quality monitors available, but data is typically not available for those outside of the company and statistics are rarely published.

From the available statistics, including other data not published here (for example in [35, Chapter 10]) and from theoretical insight in the relation between voltage

dips and faults, among others the following conclusions can be drawn concerning voltage-dip statistics.

- Most voltage dips are shallow (high residual voltage; small voltage drop) and/or short duration. Voltage dips that are both long and deep are rare.
- The number of voltage dips per location per year varies between different transmission systems.
- The number of voltage dips per year varies between different locations.
- The number of voltage dips at one location varies from year to year.

When voltage-dip statistics for a specific location are needed, for example to define immunity requirements for equipment in an industrial installation, the recommendation is to use local measurements over a longer period or (when such data is not available) to use simulations based on fault statistics.

The immunity requirements depend on the voltage-dip statistics and on the consequences of equipment not being immune. For some of the auxiliary equipment in a nuclear power station, the consequences of equipment tripping or damage can be very severe. Such equipment should be immune even to rare events, which are difficult to obtain from monitoring; monitoring will also not give insight in changes in voltage-dip statistics due to changes in the network.

All the statistics shown in the previous section considered residual voltage and dip duration only. No statistical data is available on other characteristics of voltage dips at transmission systems.

3 Measured voltage dips

3.1 PROPAGATION FROM 130 kV TO 10 kV AND 400 V

Figure 2 exemplifies the dip propagation through measurements at different voltage levels in transmission and distribution systems. The subfigure top-left shows a voltage dip type A measured at 130 kV somewhere in Sweden, not far from a bigger city. The subfigure top-right shows the dip, recorded at the same time, in the 10 kV network in the city. The 10-kV network consists almost exclusively of underground cables. The subfigures below show the dip at two different locations at 400 V. This event occurred on 20 August 2000 and was, according to the network operator, caused by a three-phase fault due to a lightning stroke to a 130-kV line.

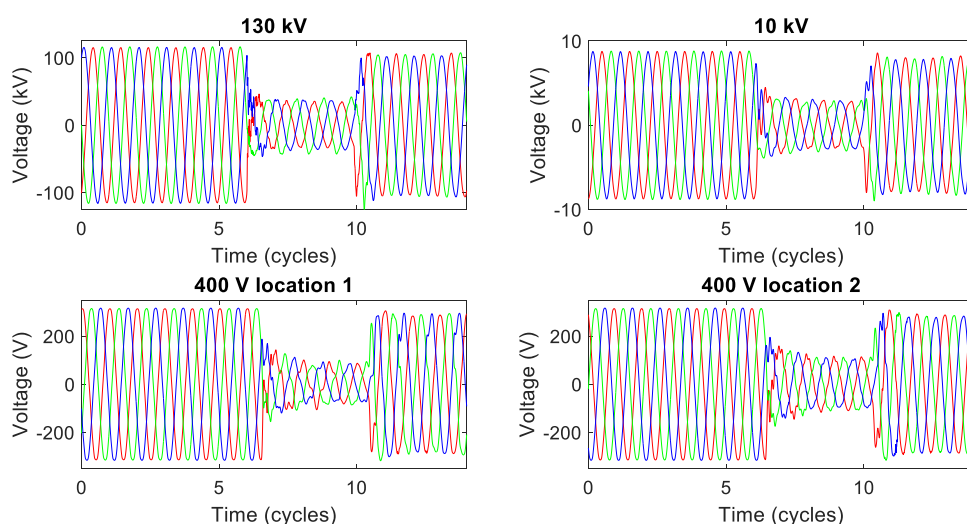


Figure 2. Measurements at four locations of the voltage dip due to a three-phase fault at 130 kV: measurement at 130 kV (top ← left), at 10 kV (top right →), at 400 V (bottom ← left), and at another 400 V location (bottom right →).

The figure shows some of the common characteristics of voltage dips, where the “actual dip” (the short-duration reduction in voltage magnitude) is the most obvious one. The duration of the reduction in voltage magnitude is in this case about 80 ms (four cycles), which is a very common duration for voltage dips.

There are also some other characteristics, which are not normally quantified, but which may have an impact on grid-connected equipment exposed to the dip.

- Oscillations are visible at the beginning of the voltage dip; more about those later.
- During the dip, the voltage is more distorted than before the dip. This is especially noticeable at 400 V location 1 (bottom left).
- The voltage magnitude remains about constant during the dip at the 130-kV location, whereas the magnitude goes down somewhat during the dip at the other locations. This is especially noticeable at the two 400-V locations.
- Oscillations are visible with voltage recovery; this will again be discussed later.

- The voltage recovery is not complete; the voltage magnitude immediately after dip ending is somewhat lower than the voltage magnitude before the dip.
- The voltage is unbalanced after voltage recovery.
- The voltage after recovery is distorted at 400 V location 1.

Details of the oscillations at the beginning of the dip, for the same four locations, are shown in Figure 3. A voltage-dip transient is visible at all four locations, but the shape of the transient is different. The transient at 130 kV contains more higher frequencies than the ones at the other locations. Also, the damping is different at different locations. Mathematical tools exist to quantify these transients and to better describe their differences; examples are the digital Fourier transform, the spectrogram, wavelets, and ESPRIT [35]. Further discussion of those mathematical tools is beyond the scope of this report.

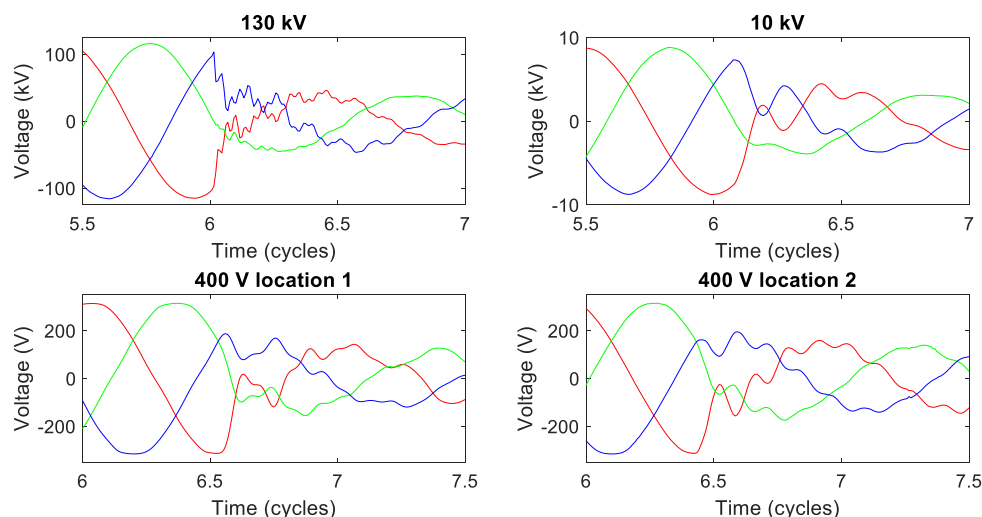


Figure 3. Voltage dip transients at the start of the voltage dip; measurements at four locations due to the same three-phase fault.

Details of the voltage-dip transient at voltage recovery, for the four locations, are shown in Figure 4. Like with the transient at the beginning of the dip, oscillations are present at all four locations and again with different shapes. A comparison with Figure 3 shows that the waveshapes at beginning and ending of the dip are not the same.

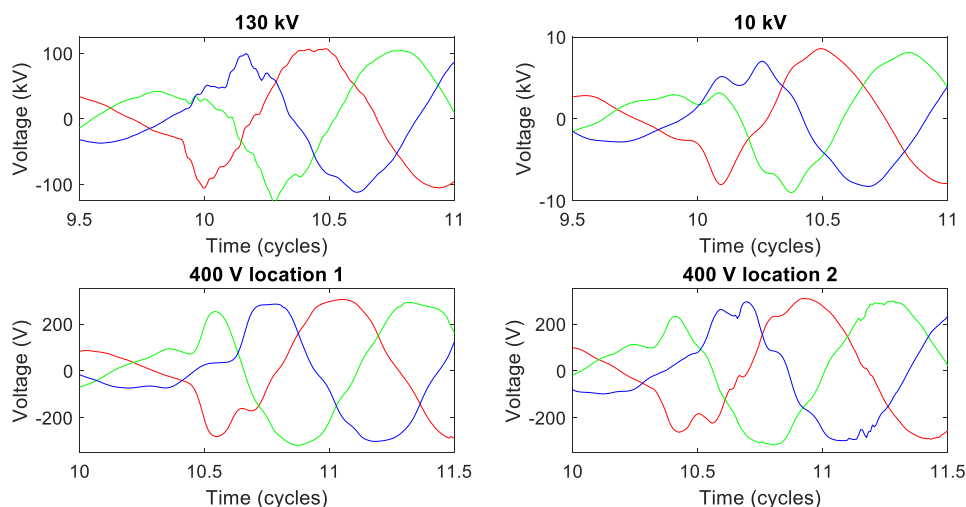


Figure 4. Voltage dip transients at the ending of the voltage dip; measurements at four locations due to the same three-phase fault.

The voltage-dip transients, at beginning and ending of the dip, due to a single-phase fault in the 400-kV grid are shown in Figure 5. The event was measured at three of the four locations from the event in the previous figures but occurred at a different instant due to another fault. The waveform of the transients is different than in the previous figures and generally less severe. Like before, the three locations show different waveforms for the voltage-dip transients.

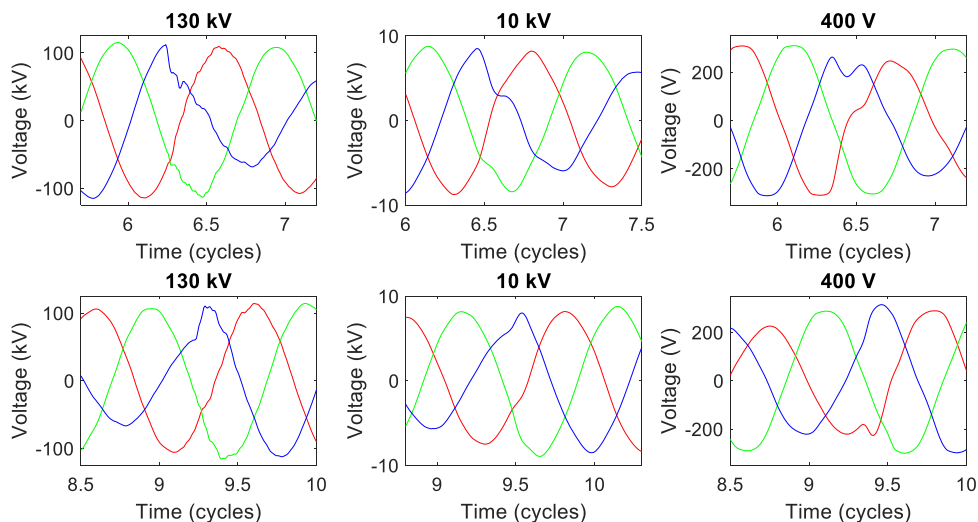


Figure 5. Voltage dip transients at the beginning (top row) and ending (bottom row) of the voltage dip; measurements at three locations due to the same single-phase fault.

3.2 MEASUREMENTS AT 130 KV

Several recordings of voltage-dip transients are shown in the forthcoming figures. All voltage-dip transients were recorded at the same 130-kV location as in the previous section, but at different instants and due to different faults. The faults that resulted in the dips occurred either at 130 kV or at 400 kV.

Different voltage-dip transients are shown in Figure 6, Figure 7, and Figure 8; some at the beginning of a dip and others the ending of a dip. Event 1 and Event 2 are the ones shown in Section 3.1, hence the first one in Figure 6 being Event 3. With some of the transients, the oscillations appear only in one or two of the phases, whereas they appear in all three phases for other events. The amplitude and shape of the transients also differ for different dips.

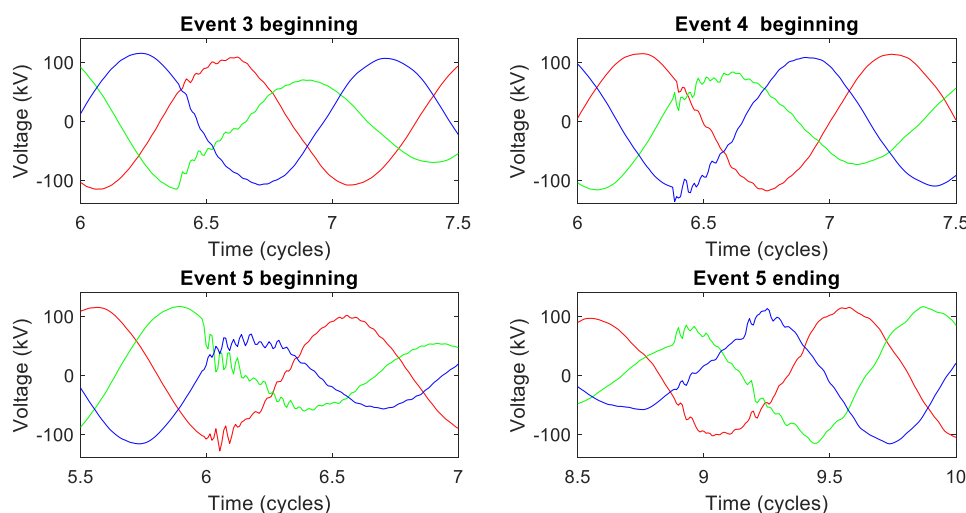


Figure 6. Voltage-dip transients with three different dips, all recorded at the same 130-kV location.

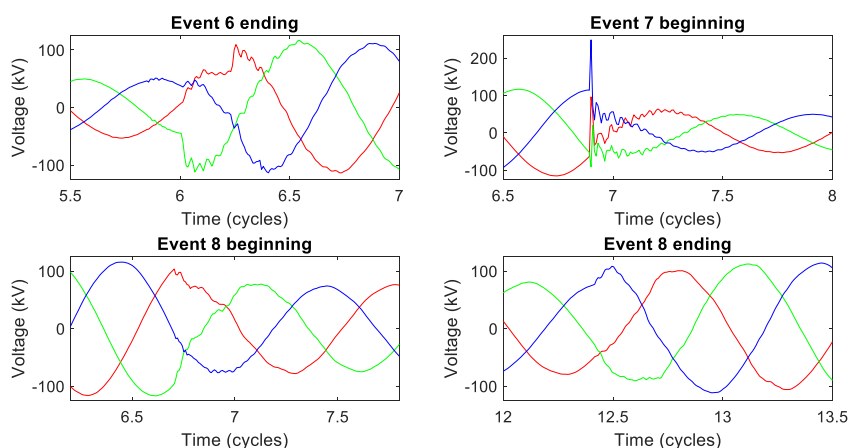


Figure 7. Voltage-dip transients with three different dips, all recorded at the same 130-kV location.

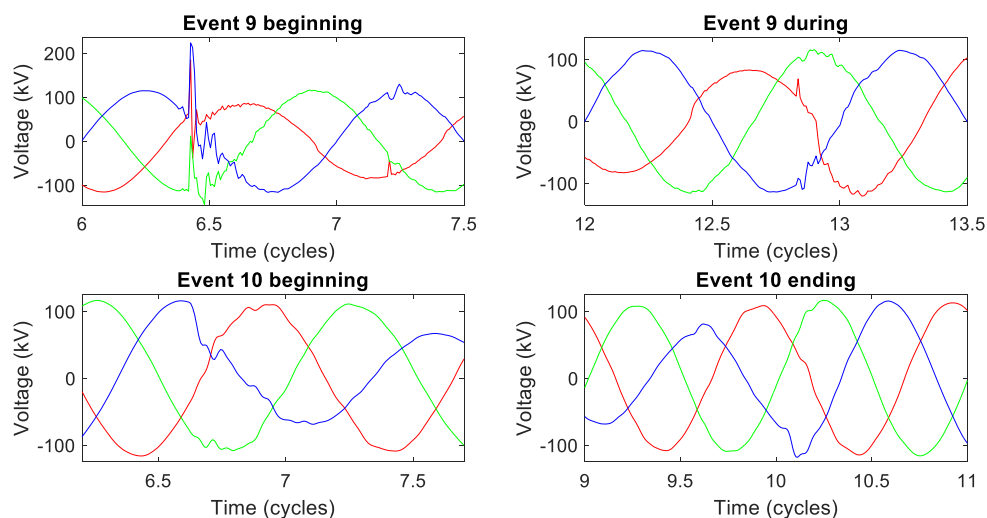


Figure 8. Voltage-dip transients with two different dips, both recorded at the same 130-kV location.

Event 7 and Event 9 show some characteristics different from other voltage dips. Both show an impulsive transient followed by an oscillatory transient at the beginning of the dip. In both cases, the impulsive transient is visible in all three phases but about twice as high in the blue phase as in the two other phases. The origin of this impulsive transient is unknown. Event 9 further shows oscillations during the actual dip.

With some voltage dips, the ending occurs in two or three stages. This is visible with Event 5 and Event 10. Because of the multi-stage recovery, the transients are different for such events.

An overall conclusion, already from this small set of voltage dip recordings, is that there are big differences in the voltage-dip transients for dips due to different faults and for dips due the same fault at different locations.

3.3 MEASUREMENTS OF VOLTAGE DIPS IN NUCLEAR POWER PLANTS

Figure 9, Figure 10, and Figure 11 show measurements of a voltage dip that was recorded on 7 June 2022 with a nuclear power station. One nuclear unit was in operation and its auxiliary supply was fed from the 400 kV-grid; the other unit was not in operation and the auxiliary supply was fed from the 130 kV grid. The recordings in Figure 9 and Figure 10 were obtained at the same voltage level inside of the auxiliary supply, but for different units: Figure 9 with the unit that was in operation; Figure 10 with the unit that was not in operation. The measurement shown in Figure 11 refers to voltage recordings from the generator at its 20 kV busbar.

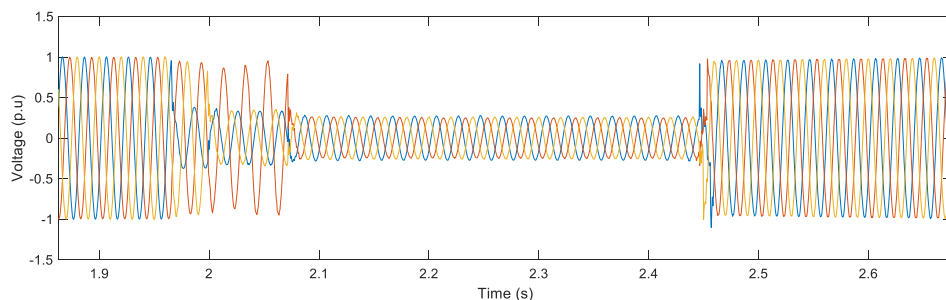


Figure 9. Recorded voltage dip: point-of-connection of the auxiliary supply; synchronous generator not in operation.

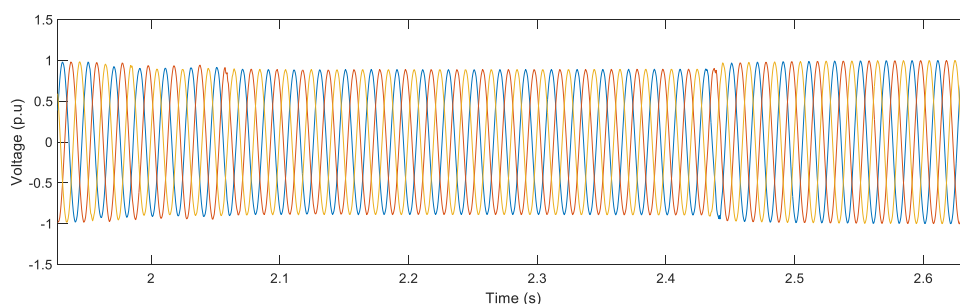


Figure 10. Recorded voltage dip: point-of-connection of the auxiliary supply; synchronous generator in operation.

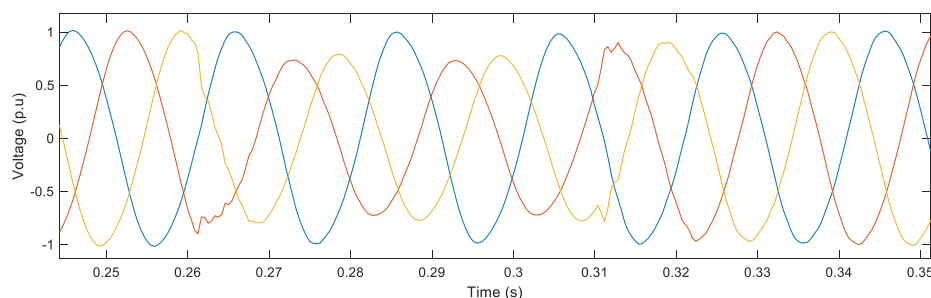


Figure 11. Recorded voltage dip: 20 kV generator bus.

Although the voltage dips in Figure 9 and Figure 10 originate from the same event, their characteristics are very different based on whether the generation unit is in operation or not. The different stages of the fault leading to the voltage dip are prominently visible in Figure 9; it starts as a single-phase fault lasting for about two cycles; followed by a phase-to-phase fault lasting for about three cycles; and a three-phase fault lasting for about eighteen cycles. The lowest voltage magnitude for the voltage dip in Figure 9 is about 40% and occurs during the three-phase fault. For the generation unit in operation (Figure 10), the multiple stages are less visible, and the voltage dip is shallow when compared to Figure 9.

A measurement at 400 kV, at the switchyard near a nuclear power station, is shown in Figure 12. The three-phase fault that resulted in this dip, was due to lighting. The dip was measured at the 400-kV switchyard and in the medium-voltage auxiliary network. The latter one is not shown here, as the recording only contained the rms voltages.

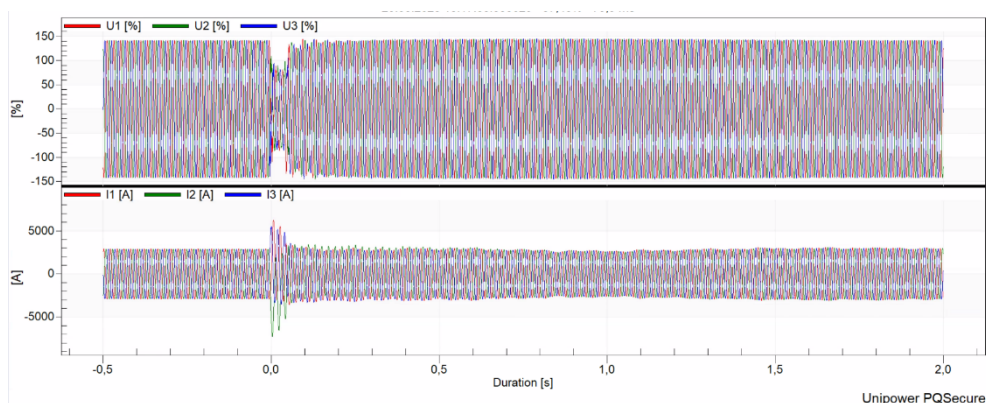


Figure 12. Voltage dip due to a three-phase fault measured at 400 kV close to a nuclear power station.

3.4 VOLTAGE-DIP TRANSIENTS AT LOWER VOLTAGE LEVELS

Some measurements of voltage-dip transients in the low-voltage network were already shown before. In this section some more recordings will be shown.

Figure 13 and Figure 14 show voltage-dip measurements at the terminals of a PV installation in Northern Sweden. Figure 13 shows the dip for a symmetrical (three-phase) fault; Figure 14 for a non-symmetrical fault. Voltage-dip transients are present at the beginning and at the ending of the dip, for both cases. The dip due to the three-phase fault also shows voltage distortion after voltage recovery. The shape of the voltage in the green phase points to high levels of even harmonics, due to transformer saturation upon voltage recovery. That dip also shows a transient during the dip, about one cycle before the voltage recovery.

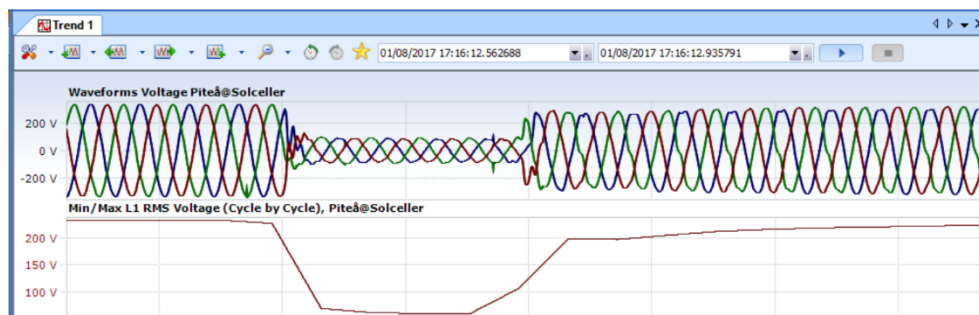


Figure 13. Voltage dip due to a three-phase fault at the terminals of a PV installation.

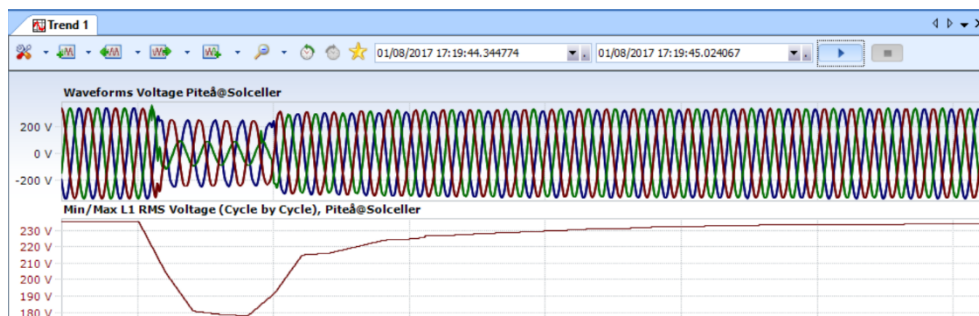


Figure 14. Voltage dip due to a non-symmetrical fault at the terminals of a PV installation.

Figure 15 shows a voltage dip that was recorded recently (17 October 2024) on the low-voltage side of a distribution transformer supplying part of the offices at the university campus in Skellefteå. Oscillations are also here visible at the beginning and ending of the voltage dip. The oscillations are more prominent in the current at the start of the dip.

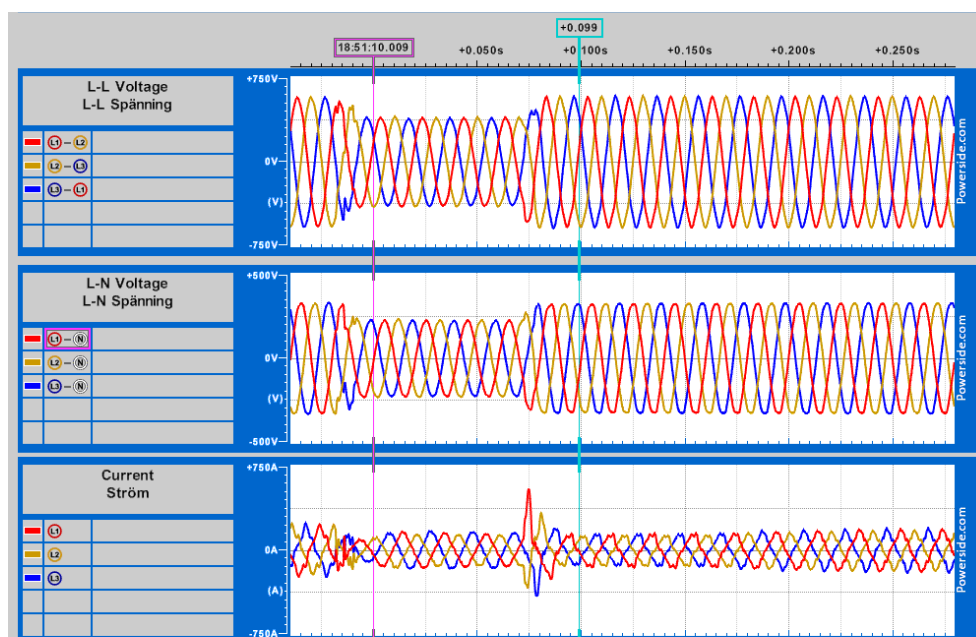


Figure 15. Voltage dip at the LV side of a transformer supplying a few office buildings: phase-to-phase voltages (top); phase-to-neutral voltages (middle); currents (bottom).

3.5 FAULT TYPES FOR ALL AND FOR SEVERE DIPS

Most faults in transmission systems are single-phase-to-ground faults, with two-phase and three-phase faults being a minority. A study done recently by Eindhoven University of Technology [74] obtained information on the number of faults for all dips and for severe dips, in relation to the fault type. Severe dips were in this study defined as dips with:

- Duration up to 200 ms and residual voltage less than 40 %
- Duration between 200 ms and 500 ms and residual voltage less than 70 %
- Duration more than 500 ms and residual voltage less than 80 %.

For all dips, 40 % were due to single-phase faults, 10 % due to two-phase faults, and 2 % due to three-phase faults. Considering severe dips, the ones that are expected to have a high risk of equipment tripping, only 4 % were due to single-phase faults, 68 % due to two-phase faults, and 20 % due to three-phase faults. The sum of the percentages is less than 100 %, especially for the non-severe faults. The remaining dips were not associated with recorded faults within the country; they may have been due to faults in neighboring countries.

4 Simulation of voltage dips and voltage-dip transients

4.1 MODELS, CASES, AND RESULTS PRESENTED

4.1.1 Model of the transmission system

The model of the transmission system used for the simulations is presented in Figure 16; a simplified model of the west-coast transmission system is used here. The effect of different transmission-system loading conditions, details of the line and substation configuration, and other operational and system details has been outside of the scope of the project.

This simplified system has been modelled in DigSilent PowerFactory. The nuclear-power station modelled consists of four units (GEN1, GEN2, GEN3 and GEN4). Units GEN3 and GEN4 are out of operation for all cases; GEN2 is in operation for all cases; both cases with GEN1 on and with GEN1 off have been studied. Voltage dips have been calculated at substation A and substation C for faults between substation A and substation B. The lengths of the overhead lines or cables at 400 kV are also indicated in the figure.

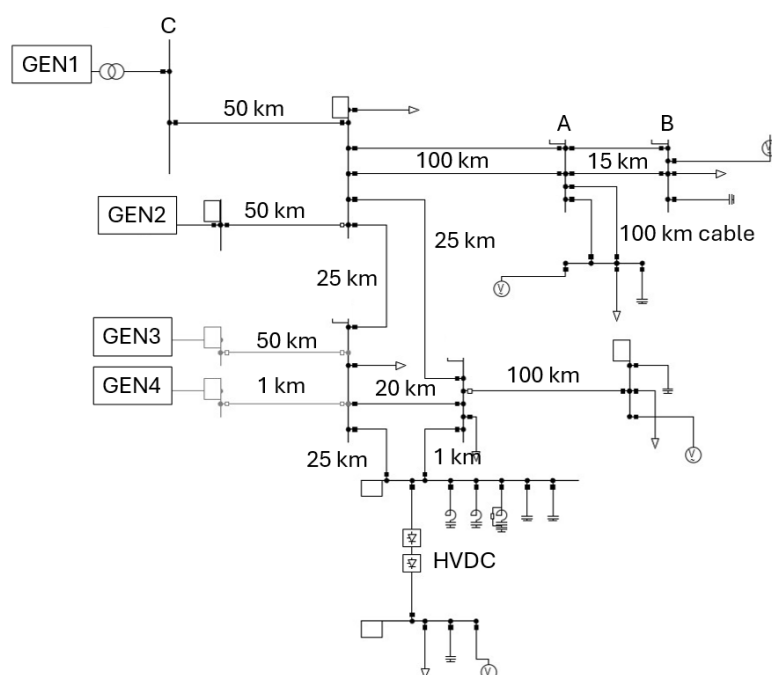


Figure 16. The transmission-grid modelled.

4.1.2 Model of the nuclear power station

The internal grid of the nuclear power station, supplying the auxiliary equipment, is shown in Figure 17. Generic simulation models and data have been used with corresponding limits in the results for the accuracy compared with the transients as

they will occur and propagate in the actual installation. The generator (“GEN1”) is the same one as in Figure 16. The internal grid consists of three voltage levels: 22 kV, 6 kV and 525 V. Voltage-dip waveforms are shown for the indicated 22 kV and 6 kV busses.

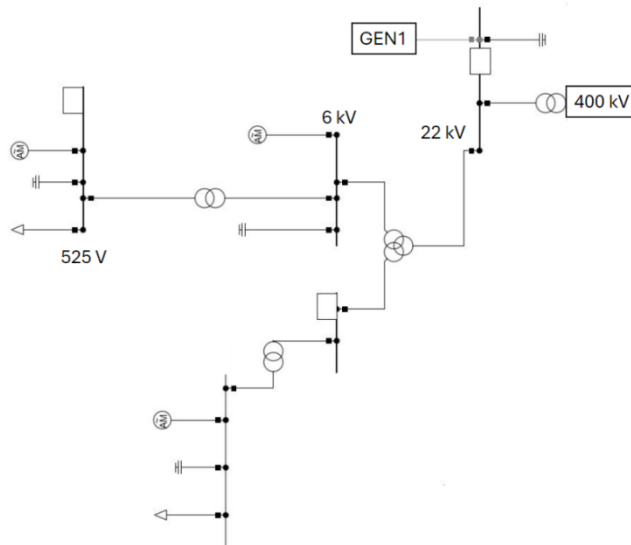


Figure 17. The internal grid of the nuclear power station.

4.1.3 Cases studied

The main results presented in the forthcoming sections are for a fault halfway between substation A and substation B in Figure 16. The fault occurs, in all cases, at time 2.0 s and is cleared at time 2.1 s; the fault-clearing time is 100 ms. The fault occurs at the maximum voltage in one of the faulted phases, for each of the cases studied.

The voltage dips shown in the different figures are obtained at two locations in the 400 kV grid and three locations in the internal grid of the nuclear power station.

- 400-kV substation A in Figure 16, at the terminals of the faulted line.
- 400-kV substation C in Figure 16, close to the nuclear power station.
- The 22-kV bus, indicated in Figure 17, part of the auxiliary grid of the nuclear power station.
- The 6-kV bus, indicated in Figure 17, part of the auxiliary grid of the nuclear power station.
- The 525-V bus, indicated in Figure 17, part of the auxiliary grid of the nuclear power station.

The simulations have been performed for two cases: the nuclear power generator (GEN1 in Figure 16 and Figure 17) in operation and the nuclear power generator out of operation. The auxiliary equipment is in operation for both cases.

Four fault-types have been studied: single-phase-to-ground fault; phase-to-phase fault; two-phase-to-ground fault; and three-phase-to-ground fault.

The results of these two base cases are presented in four separate sections. The voltage dips at the two transmission substations are shown in Section 4.2 when the generator is in operation, and in Section 4.3 when the generator is not in operation. The voltage dips at the two locations in the auxiliary grid are shown in Section 4.4 when the generator is not in operation and in Section 4.5 when the generator is in operation.

A comparison of the voltage-dip transients for different fault types and the two cases (generator on and generator off) is presented in Section 4.6. A comparison is made for each of the four locations.

The results of a small sensitivity analysis are presented in Section 4.7. The sensitivity analysis has been performed for a three-phase-to-ground fault, as this fault type showed the most severe voltage-dip transients. The voltage-dip transients are shown in Section 4.7.1 for four different fault locations along the line. The voltage-dip transients are shown in Section 4.7.2 for the case where the faulted line is replaced with a cable. The voltage-dip transients are shown in Section 4.7.3 for the case where there is an additional line in parallel with the faulted line.

A brief discussion on the propagation of transients from impedance-earthed systems to other voltage levels is presented in Section 4.8.

Section 4.9 contains a general discussion of the results and their interpretation.

4.1.4 Results presented

For each of the cases, each of the voltage-dip locations, and each of the fault types, the following results are shown:

- The complete voltage-dip waveform from about two cycles before fault initiation up to about two cycles after fault clearing.
- The waveform of the voltage-dip transient at the beginning of the dip.
- The waveform of the voltage-dip transient at the ending of the dip.
- The spectrogram of the voltage in phase A (between phase A and neutral) before, during, and after the voltage dip.

The spectrogram is a method for showing details of events in which there are both changes with frequency and changes with time. The spectrogram shows the intensity of the frequency components versus time, where a color scale is used: dark blue is the lowest intensity (typically close to zero for the spectrograms shown in this report); orange is the highest intensity; light blue, green, and yellow are intensities in between; a color scale is shown with each spectrogram. Consider as an example, the spectrogram shown on the right-hand side (→) in Figure 21. The frequency component between 200 Hz and 250 Hz has high intensity at the beginning of the dip (2.01 to 2.02 s) and at the ending of the dip (2.11 to 2.12 s).

4.2 TRANSMISSION SYSTEM – GENERATOR ON

In this section, the results are presented for the four different fault types at two substations in the transmission system when the generator is on.

4.2.1 Single-phase-to-ground fault

The voltage dips, at the two 400-kV substations, due to a single-phase-to-ground fault, are shown in Figure 18. The dips are similar at the two locations: with a drop in voltage magnitude in one phase (the faulted phase) and a small rise in voltage magnitude for the two non-faulted phases.

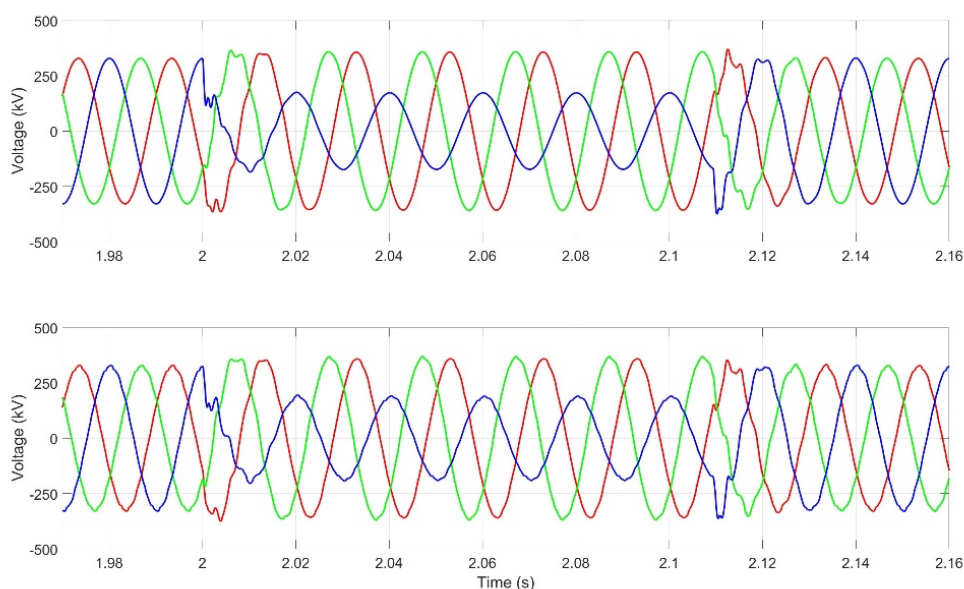


Figure 18. Voltage dip due to single-phase-to-ground fault when the generator is on, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station.

Details of the voltage dip transients are shown in Figure 19 and Figure 20 for voltage-dip beginning and voltage-dip ending, respectively. Oscillations are present, at beginning and ending, for both locations, in all three phases. For the voltage-dip transient at dip ending, some overshoot occurs. The peak voltage is 114% of nominal peak voltage at the terminals of the faulted line, and 110% of nominal peak voltage near the nuclear power station. The oscillations at the beginning of the dip disappear in about one half-cycle and in about one cycle at the ending of the dip.

The spectrogram covering the whole voltage dip is shown in Figure 21. The broadband emission at beginning and ending of the dip corresponds to the sharp steps in voltage in time domain. Next to this, narrowband emission is visible with both beginning and ending of the dip. This narrowband emission corresponds to the oscillations that are visible in time domain (Figure 18, Figure 19, and Figure 20). The spectrogram in Figure 21 shows that the transient at dip ending contains different frequency components than the one at dip starting. The spectrogram also shows that the oscillations are stronger near the nuclear power station (right-hand figure) than in the terminals of the faulted line (left-hand figure).

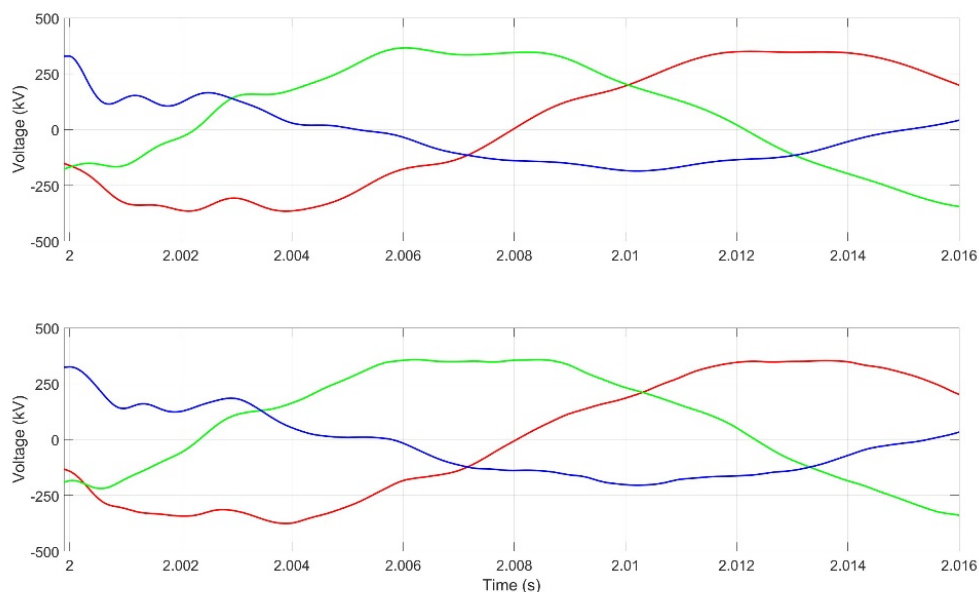


Figure 19. Voltage-dip transient at the beginning of the dip due to single-phase-to-ground fault when the generator is on, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station.

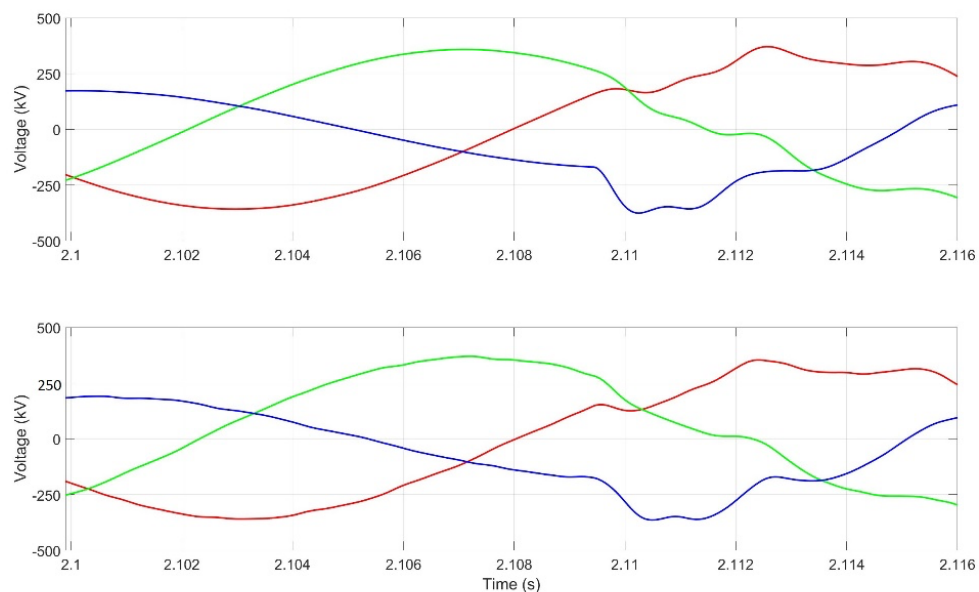


Figure 20. Voltage-dip transient at voltage recovery due to single-phase-to-ground fault when the generator is on, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station.

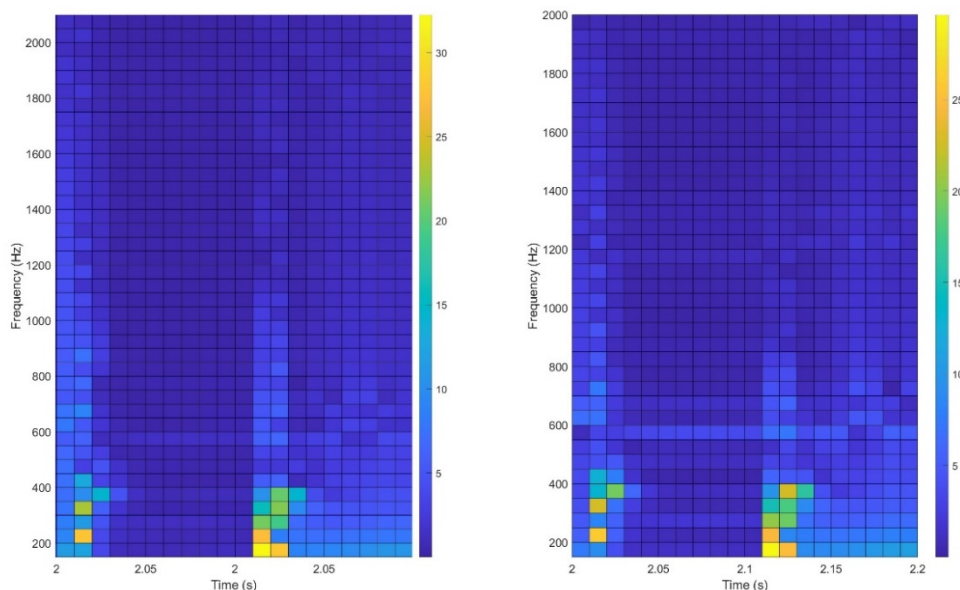


Figure 21. Spectrogram analysis for start and recovery of the voltage dip due to single-phase-to-ground fault when the generator is on, at the terminals of the faulted line (← left) and at the 400-kV substation close to the nuclear power station (right →)

4.2.2 Phase-to-phase faults

The results for a phase-to-phase fault are shown in Figure 22 through Figure 25. Figure 22 shows the complete waveform of the voltage dip; a drop in voltage magnitude is visible in the two faulted phases; the magnitude of the non-faulted phase is not noticeably affected. The voltage close to the nuclear-power station shows minor waveform distortion before the dip; during the dip, the waveform distortion increases in the faulted phases.

Figure 23 shows details of the voltage-dip transient at the beginning of the dip. The oscillations take place between the two faulted phases; also here, the non-faulted phase is not affected. The oscillations are lower in magnitude near the nuclear power station.

Figure 24 shows details of the voltage-dip transient at the ending of the dip. The oscillations again take place in the faulted phases only; and their amplitude is again less near the nuclear power station.

Figure 25 shows the spectrogram at the two locations, again with clear differences between the locations and between the beginning and ending of the dip. The spectrogram for the location close to the nuclear-power station (right-hand plot) shows a constant waveform distortion during the actual dip and higher distortion after voltage-dip ending.

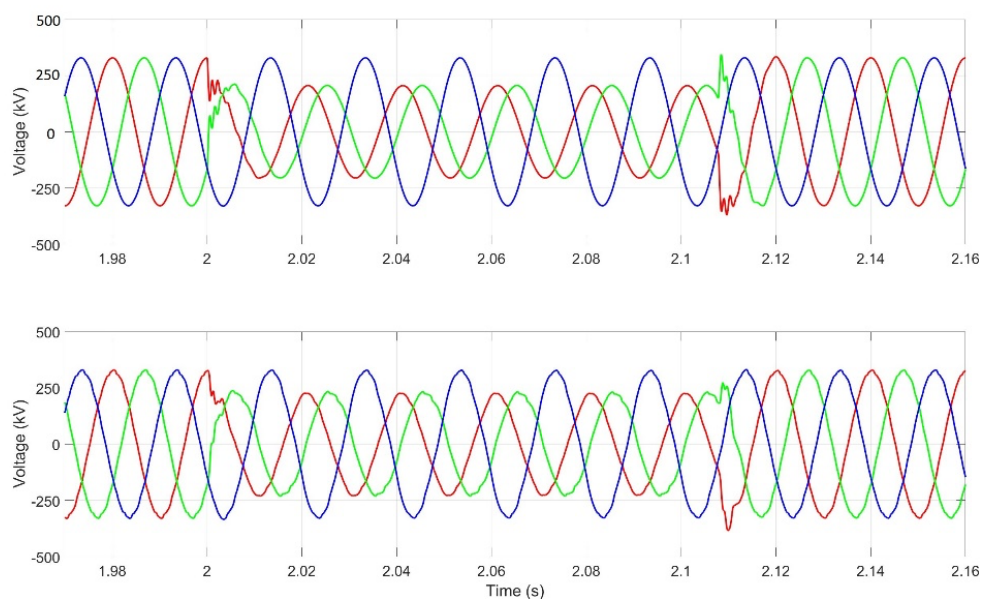


Figure 22. Voltage dip due to phase-to-phase fault when the generator is on, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station.

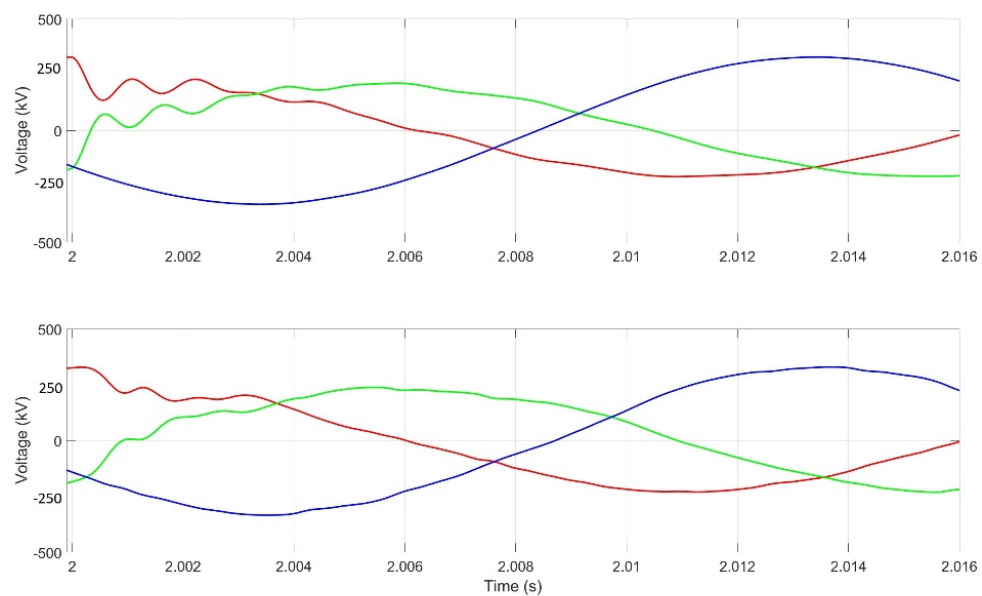


Figure 23. Voltage-dip transient at the beginning of the dip due to a phase-to-phase fault when the generator is on, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station.

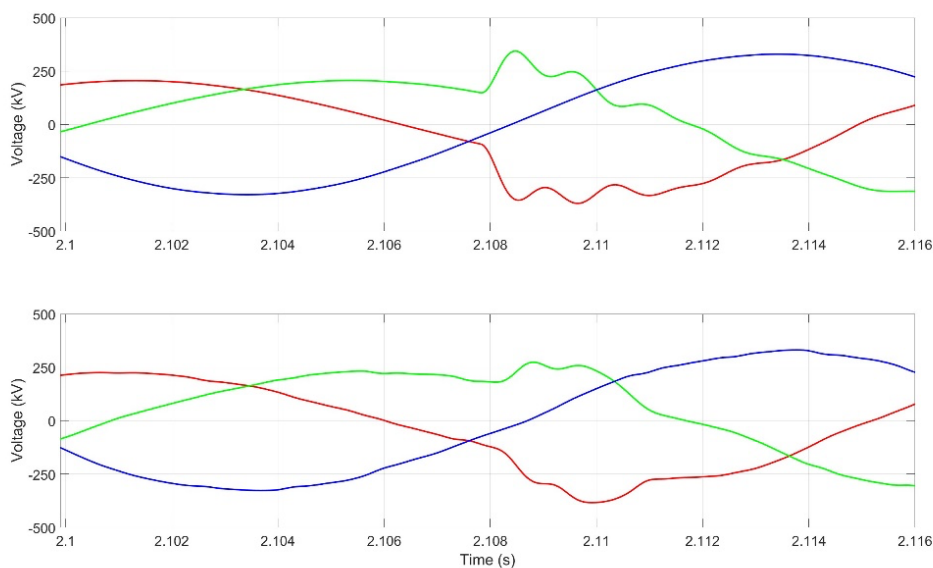


Figure 24. Voltage-dip transient at voltage recovery due to phase-to-phase fault when the generator is on, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station

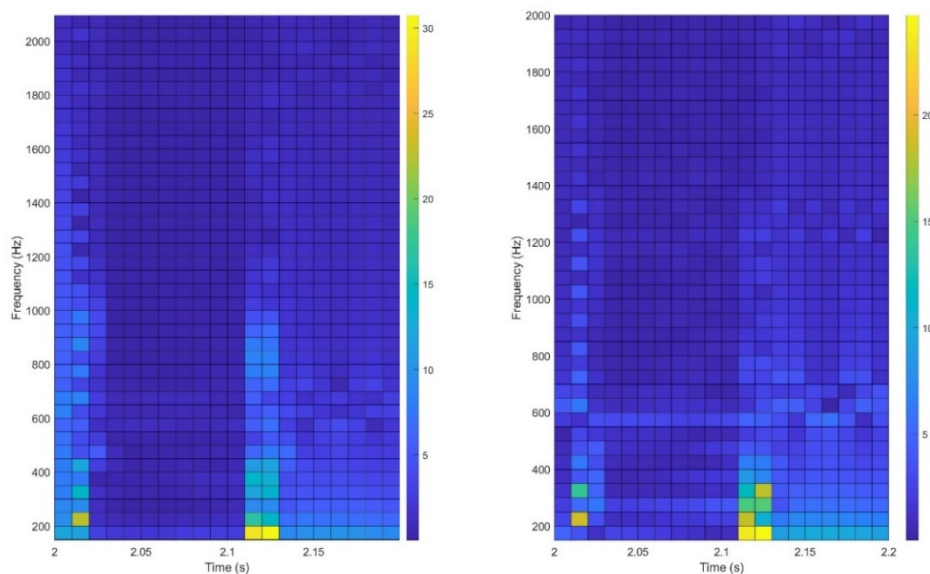


Figure 25. Spectrogram analysis for start and recovery of the voltage dip due to phase-to-phase fault when the generator is on, at the terminals of the faulted line (← left) and at the 400-kV substation close to the nuclear power station (right →).

4.2.3 Two-phase-to-ground faults

The results for a two-phase-to-ground fault are shown in Figure 26 through Figure 29. Figure 26 shows the complete voltage-dip waveform. The voltage magnitude drops in the two faulted phases and shows a minor increase in the non-faulted phase.

Figure 27 shows the voltage-dip transient at the beginning of the dip. The oscillations in the faulted phases are like the ones for the phase-to-phase fault; for the two-phase-to-ground fault, there are some minor oscillations present in the non-faulted phase.

Figure 28 shows the voltage-dip transient at the ending of the dip; oscillations are present in all three phases. The plot also clearly shows that the voltage recovery takes place in two stages, as the fault clearing takes place at different instants in the two faulted phases. The oscillations are different, but of similar amplitude, at the two locations.

Figure 29 shows the spectrogram. The transients at beginning and ending of the voltage dip again show different frequency components. The transient at voltage-dip ending is more severe at the terminals of the faulted line.

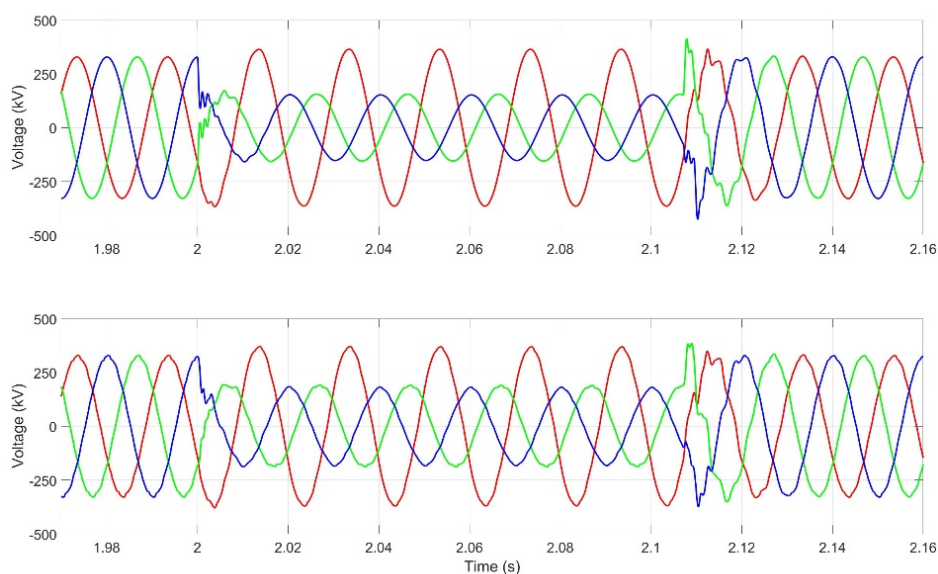


Figure 26. Voltage dip due to two phase-to-ground fault when the generator is on, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station

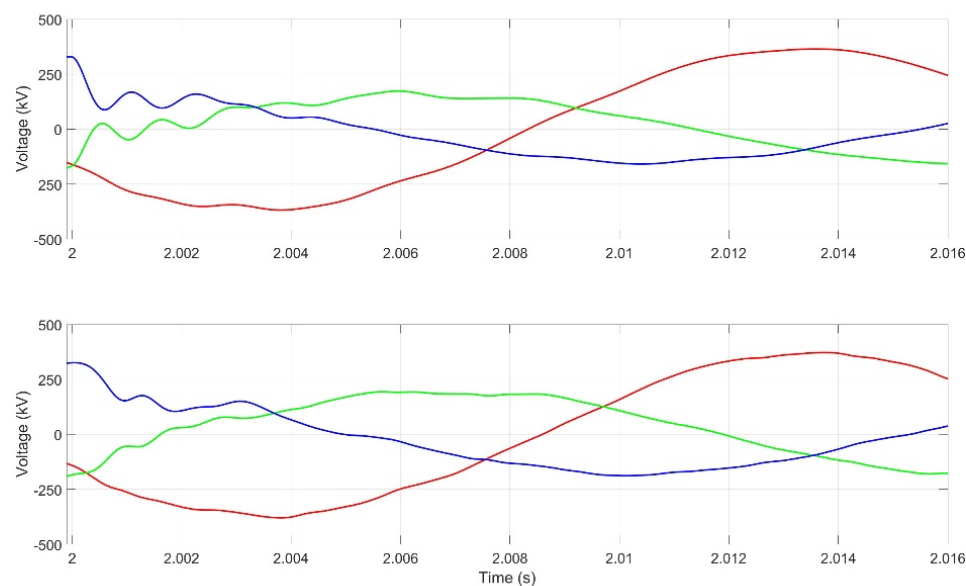


Figure 27. Voltage-dip transient at the beginning of the due to a two phase-to-ground fault when the generator is on, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station.

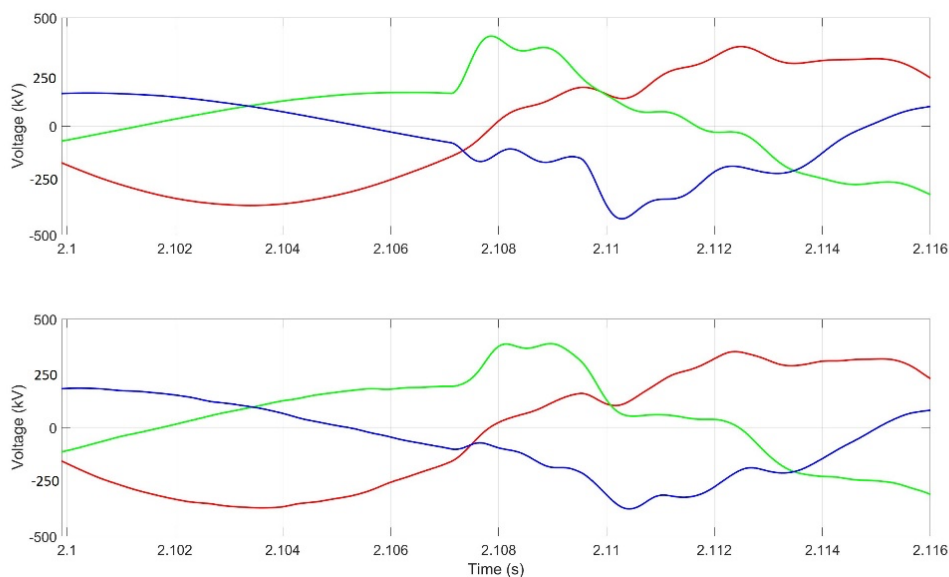


Figure 28. Voltage-dip transient at voltage recovery due to a two phase-to-ground fault when the generator is on, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station.

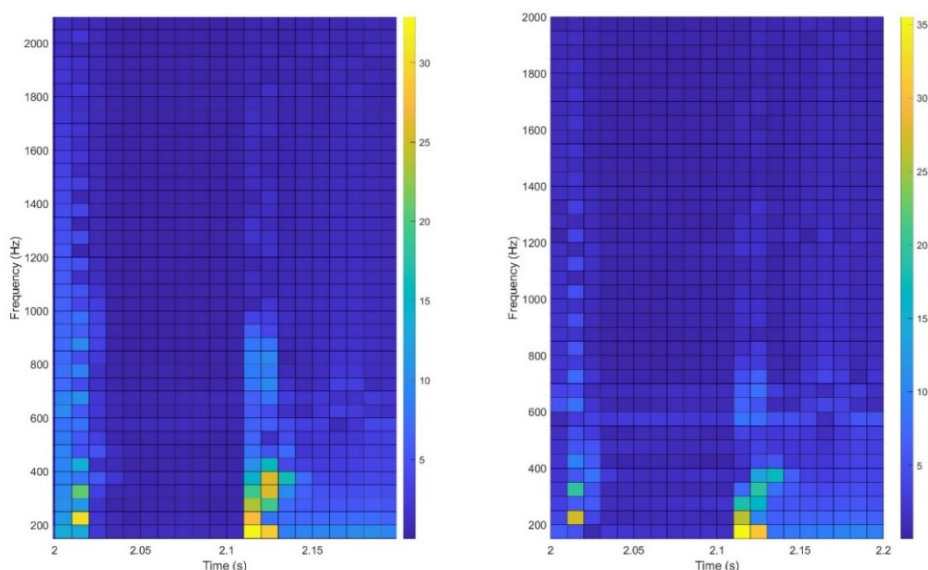


Figure 29. Spectrogram analysis for start and recovery of the voltage dip due to a two phase-to-ground fault when the generator is on, at the terminals of the fault line (← left) and at the 400-kV substation close to the nuclear power station (right →).

4.2.4 Three-phase faults

The results for a three-phase-to-ground fault are shown in Figure 30 through Figure 33. Figure 30 shows the complete voltage-dip waveform; the voltage magnitude shows the same drop in all three phases. Figure 31 shows the voltage-dip transient at the beginning of the dip; oscillations are present in all three phases and of similar amplitude. Figure 32 shows the voltage-dip transient at the ending of the dip; the oscillations occur in all three phases and are also here of similar amplitude. The oscillations at the ending of the dip last longer than those at the beginning of the dip. The voltage recovers in three stages for this dip; this is always

the case for a three-phase-to-ground fault. For a three-phase fault without ground connection, the voltage recovers in two stages and the voltage-dip transient at dip ending will be different.

Figure 33 shows the spectrogram; the overall shapes look similar to the ones for the two-phase-to-ground fault, as was shown in Figure 29.

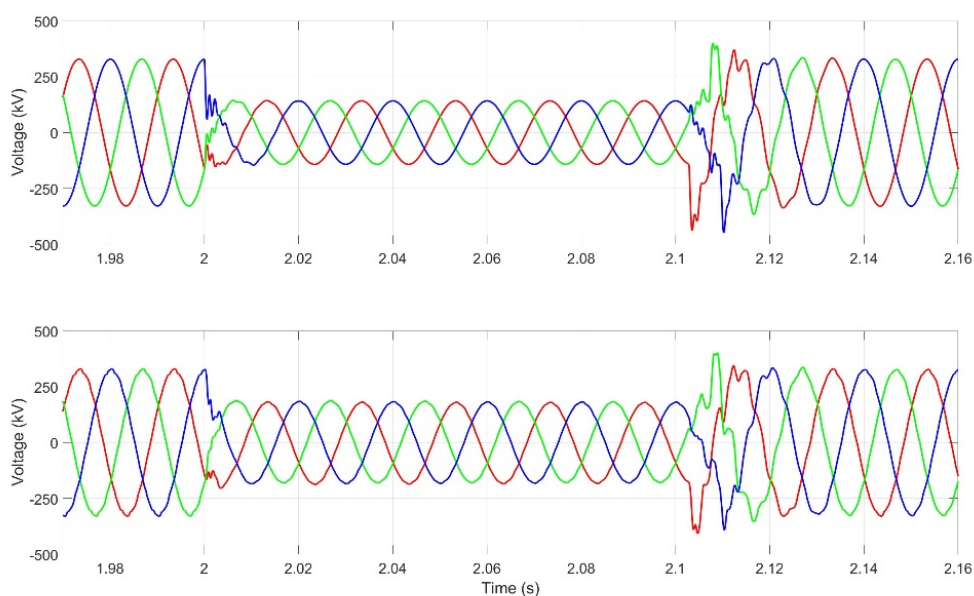


Figure 30. Voltage dip due to three-phase fault when the generator is on, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station.

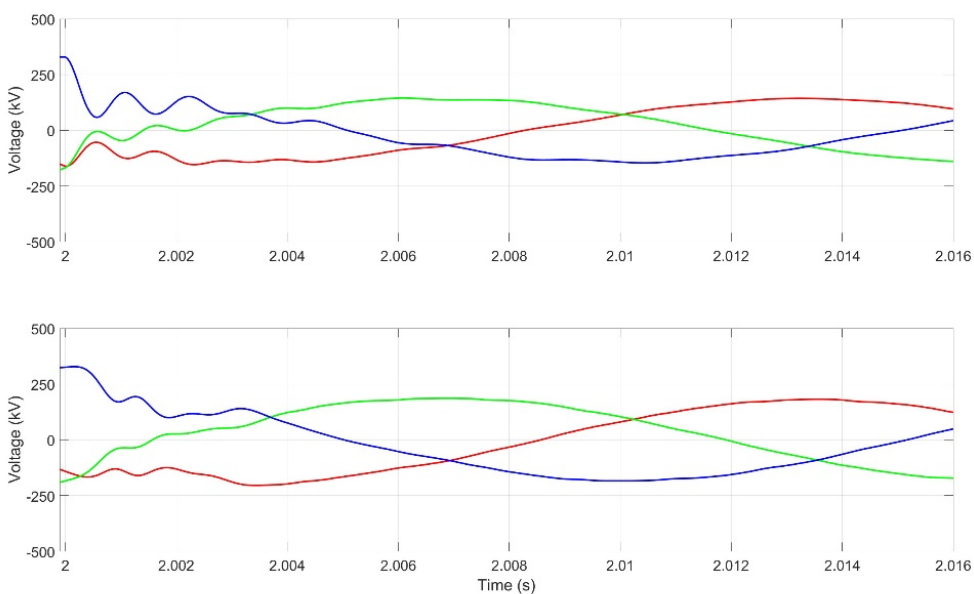


Figure 31. Voltage-dip transient at the beginning of the dip due to three-phase fault when the generator is on, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station.

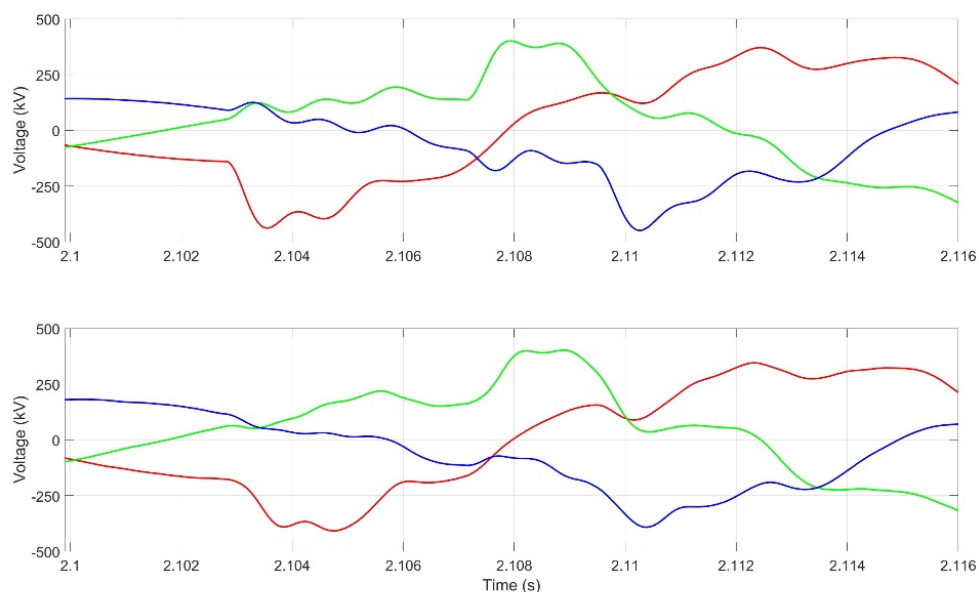


Figure 32. Voltage-dip transient at dip ending due to three-phase fault when the generator is on, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station.

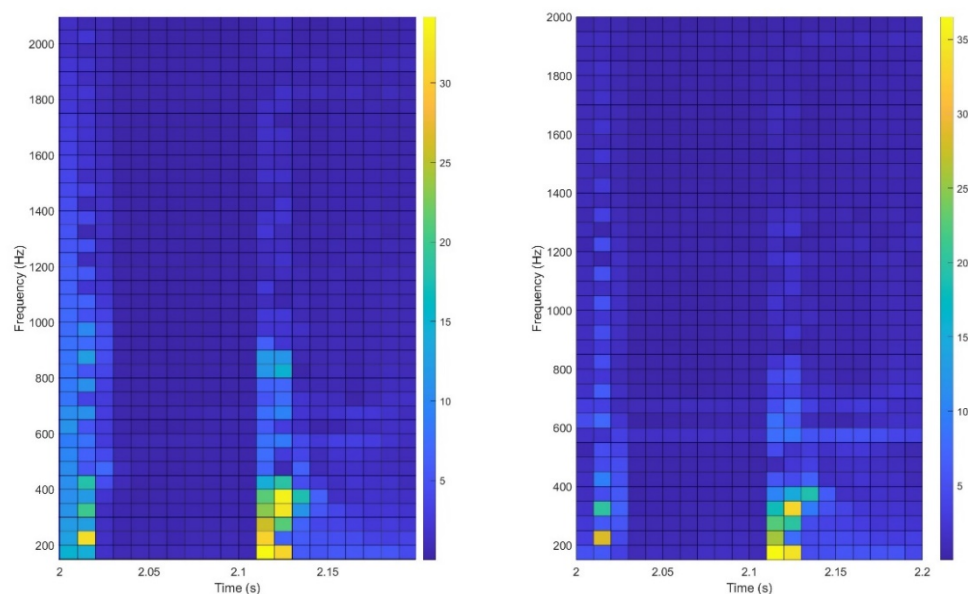


Figure 33. Spectrogram analysis for start and recovery of the voltage dip due to three-phase fault when the generator is on, at the terminal of fault line (← left) and at the 400-kV substation close to the nuclear power station (right →).

4.3 TRANSMISSION SYSTEM – GENERATOR OFF

The results for the case with the nuclear-power station not in operation (“generator off”) are presented in the forthcoming sections. The waveforms are similar to the ones for the case with generator on, shown in the previous section. The results are shown here without further comments.

4.3.1 Single-phase-to-ground fault

The results for a single-phase-to-ground fault are shown in Figure 34 through Figure 37.

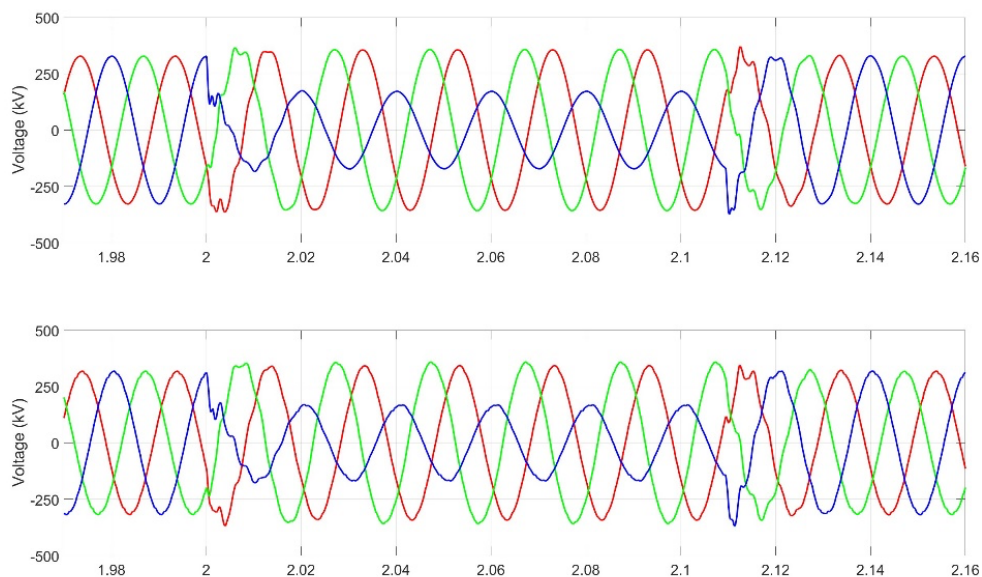


Figure 34. Voltage dip due to a single-phase-to-ground fault, when the generator is off, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station.

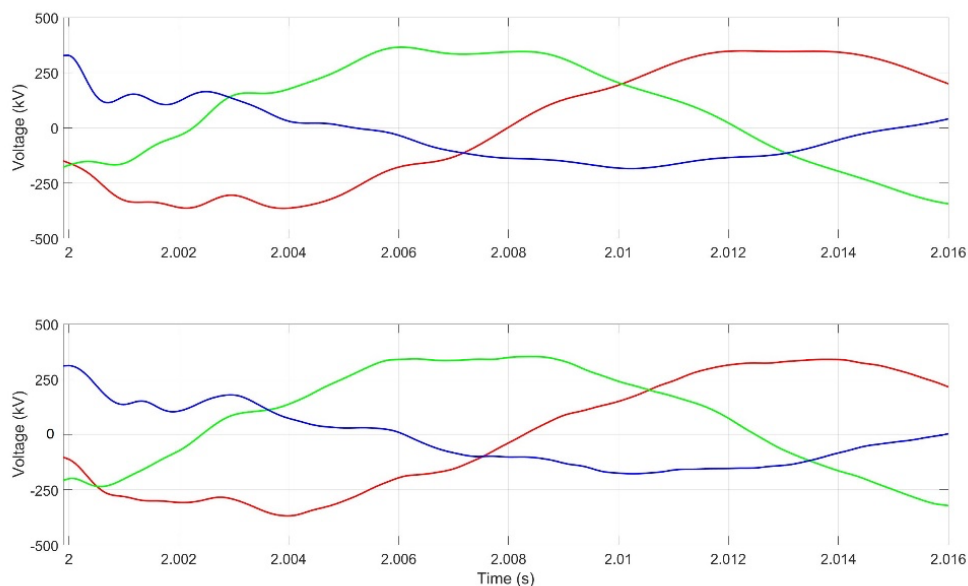


Figure 35. Voltage dip transient at the beginning of the dip due to a single-phase-to-ground fault, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station.

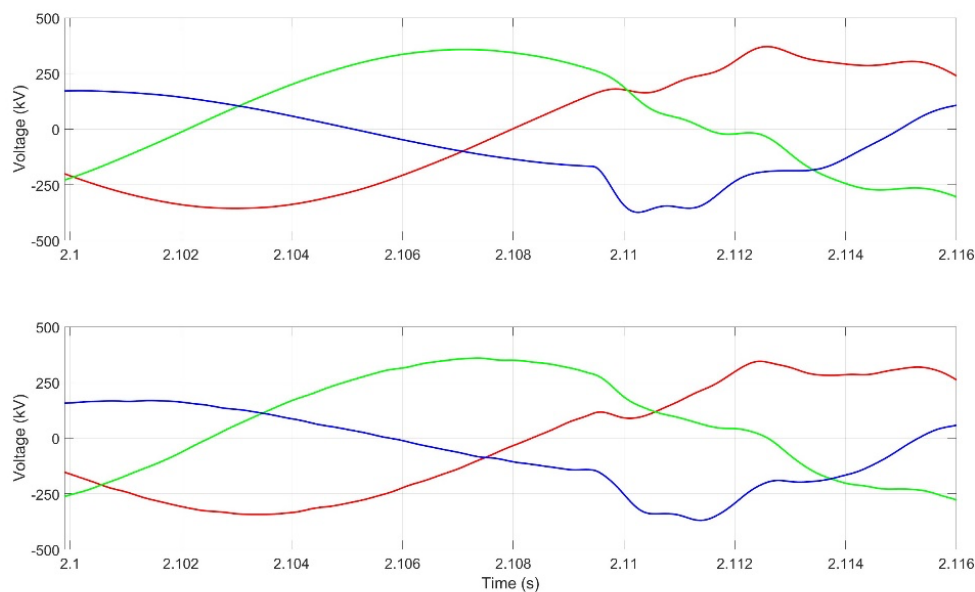


Figure 36. Voltage dip transient at the ending of the dip due to a single-phase-to-ground fault, when the generator is off, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station (bottom).

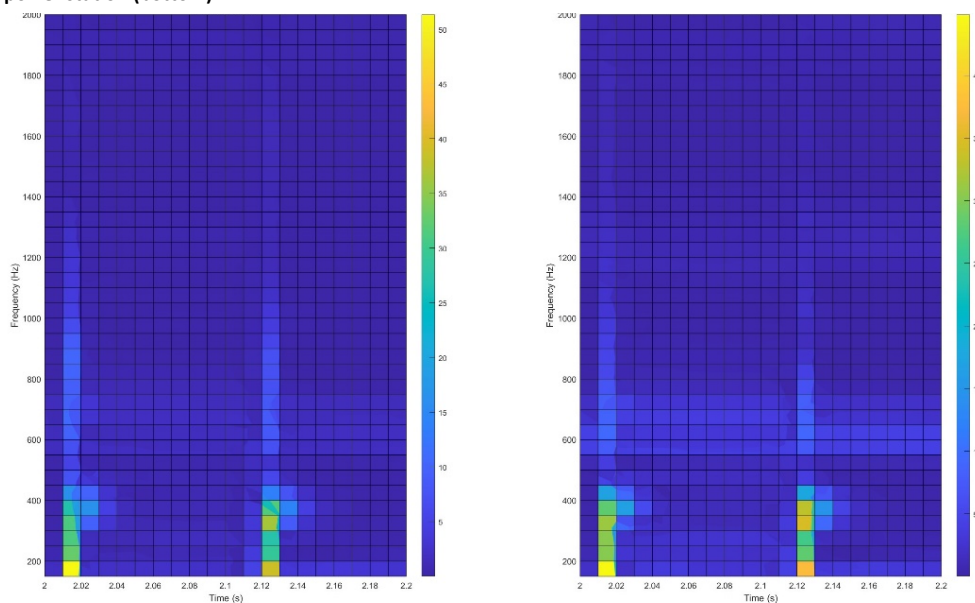


Figure 37. Spectrogram of the dip due to a single-phase-to-ground fault, when the generator is off, at the terminals of the faulted line (← left) and at the 400-kV substation close to the nuclear power station (right →).

4.3.2 Phase-to-phase faults

The results for a phase-to-phase fault are shown in Figure 38 through Figure 41.

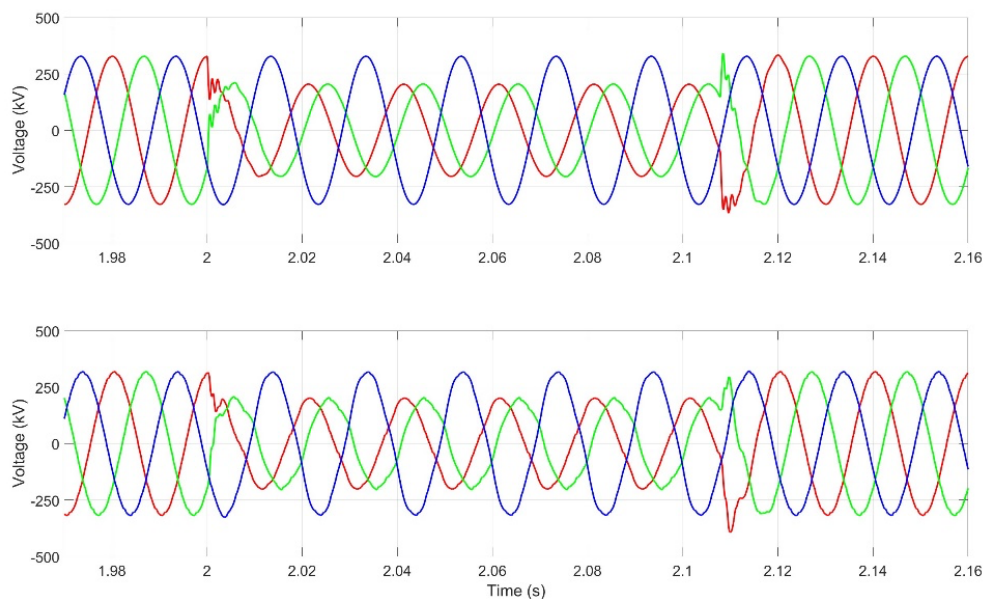


Figure 38. Voltage dip due to a phase-to-phase fault, when the generator is off, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station (bottom).

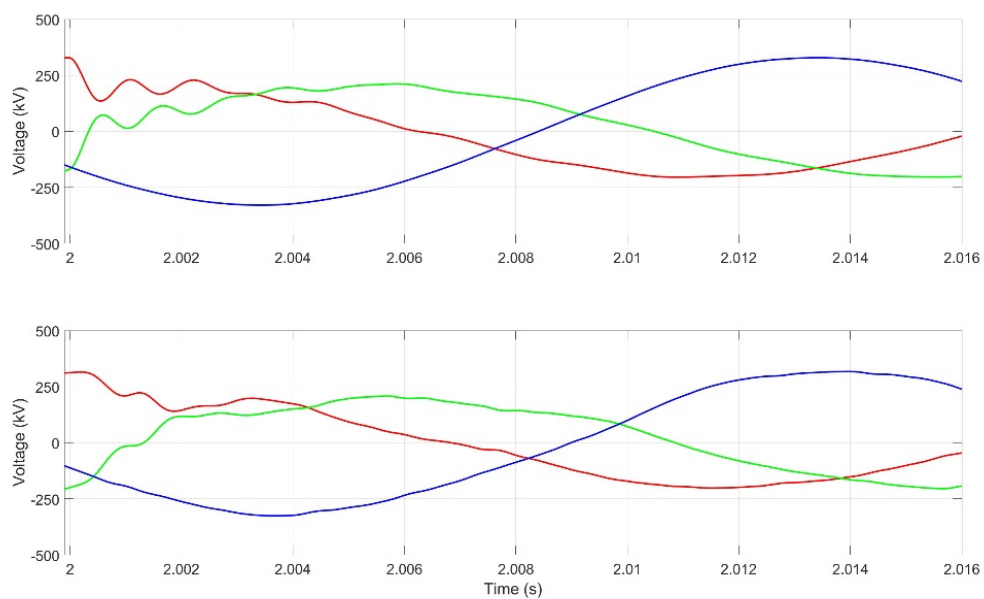


Figure 39. Voltage dip transient at the beginning of the dip due to a phase-to-phase fault, when the generator is off, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station (bottom).

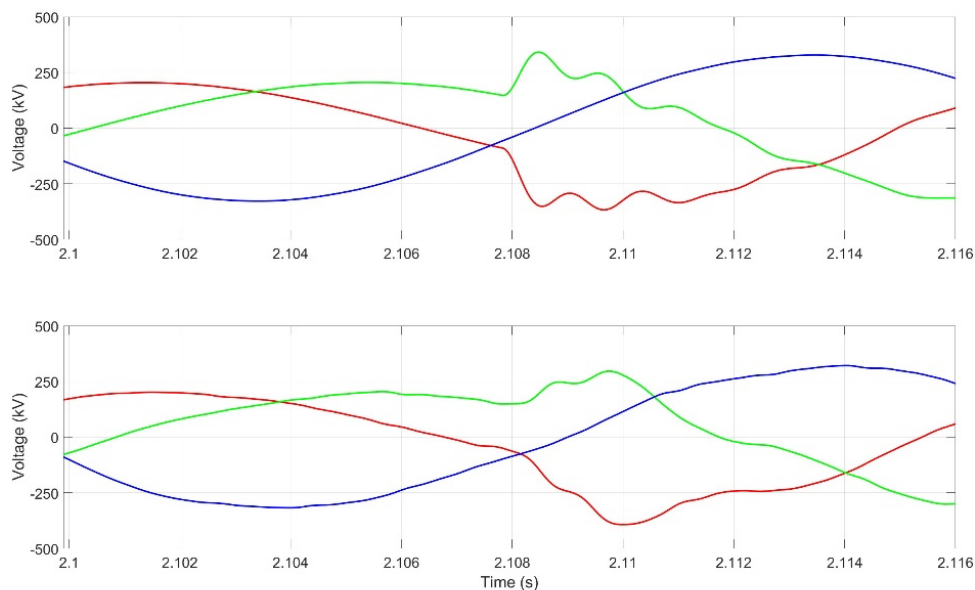


Figure 40. Voltage dip transient at the ending of the dip due to a phase-to-phase fault, when the generator is off, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station (bottom).

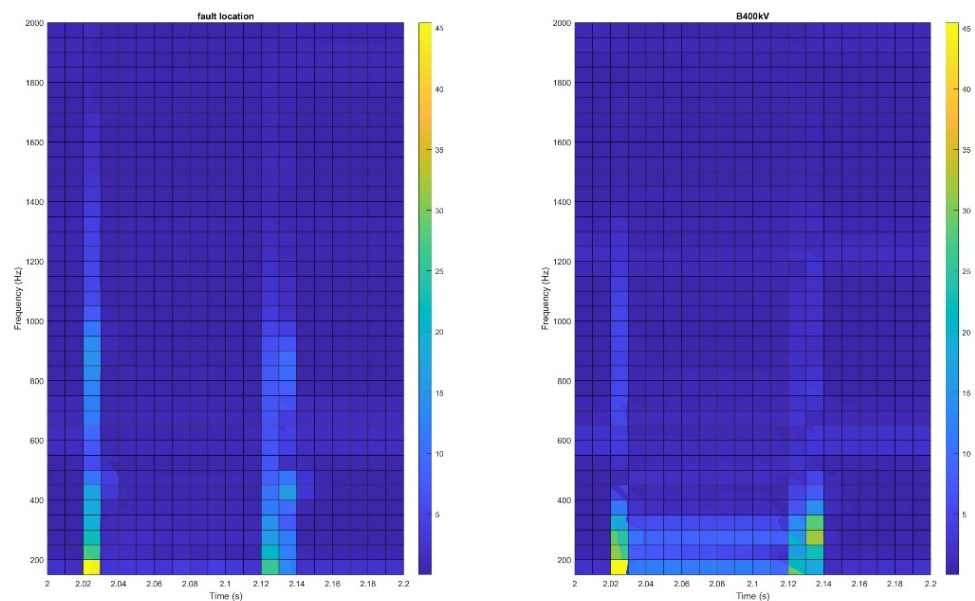


Figure 41. Spectrogram of a voltage dip due to a phase-to-phase fault, when the generator is off, at the terminals of the faulted line (← left) and at the 400-kV substation close to the nuclear power station (right →).

4.3.3 Two-phase-to-ground faults

The results for a two-phase-to-ground fault are shown in Figure 42 through Figure 45.

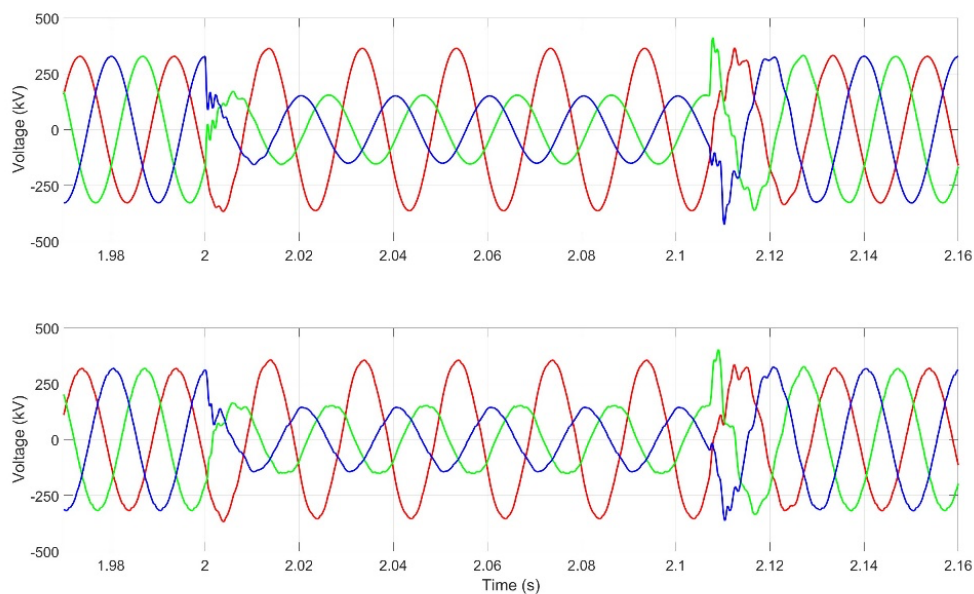


Figure 42. Voltage dip due to a two-phase-to-ground fault, when the generator is off, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station (bottom).

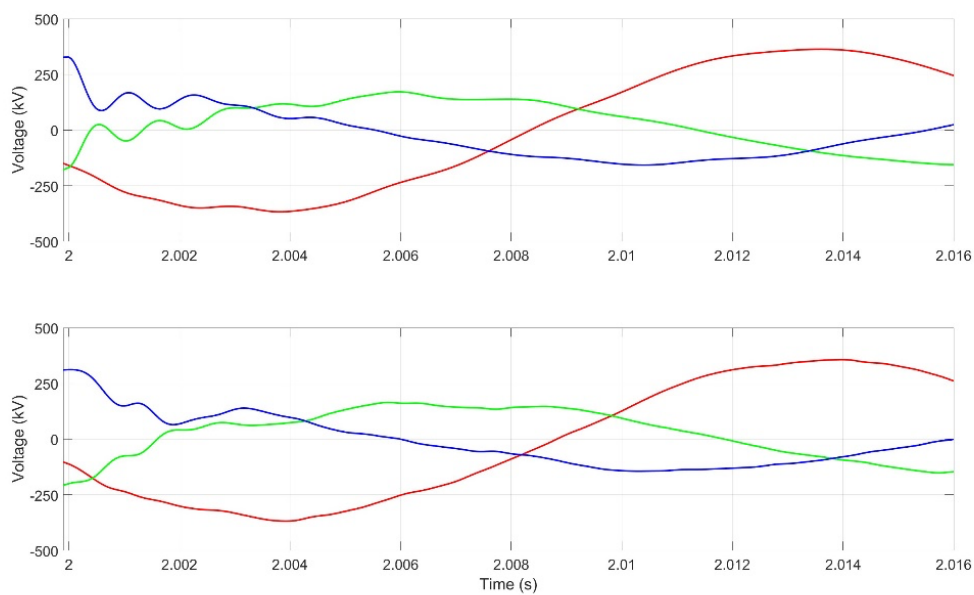


Figure 43. Voltage dip transient at the beginning of the dip due to a two-phase-to-ground fault, when the generator is off, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station (bottom).

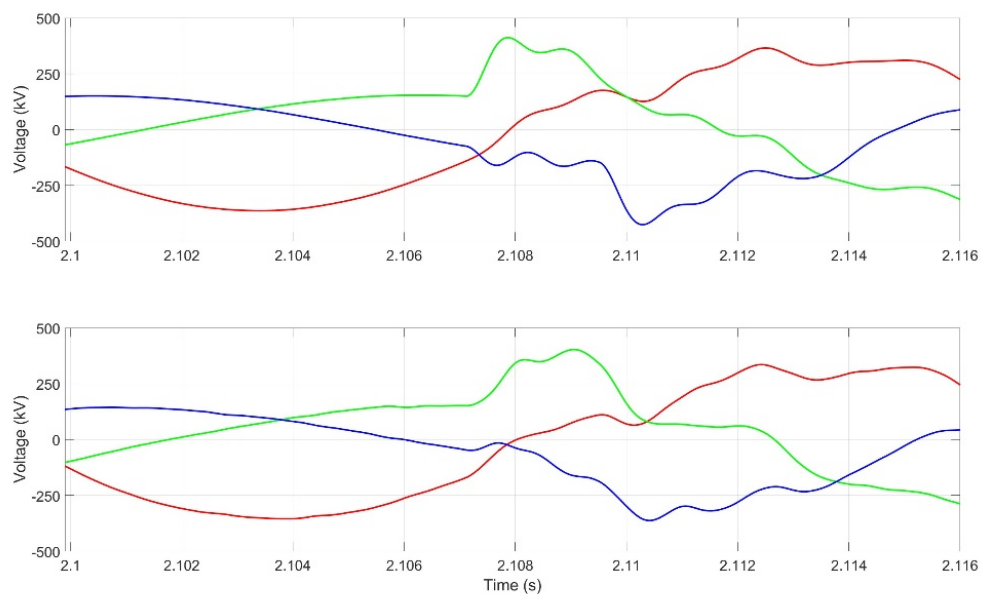


Figure 44. Voltage dip transient at dip ending due to a two-phase-to-ground fault, when the generator is off, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station (bottom).

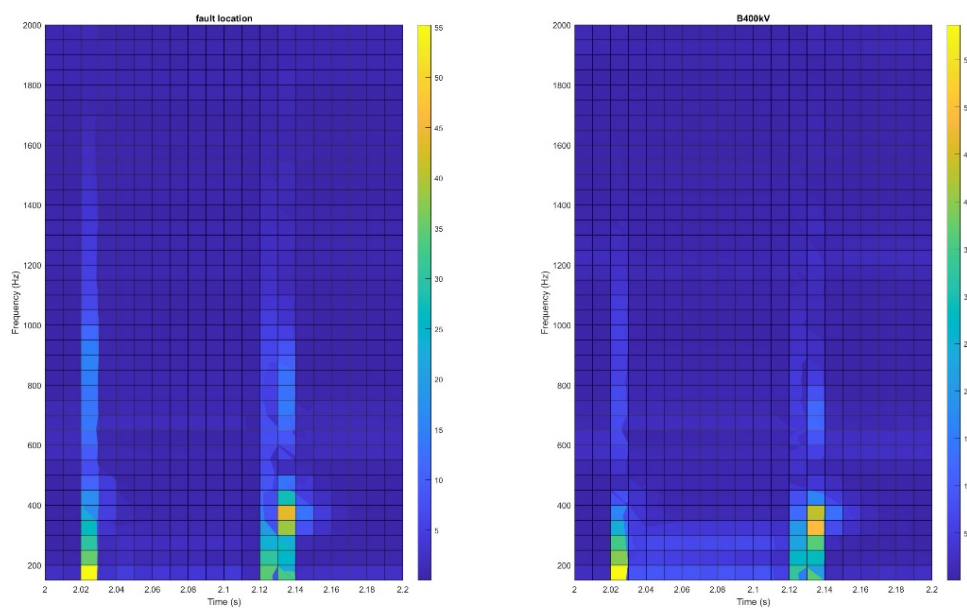


Figure 45. Spectrogram for the voltage dip due to a two-phase-to-ground fault, when the generator is off, at the terminals of the faulted line (← left) and at the 400-kV substation close to the nuclear power station (right →).

4.3.4 Three-phase faults

The results for a three-phase-to-ground fault are shown in Figure 46 through Figure 49.

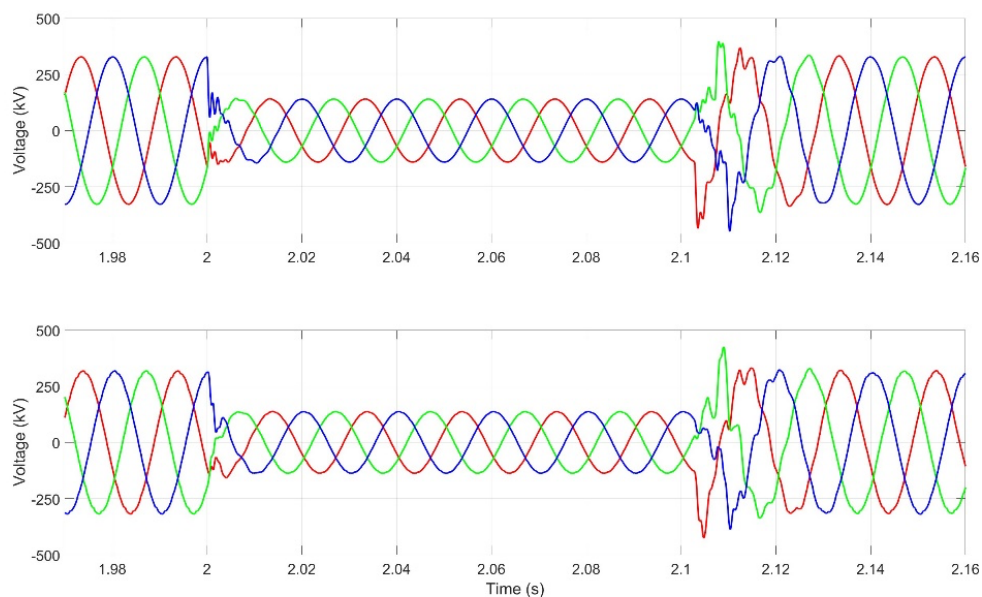


Figure 46. Voltage dip due to a three-phase fault, when the generator is off, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station (bottom).

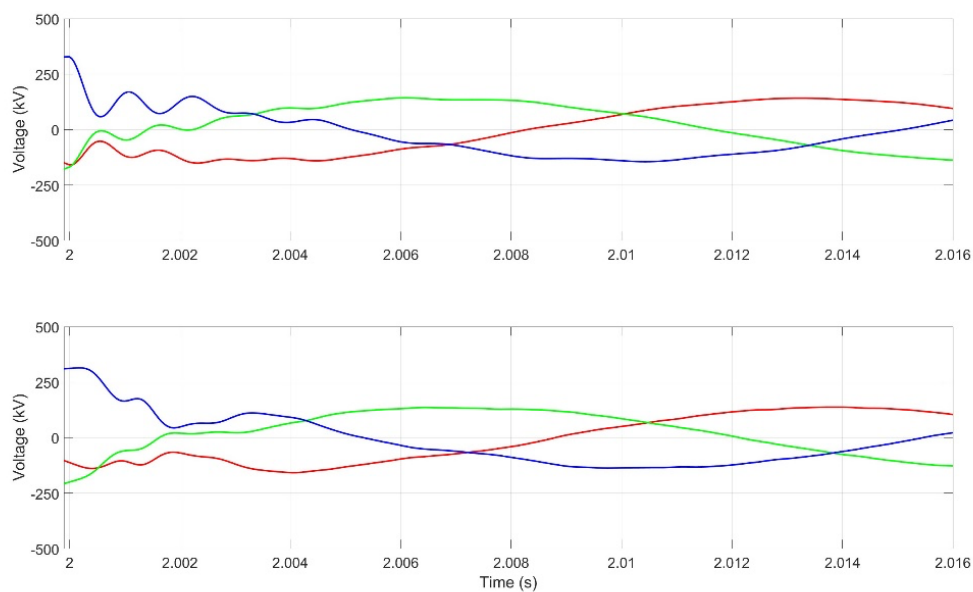


Figure 47. Voltage dip transient at dip beginning due to a three-phase fault, when the generator is off, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station (bottom).

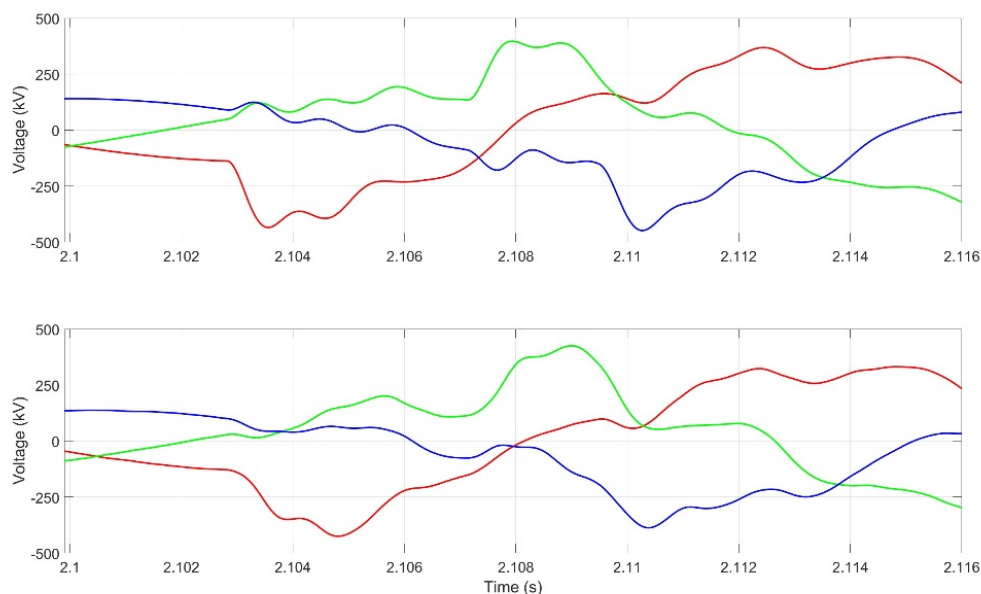


Figure 48. Voltage dip transient at dip ending due to a three-phase fault, when the generator is off, at Substation A, terminals of the faulted line (top) and at Substation C, close to the nuclear power station (bottom).

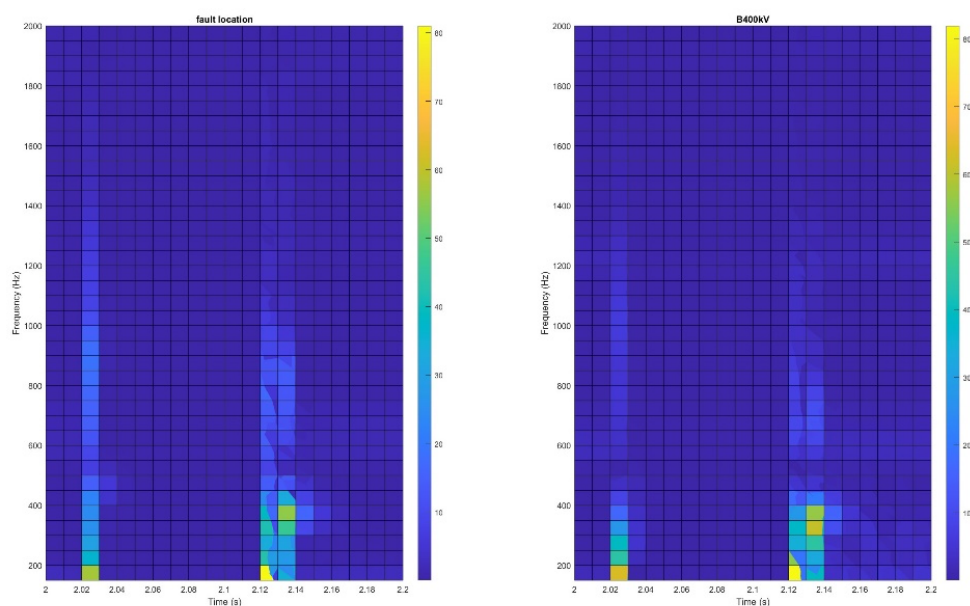


Figure 49. Spectrogram of the voltage dip due to a three-phase fault, when the generator is off, at the terminals of the faulted line (← left) and at the 400-kV substation close to the nuclear power station (right →).

4.4 NUCLEAR POWER STATION – GENERATOR OFF

Voltage-dip waveforms have also been calculated for three busses inside of the nuclear power station, the 22-kV bus, the 6-kV bus and the 525-V bus shown in Figure 17. These three busses are part of the supply to auxiliary equipment. The calculations have been performed for the nuclear generation on (results in Section 4.5), and for the generator off (in the forthcoming subsections).

4.4.1 Single-phase-to-ground faults

The results for a single-phase-to-ground fault are shown in Figure 50 through Figure 53.

Figure 50 shows the waveform for the complete voltage dip. The voltage magnitude shows a drop in two of the three phases at the 22-kV bus (top figure) and at the 525-V bus (bottom); it shows a voltage drop in one of the three phases at the 6-kV bus. This difference is due to the winding connections of the transformers between the 400-kV grid and these busses. The busses in the internal grid show more voltage distortion than for the 400-kV bus; especially the 525-V bus shows strong distortion. The waveform distortion is bigger during the dip than before the dip.

Figure 51 shows the voltage-dip transient at the beginning of the dip. The oscillations at the three busses are of the same frequency but the amplitudes are different. The highest amplitude is visible for the oscillations at the 525-V bus (bottom) and the lowest one for the oscillations at the 22-kV bus (top). This difference is due to the resonance frequencies of the systems in relation to the oscillation frequency of the voltage-dip transient at it occurs at 400 kV. The increase in amplitude when moving to lower voltage levels is probably a coincidence and no general conclusion can be drawn from that.

Figure 52 shows the voltage-dip transient at the ending of the dip. The amplitude of the oscillations is again highest at the 525-V bus.

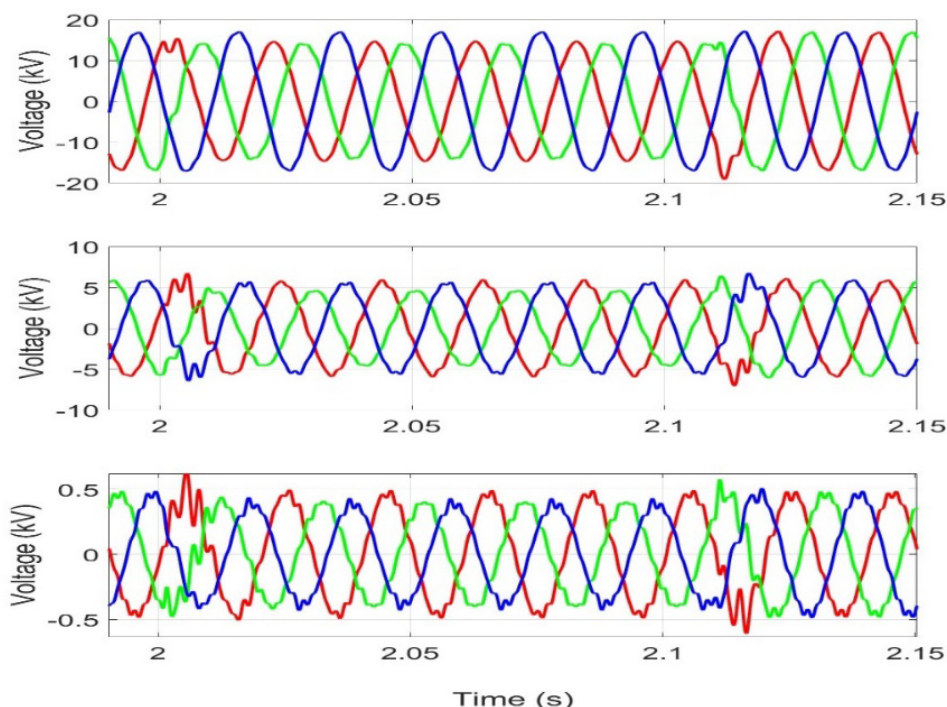


Figure 50. Voltage dip due to a single-phase fault, when the generator is off, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

Figure 53 shows the spectrogram. At the 22-kV bus (left) voltage-dip beginning and voltage-dip ending show different frequency components. At 6 kV, the two voltage-dip transients contain similar frequency components.

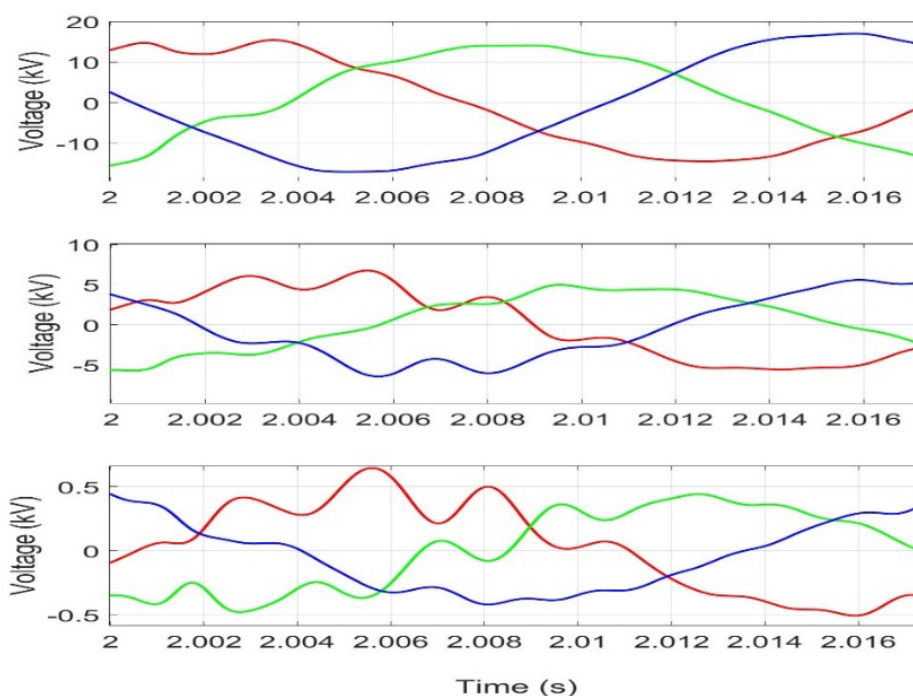


Figure 51. Voltage dip transient at dip beginning due to a single-phase fault, when the generator is off, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

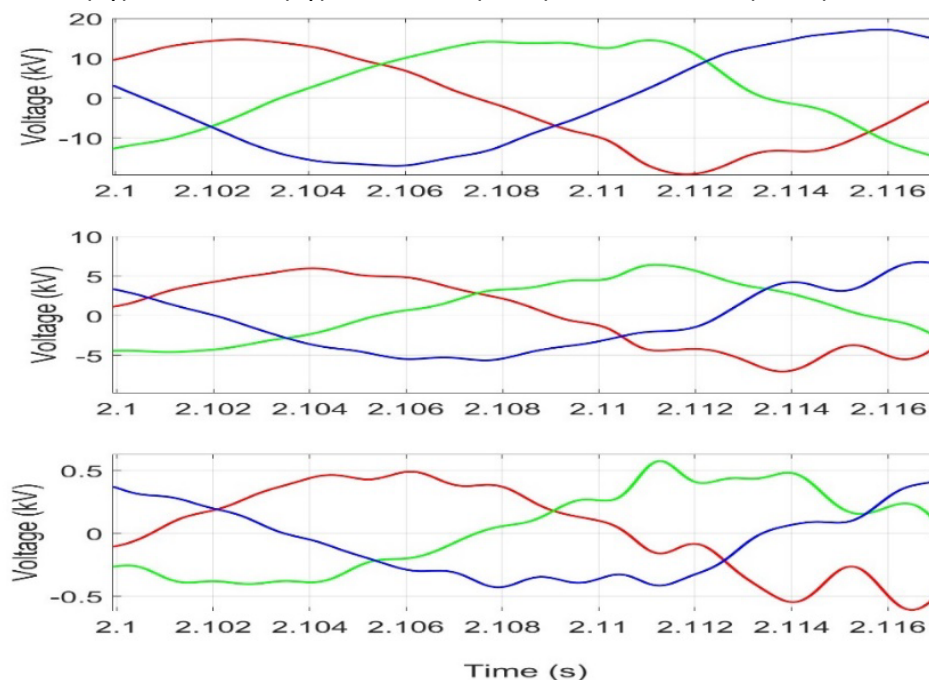


Figure 52. Voltage dip transient at dip ending due to a single-phase fault, when the generator is off, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

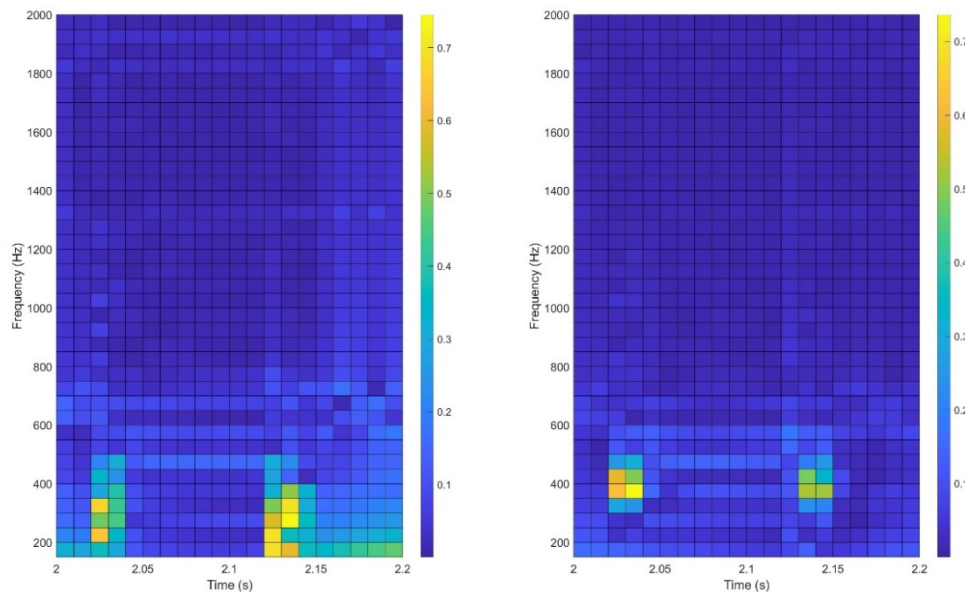


Figure 53. Spectrogram of the voltage dip due to a single-phase fault, when the generator is off, at the 22-kV bus (← left), and at the 6-kV bus (right →).

4.4.2 Phase-to-phase faults

The results for a phase-to-phase fault are shown in Figure 54 through Figure 57.

The voltage waveforms are shown in Figure 54. Like before, the oscillations of the transient at beginning and ending of the dip are highest at the lowest voltage level. During the dip, the voltage magnitude drops in two phases at 22 kV and at 525 V; it drops in one phase at 6 kV.

The transients at voltage-dip beginning are shown in more detail in Figure 55. The oscillations are similar at 6 kV and at 525 V. At 22 kV, the oscillations are of lower amplitude.

The transients at voltage-dip ending are shown in more detail in Figure 56. The amplitude of the oscillations are similar, but the oscillations are of different shape for the three voltage levels.

The spectrogram, before, during and after the dip, is shown in Figure 57. The difference in character between the 22 kV and the 6 kV bus is clearly visible.

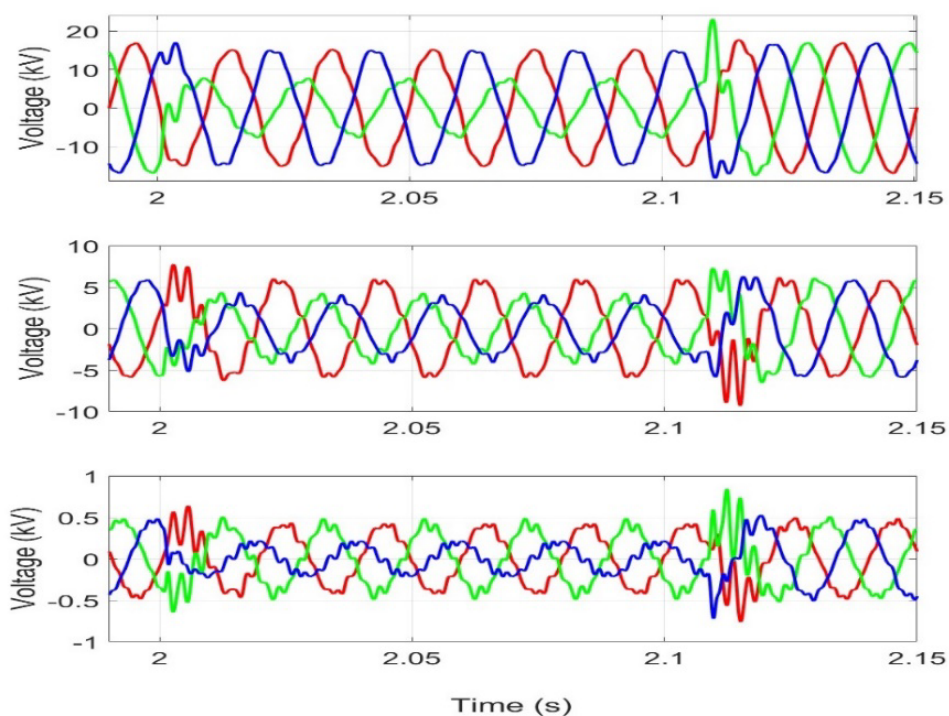


Figure 54. Voltage dip due to a phase-to-phase fault, when the generator is off, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

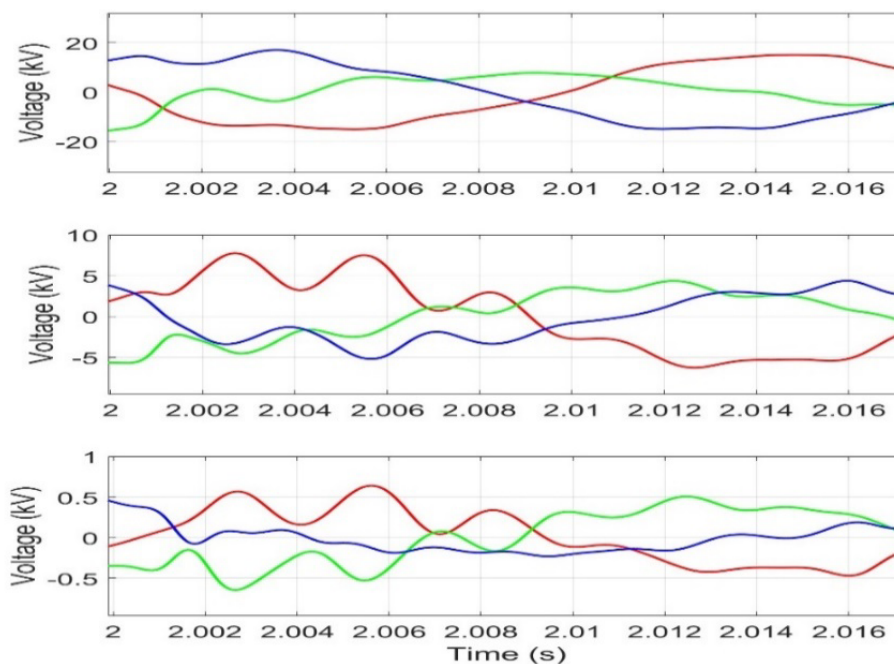


Figure 55. Voltage dip transient at dip beginning due to a phase-to-phase fault, when the generator is off, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

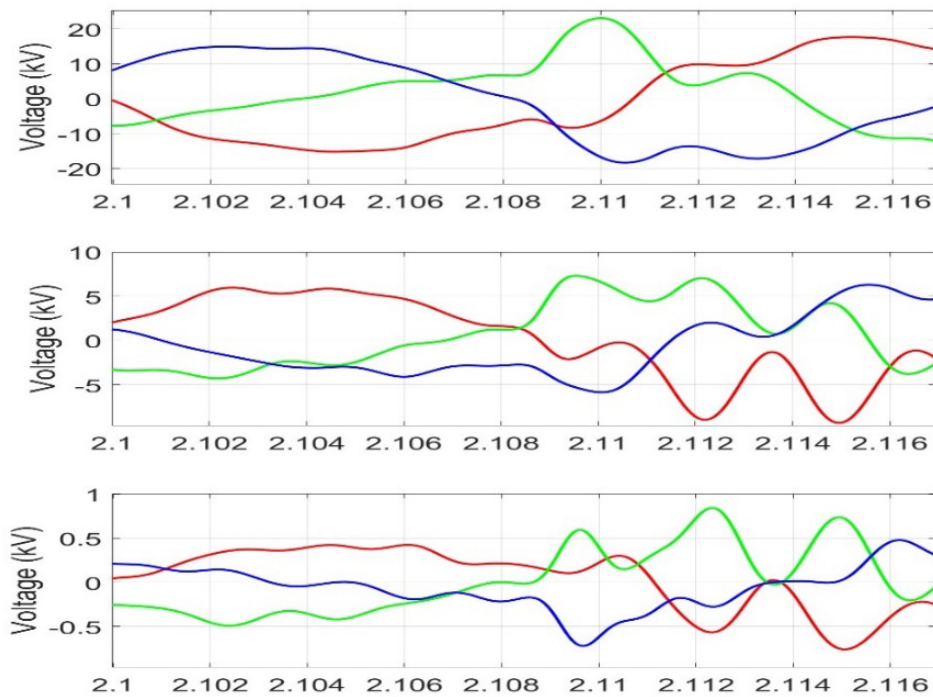


Figure 56. Voltage dip transient at dip ending due to a phase-to-phase fault, when the generator is off, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

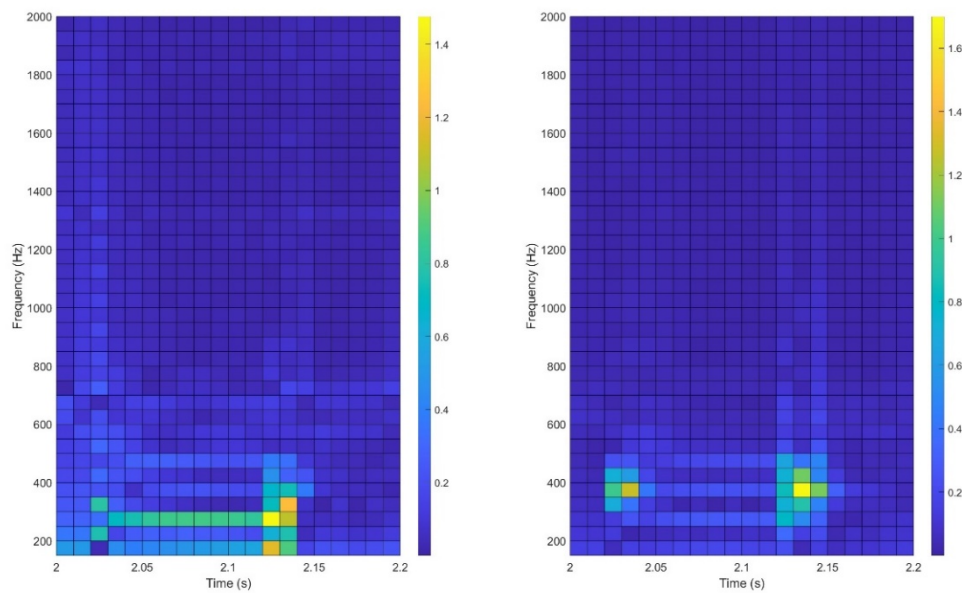


Figure 57. Spectrogram of the voltage dip due to a phase-to-phase fault, when the generator is off, at the 22-kV bus (← left) and at the 6-kV bus (right →).

4.4.3 Two-phase-to-ground faults

The results for a two-phase-to-ground fault are shown in Figure 58 through Figure 61.

Figure 58 shows the complete voltage-dip waveform; the voltage magnitude shows a major drop in one phase at the 22-kV and 525-V busses and in two phases at the 6-kV bus. The other phases show a minor drop in voltage magnitude. The voltage distortion is especially strong at the 525-V bus during the dip.

Figure 59 shows the voltage-dip transient at the beginning of the dip; the amplitude of the oscillations is clearly bigger at the 6-kV and 525-V busses. The oscillations are also spread differently over the three phases at the different voltage levels.

Figure 60 shows the voltage-dip transient at the ending of the dip. The observations for are similar to ones for the previous figure.

Figure 61 shows the spectrogram of the voltage dip, where there is again a difference in character between the transients at 22 kV and at 6 kV.

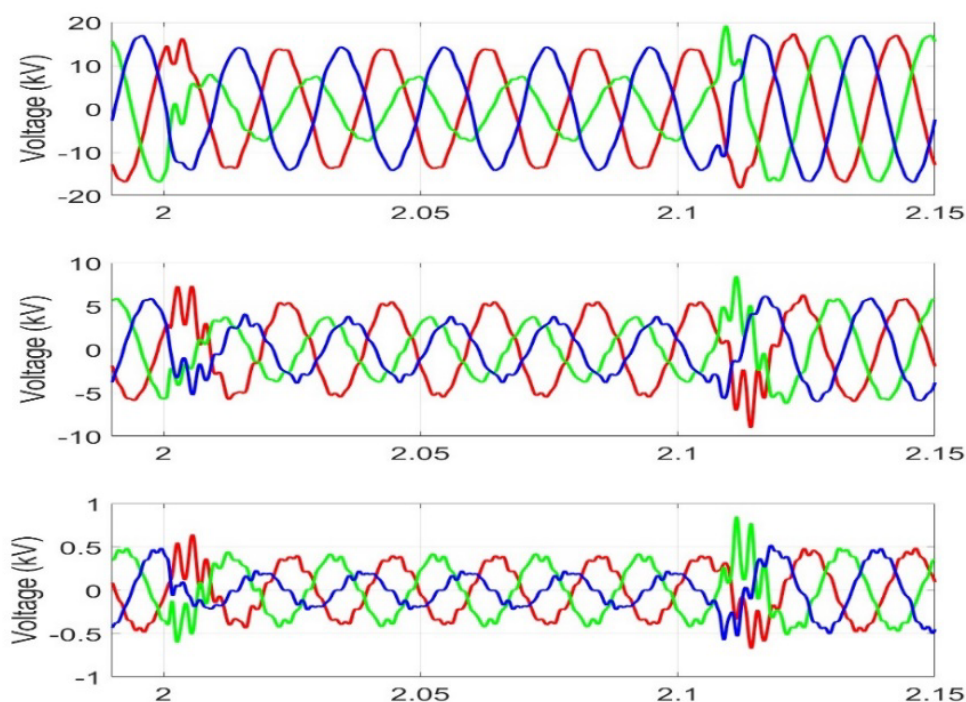


Figure 58. Voltage dip due to a two-phase-to-ground fault, when the generator is off, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

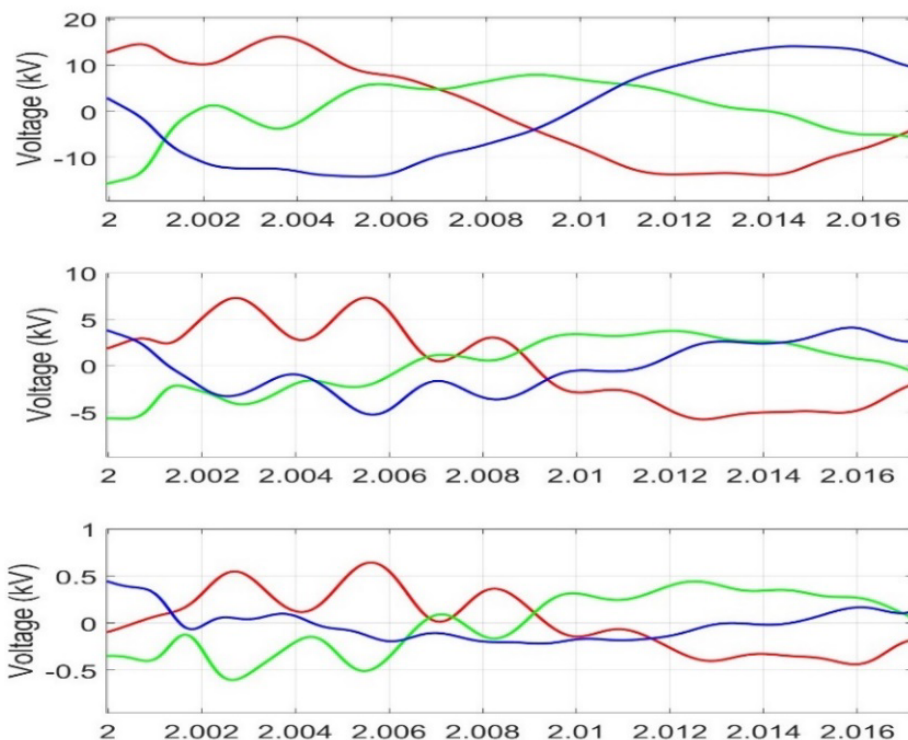


Figure 59. Voltage dip transient at dip beginning due to a two-phase-to-ground fault, when the generator is off, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

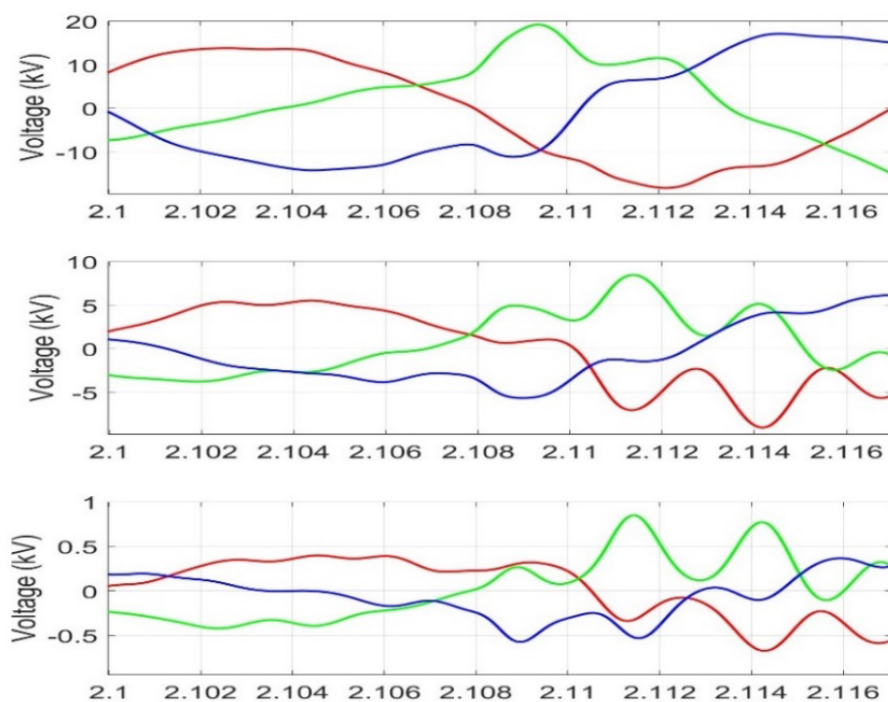


Figure 60. Voltage dip transient at dip ending due to a two-phase-to-ground fault, when the generator is off, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

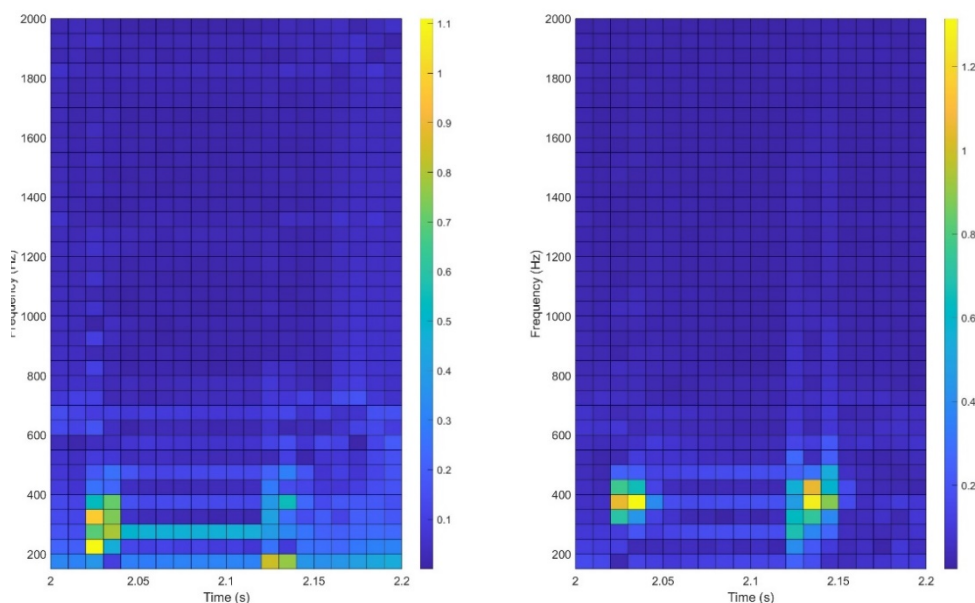


Figure 61. Spectrogram of the voltage dip due to a two-phase-to-ground fault, when the generator is off, at the 22-kV bus (← left) and at the 6-kV bus (right →).

4.4.4 Three-phase faults

The results for a three-phase-to-ground fault are shown in Figure 62 through Figure 65.

Figure 62 shows the complete voltage-dip recording. The voltage magnitude shows the same drop in all three phases, for both locations. The voltage-dip transients are rather severe at all three voltage levels, especially at voltage-dip ending. This is partly due to the recovery after a three-phase-to-ground fault taking place in three stages.

Figure 63 shows the voltage-dip transient at the beginning of the dip; the transient is more severe at the 6-kV and 525-V busses and continues for more than one cycle.

Figure 64 shows the voltage dip transient at the ending of the dip; the transient is severe at all three voltage levels but appears to have more damping at 22 kV.

Figure 65 shows the spectrogram; at voltage-dip beginning the transients appear of different character, but at dip ending they are rather similar.

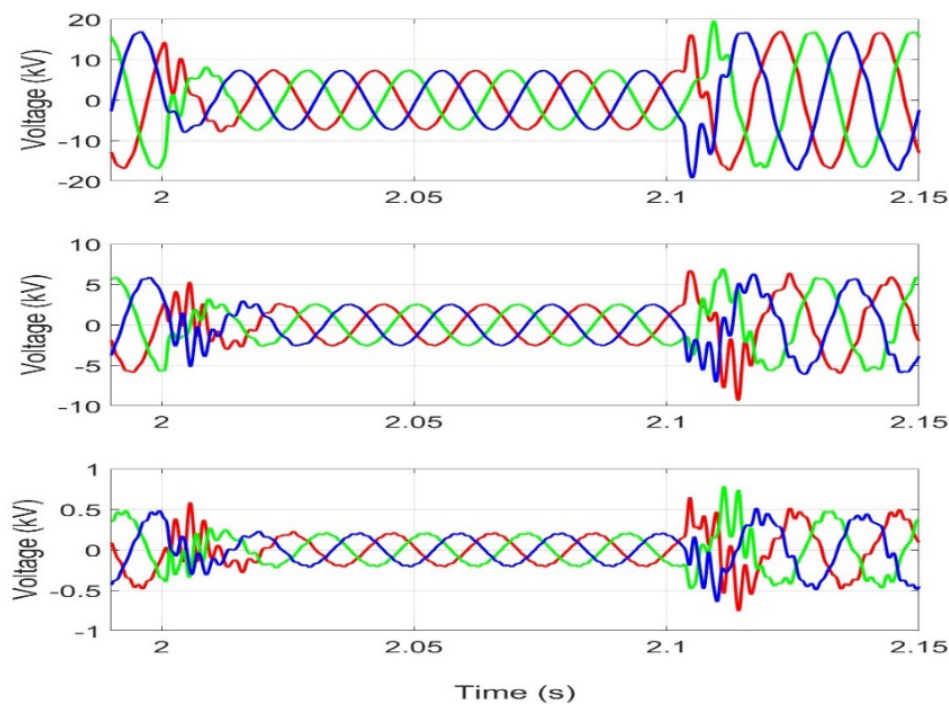


Figure 62. Voltage dip due to a three-phase-to-ground fault, when the generator is off, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

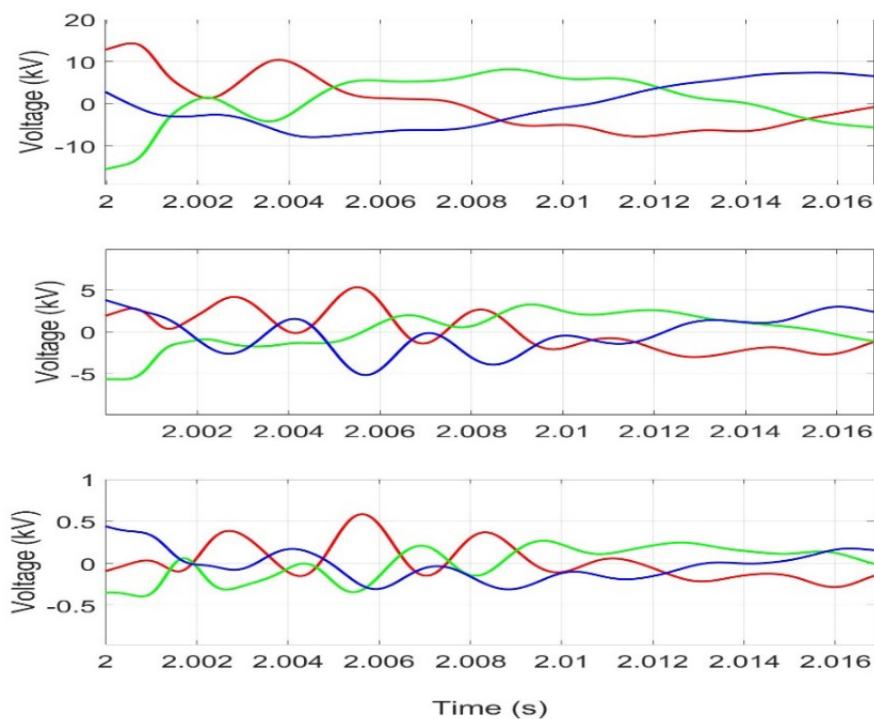


Figure 63. Voltage dip transient at dip beginning due to a three-phase-to-ground fault, when the generator is off, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

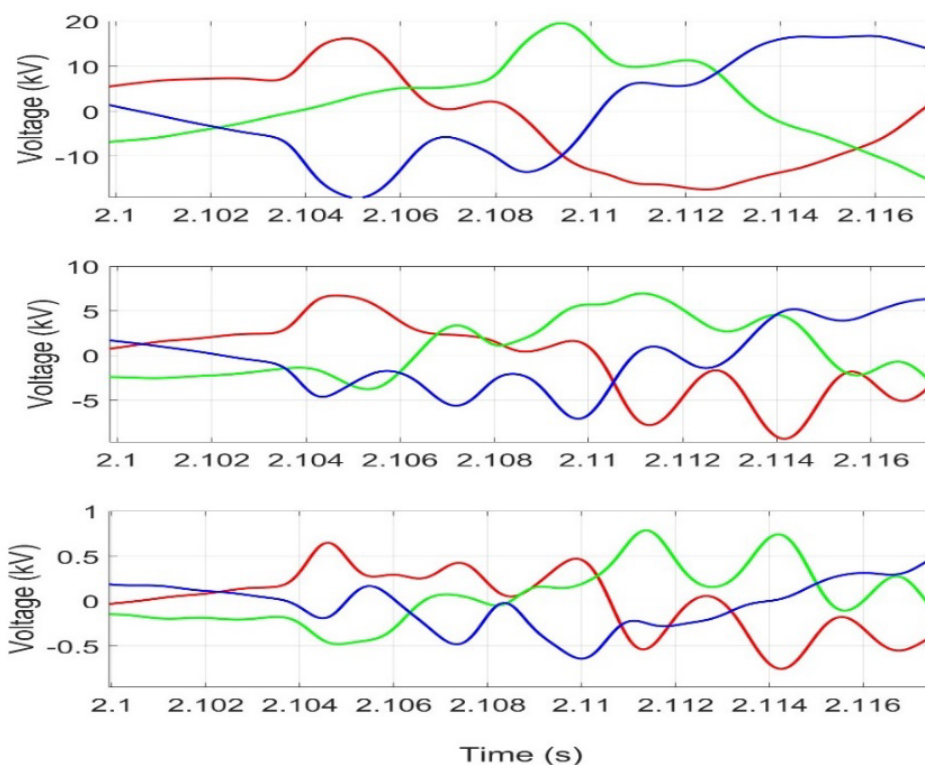


Figure 64. Voltage dip transient at dip ending due to a three-phase-to-ground fault, when the generator is off, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

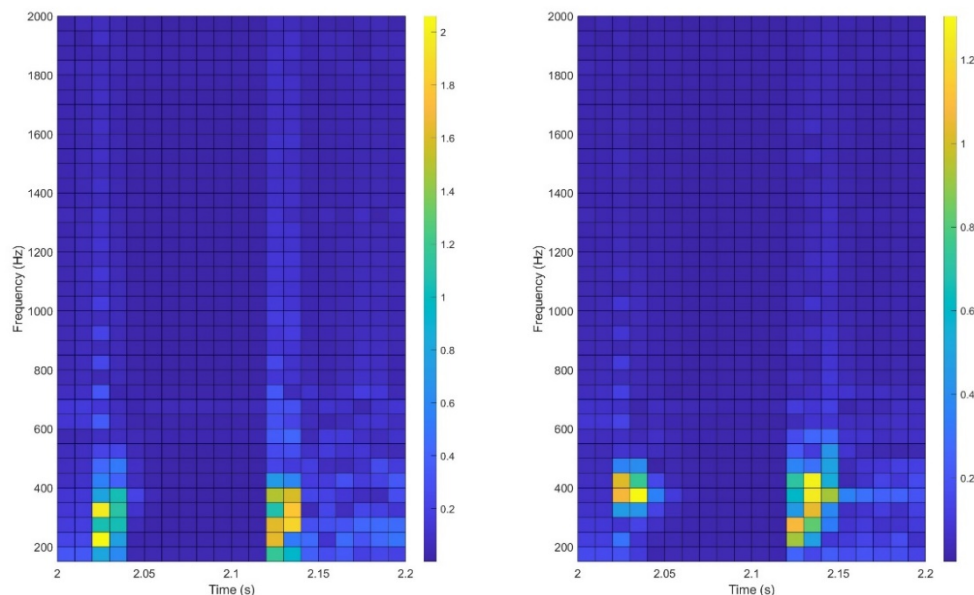


Figure 65. Spectrogram of the voltage dip due to a three-phase-to-ground fault, when the generator is off, at the 22-kV bus (← left) and at the 6-kV bus (right →).

4.5 NUCLEAR POWER STATION – GENERATOR ON

The simulations have been repeated for the case with the generator on. The oscillations with beginning and ending of the dip are of lower amplitude. The results are presented in the forthcoming section, without further comments.

4.5.1 Single-phase-to-ground fault

The results for a single-phase-to-ground fault are shown in Figure 66 through Figure 69.

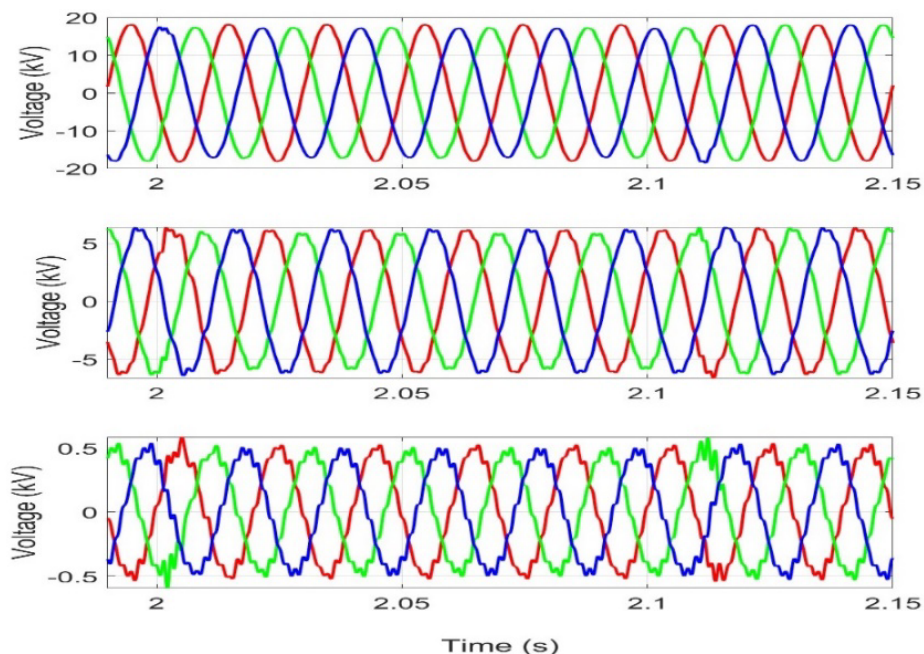


Figure 66. Voltage dip due to a single-phase-to-ground fault, when the generator is on, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

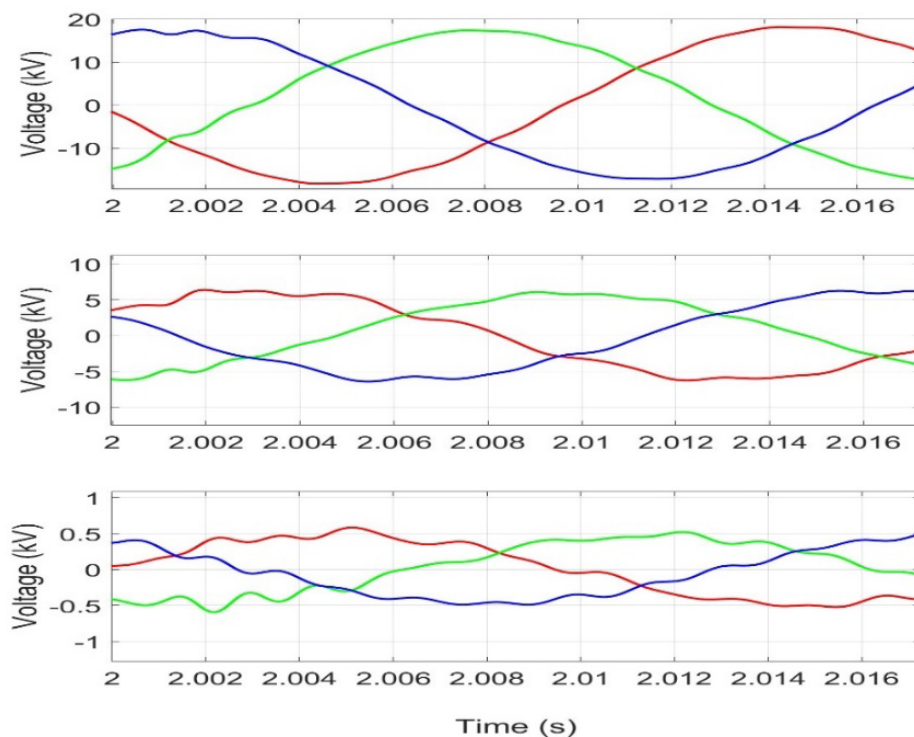


Figure 67. Voltage dip transient at dip beginning due to a single-phase-to-ground fault, when the generator is on, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-kV bus (bottom).

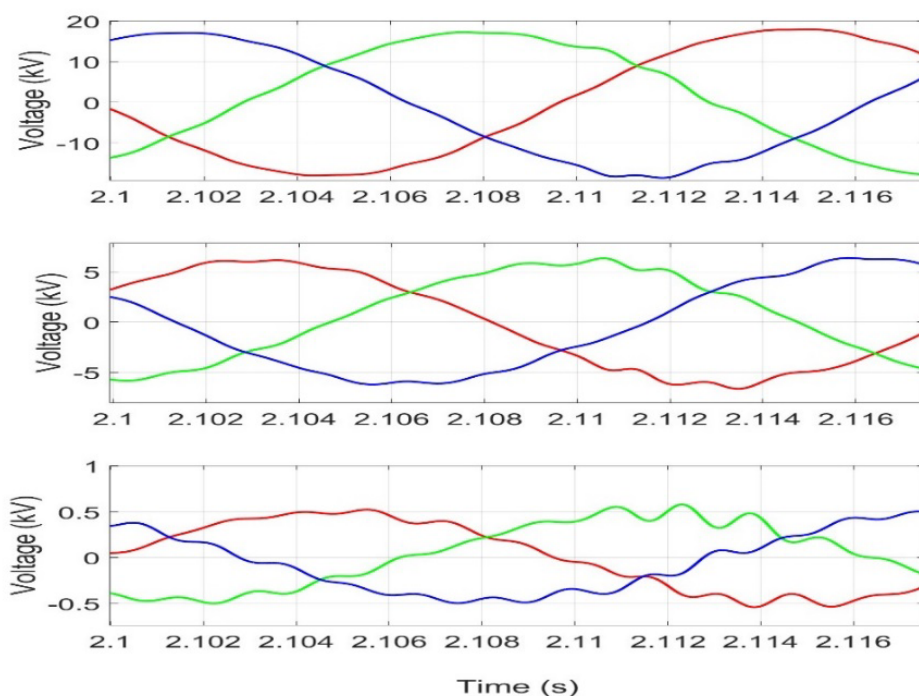


Figure 68. Voltage dip transient at dip ending due to a single-phase-to-ground fault, when the generator is on, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

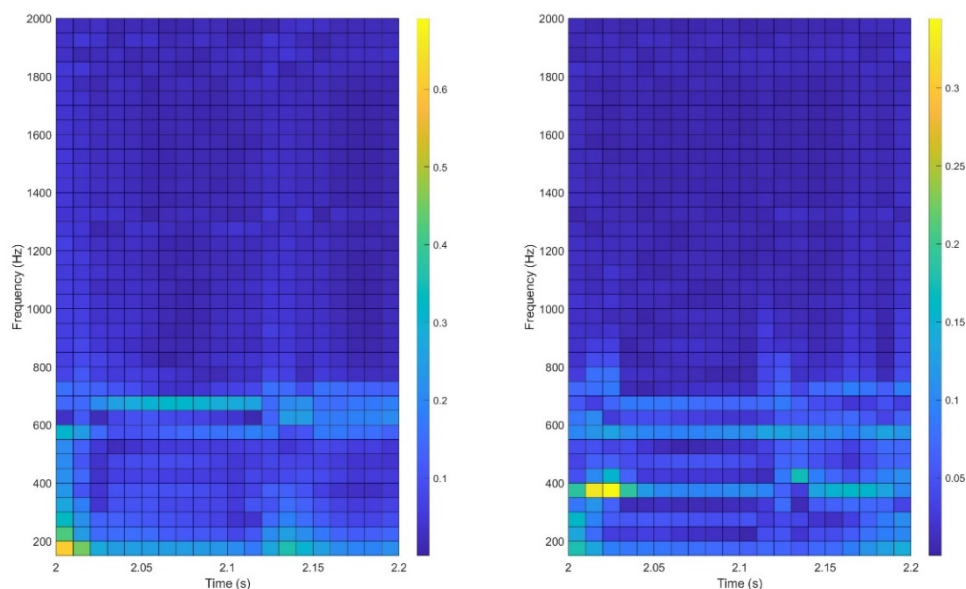


Figure 69. Spectrogram of the voltage dip due to a single-phase-to-ground fault, when the generator is on, at the 22-kV bus (← left) and at the 6-kV bus (right →).

4.5.2 Phase-to-phase faults

The results for a phase-to-phase fault are shown in Figure 70 through Figure 73.

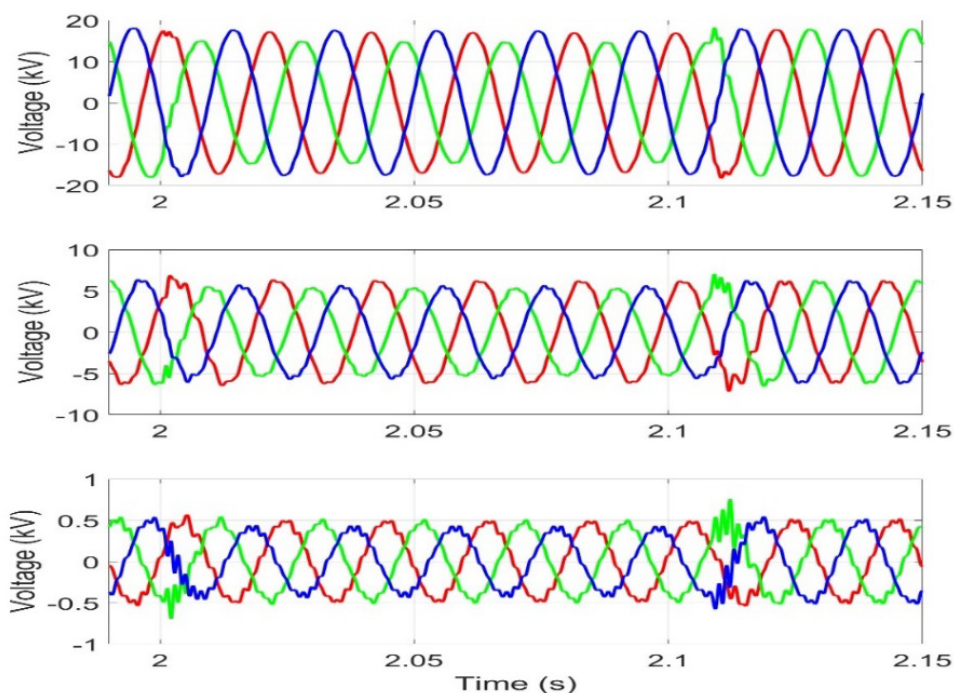


Figure 70. Voltage dip due to a phase-to-phase fault, when the generator is on, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

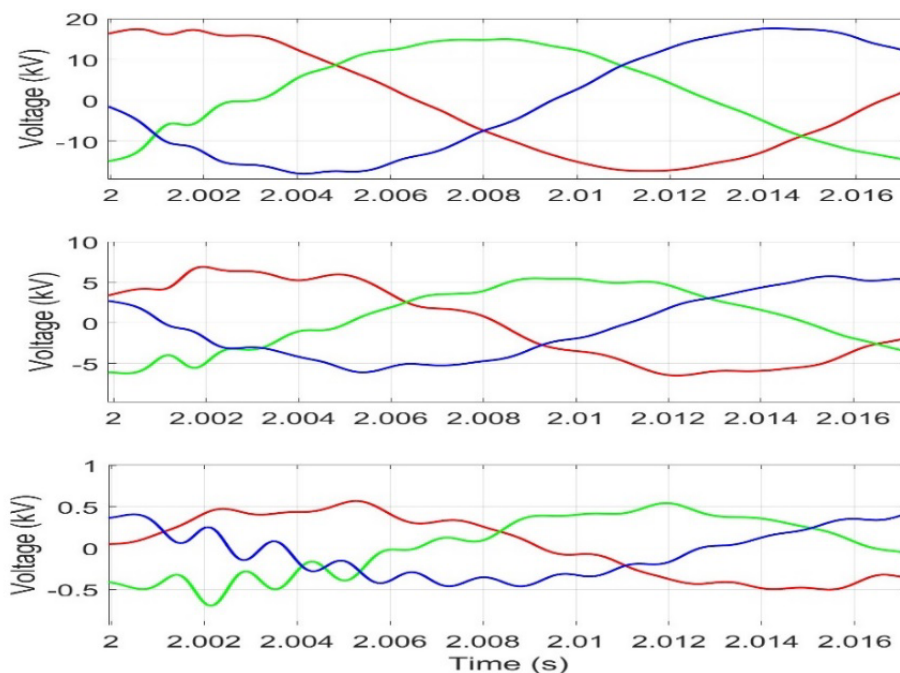


Figure 71. Voltage dip transient at dip beginning due to a phase-to-phase fault, when the generator is on, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

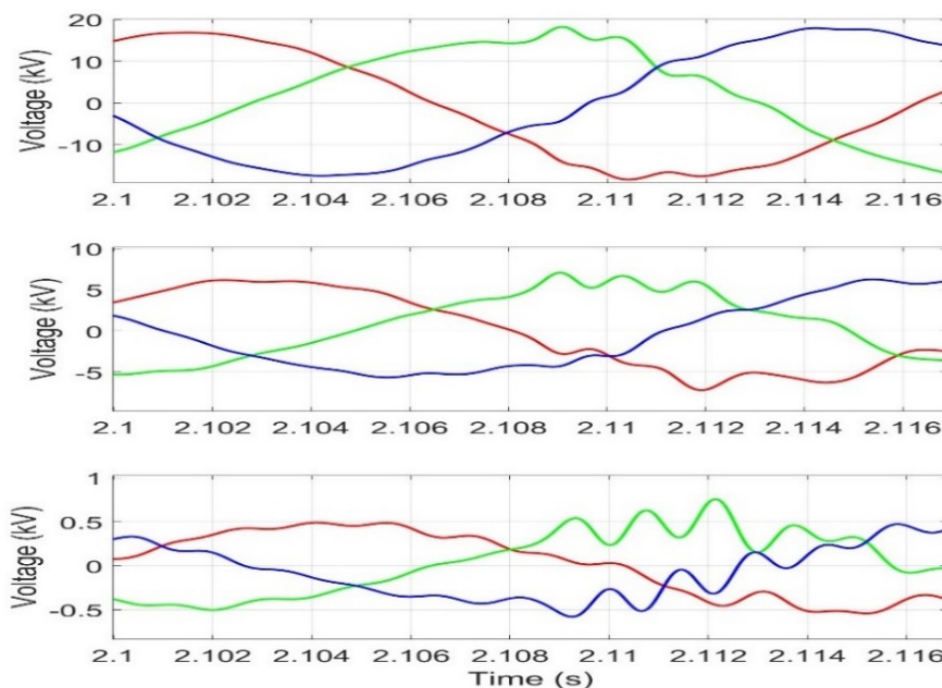


Figure 72. Voltage dip transient at dip ending due to a phase-to-phase fault, when the generator is on, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-kV bus (bottom).

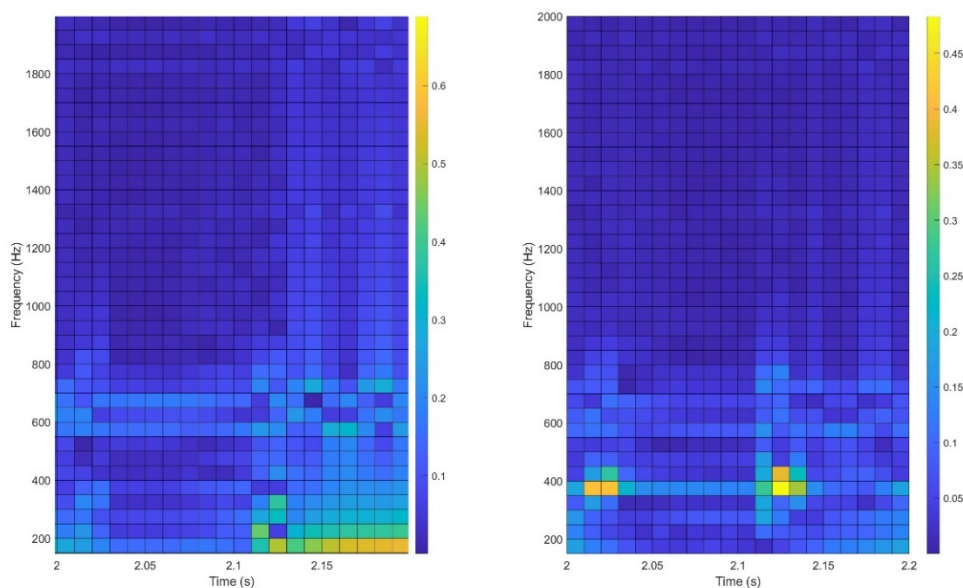


Figure 73. Spectrogram of the voltage dip due to a phase-to-phase fault, when the generator is on, at the 22-kV bus (← left) and at the 6-kV bus (right →).

4.5.3 Two-phase-to-ground faults

The results for two-phase-to-ground faults are shown in Figure 74 through Figure 77.

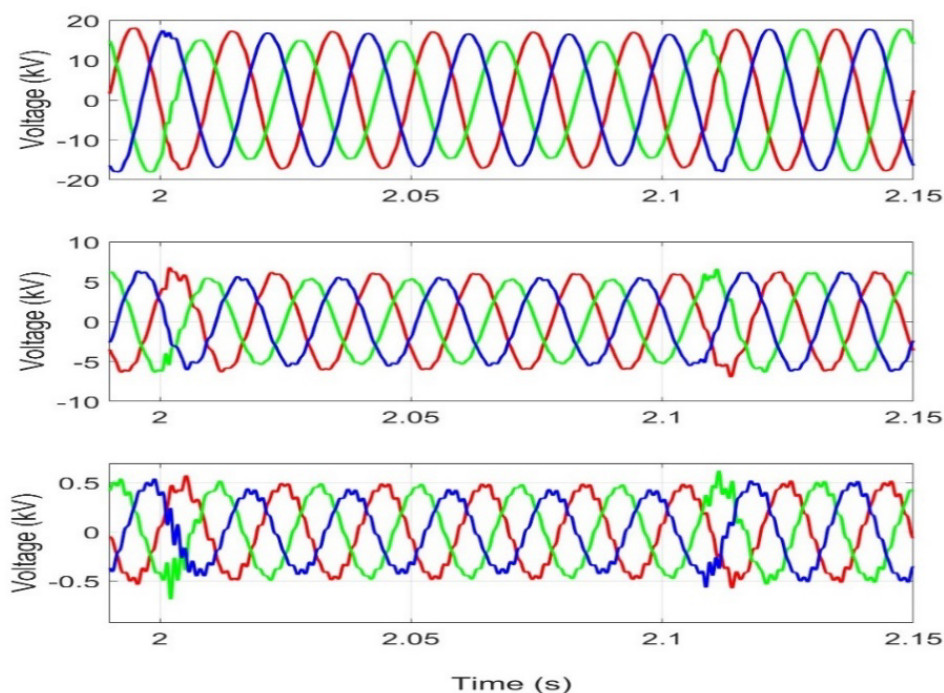


Figure 74. Voltage dip due to a two-phase-to-ground fault, when the generator is on, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

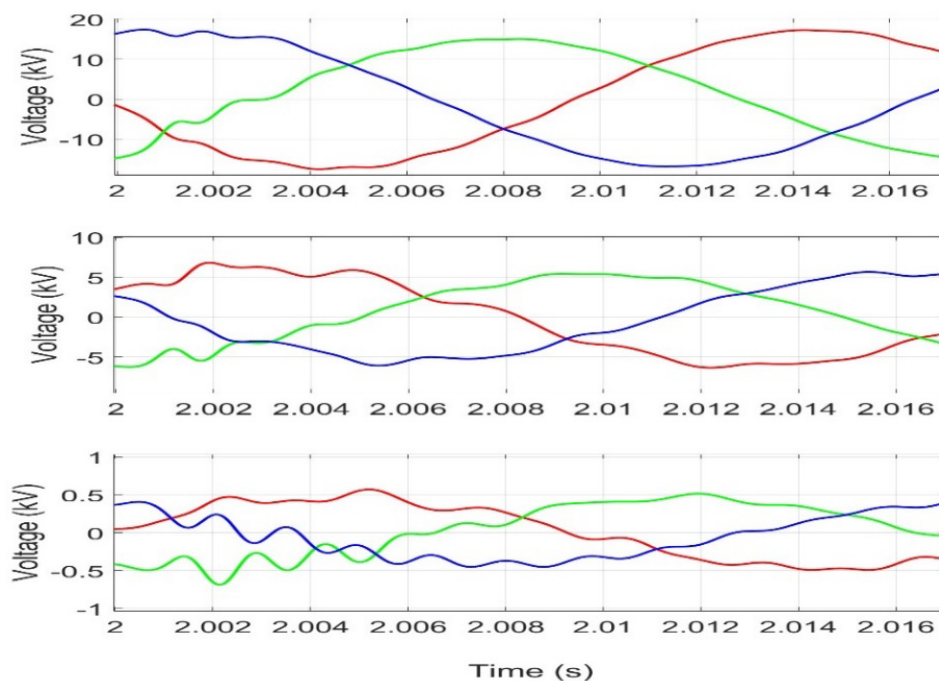


Figure 75. Voltage dip transient at dip beginning due to a two-phase-to-ground fault, when the generator is on, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

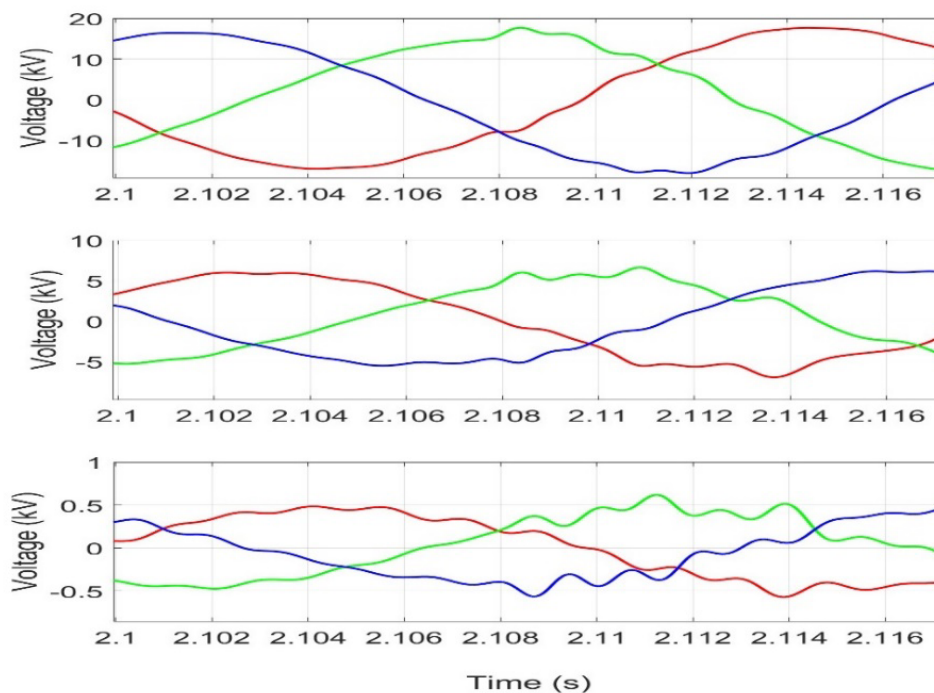


Figure 76. Voltage dip transient at dip ending due to a two-phase-to-ground fault, when the generator is on, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

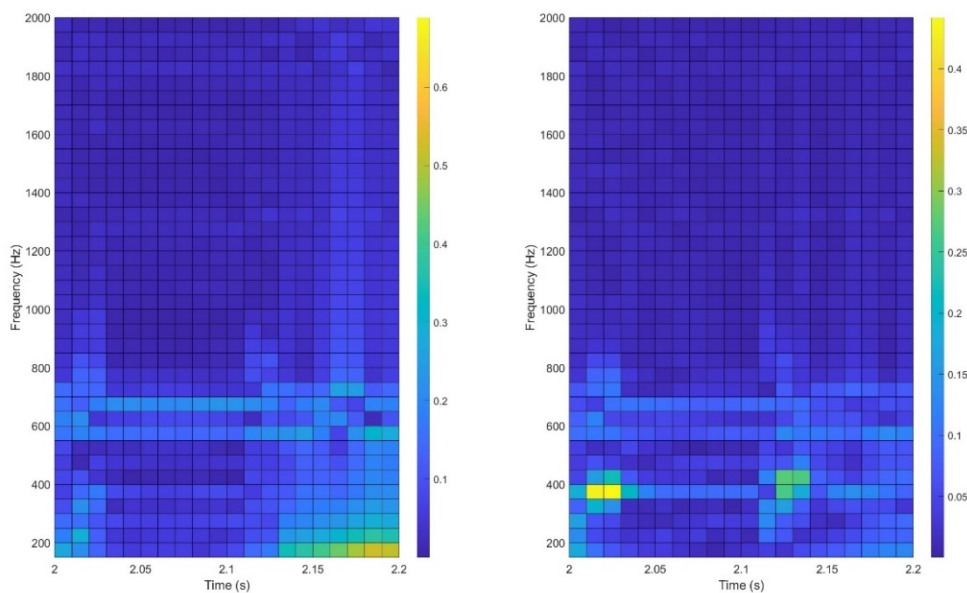


Figure 77. Spectrogram for the voltage dip due to a two-phase-to-ground fault, when the generator is on, at the 22-kV bus (← left) and at the 6-kV bus (right →).

4.5.4 Three-phase faults

The results for a three-phase-to-ground fault are shown in Figure 78 through Figure 81.

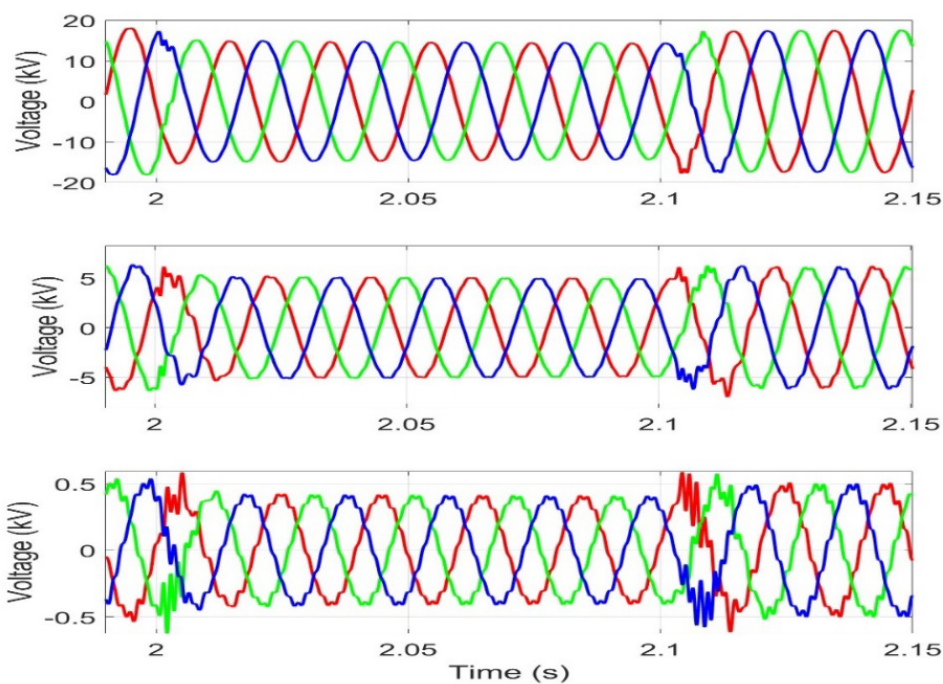


Figure 78. Voltage dip due to a three-phase-to-ground fault, when the generator is on, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

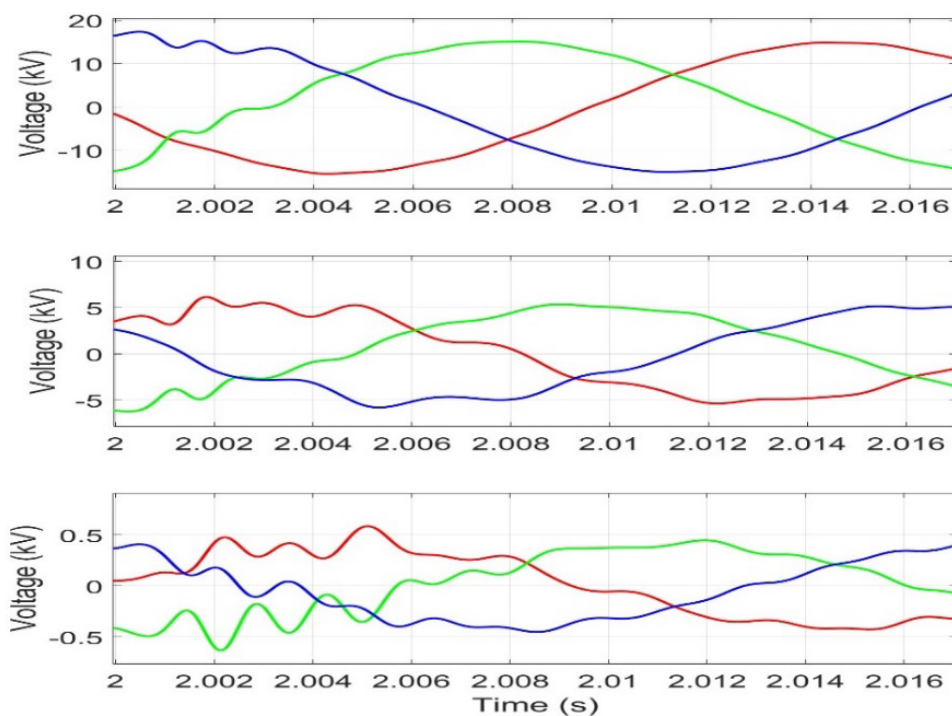


Figure 79. Voltage dip transient at dip beginning due to a three-phase-to-ground fault, when the generator is on, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

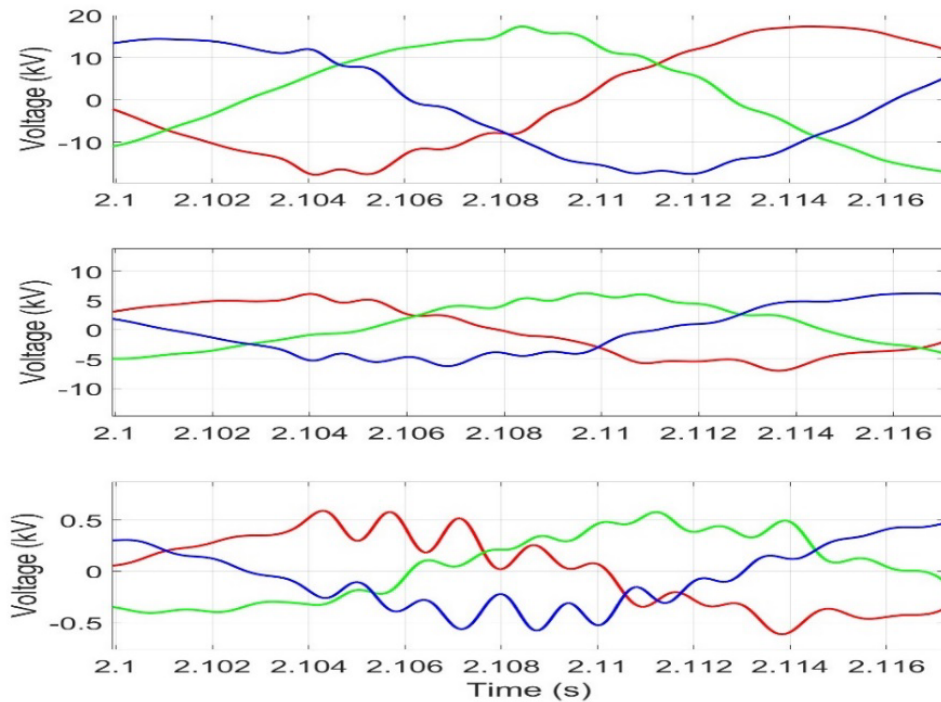


Figure 80. Voltage dip transient at dip ending due to a three-phase-to-ground fault, when the generator is on, at the 22-kV bus (top), at the 6-kV bus (middle), and at the 525-V bus (bottom).

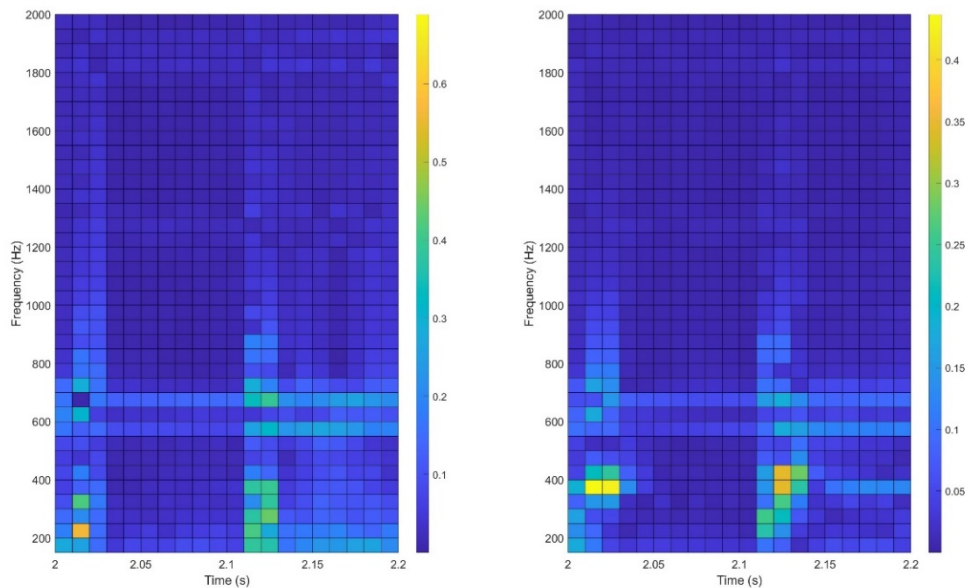


Figure 81. Spectrogram of the voltage dip due to a three-phase-to-ground fault, when the generator is on, at the 22-kV bus (← left) and at the 6-kV bus (right →).

4.6 COMPARISON OF THE VOLTAGE-DIP TRANSIENTS

Some of the observations from the simulations presented in the previous sections have been summarized in the forthcoming sections. The observations are presented in the form of comparison of the voltage-dip transients between different cases for different fault types. Only voltage-dip transients for the two locations inside of the auxiliary grid are shown; these are the voltage-dip transients

that potentially impact the performance of the auxiliary equipment in the nuclear power station.

4.6.1 Beginning of the voltage dip at 22-kV

The voltage-dip transients at the 22-kV bus, for the beginning of the dip, are shown in Figure 82. When comparing the different fault types, we see that the oscillations have highest amplitude for the three-phase-to-ground fault. Comparing the two cases shows that the oscillations are of lower frequency and higher amplitude when the generator is not in operation.

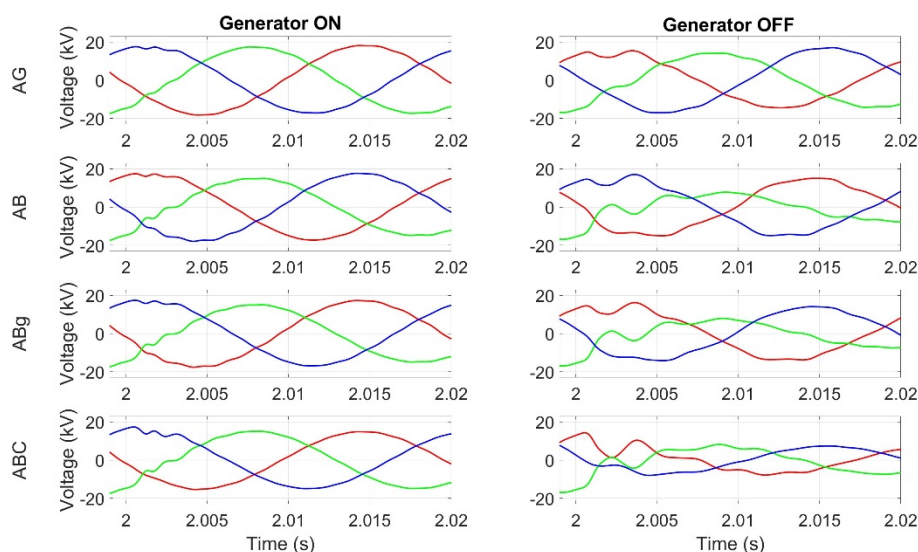


Figure 82. Comparison of transients at voltage-dip beginning for the 22-kV bus.

4.6.2 Beginning of the voltage dip at 6 kV

The voltage-dip transients at the 6-kV bus, for the beginning of the dip, are shown in Figure 83. The observations are similar as for the 22-kV substation: the oscillations are highest for the three-phase-to-ground fault; the oscillations are of lower frequency and higher amplitude when the generator is not in operation.

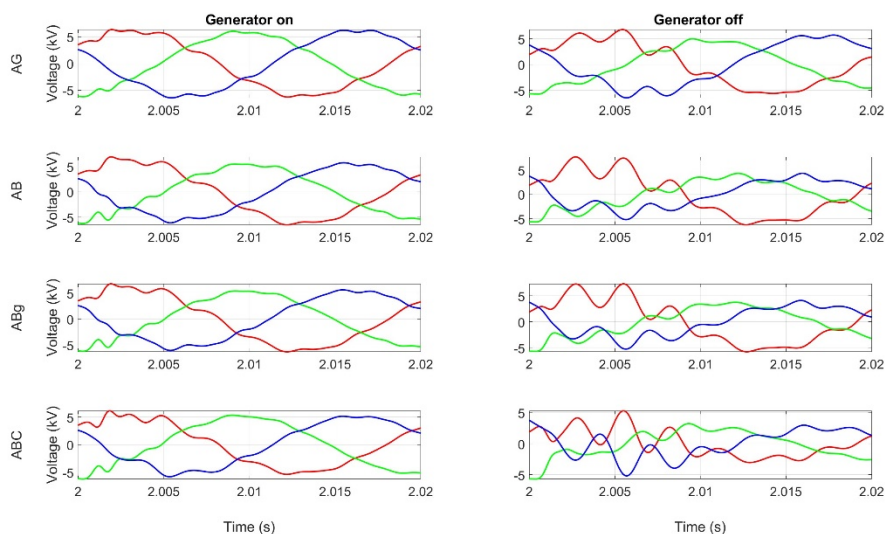


Figure 83. Comparison of transients at voltage-dip beginning for the 6-kV bus.

4.6.3 Beginning of the voltage dip at 525 V

The voltage-dip transients at the 525-V bus, the beginning of the dip, are shown in Figure 84. When the generator is off, the oscillations are of higher amplitude and lower frequency. This holds for all four fault types. Another observation is that the main oscillations are in the green phase with generator on and in the red phase with generator off. More details studies are needed to explain this and especially to find out if this is a general behavior or just specific for this example.

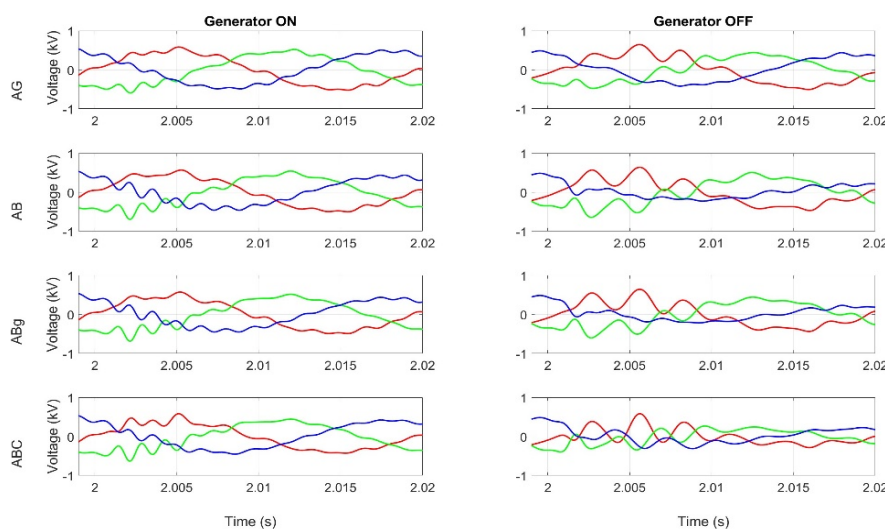


Figure 84. Comparison of transients at voltage-dip beginning for the 525-kV bus.

4.6.4 Ending of the voltage dip at 22 kV

The voltage-dip transients at the 22-kV bus, for the ending of the dip, are shown in Figure 85. The same observations can be made here as for in the previous two

subsections.

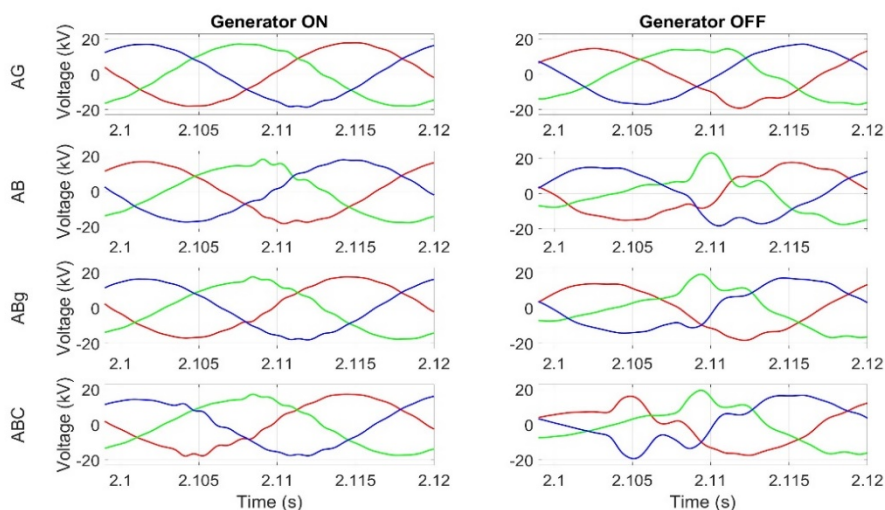


Figure 85. Comparison of transients at voltage-dip ending for the 22-kV bus.

4.6.5 Ending of the voltage dip at 6 kV

The voltage-dip transients at the 22-kV bus, for the ending of the dip, are shown in Figure 86. Similar observations can be made here as for in the previous subsections; the main difference is that the oscillations in the red phase after the phase-to-phase fault are of similar amplitude as the oscillations after the three-phase fault.

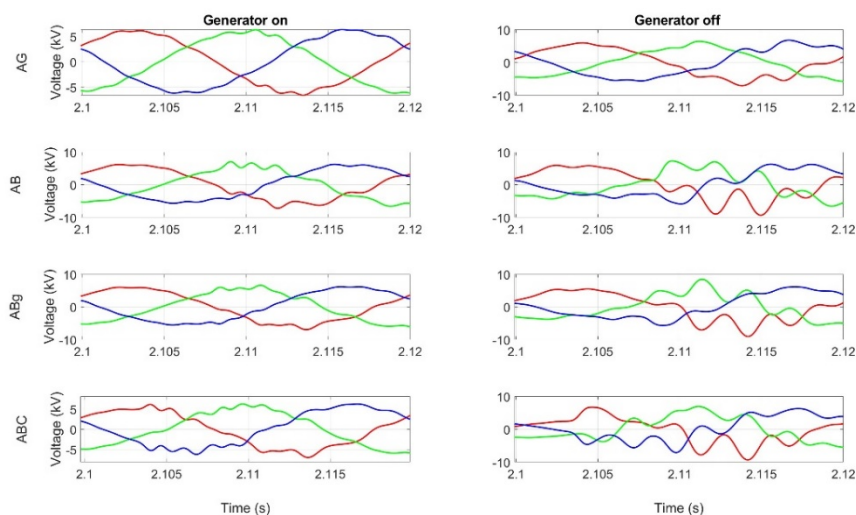


Figure 86. Comparison of transients at voltage-dip ending for the 6-kV bus

4.6.6 Ending of the voltage dip at 525 V

The transients at voltage-dip ending, at the 525-V bus, due to a three-phase-to-ground fault, are shown in Figure 87. The comparison shows a similar pattern as for the transient at voltage-dip beginning, shown in the previous section. The oscillations are

of higher amplitude and lower frequency when the generator is off. The involvement of different phases in the transient is also different, based on the generator being on or off.

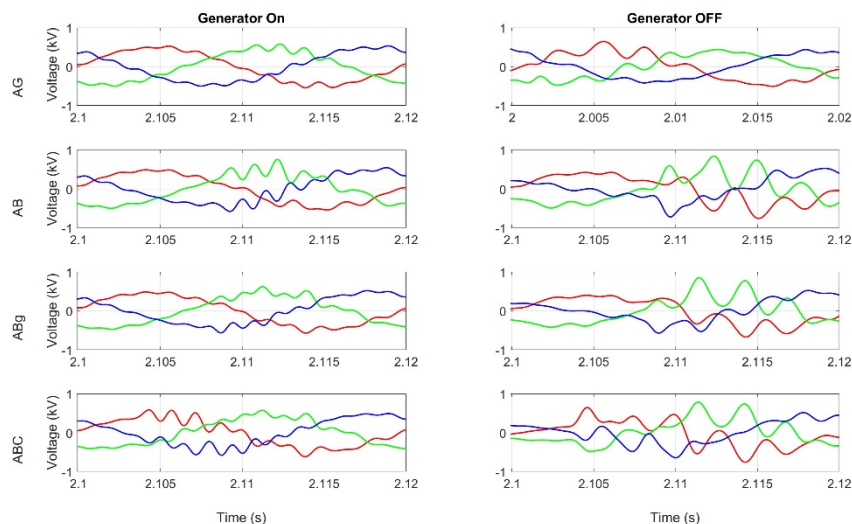


Figure 87. Comparison of transients at voltage-dip ending for the 525 V bus

4.7 SENSITIVITY ANALYSIS

4.7.1 Different fault locations

The voltage-dip transients have been calculated for different fault locations on the same 400-kV line. Figure 88 shows the results for a three-phase fault and the generator not in operation at 6-kV bus. There are some minor differences at the beginning of the dip, but at voltage-dip ending the initial oscillations are very similar. There are differences in the voltage waveform, for different fault locations, after the initial voltage-dip transient at dip ending.

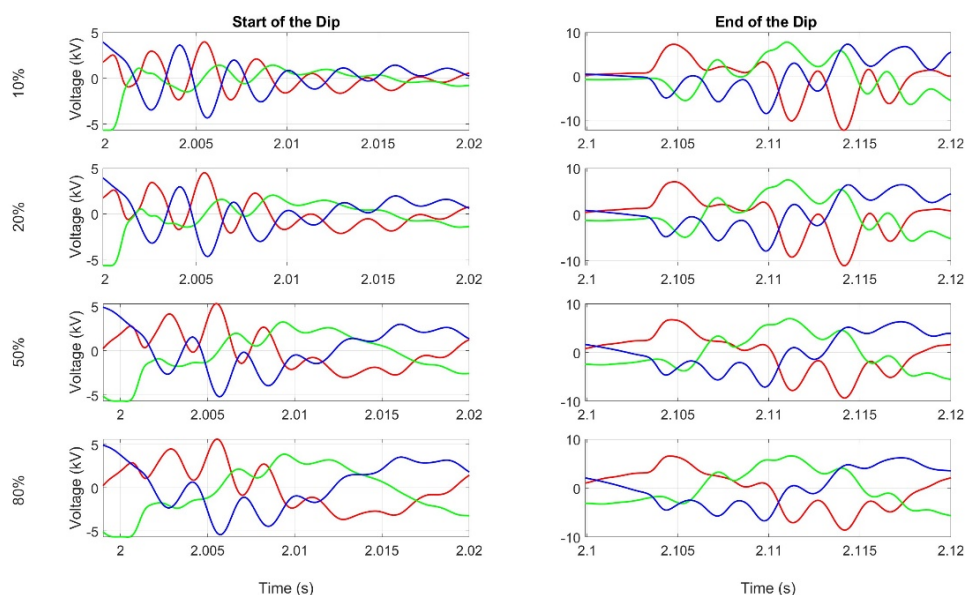


Figure 88. Voltage dip transients at beginning and ending of the dip for different fault locations, from Bus A.

4.7.2 Cable fault versus line fault

To obtain another comparison, a fault was modelled in the cable originating from Substation A in Figure 16, instead of in the line between Substation A and Substation B. The voltage-dip transients for the base case (fault in the line) have been compared with the voltage-dip transients due to a fault in the cable. In both cases a three-phase-to-ground fault occurred in the middle of the line or cable, and the generator was not in operation. Figure 89 compares the voltage-dip transients for the 6-kV bus. The oscillations are of higher amplitude for the cable fault, especially at voltage-dip ending.

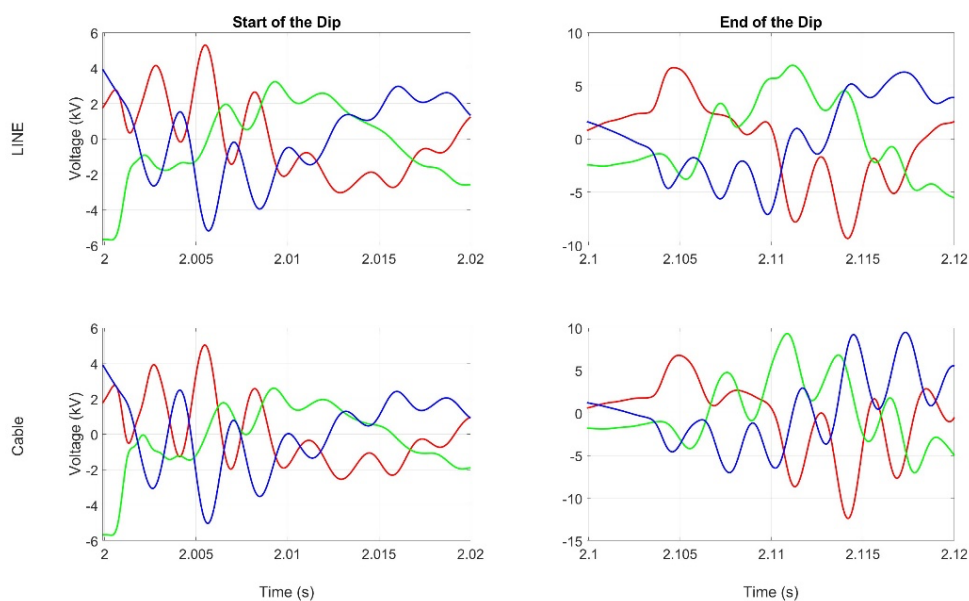


Figure 89. Voltage-dip transients at the 6-kV bus, at beginning and ending of the dip, for a cable fault and a transmission-line fault.

4.7.3 Add line to the system

Another comparison is shown in Figure 90 the base case is the one presented in the earlier sections. For the alternative case, an additional line is present in parallel with the line between Substation A and Substation B in Figure 16. A three-phase-to-ground fault was simulated, and the generator was out of operation. The comparison shows that the presence of an additional line results in lower amplitude for the oscillations with the voltage-dip transients.

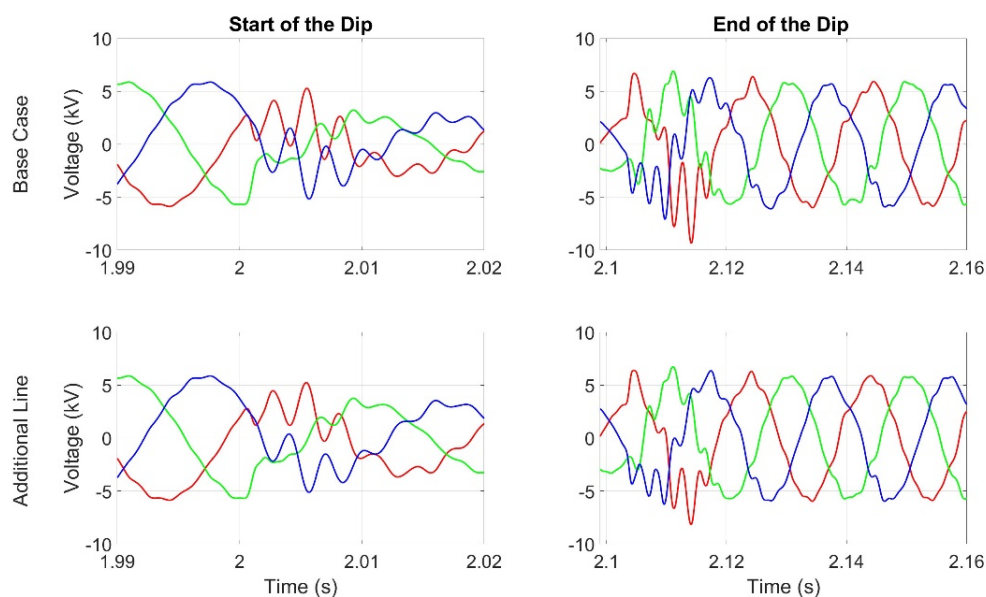


Figure 90. Voltage-dip transients at the 6-kV bus for the base case and for the case with an additional line in parallel with the faulted line.

4.7.4 Transformer saturation

Transformer saturation typically occurs during energizing of a non-loaded transformer. The current taken by a saturated transformer contains high levels of harmonics, where especially the even harmonics are much higher than during normal operation. The result is high harmonic voltage distortion, where the even harmonics are, again, much higher than during normal operation. Transformer saturation may also occur due to the voltage recovery at the ending of a voltage dip. For a fault in the transmission grid, multiple transformers may be saturated and emit even harmonic current distortion. The result is that high levels of even harmonic voltages may appear over a large geographical area and propagate to the lower voltage levels.

The level of saturation, and especially the time it takes for the voltage waveform to recover, depend strongly on the loading of the transformer. The lower the loading, the longer the saturation, and thus the voltage and current distortion, remains present. High levels of even harmonic distortion after a voltage dip are especially expected for faults appearing during the low-load periods at night. In systems with substantial amounts of solar power, load transformer loading may also occur during the day when solar power production and consumption downstream of a transformer are similar to each other. Modelling the transformer saturation

requires significant details of the transformer parameters, the transformer loading, and the network configuration. Below we will compare the simulation results, where only limited transformer saturation has been included in the model, and measurements of a case with major transformer saturation.

As a reference, Figure 91 shows the voltage waveform, after dip ending, due to a three-phase fault, for a standard case presented before. Some mild distortion due to transformer saturation is visible in the red phase, slightly after 2.12 s. The measurement results are shown in Figure 92 through Figure 95; much more severe distortion is visible in those recordings.

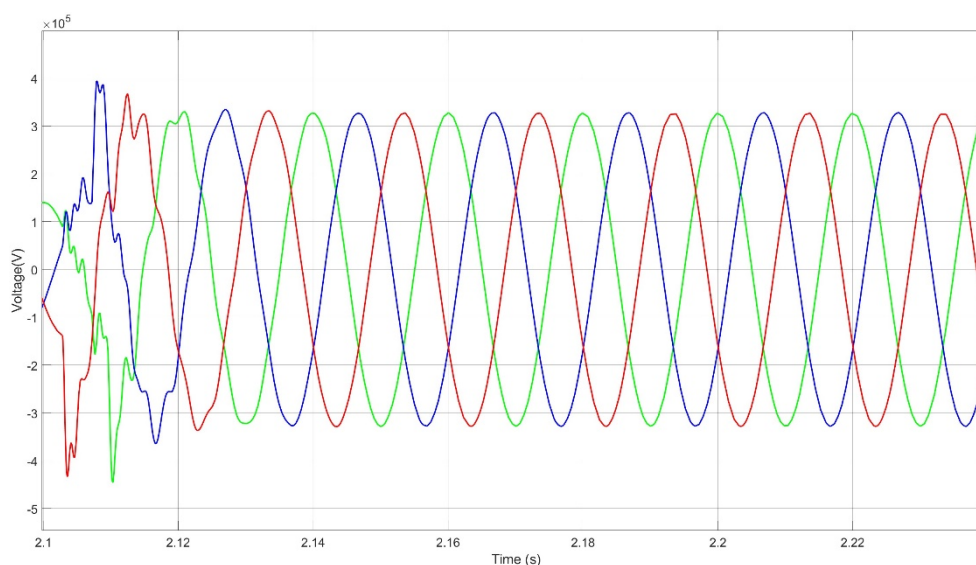


Figure 91. Voltage waveforms at primary side without considering the saturation; simulation results for a three-phase-to-ground fault in line 9.

The recordings are due to a fault occurring half an hour after midnight in the night between Tuesday and Wednesday, during Autumn 1999, somewhere in the Swedish west coast. This voltage dips due to this event were recorded at 400 V, 10 kV and 132 kV and described in detail in [116]. The recordings at 10 kV are shown in Figure 92 through Figure 95.

The fault occurred as a two-phase-to-ground fault, followed by a single-phase-to-ground some 500 ms later during the automatic reclosing. The first dip, due to the two-phase-to-ground fault, is shown in Figure 92. Voltage-dip transients are visible at voltage-dip beginning and voltage-dip ending. The latter one is of small amplitude. After the voltage-dip ending transient waveform distortion remains. This waveform distortion contains a significant even-harmonic component, which is visible because the waveform distortion is not symmetrical between the two half cycles.

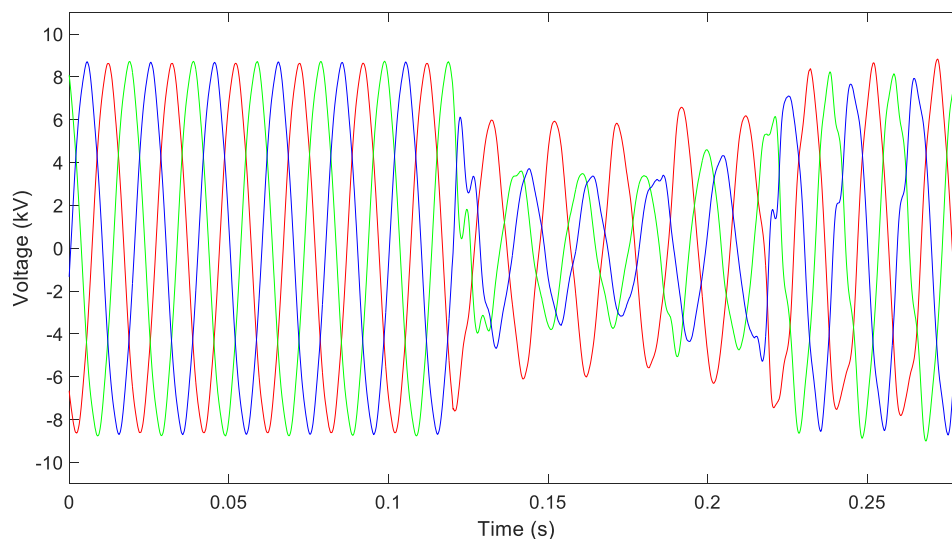


Figure 92. measured voltage dip, at 10 kV, due to a two-phase-to-ground fault at 400 kV.

The voltage dip due to reclosing (single-phase-to-ground fault) is shown in Figure 93 and with higher time resolution in Figure 94 and Figure 95. Before the start of the second dip, i.e. some 500 ms after the end of the previous dip, there is still a clearly noticeable even-harmonic distortion present in the voltage. The voltage recovery of this second dip results in additional transformer saturation, which is visible from the increased even-harmonic distortion in Figure 95. Looking back at Figure 93 shows that this increased distortion remains present till beyond the end of the recording.

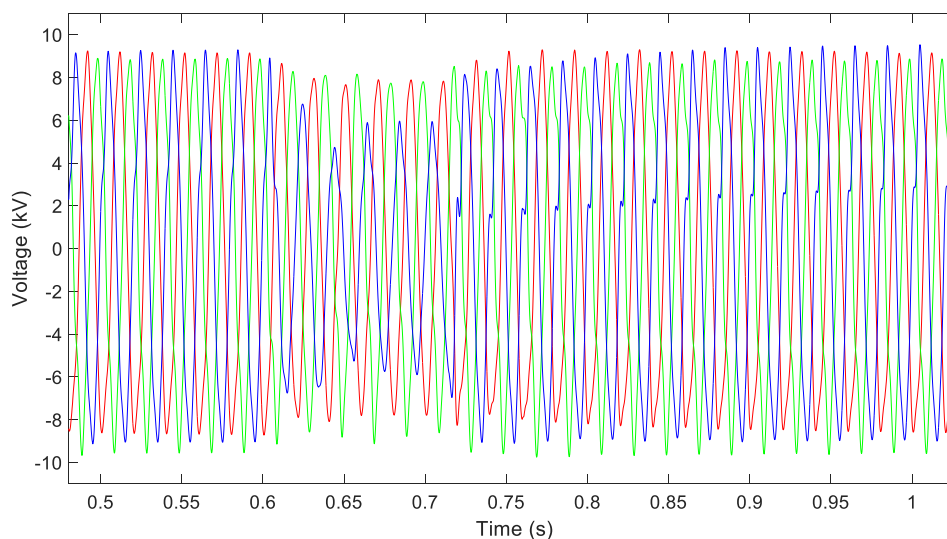


Figure 93. Measured voltage dip, at 10 kV, due to a single-phase-to-ground fault at 400 kV, occurring some 500 ms after the one in Figure 92.

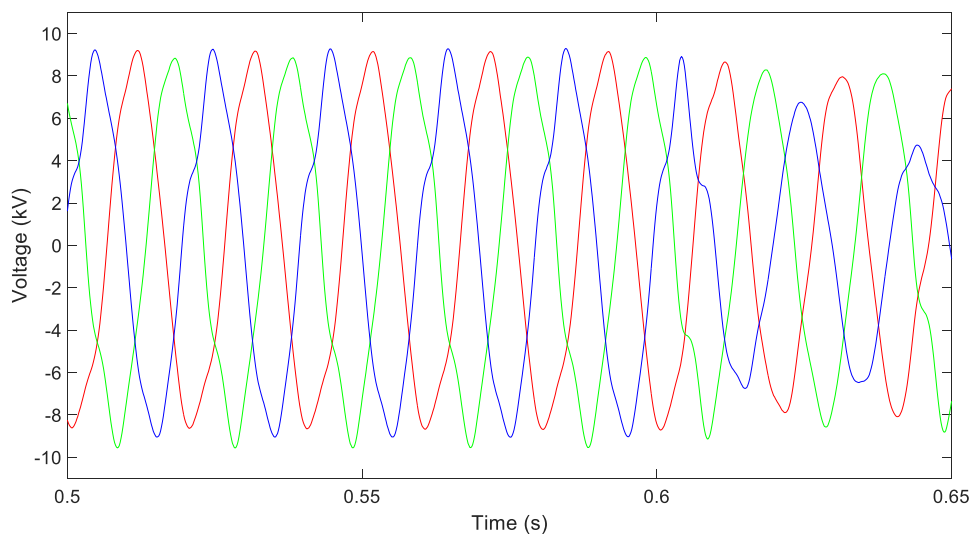


Figure 94. Details of the pre-fault waveform and the fault initiation (voltage-dip beginning) of the dip in Figure 93.

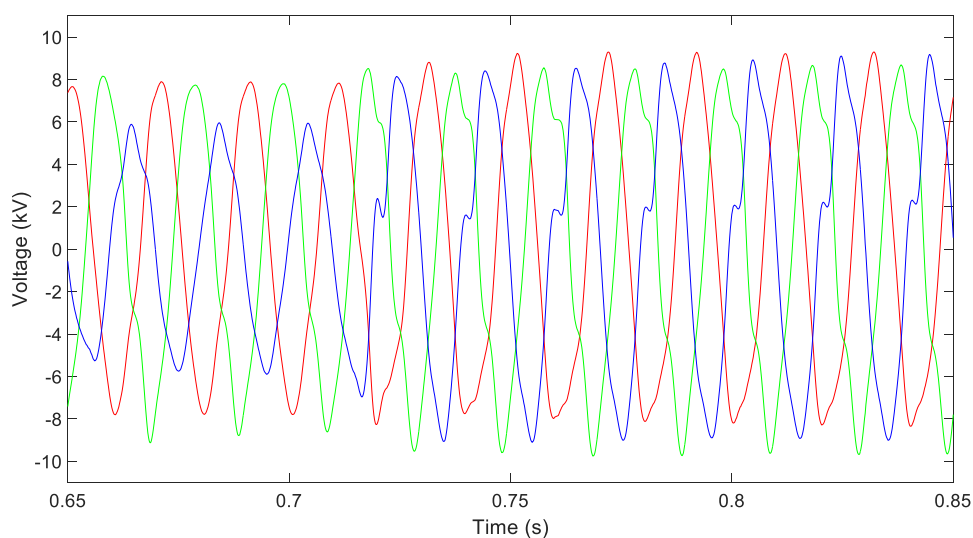


Figure 95. Details of the voltage recovery (voltage-dip ending) for the dip in Figure 93.

4.8 IMPEDANCE-EARTHED SYSTEMS

The system earthing (also known as neutral-point earthing) impacts the fault current and voltage dip due to earth faults. The main impact is for single-phase-to-ground faults. In a solidly-earthed system (like the 400-kV grid), the fault current is similar for a three-phase fault as for a single-phase fault. After propagation to lower voltage levels, a major voltage drop remains due to a single-phase fault, in one or two phases, depending on the transformer winding connections.

In a non-solidly earthed system (also known as impedance-earthed system) the fault current due to a single-phase-to-ground fault is much smaller than for a three-phase fault. A single-phase fault results in a voltage drop in the faulted phase

and voltage rises in the non-faulted phases. After propagation to lower voltage levels, there is only a minor drop in one or two phases, which is often not detected by any monitor. The limited impact of single-phase faults on rotating machines, even those connected to the voltage level at which the fault occurs, is a major advantage of such system earthing.

This reasoning holds for the 50-Hz component of the voltages and currents, but no information was found in the literature about the propagation of voltage-dip transients to lower voltage levels for faults in impedance-earthed systems. To obtain a first impression of this propagation, a simple 70/20-kV grid was modelled using DigSilent PowerFactory and a single-phase-to-ground fault was applied in this model. The grid studied is shown in Figure 96; the voltages in one of the 70-kV substations are shown in Figure 97; the voltages at 20 kV are shown in Figure 98. Neither the transients, not the 50-Hz component propagate to the lower voltage level, in this model. As a rather simple model was used, for example not covering the asymmetry in the 70-kV grid and in the 70/20-kV transformer, and neither the details of the fault detection and clearing, this conclusion is preliminary. Either detailed simulations or appropriate measurements on both sides of a transformer could be way of confirming this preliminary conclusion.

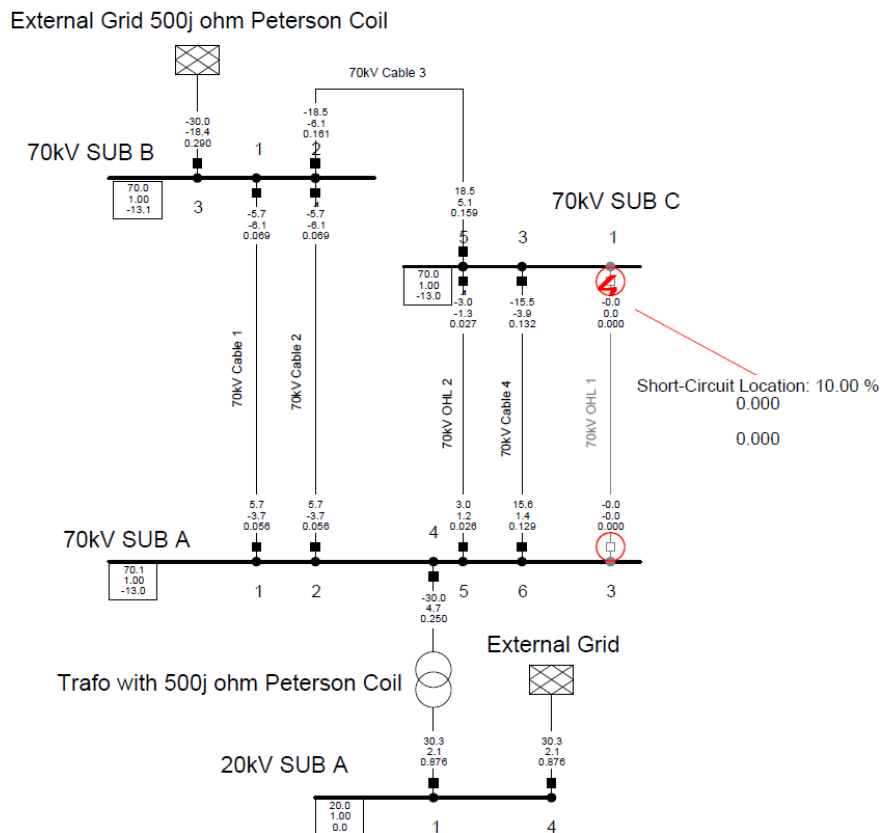


Figure 96. Example network, 70 kV and 20 kV.

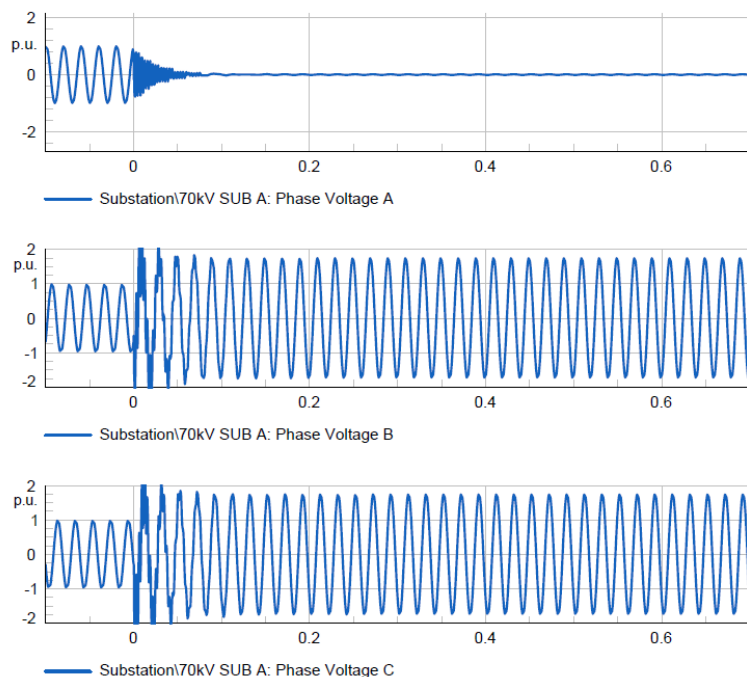


Figure 97. Simulated voltage, at 70 kV, during a single-phase-to-ground fault at 70-kV.

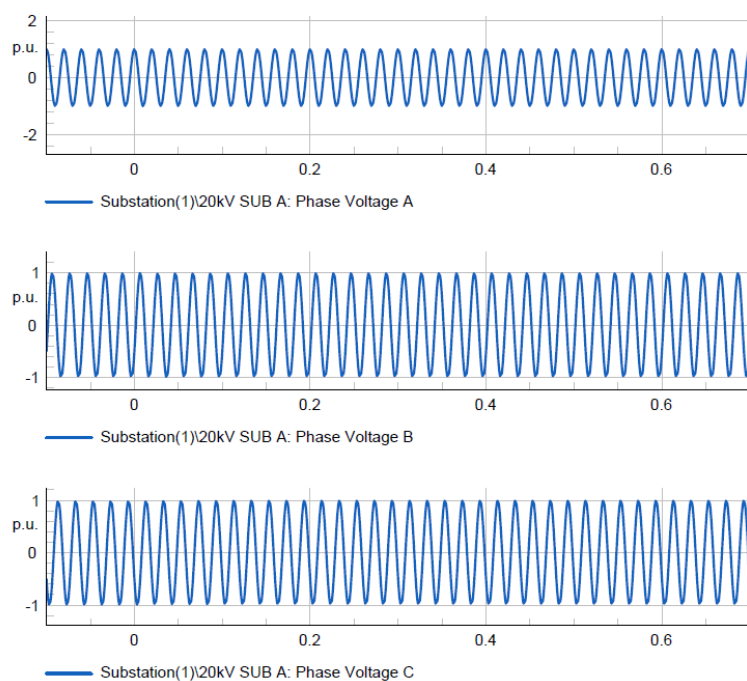


Figure 98. Simulated voltage, at 20 kV, during a single-phase-to-ground fault at 70-kV.

4.9 DISCUSSION OF THE RESULTS

An important finding from the results presented in this chapter is that voltage dips due to faults are associated with voltage-dip transients at beginning and ending of the dip. The study also shows that the frequency and amplitude of the oscillations are different for different types of faults, different fault locations, different grid configurations, and different voltage levels. It was shown that the amplitude of the oscillations at the terminals of grid-connected equipment can be bigger than the amplitude in the transmission grid.

The voltage-dip waveforms that were presented in this chapter, are based on a simplified version of the Swedish transmission grid, and on a simplified model of the auxiliary grid. To obtain insight in the actual frequency and amplitude of the oscillations with the voltage-dip transients, much more detailed and accurate models are needed. Recommendations on what to include in the models are presented and discussed in Section 7.1.

Certain aspects of the voltage-dip waveform have been modelled not at all or very limited in the study presented here. Transformer saturation upon voltage recovery will result in an extended period with higher harmonic voltage distortion. Including this requires accurate modelling of the non-linear characteristics of transformers. This has not been included in this study, as the emphasis has been on the voltage-dip transients. An example is shown in Section 4.7.4 to illustrate the kind of waveforms that can be expected due to severe transformer saturation after a voltage dip.

Some of the voltage-dip waveforms show increased harmonic distortion during the actual dip. This distortion is due to the impact of the reduced voltage magnitude on the current distortion from grid-connected equipment. An accurate reproduction of this during-dip distortion requires accurate models of the grid-connected equipment. This has not been included in this study, as the emphasis has been on voltage-dip transients, but also because such models for equipment are not generally available.

All the faults studied in this report occurred in the solidly-earthed 400 kV grid. Voltage dips and voltage-dip transients due to earth faults in non-solidly earthed systems propagated differently. From the simulations shown in Section 4.8 it was concluded that such transients do not propagate, in a significant amount, to lower voltage levels.

5 Impact of voltage dips and voltage-dip transients on equipment

In this chapter, the impact of voltage-dip on auxiliary equipment is studied. Three specific dips are used for this:

- The voltage dip at the 525-V bus in the auxiliary grid due to a three-phase fault occurring on 400-kV Line 9, at the midpoint (50% of the line's length), when the nuclear generator is off. The voltage-dip waveform is obtained from the simulations presented in Chapter 4. It is referred to as “simulated dip” and used to study the impact on induction motors and converters.
- The voltage dip at the 6-kV bus during the same fault, again obtained from the simulations presented in Chapter 4. It is referred to as “simulated dip” and used to study the impact on synchronous motors.
- A synthetic dip with similar residual voltage and duration as the simulated dip; the voltage waveform does not contain any harmonic components, and the voltage magnitude is constant during the dip; after the dip, the voltage recovers instantaneously to its pre-dip value. This voltage dip is referred to as “synthetic dip” and used for all equipment,

5.1 INDUCTION MOTORS

The induction motor analyzed in this study is a modified model available in DIgSILENT PowerFactory. The motor has a rated voltage of 525 V, is connected to the 525-V bus and is part of the auxiliary equipment for the nuclear generator. The detailed parameters of the motor are provided in Table 12.

Table 12. Electric Parameters of the induction motor

Parameter	Value
Rated voltage	525 V
Rated Mechanical Power	7 kW
Connection	D
Rotor	Single cage
Stator reactance (X_s)	0.01 p.u.
Mag.reactance (X_m)	4 p.u.
Rotor resistance (R_rA)	0.01 p.u.
Rotor reactance (X_rA)	0.1 p.u.
Active Power	7 kW
Reactive power	3.09 kvar

The impact of a voltage dip on an induction motor is shown in Figure 99. The voltage dip is synthetically generated, with an instantaneous drop in voltage magnitude, constant voltage magnitude before, during and after the dip, and an instantaneous voltage recovery. The voltage dip starts at voltage maximum in the red phase and ends 5 cycles later. Residual voltage and duration are selected similar to those for a voltage dip resulting from a simulation, to be discussed

below. Note that the figure showing the voltage-dip waveform has a different horizontal scale than the other three figures.

The electrical torque shows 50-Hz oscillations during the voltage dip. After the voltage recovery, a slower oscillation remains returning the torque to its pre-dip value in about 10 cycles. The rotor speed shows a quick drop at the beginning of the dip, oscillations during the dip, and recovery after the dip ends. The amplitude of the speed oscillations depends on the total inertia of motor and mechanical load. The same oscillations as in electrical torque and rotor speed are also present in the rotor current.

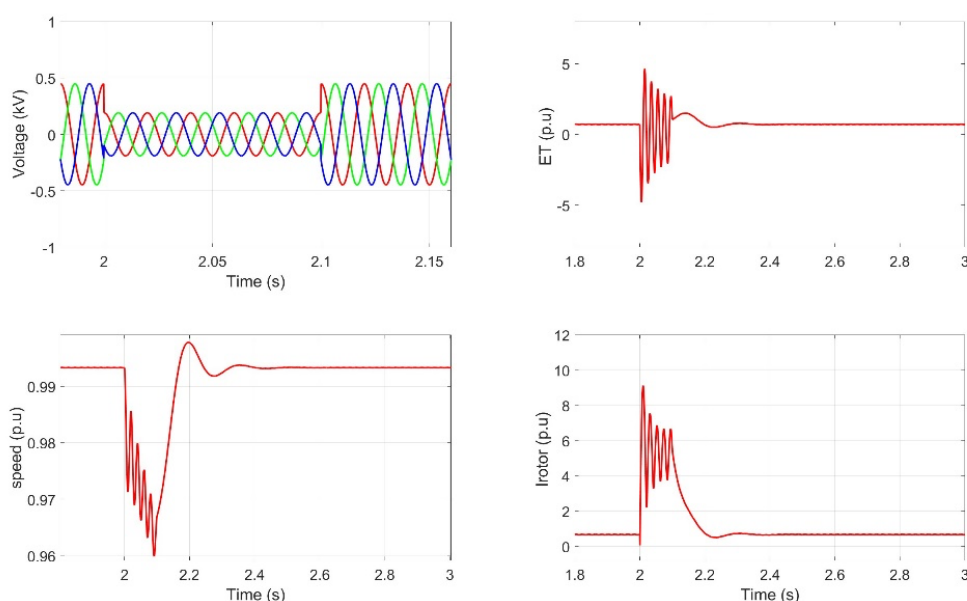


Figure 99. Impact of synthetic voltage dip on an induction motor; voltage-dip waveform (top ← left); electric torque (top right →); rotational speed (bottom ← left); rotor current (bottom right →).

The calculations resulting in Figure 99 have been repeated for a voltage dip resulting from one of the simulations presented in Chapter 4. The simulated dip has similar residual voltage and duration as the synthetic dip; the results for the simulated dip are shown in Figure 100. The simulated voltage dip (top left) shows strong oscillations at the beginning and ending of the dip. There is also voltage distortion before and during the dip and severe voltage distortion after the dip.

The oscillations in electrical torque are stronger during the dip (note the difference in vertical scale compared with the previous figure). Also, the oscillations in rotor current are stronger for the simulated dip; the oscillations in speed are smaller, during the dip, for the simulated dip. Apart from the differences in amplitude, the oscillations during the dip are similar for the synthetic and the simulated voltage dip.

After voltage recovery, the results are completely different; the oscillations in electrical torque, rotor speed, and rotor current continue for about one second. The oscillations in electrical torque, over such a long period, could result in mechanical damage. If a second dip would occur within one second from the first one, the mechanical impact could be especially severe. The most likely reason for a second dip is automatic reclosing.

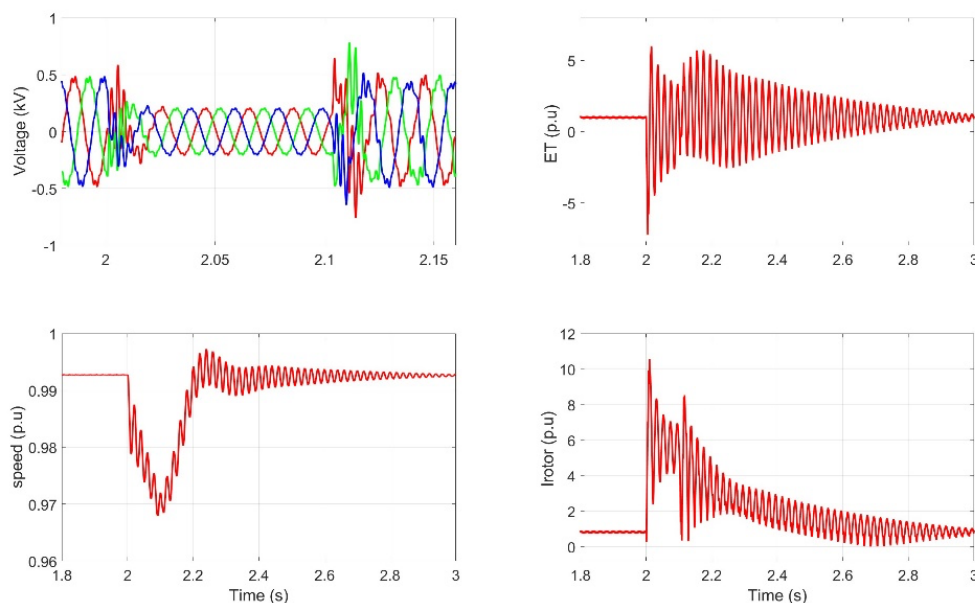


Figure 100. Impact of simulated voltage dip on an induction motor; voltage-dip waveform (top ← left); electric torque (top right →); rotational speed (bottom ← left); rotor current (bottom right →).

5.2 SYNCHRONOUS MOTORS

The calculations have been repeated for a synchronous motor. The investigated synchronous motor is connected to Bus B6V(1) in the auxiliary supply; this bus has rated voltage of 6 kV. The motor parameters are presented in Table 13; the results are shown in Figure 101 and Figure 102. The q-axis flux is shown instead of the rotor current.

Table 13. Electric Parameters for the Synchronous Motor

Parameter	Value
Nominal Apparent Power	87.5 kVA
Nominal Voltage	6 kV
Power Factor	0.85
Connection	YN
Stator reactance (x_l)	0.172 p.u.
Active Power	87.5 kW
Reactive Power	52.5 kvar
Zero sequence reactance (x_0)	0.1 p.u.
Negative sequence reactance (x_2)	0.2 p.u.

In a synchronous machine, the q-axis flux is fundamental to torque production and the management of the machine's reactive power behavior. Torque is generated by the interaction between the d-axis and q-axis flux components, with the q-axis flux being produced by the q-axis component of the stator current. This flux directly influences the electromagnetic torque of the machine.

Reactive power control in synchronous machines is achieved by adjusting the field excitation (d-axis) and the q-axis stator current. By varying the q-axis flux through

changes in the stator current, the reactive power exchange between the machine and the electrical grid can be effectively regulated.

The observations for the synchronous motor are similar to the ones for the induction motor. During the voltage dip, oscillations occur both for the synthetic dip and for the simulated dip. The amplitude of the oscillations in electrical torque, during the dip, is higher for the simulated dip. After the synthetic dip, the torque shows a slow oscillation for the electrical torque. After the simulated dip, high-amplitude oscillations at 50 Hz are superimposed on the slow oscillation.

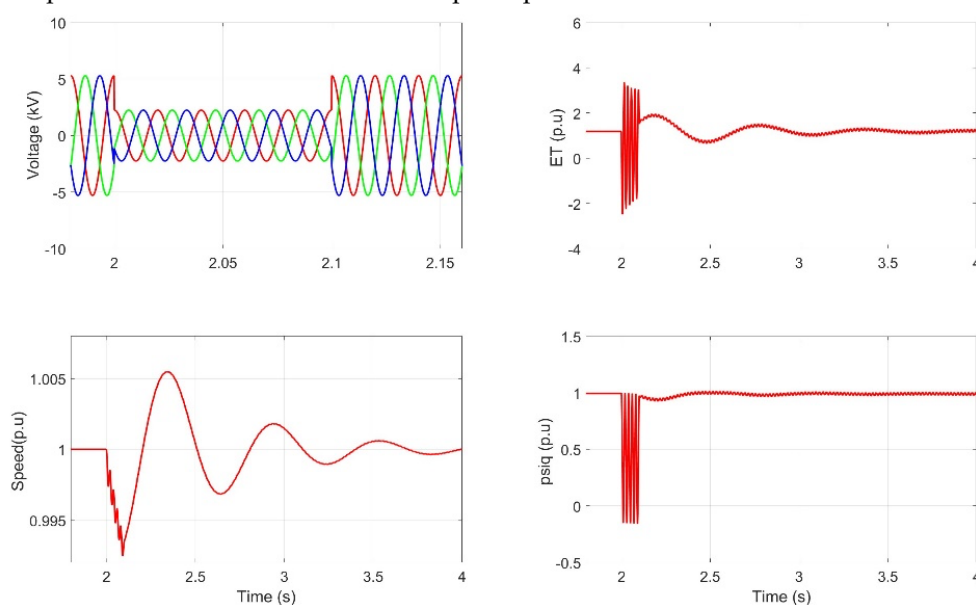


Figure 101. Impact of synthetic voltage dip on a synchronous motor; voltage-dip waveform (top ← left); electric torque (top right →); rotational speed (bottom ← left); q-axis flux (bottom right →).

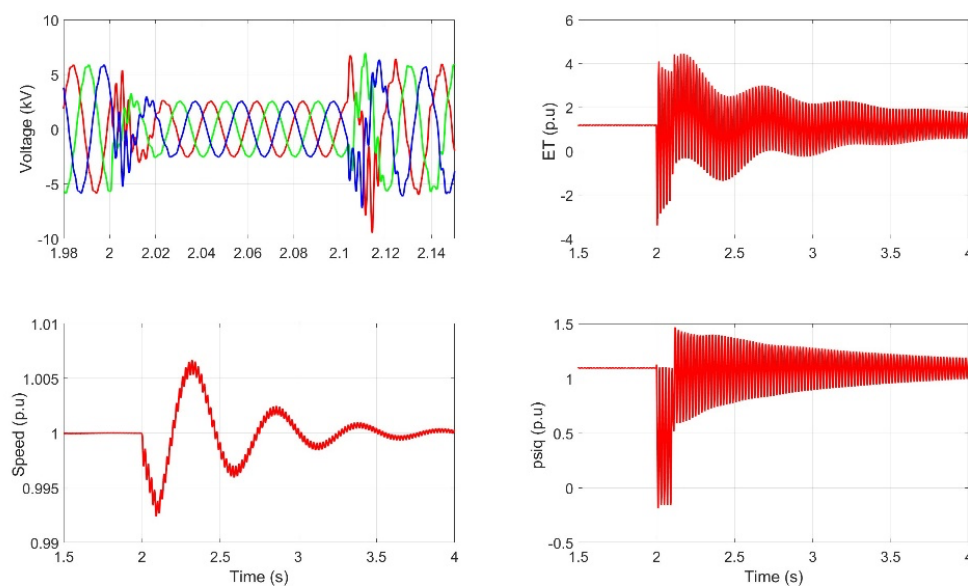


Figure 102. Impact of simulated voltage dip on a synchronous motor; voltage-dip waveform (top ← left); electric torque (top right →); rotational speed (bottom ← left); q-axis flux (bottom right →).

5.3 DIODE RECTIFIERS FOR THREE-PHASE ADJUSTABLE-SPEED DRIVES

A simplified model for a 12-pulse rectifier is used to investigate the impact of voltage dip transients on diode rectifiers. The model consists of a three-phase three windings transformer, 12 diodes, and an R-L (resistance – inductance) series connection on the dc side of the rectifier. As there is no dc-side capacitor present, the rectifier behaves like a “constant dc-current” device. The model parameters are presented in Table 14.

Table 14. Diode rectifier parameters

Transformer	
Transformer connection	D1-Y-D11
Nominal Power	500 kVA
Winding 1, Ph-Ph(Vrms)	525 V
Winding 2, Ph-Ph(Vrms)	250 V
Winding 3, Ph-Ph(Vrms)	250 V
Diodes Parameters	
Resistance Ron	0.001 Ω
Forward Voltage Vf	0.8 V
Load Parameters	
Resistance	50 Ω
Inductance	650 mH

The results are shown in Figure 103 for the synthetic voltage dip and in Figure 104 for the simulated dip. Because of the inductive character of the dc-side load (“constant dc current”), the dc-side current gradually decays from its pre-dip value to its during-dip value. The amplitude of the ac-side current decays and recovers in a similar way. The dc-side voltage drops and recovers instantaneously, due to the absence of a dc-side capacitor.

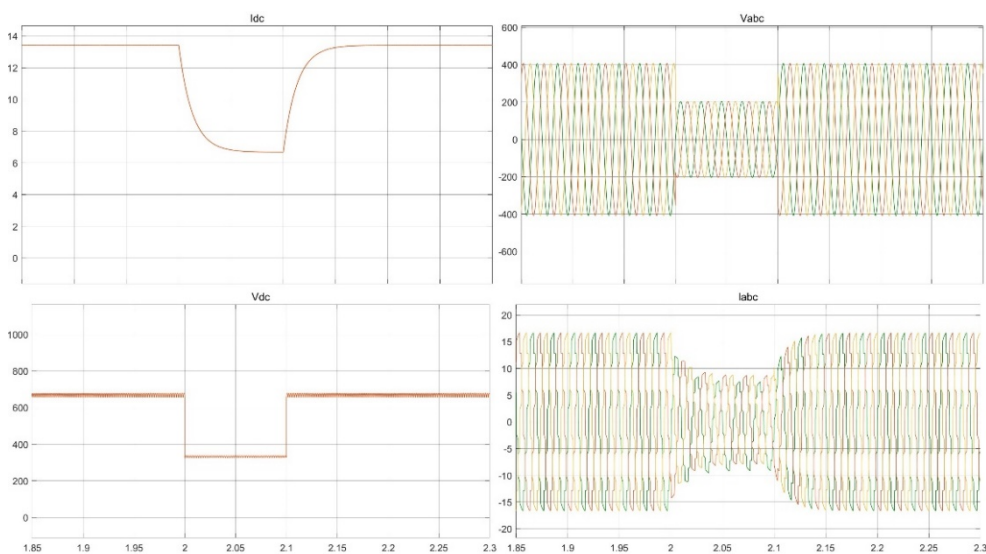


Figure 103. Impact of synthetic voltage dip on a diode rectifier; DC current (top $\leftarrow$ left); three phase AC voltage (top right $\rightarrow$); DC voltage (bottom $\leftarrow$ left); three phase AC current (bottom right $\rightarrow$).

The simulated dip (Figure 104) shows a similar decay and recovery for dc-side current and amplitude of ac-side current. The oscillations due to the voltage-dip transients are also visible in the ac-side current and during the recovery of the dc-side current. The amplitude of those oscillations is small, and they do not cause any overcurrents.

The oscillations in dc-side voltage are more severe and cause overvoltages of about 1.5 pu at the ending of the voltage dip. Such overvoltages could damage converter components and/or cause the protection to trip the converter.

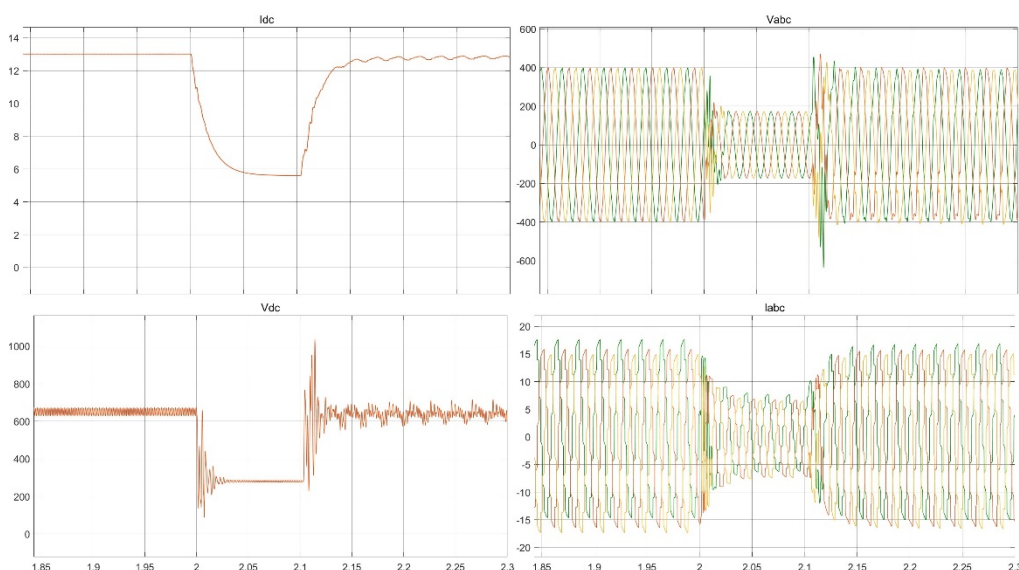


Figure 104. Impact of simulated voltage dip on a diode rectifier; DC current (top ← left); three phase AC voltage (top right →); DC voltage (bottom ← left); three phase AC current (bottom right →).

5.4 RECTIFIERS WITH ACTIVE FRONT END

A Simulink model of a MOSFET rectifier with active front end has been used in this study. The PWM block used is the standard one in the Simulink library. The complete parameters of the model are presented in Table 15.

Table 15. Parameters of Rectifier with active front end

Mosfet	
FET resistance (R_{on})	0.1 Ω
Internal Diode resistance (R_d)	0.01 Ω
Source impedance	
Resistance	1 Ω
Inductance	1 μH
Load Parameters	
Resistance	50 Ω
Inductance	650 mH
Converter side capacitor	720 μF

The results are shown in Figure 105 for the synthetic dip and in Figure 106 for the simulated dip. The ac-side current shows strong high-frequency components due to the switching of the active converter. These are in practice removed by an EMC filter; such a filter has not been included in the model used here. The dc-side voltage and ac-side current amplitude show a fast drop and recovery; the dc-side current follows the steps in ac-side voltage magnitude with a certain delay.

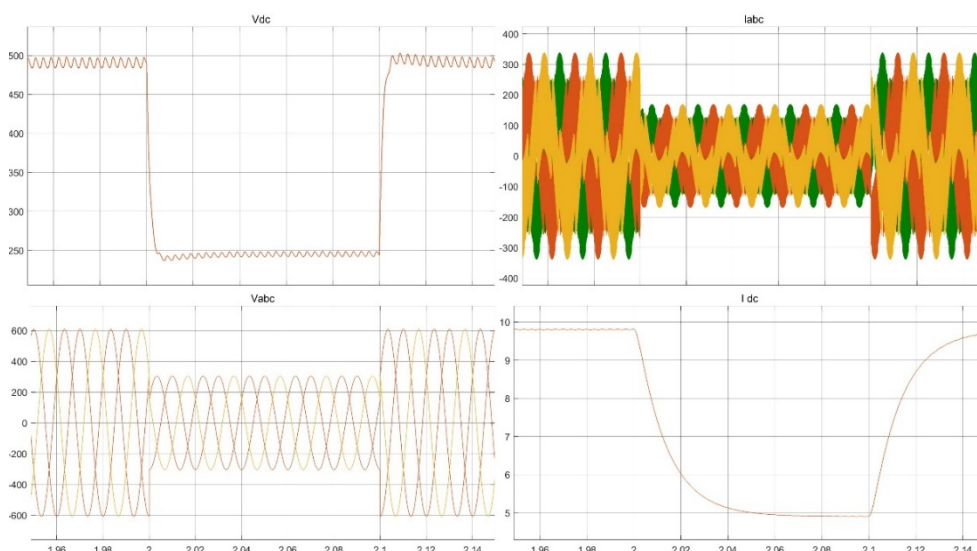


Figure 105. Impact of synthetic voltage dip on a rectifier with active front end; DC voltage (top $\leftarrow$ left); three phase current (top right $\rightarrow$); three phase voltage (bottom $\leftarrow$ left); DC current (bottom right $\rightarrow$).

The oscillations due to the voltage-dip transient are visible in dc-side voltage and ac-side current. The oscillations give overvoltage and overcurrent; this can result in equipment damage and/or protection tripping.

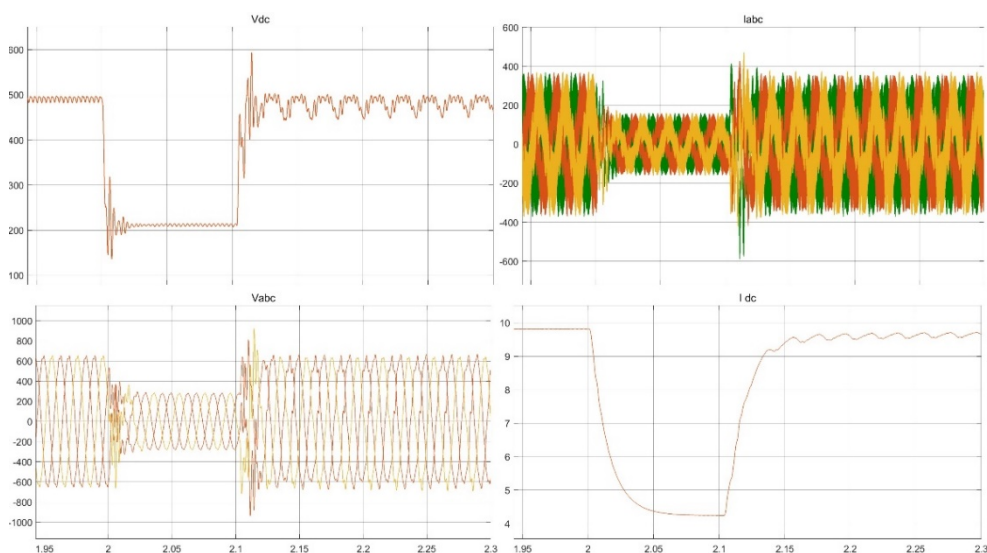


Figure 106. Impact of simulated voltage dip on a rectifier with active front end; DC voltage (top $\leftarrow$ left); three phase current (top right $\rightarrow$); three phase voltage (bottom $\leftarrow$ left); DC current (bottom right $\rightarrow$).

5.5 PROTECTION RELAYS

The aim of the power-system protection is to intervene when there is a fault or another seriously-unwanted situation in the grid or in equipment connected to the grid. Where it concerns the potential impact of voltage-dip transients on power-system protection, it is important to distinguish between protection for faults occurring in the grid and protection to avoid equipment damage.

Most of the work and studies on power-system protection concerns protection whose aim it is to limit the impact of a fault. Faults are associated with large currents and/or low voltage magnitude and therefore relatively easy to detect. This kind of protection does not actually protect against faults but limits the consequences of faults. Faults do however have a rather severe impact, and the protection must therefore react very fast. The need for protection coordination and fast backup protection makes that the protection must dependably detect a fault even faster. Detection times, between the occurrence of the fault and the relay sending a tripping signal to a circuit breaker, can be as short as one or two cycles (20 – 40 ms). This high speed makes that certain assumptions are needed within the relay algorithm when deciding about generating a tripping signal or not. The presence of voltage-dip transients may make that these assumptions no longer hold, and the relay may make the wrong decision. For protection relays in the auxiliary grid or in the radial transmission line to the nuclear power station, the concern are unwanted trips. The oscillations in voltage (what we call the voltage-dip transients in this report) will result in oscillations in current. Together these two could make that the relays wrongly concludes that there is a fault that requires immediate intervention causing the unwanted tripping of individual devices or large parts of the auxiliary supply. This is where, again, resonances should be considered. The simulations in the earlier chapter showed higher amplitude of the voltage oscillations due to resonances. These resonances typically also result in higher amplitude current oscillations. Many protection principles are current-based, so that these oscillations must be considered when studying the impact of voltage-dip transients on protection relays.

A literature search on protection mal-trip due to transients did not provide use relevant information. There are however similarities to be expected between the sensitivity of protection relays against (voltage-dip) transients and their sensitivity against harmonics. The impact of harmonics has been studied by some authors [113, 114, 115]. The main challenge, for a user of the relays, is that the impact of the voltage-dip transients depends strongly on the details of the implementation of the protection algorithm in the relay. This may vary between different manufacturers and details may be hard to obtain. Still, a recommendation is to investigate this in more detail, for example using generic protection-relay models. Next to that, existing protection relays may be exposed to recorded waveforms, including those following from simulations of extreme cases.

The situation with the protection of equipment (for example motor protection or the protection of a power-electronics drive) is rather different. The aim of such a relay is to protect a device (the motor in the example) against damage. A range of protection functions is present with modern equipment. Overcurrent protection is one such function, which we will use here to illustrate.

Overcurrent protection trips the device to be protected once the current exceeds a specific value for longer than a specific duration. The protection may use rms current or instantaneous current, the basic principle remains the same. The setting of the thresholds is a trade-off between:

- The risk of tripping the device if no damage would occur when it would not be tripped (unnecessary trip).
- The risk of not tripping a device when damage will occur (fail-to-trip).

Most guidelines for protection setting put strong emphasis on the second one, as that is obviously the task of the protection. That may however, as this is a trade-off, result in a high probability that a device trip was not necessary. How high this probability is, depends on a lot of local details, on device sensitivity, and more. No general comments can be made about this.

Voltage-dip transients can have two types of impacts on the operation of the protection. They can result in voltage or current values that damage the device. In that case, tripping of the device by the protection is necessary, despite the adverse consequences of the device being tripped. To avoid these adverse consequences, devices are needed that are more tolerant against voltage-dip transients.

Voltage-dip transients can also result in voltage and current values that cause the device to be tripped whereas that may not have been necessary. Those are unwanted trips that can be avoided by changing the settings of the protection. Those changed protection settings may however increase the risk of damage to the device due to other events.

The protection of individual devices in the auxiliary supply can also make incorrect decisions because of the voltage-dip transient, in the same way as mentioned before with the protection to remove faults in the grid. This again depends strongly on the details of the way in which the protection algorithm is implemented.

The EMC filter, present with most power-electronic converters, is an important component to be included in studies after the impact of voltage-dip transients on protection relays. The configuration of the filter (for example CLC or LCL) plays an important role here. The filter may amplify the current oscillations or amplify the voltage oscillations. The oscillations detected by the grid-side protection relay may be rather different from the one that the device is exposed to. That will make it more difficult for the relay to make the correct decision.

The main challenge here is the appearance of new types of equipment, power-electronic drives based on voltage-source converters, where individual devices can differ quite a lot in the details. Both the sensitivity of the device to voltage-dip transients and the current oscillations due to a voltage-dip transient will differ between individual devices. That may make it difficult to draw general conclusions about the above-mentioned balance for such equipment.

5.6 OBSERVATIONS

Simulations are presented in this chapter of four different auxiliary devices; an induction motor; a synchronous motor; a 12-pulse diode rectifier and a 6-pulse VSC-rectifier.

The voltage-dip transients result in torque oscillations lasting much longer for both the induction motor and the synchronous motor. This could result in increased wear on the mechanical side and in excess heating of the motor. For the latter, the building of hot-spots due to the high-frequency oscillations could have a major impact. Voltage-dips with severe voltage-dip transients are however not expected to occur very often (note that the most severe case has been used for the simulated dip), so that the impact will still be limited. Induction and synchronous motors have also been around for many years and thus been exposed to voltage dips and voltage-dip transients for many years. Cases of premature failure of electrical motors or the mechanical load driven by them, should still be investigated to determine if severe voltage-dip transients could have been the cause. Overall, the conclusion of the authors is that voltage-dip transients are not a serious concern for induction motors and synchronous motors.

The voltage-dip transients also result in overvoltage and overcurrent for both types of rectifiers. This could result in damage to equipment and/or tripping of the rectifiers. Which one is more likely to happen, depends on the protection setting. In most cases, the protection is set rather sensitive to avoid equipment damage. This will however increase the probability of tripping of the rectifier.

Two simplified rectifier models have been used, to illustrate the impact. Modern rectifiers come in different forms, especially where it concerns the details of configuration and control system. The impact of voltage dips and voltage-dip transients is likely to be different for different rectifiers and rectifier-specific studies are recommended. The authors see a potentially serious impact of voltage-dip transients on power-electronic converters especially because of the diversity in behavior for different individual devices. The lack of knowledge is a serious concern.

The impact of voltage-dip transients on protection relays will depend strongly on the details of the relay and on the application of the relay. Information on the details of the relay requires collaboration with relay manufacturers. The authors see as the major concern the behavior of relays used for the protection of power-electronic converters. The above-mentioned lack of knowledge also holds here.

6 Other voltage disturbances

This report focuses on voltage dip transients during the starting and ending of voltage dips due to transmission-system faults. However, also other power system phenomena potentially impact the performance of the auxiliary equipment in a nuclear power plant. Furthermore, other characteristics of voltage dips, beyond residual voltage, dip duration, and voltage-dip transients, could have an impact. This chapter briefly introduces those other disturbances and characteristics.

6.1 HIGH LEVELS OF EVEN HARMONICS DUE TO GEOMAGNETICALLY INDUCED CURRENTS

When there is a “coronal mass ejection”, the plasma that leaves the solar surface hits the Earth’s magnetosphere, compresses it and results in changes in currents through the magnetosphere and ionosphere. These currents result in the northern lights (and southern lights for our antipodes) and show oscillations at time scales of minutes. Those oscillations induce currents, with equally low frequencies, in long overhead power lines and other long conducting installations. These currents are called geomagnetically-induced currents (GIC). GIC has been a concern for different installations in high latitudes, such as electricity transmission networks, oil and gas pipelines, railway grids, and communication networks.

GIC results in half-cycle saturation of transformers, making them trip or in some cases even be damaged. When the transformer undergoes half-cycle saturation, both odd and even harmonics are generated resulting in increased levels of harmonic voltage distortion over a large geographical area. Although both odd and even harmonics are impacted, the phenomenon is best observable through the even harmonics. Their levels are very low normally, whereas they reach easily detectable levels during GIC.

The voltage spectrum during GIC is similar to the voltage spectrum during transformer energizing, with some differences. GIC typically lasts longer than transformer energizing, and large GIC amplitudes can increase the saturation level of transformers. Thus, low GIC frequencies can cause the simultaneous saturation of transformers throughout a large part of the transmission grid. Furthermore, the harmonic distortion emitted by the transformer can cause cascade problems due to the possibility of unwanted trip of protection, further impacting the operational security of the transmission grid.

The most severe reported event was Canada’s collapse of the Hydro-Quebec power grid during a geomagnetic storm on 13th March 1989. The GIC originated due to the geomagnetic storm that resulted in the spread of transformer saturation within a few minutes, causing a power outage that lasted about nine-hours. Another example is the geomagnetic storm in the Swedish high-voltage power system between the 29th and 31st of October 2003. The storm, also known as the “Halloween storm,” caused an outage in part of southern Sweden’s power transmission system. The outage lasted for an hour and left about 50,000 customers without electricity. The leading cause was the unwanted tripping of circuit

breakers for several power lines and transformers due to the high harmonic content.

More recently, a severe geomagnetic disturbance (solar storms) occurred over Sweden between Friday 10 May and Sunday 12 May 2024. The Kp-index (a measure of the geomagnetic activity over a three-hour period) was high (7 or higher) for 11 consecutive three-hour periods. The geomagnetic activity resulted in auroral activity (northern lights) visible over the whole of Sweden and the detection of geomagnetically-induced currents with at least one transformer connected to the transmission grid. It also was the likely cause for the tripping of an HVDC link.

The relevance of geomagnetically-induced currents for auxiliary equipment in nuclear power station is much indirect. Geomagnetically-induced currents result in transformer saturation, which in turn results in increased levels of harmonic voltages and currents. The increased levels of harmonic voltages propagate to lower voltage levels and can even be measured at the wall outlet with domestic customers. The increase is especially visible with even harmonics, as those levels are typically very low. The phenomenon is described in detail among others in [75]-[77]. The even harmonics during a one-hour period of the May-2024 solar storm, measured at a wall outlet somewhere in Gothenburg, are shown in Figure 107.

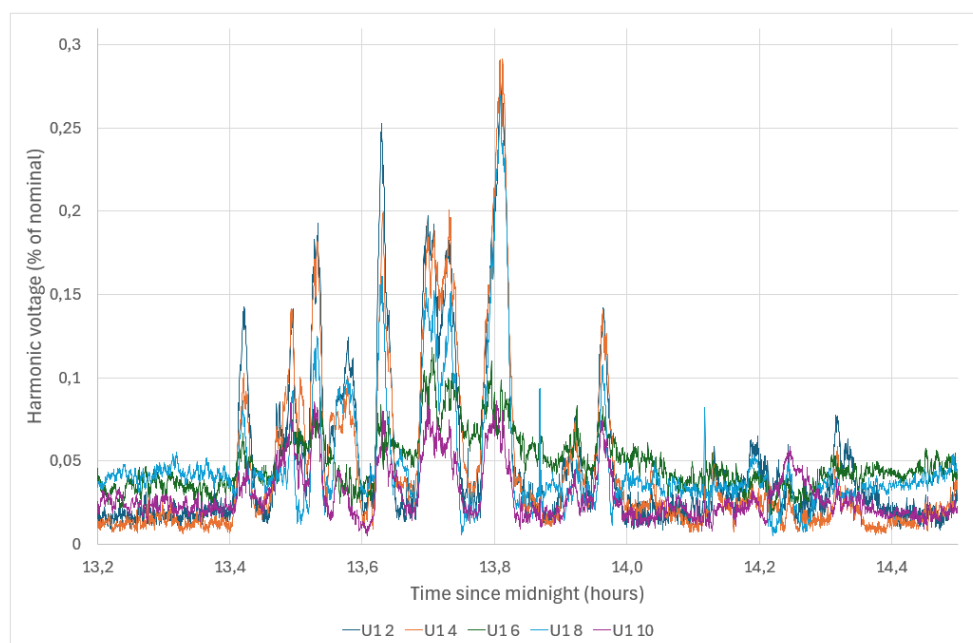


Figure 107. Even harmonic distortion (harmonic 2 through 16), 11 May 2024, during a major geomagnetic storm.

Even harmonics can have a negative impact on certain control algorithms; it is recommended to add immunity to these levels to the requirements for auxiliary equipment in a nuclear power station. Further studies, including measurement campaigns, are needed to map the levels of even harmonics that can be expected during severe solar storms.

More information on this phenomenon, including measurements in Sweden, is found among others in [75, 76, 77].

6.2 HARMONICS

Harmonic levels are generally low in transmission systems. Resonances in the internal grid of a nuclear power station can amplify these levels, especially in a grid with small amount of resistive load (load which can provide damping at the resonant frequency). Harmonic voltages in the internal grid will be further increased by the emission from auxiliary equipment. This is normally a bigger contribution than the one from the transmission grid. Even here, resonances and the lack of damping during certain operational states (with small amounts or no resistive load at all) could give high levels of harmonic voltage distortion.

Harmonic voltages not expected to be a serious issue, but as harmonic voltages are easy to monitor (as a kind of spin-off from voltage-dip measurements, see Section 7.2.2) it is recommended to keep track of the levels, to include those levels with post-interference analysis (Section 7.2.4) and to take measures (which may include further studies) when levels are deemed exceptionally high.

With purchase of new equipment, it is recommended to require that they can at least tolerate the harmonic voltage levels defined in IEC 61000-4-13 [78].

6.3 SUPRAHARMONICS

Supraharmonics are frequency components in the voltage or current between 2 kHz and 150 kHz. The lower limit of this band is the border with harmonics and interharmonics; the upper limit is where strict emission limits have been in place for many years already, to avoid radio interference with long-wave radio broadcasting.

The study of supraharmonics is a relatively new subject. The first papers on disturbances in these frequency ranges appeared around 2005. Only after the term was coined in 2013 did the number of papers on disturbances in this frequency range increase quickly. Most papers on supraharmonics concerns the emission by low-voltage equipment; papers are also published on interference due to supraharmonics; on propagation of supraharmonics and on methods to quantify supraharmonics. There is no consensus yet on how to quantify the level of supraharmonics; IEC 61000-4-30 contains two different methods in an informative annex.

An overview of the state-of-the-art on supraharmonics, around 2017, is presented in [79]. Supraharmonics are also treated in several doctoral dissertations from Luleå University of Technology [80]-[85].

The origin of supraharmonics is mainly in active switching of power-electronic converters and power line communication. The latter takes place, in some European countries, in the frequency range of 9 kHz to 95 kHz. The main emission from end-user equipment in the supraharmonic range is in the remnants from the switching frequency. This frequency can be anywhere between a few kHz and

above 150 kHz. Zero-crossing oscillations with power-electronic converters are another source of supraharmonics, with a frequency of typically a few kHz.

There are plenty of examples of interference due to supraharmonics. Failed capacitors with equipment and noise coming from lamps and other devices are the examples that are most often mentioned. Both are relatively easy to explain and understand. Less easy to understand and explain are cases where equipment behaves strangely under the presence of supraharmonics; that can be equipment that starts or stops unexpectedly; equipment that suddenly changes position; or lamps that cannot be switched on or off anymore. High levels of supraharmonics are also mentioned as the cause of unwanted tripping of residual current devices and interference with power-line communication. However, alternative explanations exist in both cases.

A wide range of other interference cases due to supraharmonics have been reported, where the detailed mechanism behind the interference is often unknown. A major contribution towards understanding those mechanisms was made in [86] by showing that the non-synchronization between a supraharmonic signal and the power-system frequency results in a low-frequency signal (below 25 Hz) on the DC side of a rectifier. The study was directed towards finding causes for visible light flicker. However, the low-frequency signal could also trigger resonances in the control algorithms possibly resulting in spurious trips of electric drives or other equipment powered through a rectifier. This low-frequency signal may also be transferred by any inverted connected to this DC bus to any motor or other load they are supplying. This could result in the motor being exposed to varying electrical torque with frequencies up to 25 Hz.

Supraharmonics originating in the transmission grid, beyond the point-of-common coupling (see Section 7.4.1), will propagate to multiple drive trains, could be amplified due to resonances, and may result in tripping of multiple drive trains.

There is a serious lack of knowledge on the levels of supraharmonic voltages in the transmission system. An important reason for this lack of knowledge is that measurements of those relatively high frequencies at transmission voltages requires dedicated equipment.

Supraharmonics may also originate from auxiliary equipment and in that way result in high levels of supraharmonic voltage distortion. For supraharmonics with such origin, the probability of multiple drive trains being impacted at the same time, is smaller, unless there exist strong similarities in the supply and connected equipment for the different drive trains.

It is recommended to perform measurements of supraharmonic voltages and currents near the terminals of auxiliary equipment. Some short-term measurements, for example one week, could give a first impression of the levels and about the need for additional immunity requirements.

6.4 INTERHARMONICS

Interharmonics are components at frequencies that are not an integer multiple of the power-system frequency (50 Hz), for example 16 Hz, 182 Hz or 1845 Hz.

Frequency components at integer multiples of the power-system frequency are referred to as “harmonics” (see Section 6.2). Most devices only emit small levels of interharmonic currents and the levels of interharmonic voltages are typically small as well.

Classical sources of interharmonics are large industrial frequency converters and arc furnaces. More recently, wind turbines and solar-power inverters have been identified as sources of interharmonics. Low-voltage equipment connected via a single-phase diode rectifier, which includes most low-voltage equipment, can be a source of subharmonics (components below 50 Hz) when exposed to interharmonics or supharmonics.

The consequences of interharmonics are all related to the fact that interharmonics are not synchronized with the power-system frequency. This “non-synchronization frequency” can appear on dc side of a rectifier and cause interference there. Light flicker with compact fluorescent and LED lamps is a commonly cited example. There are indications that interharmonics potentially lead to instability of power-electronic converters, but the subject has not been studied in any detail.

There is limited attention for interharmonics in the literature and the main subjects addressed are sources of interharmonics and methods to accurately quantify interharmonic components with high time and frequency resolution.

6.5 TRANSIENTS DUE TO CAPACITOR-BANK ENERGIZING

Energization of capacitor banks results in an oscillatory transient; the frequency of the oscillation depends on the size of the capacitor bank and the short-circuit capacity at the location where the capacitor bank is connected.

These oscillations can result in overvoltages that trip grid-connected equipment. For energizing of capacitor banks at higher voltage levels, resonances can result in even higher overvoltages at lower voltage levels. For capacitor banks at transmission levels, there are many low-voltage grids and installations downstream and there is a significant probability that at least one of them will show magnification.

The amplitude of the oscillations can be reduced a lot by means of synchronized switching. Synchronized switching is common for capacitor-banks connected to the transmission grid and for those that get switched often. Due to magnification and synchronization errors, rather high amplitudes of the oscillations can still occur.

Switching transients due to energizing of a capacitor bank have been the cause of tripping of adjustable-speed drives [86]. With a capacitor energizing taking place in the transmission grid, amplification of the transients can occur at a lower voltage level. Transient overvoltages up to 3 p.u. have been reported [87]. The phenomenon is very similar to the amplification of voltage-dip transients in the internal grid (see Section 7.1.5). To avoid overvoltages due to amplification of the transients in the low and medium-voltage grids, most capacitor banks are equipped with synchronized switching. But some banks that are rarely switched

may not be equipped with synchronized switching or due to a failure the synchronization may fail.

With multiple capacitor banks being located close together, multi-frequency transients can occur during switching of one of them while the others remain connected. This so-called “back-to-back energizing” can result in transient overvoltages significantly higher than during normal capacitor-bank energizing. This back-to-back component in the energizing transient can be mitigated by equipping at least one of the capacitor banks with a small inductance.

6.6 TRANSIENTS DUE TO CABLE ENERGIZING

The transient due to cable energizing is similar in waveform and propagation to the one due to capacitor-bank energizing.

The main difference is the range in oscillation frequencies. The oscillation frequency depends on the total cable length and the short-circuit capacity. As was mentioned in Section 2.4, oscillation frequencies as low as 100 Hz have been mentioned and are considered in some studies. These lower oscillation frequencies can have unknown impacts on grid-connected equipment.

Long transmission-system cables, the ones resulting in low oscillation frequencies, are equipped with synchronized switching. The same risks of high oscillation amplitudes remain here as for capacitor-bank energizing. For the lowest oscillation frequencies, the risk of amplification at lower voltage levels is less because such low resonant frequencies do not occur at lower voltage levels.

An estimation of the resonant frequency for AC cables in a transmission grid is presented in [88, Section 6.4.5.4]. The results are reproduced in Table 16. The fault levels used in the table are 5% and 95% values of the fault levels for the UK transmission grid.

Table 16. Resonant frequency for cables connected at different transmission voltages at connection points with different fault levels [88].

	66 kV		132 kV		275 kV		400 kV	
	0.75 GVA	2.6 GVA	1 GVA	4.1 GVA	6 GVA	15 GVA	9 GVA	32 GVA
5 km	1350 Hz	2520 Hz	780 Hz	1580 Hz	917 Hz	1450 Hz	772 Hz	1460 Hz
10 km	780 Hz	1450 Hz	450 Hz	912 Hz	529 Hz	837 Hz	446 Hz	840 Hz
50 km			247 Hz	500 Hz	290 Hz	459 Hz	244 Hz	461 Hz
100 km					205 Hz	324 Hz	173 Hz	326 Hz

The resonant frequencies in the table have been calculated assuming a cable capacitance of 150 nF/km. The resonant frequency, as shown in the table, is also the oscillation frequency with energizing of a cable with the indicated length, when no other cables are connected close to the cable being energized. Oscillation frequencies below 1 kHz occur already for a few kilometers of cable. The cable length here is the length of all cable circuits.

When a cable is energized close to other cables, a multi-frequency oscillation will occur, where the value in the table is one of the frequency components. The resulting switching transient will be similar to the one due to back-to-back capacitor energizing.

6.7 ABNORMAL SWITCHING TRANSIENTS

As discussed in Section 2.4, abnormal switching transients are rare but can result in high transient overvoltages. The interest in such transients has been mainly due to their impact on circuit breakers. The propagation of abnormal switching transients and their impact on grid-connected equipment have not been extensively studied.

6.8 VOLTAGE DIPS DUE TO TRANSFORMER ENERGIZING

In this report, the emphasis has been on voltage dips due to faults. Another cause of voltage dips at transmission level is transformer energizing. Transformer energizing results in a smaller reduction in voltage than a fault, but its duration is longer. An important characteristic of voltage dips due to transformer energizing is that they are associated with high levels of harmonic distortion. Both odd and even harmonics are involved here but in the same way as in Section 6.1, the increase is especially noticeable for even harmonics.

Like with capacitor and cable energizing, synchronized switching can reduce the voltage dip and the harmonic levels.

Energizing of non-loaded transformers results in saturation of those transformers and high levels of harmonic voltage distortion lasting several seconds. The measurement campaign for voltage dips, discussed in Section 7.2.1 will also capture these events.

Energizing of multiple transformers close to each other is not something that is supposed to happen as their energizing is a manual action. The so-called sympathetic inrush current, by transformers electrically close to the one being energized, could however make the voltage distortion more severe and of longer duration.

6.9 TRANSFORMER SATURATION UPON FAULT CLEARING

As was shown in some of the recordings in Chapter 3, the voltage recovery upon fault clearing can result in saturation of multiple transformers. This results in high levels of harmonic voltage distortion. For a transmission-system fault, transformers over a large geographical area may be impacted. The phenomenon is especially severe when the transformers are lightly loaded. This was traditionally the case at night but in areas with large amounts of solar power such can also occur around noon on a sunny day.

The instant of fault clearing is determined by the instant of current zero crossing for the breaker or breakers that clear the fault. Any form of synchronization to limit the severity of the resulting transformer saturation is not possible.

Furthermore, as multiple transformers will be saturated, the resulting levels of waveform distortion will likely be higher than for the energization of a single transformer.

The phenomenon and the characteristics of the resulting voltage dip are known but there is very limited information on the impact such dips on modern grid-connected equipment. There is anecdotal evidence that severe transformer saturation upon fault clearing can result in tripping of computer servers, but no systematic study on this has been done.

6.10 LARGE VOLTAGE UNBALANCE

Voltage unbalance is the term used to refer to a difference between the phase voltages, either in magnitude or in phase angle. The unbalance in the transmission is typically less than 1 % and this is not expected to be an issue for auxiliary equipment. There is limited information on the present levels of voltage unbalance in the Swedish transmission grid. Typical values are expected to be below 1 %, although levels up to 2 % are considered as acceptable voltage quality under Swedish regulation [89]. For sustained levels above 1 %, at the terminals of rotating machines, derating may be needed according to IEC 60034 [90]. Information on voltage unbalance will be obtained as a spin-off from the power-quality monitoring campaign mentioned in Section 7.2.

Short duration severe unbalance occurs during non-symmetrical faults, as is briefly addressed in Section 6.12.

Long-duration severe unbalance occurs during single-phase and two-phase interruptions. This phenomenon has been investigated in detail for nuclear power stations and it is not further discussed here.

6.11 TEMPORARY OVERVOLTAGES UPON FAULT-CLEARING

The presence of capacitor banks or long AC cables can result in an additional dimension for transformer saturation upon fault-clearing. The capacitor bank or cables form a resonance circuit with the inductive part of the source impedance; this resonance circuit will amplify harmonics close to the resonant frequency. For resonant frequencies close to low-order harmonics (2, 3, 4, 5, 6, 7) high levels of voltage distortion can occur. The harmonic voltage component may be so high that the peak value of the voltage waveform will be significantly increased. This phenomenon is referred to as “temporary overvoltages” and is among others a concern with the transition from overhead lines to cables in transmission and subtransmission systems. See Table 16 for values of resonant frequencies in transmission systems with long AC cables.

6.12 OTHER CHARACTERISTICS OF VOLTAGE DIPS DUE TO FAULTS

Two of the voltage-dip characteristics, residual voltage and dip duration, are well defined in standards and part of voltage-tolerance and fault-ride-through requirements and recommendations.

Voltage dip transients have been discussed in this report in detail and this discussion will be continued in Chapter 7.

Other voltage dip characteristics may also impact equipment performance. Three-phase unbalance is taken up in the scientific literature and is part of an IEEE standard on voltage-dip immunity testing. Phase-angle jump and point-on-wave are covered somewhat less in the scientific literature but are not completely forgotten. The origin of the phase-angle jump is well understood and even the way it changes when the dip propagates through the grid. Its impact on modern equipment is less well understood.

The point-on-wave of starting and point on wave of ending point of a voltage dip are related to voltage dip transients. A study on voltage-dip transients will include point-on-wave as well.

7 Findings and recommendations

7.1 SIMULATIONS OF VOLTAGE DIPS AND VOLTAGE DIP TRANSIENTS

7.1.1 The need for simulations

Simulations are needed to understand nature and properties of voltage dips and voltage-dip transients. Measurements provide further information about this and are an important complement to the simulations, as discussed in Section 7.2. However, there is information which is not possible or much harder to obtain without simulations. It is for example difficult to obtain a good overview of which properties of the grid (e.g. fault level) impact the properties of the voltage dip transients (frequency, magnitude and damping). It is also not expected that measurements alone would get insight in rarely occurring extreme cases. Insight in these extreme cases is most relevant for critical loads like the auxiliary equipment in nuclear power stations. Using only measurements, it will also not be possible to predict how changes in the transmission system will impact the characteristics of the voltage dips or voltage-dip transients.

There is thus a strong argument for doing simulations and the forthcoming sections will discuss some of the things that should be considered when doing such simulations. A distinction will thereby be made between two types of studies:

- The first type of studies concerns the propagation from the fault location to the 130 kV or 400 kV substation from which the auxiliary equipment in the nuclear power station is supplied. It is recommended to perform these studies in time domain, resulting in the waveform of the voltage, during and shortly after the fault, in the mentioned substation. There are expected to be voltage-dip transients with a wide range of properties depending on the fault location and the properties of the transmission grid. More about these studies in Section 7.1.2, 7.1.3, and 7.1.4.
- The second type of studies concerns the propagation from the mentioned substation to the terminals of important auxiliary equipment in the nuclear power station. These studies can be done in time domain, which allows for a direct study of the impact of the voltage dip transients on auxiliary equipment. Examples of such studies are shown in Chapter 4. It is however recommended to at least also do a study in frequency domain, calculating the voltage transfer as a function of frequency from the mentioned substation to the auxiliary equipment. More about these studies in Section 7.1.5 and 7.1.6.

7.1.2 Propagation in the transmission grid

The modelling detail needed for these types of studies is similar to the one for harmonic propagation studies and for line energization as part of insulation coordination.

Recommendations for components and system modelling for harmonics propagation studies should be considered for these studies as well, for example as in CIGRE Technical Brochure 766 [118]. A limited number of studies have been

done comparing measurements and simulations for harmonic propagation studies at transmission level. A transmission-system model appropriate for harmonic propagation studies is also appropriate for the study of propagation of voltage-dip transients. Harmonic propagation studies are, however, almost exclusively performed in frequency domain, whereas it is strongly recommended to perform the propagation studies of voltage-dip transients in time domain. This may require some changes in the model and calculation methods used.

Recommendations for modelling of system and components with line-energization studies could be considered as well. However, with line energization, one also needs to cover the fast phenomena when the first waves from the energization reach the open-ended line terminal. Frequencies up to about 100 kHz are of relevance here. A transmission-system model appropriate for line energization is also appropriate for propagation studies of voltage-dip transients. As both types of studies are done in time domain, there is limited need for additional modelling. There may however be a need for additional modelling of transformers to include their saturation upon voltage recovery at the end of the voltage dip. Another difference is in the extent of the grid to be studied. With line energization, the interest is in the voltage at the open-ended line terminal. The rest of the transmission system is often modelled through an equivalent network or simplified in another way. With the study of voltage-dip transients, a larger part of the transmission system needs to be modelled.

With voltage-dip transients, the interest is in the frequency, initial amplitude and damping of the oscillations. These properties are determined by the inductances, capacitances and resistances of the components in the transmission system. It is therefore important that these are correctly modelled.

Inductances are generally well known in power system studies, because these are dominating at 50 Hz. They also do not show any significant frequency dependence at the frequencies of interest.

The values of capacitances are somewhat less known. For transmission-system studies, the following sources of capacitance should be considered:

- Capacitance of overhead lines. All overhead lines over a large geographical area need to be included in the model. It is not possible to give general rules on how extended this geographical area should be. A recommendation is to at least include up to the strong nodes (large power stations) at transmission level. Further studies are needed to give recommendations on this.
- Capacitance of AC cables. The capacitance of a cable is about 20 times the capacitance of an overhead line, so that even relatively short cables can have an important impact. The number of 400-kV cables is limited in most transmission systems. It is recommended to also include cables at the voltage levels below the main transmission system, in case of Sweden that would be 220 kV in Stockholm and 130 kV in and around the other major cities.
- Capacitor banks connected to the transmission system: 400 kV, 220 kV, and 130 kV.
- Passive harmonic filters with HVDC installations and other installations connected to the transmission system. In the case of southern Sweden, there

are several such installations, so that it is important to consider these.

Additional studies are needed to determine how significant their impact is. Depending on the geographical extent, it may be needed to also consider the harmonic filters with HVDC installations in Eastern Denmark and Southern Norway.

- The capacitance of the cables in the collection grid of large wind parks; capacitor banks and other equipment connected to lower voltage levels. Some of these will have an impact, whereas others may not. It will obviously not be possible to model each individual capacitance at any voltage level. Additional studies are recommended to quantify the impact of this, to get an idea of the uncertainty introduced by for example not modelling the capacitances at medium and low-voltage levels. Further studies are needed to obtain rules on how much of this should be included.

The modelling of the resistance is important because it impacts the damping of the voltage-dip transients and therewith its severity. The resistance of the transmission system components at 50 Hz is rather well known, but the resistance shows a strong dependence on the frequency. Studies for line energization transients have shown that the skin effect of overhead lines needs to be included to accurately reproduce the damping of the transients. Cables are still rare at transmission levels, but for systems with a large fraction of cables, it can be assumed that the skin effect also should be included for those cables. With cables, the proximity effect also has a significant impact on the resistance, and this should therefore be included in the model as well.

Electricity networks, components and connected equipment at lower voltage levels will also impact the damping and thus the severity of the voltage-dip transients. Harmonic propagation studies have however shown that very little is known of impedance and resistance of grid-connected equipment at harmonic frequencies. Additional studies are needed to determine the impact of this. It is not possible to include all low-voltage equipment. Such additional studies will thus only give an impression of the error made by not including the damping due to the lower voltage levels. Comparison between measurements and simulations is also important in getting further insight in this error.

7.1.3 Operational states of the transmission system

The characteristics of the voltage-dip transients depend on the operational state of the transmission system and occasionally also on the state of the system at a lower voltage level. It will not be possible to study all possible states; a selection will have to be made. The state of the following components should be considered in the selection of the operational states to be considered.

Large conventional power stations. The simulations should be repeated for such stations in operation and for them not in operation. The number of large power stations is limited, at least in Southern Sweden, so that it is possible to include a large part of the combinations, for instance all combinations with up to three large production units out of operation. An alternative is to look at the combinations of units that can be expected for certain consumption and wind/solar production combinations. Historical data can also be used here.

Cables and transmission lines. It is recommended to repeat the simulations for all combinations with one or two cables or long transmission lines out of operation. Whether one or two component outages are considered depends on the number of combinations, the available time, and how much this impacts the results. The number of cables and lines is too big to consider a large fraction of the combinations with three or more lines out of operation. If certain combinations of lines or cables are likely to be out of operation together, it is recommended to include these combinations as well.

HVDC connections. The HVDC connection itself or its power flow does not impact the characteristics of the voltage-dip transients. It is instead the harmonic filter associated with the HVDC link that impacts the voltage-dip transients. Different combinations should be studied of such filters in operation.

Large wind parks. Like with HVDC connections, the impact is not due to the wind turbines themselves. Instead, it is the capacitance of the collection grid that impacts the voltage-dip transients. There is a limited number of HVDC connections, so that it is possible to study a large fraction of all possible combinations. The dilemma here is to decide which and how many wind parks to include in the model. Further studies are needed to obtain recommendations on this.

7.1.4 Impact of fault position

The main uncertainties in predicting properties of voltage dips and voltage-dip transients are the location and properties of the fault. The fault type can be one of a limited number of types: single-phase-to-ground, phase-to-phase, etc. It is straightforward to perform the simulations for all fault types, as was done in Chapter 4. The fault position can however be anywhere in the transmission system; in a substation or along a line of cable. Each fault location will give a different voltage-dip transient. The relation between fault location and the dominant frequency of the voltage-dip transient has been used in some studies to determine the distance to the fault [91]-[92]. It was shown that the relation is not unique; the same dominant frequency could be due to different fault locations. This made the method not suitable for power-system protection, but the method has been used for fault-location. The main conclusion, that the frequency of the voltage-dip transient is impacted by the fault location, however still holds.

Faults can occur anywhere in the transmission system, which means that it is not possible to determine beforehand which frequency or frequencies will be present in the voltage-dip transient. Magnitude, damping, and type (as defined in [117]), of the voltage-dip transient may also be impacted by the fault location, but limited information is available on that in the literature [93].

The expected voltage-dip transients at the substation from which the nuclear power station is supplied will have a range of dominant frequencies with different values of magnitude and damping. The same holds for voltage-dip transients at the terminals of auxiliary equipment in the nuclear power station.

The aim of the studies after propagation in the transmission system is therewith not to determine the exact properties of the voltage dip and voltage-dip transient,

as these too strongly depend on the fault location, but to determine the range of properties that can be expected.

7.1.5 Propagation in the nuclear power station

The next step is to study the propagation of the voltage-dip transient from the transmission system to the terminals of auxiliary equipment. These studies can be done in time domain or in frequency domain.

For time-domain studies, the internal grid of the nuclear power station should be modelled in the same way as the transmission system. The main challenge here is the modelling of equipment connected to the internal grid. Equipment impedance for 50 Hz is generally well known, but for higher frequencies this impedance can be rather different and is often unknown. Specific studies may be needed after the modelling of individual devices.

There is limited amount of work done on the modelling of grid-connected equipment at relevant frequencies. The main work done concerns harmonic propagation in distribution networks [94]-[97]. The main conclusions from that work are that there is a large lack of knowledge on equipment models and that the shunt capacitance of equipment has a major impact on the harmonic propagation. A detailed sensitivity study and comparison between measurements and simulations are needed together with the modelling efforts.

Furthermore, capacitor banks and any harmonic filters in the internal grid should be modelled. Data on these should be readily available.

The studies on propagation in the transmission system will result in hundreds or thousands of different voltage-dip waveforms. It is not practically possible to study the propagation and the impact on auxiliary equipment for all of them for different operational states of the internal grid.

Instead, it is suggested to consider several voltage dip transients, with different frequencies, amplitude, and damping and study the propagation of those in time domain. An alternative is to study the propagation in frequency domain as discussed in the next section.

7.1.6 Propagation in frequency domain

For frequency-domain studies, the modelling details should be similar as for the time-domain studies. Instead of considering each dip separately, a voltage-transfer function is obtained assuming that the transfer is linear. Some additional studies may be needed to determine if non-linearities in the internal grid can have a significant impact on the voltage-dip transient with the equipment terminals.

The voltage-transfer function gives the voltage transient versus frequency. The voltage transfer is defined as:

$$H(\omega) = \frac{V_{eq}(\omega)}{V_{ts}(\omega)}$$

Where $V_{eq}(\omega)$ is the voltage at the equipment terminals as a function of frequency and $V_{ts}(\omega)$ the voltage at the point-of-connection with the transmission system. Different transfer function will generally be needed for zero-sequence and non-zero-sequence components. Transfer functions and transfer impedances have been used recently to study several power-quality phenomena, including voltage unbalance [98]-[99], harmonics [100]-[103], supraharmonics [104] and voltage rise [105]-[106].

The frequency-domain transfer function will identify one or more frequencies where the transfer is high, sometimes even higher than unity. In that case, the internal grid will amplify the signal at these frequencies. A voltage-dip transient containing these frequencies will result in a severe transient at the terminals of auxiliary equipment. Those cases require specific attention.

7.2 PERMANENT MEASUREMENTS

A general rule for power-quality measurements, although admittedly heavily influenced by research experience, is to measure everything, always and everywhere. This is obviously not possible in practice, but it is still recommended to measure over long periods, at multiple locations, and well beyond the standard-setting of power-quality monitors. Recommendations on how to set up and conduct long-term power quality monitoring are given, among others, by the Council of European Energy Regulators [107] and by CIGRE [108]-[109].

With power-quality monitoring, as with many power-quality studies, a distinction between two types of power-quality disturbances should be made: “power-quality events” and “power-quality variations” (“events” and “variations” in short). The difference between these two types of events will be explained in the forthcoming sections.

7.2.1 Events: voltage dips and transients

Voltage dips and transients are examples of power-quality events: large deviations from the ideal voltage and current that occur occasionally. To detect an event, a threshold is needed that defines the border between a “small deviation” and a “large deviation”. For voltage dips this triggering mechanism is well-defined in standards, for transients there is no such standardization.

For voltage dips it is recommended to use the standard triggering method as defined in IEC 61000-4-30 [10], as implemented in most commercially available power-quality monitors. It is recommended to set the threshold at 90 % of nominal or pre-event rms voltage. This is also the typical manufacturer setting.

For transients, there is no standard or commonly used triggering method. But most power-quality instruments do use some kind of method and are able to detect transients. It is recommended to accept whatever triggering method the manufacturer uses, together with a sensitive setting of the thresholds. Here it is also recommended to follow up the setting to avoid that the data storage fills up by many small transients.

The triggering of a transient or voltage dip results in a time-domain waveform being recorded and analyzed. The analysis results in certain event characteristics, for example magnitude and duration. These are useful for studies and for keeping statistics and such. However, the importance is in the actual waveforms, as these contain the information needed. It is thus important to choose a power-quality monitor that records the event waveform of voltage dips and transients for future analysis.

For voltage dips, the waveform covers the period when the rms voltage is below the threshold, a certain pre-trigger period (ending at fault initiation, i.e. before the beginning of the dip), and a certain post-trigger period (starting a fault clearing, i.e. after the ending of the dip). For transients there is typically only a pre-trigger period (before the start of the transient) and a post-trigger period (after the start of the transient). The values of these vary between manufacturers. It is recommended to take several cycles (of the 50-Hz fundamental frequency) as pre-trigger and as post-trigger. For voltage dips, a longer post-trigger (25 or 50 cycles) will allow detecting high levels of harmonic distortion after fault-clearing. When the interest is only in transients associated with voltage dips, one or two cycles pre-trigger and post-trigger are sufficient. However, as the amount of data is still rather small, it is recommended to take longer pre-trigger and post-trigger windows whenever possible.

A higher sample rate will generally give more information, but also here it is recommended to accept what the power-quality monitor offers. A commonly used sampling rate is 256 samples per cycle (12,8 kHz), which is sufficient for our purpose. It is however recommended to start further research towards higher frequencies present in events originating in the transmission grid.

Concerning the measurement locations, it is recommended to measure at 130-kV and 400-kV substations over a large geographical area of the grid to which the nuclear power station is connected. The aim of these measurements is to provide a mapping of the dips and transients that can be expected as well as their propagation, to verify models for propagation of voltage dips and transients, estimate the model uncertainty in the simulation model (see Section 7.1). With these measurements it is sufficient to measure the voltage waveforms, and one set of current waveforms (three or four channels). The latter is not needed for the mapping but could be of use for the verification of the models and the estimation of the modelling uncertainty.

It is also recommended to measure voltages and currents at the point-of-connection of the auxiliary equipment in the nuclear-power station to the transmission grid.

Voltage measurements are also recommended at different voltage levels in the internal grid of the nuclear power station.

Voltage and current measurements are recommended at the terminals of different types of auxiliary equipment.

Measurements in the nuclear power station are needed to verify the propagation models used in the simulations, for understanding and mapping the propagation

of voltage dips and transients through the internal grid, estimating the modelling uncertainty, and as a base for post-interference analysis, see Section 7.2.4.

7.2.2 Variations: harmonics

Waveform distortion is not within the scope of this report, but most power-quality monitors allow measurement of harmonics next to voltage dips and transients. It is therefore recommended to measure harmonics as well, among others because this is possible for limited extra costs.

Waveform distortion is a power-quality variation, where measurements are taken over pre-defined and fixed time intervals. The most used method takes the voltage and current spectra over each 10-minute window, resulting in six values per hour (144 per day, etc.) for each voltage and current channel. Requirements on power-quality performance (as for example in EN 50160 [110]) also consider 10-minute values. However, a substantial amount of information is lost in this way, and it is recommended to store 1-minute values or use an even higher time resolution, where 1-second values are considered sufficient but not always necessary.

Using 1-second values would result in $365 \times 24 \times 3600 = 31\,356\,000$ samples per channel per year. With four voltage and four current channels, this gives about 250 million samples per location. For 25 locations this gives about 6 billion samples per year. As a reference, 256 GB memory is common for a modern iphone. The challenge is not so much in finding the storage space, but in transferring the data from the monitoring equipment to the storage and in the analysis of the data.

It is recommended to record harmonics up to order 40 or 50, which is what is available in most power-quality monitors.

It is recommended to measure voltages and currents at point-of-connection of the auxiliary equipment of the nuclear-power station to the transmission grid. Voltage measurements are also recommended at different voltage levels in the internal grid of the nuclear power station. Voltage and current measurements are recommended at the terminals of different types of auxiliary equipment. These are the same locations in the internal grid as recommended for voltage dips and transients in Section 7.2.1.

7.2.3 Interharmonics and supraharmonics

Waveform distortion includes harmonics, interharmonics, and supraharmonics. Harmonics are frequency components at integer multiples of the power-system frequency (50 Hz) up to about 2 kHz. Interharmonics are frequency components at non-integer multiples of 50 Hz, up to about 2 kHz. Supraharmonics are frequency components between 2 kHz and 150 kHz.

Section 7.2.2 refers only to harmonics, which are recorded by most power-quality monitors. Recording of interharmonics and supraharmonics is not possible with most commercially-available monitors. At higher voltage levels, dedicated instrument transformers are needed to measure supraharmonics with sufficient accuracy. More about interharmonics and supraharmonics is found in Section 6.3 and Section 6.4.

7.2.4 Post-interference analysis

It is recommended to record and analyze each case of interference of auxiliary equipment, not just essential equipment but also non-essential equipment of the same type. This should even include cases of potential or possible interference and even cases where equipment behavior (for example the currents at the equipment terminals during a voltage dip or transient) deviates significantly from what would be expected.

This post-interference analysis requires the above-mentioned voltage and current recordings and a detailed description of the interference case.

For post-interference analysis it is also recommended, when possible, to measure inside of specific devices, for example the DC bus voltage in adjustable-speed drives.

Post-interference analysis may require the storage of the complete waveforms. It is however only needed to have such high time resolution when interference occurs; it is therefore not necessary to store this data for a longer period. Assume the storage of sampled waveform over a 24-hour period, with the above-mentioned sampling rate of 256 samples per cycle. That would result in $24 \times 3600 \times 50 \times 256 = 1.1$ billion samples per channel, 8.8 billion per location, 220 billion for all the 25 locations. This is a significant amount of data, but for a detailed analysis of the cause of interferences, it may be necessary to have this data available. When setting up permanent measurements, it is recommended to at least consider this option. The main challenge will again be in the communication and analyses of the data.

7.3 IMMUNITY TESTS AND REQUIREMENTS

7.3.1 Immunity requirements

The ultimate aim of all work on power quality, including the study in this report, is to reduce or limit the probability of interference. That can be achieved by reducing the emission, by impacting the propagation, and by increasing equipment immunity. Reducing emission of voltage dips and transients due to transmission-system events is generally beyond the control of the operator of the nuclear power station and even difficult for the transmission-system operator. Some recommendations on impacting the propagation are given in Section 7.4.

Improving the immunity of essential auxiliary equipment can be done by the equipment manufacturer but the operator of the nuclear power station can play a role in this improvement. One of the tools available for this is to put requirements on the immunity of essential auxiliary equipment.

Requirements exist for fault-ride-through of nuclear power stations; these are aimed at guaranteeing the continued supply of electricity to the grid. The requirements use a simplified model of a voltage dip, with residual voltage and dip duration only. Voltage-dip transients and other dip characteristics are not included in this model for fault-ride-through.

An alternative would be to shift the responsibility completely to the equipment manufacturer and require that the equipment should be immune to any voltage

disturbance originating in the transmission system. This will give a legal guarantee, but no technical guarantee. The equipment manufacturer may not have the knowledge to understand those disturbances beyond residual voltage and duration. The equipment manufacturer will almost certainly not have access to the information needed to determine the range of characteristics that must be considered to avoid interference. This alternative would create a serious risk that equipment would not be immune to severe disturbances.

Earlier work on immunity of equipment in industrial installations [13] resulted in a check list for equipment manufacturers [as discussed in Section 2.3]. Voltage-dip transients were mentioned in that checklist, but it is not known to the authors of this report to which extent that checklist is used by equipment manufacturers. The check list also does not give any quantitative values of for example oscillation frequency, which makes it more difficult for a manufacturer to make their equipment immune.

An alternative that has been discussed in standardization bodies is to create a set of representative waveforms to verify equipment immunity. One of the reasons that this was never implemented in standardization is the huge variety of waveforms that may occur at the equipment terminals. Standards are supposed to be valid at any location and not just at the location or locations where the test waveforms are obtained. When obtaining equipment for use in a nuclear power station, it may however be an appropriate alternative to create a set of representative waveforms. These will be different for the different nuclear power stations. A detailed study is needed of the kind of waveforms to be expected for each nuclear power stations (see Section 7.1 for recommendations on such a study).

Another alternative, more in line with existing immunity requirements, is to give a range for the value of the characteristics of the voltage-dip transients that can be expected. The detailed study (see Section 7.1) will give information on that range and will also allow a decision on whether the same requirements or different requirements are needed for different nuclear power stations. The range, and thus the immunity requirements, may need to be updated when major changes are made in the transmission system. Additional studies are needed to be able to assess what constitutes major changes here.

7.3.2 Verification and immunity testing

With any of the alternatives mentioned in the previous section, the question is how to verify that essential auxiliary equipment complies with the immunity requirements.

An option is to leave this up to the manufacturers to verify, as is the case with most immunity requirements for electromagnetic compatibility according to European regulation.

One could as an alternative require laboratory testing where equipment is exposed to artificially created voltage disturbances. There are several IEC standards on voltage-dip immunity testing that can be used as a base for this.

There are advantages and disadvantages with any of these verification methods and collaboration is needed between the equipment manufacturer and the operator of the nuclear power station.

Next to the above-mentioned verification before installation, there are several methods to verify and improve the immunity after installation of the equipment.

- Reporting all cases of interference and other unexpected behavior and perform post-interference analysis (see Section 7.2.4).
- Perform primary tests of the whole installation at regular intervals, for example once per year (see Section 7.3.3).

The challenge with both types of real-world testing is that it will likely not cover extreme events. For the study of immunity against these, simulations remain necessary.

7.3.3 Primary tests

With a primary test, a short-circuit fault or an earth fault is artificially created. The aim of a primary test is to verify that the protection operates as intended. However, a primary test can also be used to verify the results of power-system simulations (of the kind discussed in Section 7.1) and to verify the behaviour of auxiliary equipment in the nuclear power system. When a primary test is performed, it is strongly recommended to perform measurements of voltage and current with high time resolution at many locations in the transmission grid and in the auxiliary supply, beyond the locations mentioned in Section 7.2.

7.4 DESIGN OF INTERNAL AND EXTERNAL GRID

A nuclear power station contains multiple independent drive trains. Simultaneous tripping of more than one drive trains should be avoided as much as possible. The different drive trains have therefore separate path to the transmission grid, to avoid common-mode failures that would trip more than one drive train at the same time. There will however be a location, somewhere in the transmission grid, where different paths meet. This location is referred to as “point-of-common-coupling”. A disturbance originating at the point-of-common coupling or beyond will impact more than one drive train.

Tripping of multiple drive trains can be avoided, even for such disturbances, by making all auxiliary equipment immune to all possible disturbances, as discussed in Section 7.3.1. That could in practice be difficult, if not impossible, for several reasons. The forthcoming sections will discuss some options to further reduce the probability that multiple drive trains trip at the same time, even if not all equipment is immune against all possible disturbances.

7.4.1 Moving the point-of-common coupling

The further away the point-of-common coupling, the less disturbances will reach the drive trains through that point. The ultimate solution would be, with respect to this requirement, to have fully independent supply paths for all drive trains. A practical implementation of that would be a set of power stations, completely

separate from the rest of the grid, only to supply one of the drive trains. That would however have disadvantages for the reliability of the supply to that drive train.

Moving the point-of-common coupling further into the transmission grid could have similar disadvantages. It would not only reduce the reliability of the supply to the auxiliary equipment; it would also reduce the reliability of the supply for other customers and could put serious barriers to the functioning of the electricity market. Moving the point-of-common coupling will also result in a longer path from that point to the terminals of auxiliary equipment. That would increase the risk of amplification of voltage-dip transients.

Moving the point-of-common coupling is, generally speaking, not something recommended. Some changes may be considered but that would require a detailed study of the advantages and disadvantages.

7.4.2 Detuning the supply paths

A major risk with voltage-dip transients is their amplification in the internal grid. As discussed in Section 7.1.5, the internal grid has one or more resonant frequencies at which the amplification is strongest (or damping weakest). Voltage-dip transients containing those frequencies are the most serious ones for the auxiliary equipment. The paths, to the different drive trains, are however always somewhat different. The resonant frequencies are therefore expected to be different as well.

In case the resonant frequencies turn out to be similar, some intentional detuning can be introduced for example by adding a shunt capacitor bank or a shunt filter. Such a detuning reduces the risk of high transient magnitudes with multiple drive trains.

7.4.3 Diversifying equipment

The risk of simultaneous tripping of equipment in more than one drive train can be further reduced by ensuring that equipment is as different as possible in the different drive trains. The impact of voltage-dip transients on equipment is still very ill understood, making it difficult to intentionally diversify. Unknown issues, introduced by unexpected behavior for example of the control system, can be avoided (or at least reduced in probability) by taking equipment from two different manufacturers for the different drive trains. This holds for electrical drives, but also for protection relays.

7.5 OTHER VOLTAGE DISTURBANCES

This report treats, almost exclusively, transient oscillations at beginning and ending of voltage dips due to faults (called “voltage-dip transients” in this report). There are other voltage disturbances that potentially impact the correct operation of auxiliary equipment in a nuclear power plant. Some of those disturbances are listed and briefly discussed in Chapter 6.

The fact that these disturbances are listed does not imply that they are a threat to the correct operation of auxiliary equipment in a nuclear power station. It mainly implies that these disturbances, and their expected levels, should be considered in the design of the installation and equipment in the installation. During post-interference analysis, the disturbances listed below should be considered as possible causes for the interference.

On the other hand, the fact that a disturbance is not mentioned in Chapter 6, does not imply that it will never be a cause of interference.

7.6 FURTHER RESEARCH

This section contains some thoughts on directions for future research. These thoughts are mainly based on what was written in the previous sections of this chapter. The list is most likely not complete; on the other hand, not all this further research is equally important. Some of the further research mentioned below will probably follow from detailed and accurate studies of voltage-dip transients in existing transmission systems; other research items will need to be initiated separately.

It should also be added here that not all the further research mentioned below needs to be academic research done at a university. Several of the items can be addressed through detailed studies done by others, for example study departments with nuclear power companies, transmission network operators, or consultants familiar with transmission-system studies; see also the discussion in Section 7.6.10.

7.6.1 Extent of the geographical area

How big part of the transmission grid should be modelled to get an accurate estimation of the voltage-dip transient? How about modelling lower voltage levels?

One reason for including a large geographical area is that events far away can result in relevant voltage disturbances for the auxiliary equipment. Another reason is that properties of components far away can impact the properties of those disturbances, in our case the voltage-dip transients. For example, the oscillation frequency of the voltage-dip transients is determined by capacitance and inductance of a large geographical area.

Concerning the lower voltage levels, 220 kV and 130 kV would likely need to be included in the model. Including even lower voltage levels would quickly increase the complexity of the model, but the impact on the voltage-dip transients is likely much less than for the higher voltage levels. Such studies have been performed for the residual voltage of a voltage dip, but not for the characteristics of voltage-dip transients.

7.6.2 Harmonic filters

How relevant is the modelling of the harmonic filters with HVDC links? Over which geographic area should these be modelled? The same for harmonic filters with large industrial installations. Information on HVDC links will be relatively

easy to obtain, with help from transmission system operators and manufacturers; information on large industrial installations will be harder to obtain.

7.6.3 Grid-connected equipment

Modelling of grid-connected equipment, especially in the internal grid of nuclear power stations, at frequencies relevant for voltage-dip transients. Quantifying the impact of this on the transfer from the transmission grid to the terminals of auxiliary equipment.

7.6.4 Error made because of approximations

What is the error made in the results by neglecting or simplifying equipment connected at lower voltage levels? Comparison of measurements with simulation results could give an indication of the size of the error made due to the approximations in the grid model.

This further investigation would cover the previous three items (Section 7.6.1 through 7.6.3). The accuracy of the simulation (or error made) is a question that returns with every simulation. The answer to that question depends also on the aim of the simulations. In large parts of the discussions in for example Section 7.1, it is assumed that the aim is to obtain voltage waveforms as closely as possible to the actual ones. An alternative approach is to use the simulations to obtain a range of characteristics for the voltage-dip transients (Section 7.6.5). The latter approach may have less strict requirements on the accuracy of the model. However, the issues in Section 7.6.1 through 7.6.3 should still be addressed.

Mathematical methods introduced for estimating the accuracy of statistical experiments with many influencing variables, like “fractional factorial design”, can be used to estimate the error made because of the limited level of details of the simulation model [111]. Such studies can be conducted in parallel with the comparison between measurements and simulations.

The error made in the simulations is also impacted by the component models used in the simulation software. Frequency-dependency of resistance / damping is for example not always modelled in sufficient detail. Even when the models are available, the values for the different model parameters are not always available. The models used in the simulations may require comparison with more physical models, like those based on finite element methods, to achieve realistic models over a wide frequency range.

7.6.5 Characteristics of voltage-dip transients

Definition of the characteristics of voltage dip transients (for example magnitude, frequency, damping time constant) and methods for extracting these characteristics from recorded voltage dips. Obtaining statistics on these characteristics from measurements and from simulations. Developing methods for characterizing complicated transients, containing multiple frequencies.

There are two aspects of this part of the future research needs. One aspect is the description of the voltage-dip transients from a signal-processing viewpoint. This

requires mathematical models, where the Discrete Fourier Transform, high-pass filters, wavelet filter banks, ESPRIT and MUSIC are examples that were used in the past [35]. These methods have been developed and applied before; the novelty will be in the application and adaptation of these methods to voltage-dip transients and the interpretation of the results. In the earlier parts of this report, reference was often made to the characteristics of voltage-dip transients, like oscillation frequency, magnitude, and damping. However, no standard or broadly accepted methods exist for extracting these characteristics from measured or simulated waveforms.

The second aspect concerns the relevance of the different characteristics for the performance of essential auxiliary equipment. This is much less a mathematical challenge but an engineering challenge instead. Contacts with manufacturers of equipment, modelling generic equipment types, and post-interference analysis (Section 7.2.4) should all be within this part of the further research.

7.6.6 Data analysis

Methods for automatic and manual analysis of data from permanent measurements. Machine learning methods for finding common and deviating patterns.

The permanent measurements mentioned in Section 7.2 will result in large amounts of data. Manual analysis by power-system and power-quality experts would be preferred but is not feasible for large amounts of data as it would be far too time consuming. Some level of automatic analysis should be set up to obtain information from the data. This may be classical methods, like statistics on the characteristics mentioned in Section 7.6.5, but it is recommended to also make use of machine learning tools. Earlier studies [112] have shown that unsupervised machine learning has great potential to provide information for power-system and power-quality experts.

7.6.7 Post-interference analysis

Setting up a method for exchanging information on cases of interference and the possible causes (see Section 7.2.4). The analysis of some non-interference cases is discussed in Section 7.6.8.

The number of interference cases will likely (and hopefully) be small, so that it may be difficult to obtain general conclusions. Collaboration is needed with the owners of other installations (nuclear and non-nuclear) with similar types of equipment, to extent the amount of data allowing for more conclusions to be drawn.

7.6.8 Impact on equipment

How do voltage-dip transients impact the performance of auxiliary equipment in nuclear power plants?

Next to the post-interference analysis (Section 7.6.7), the impact of voltage dips and voltage-dip transients on equipment should be measured for non-interference cases. From the permanent measurements (Section 7.2) data will be obtained on

equipment behavior during such disturbances. This could be only the currents at the equipment terminals, but it could also include recordings of for example dc-bus voltage inside of the equipment. An initial approach would be to compare the measured voltages and currents with those obtained from a model of the equipment. Such an approach will identify model limitations that may result in unexpected interference for more severe events.

Also here, collaboration with equipment manufacturers and other types of installations is recommended.

Fundamental studies are needed where simplified or generic equipment models are used. Such studies will give general knowledge about the impact of voltage-dip transients on equipment, like which parts of the equipment are most sensitive to voltage-dip transients, and which characteristics of the transients have major influence.

Studies are also needed for the impact of voltage-dip transients on protection relays. The main concern is the protection of the auxiliary equipment. Such protection relays will be exposed to the voltage-dip transients and the resulting current transients.

7.6.9 Other voltage disturbances

Research towards better understanding of origin, propagation and impact of different voltage disturbances, including the ones listed in Chapter 6.

Research of this is already ongoing at several places, including at Luleå University of Technology. For example, a project on waveform distortion due to geomagnetically-induced currents has started recently. The main research gap in the modern power-quality field concerns the impact on modern equipment of non-standard disturbances and non-standard characteristics. This concerns a much broader application than just the auxiliary supply of nuclear power stations.

7.6.10 Spreading the knowledge

As mentioned at the start of this section, the further research discussed here can be performed by different stakeholders: universities, research institutes, nuclear power companies, transmission network operators, consultants. Some of the work will fit some of the stakeholders better than others.

However, it is not just the gathering of the knowledge that is important, also the spreading of the knowledge, including allowing for verification and opposition to the methods and findings. For this, university research has shown to be often more suitable than research with the other stakeholders. The current pressure on academics to publish (which one may agree with or not) has as an advantage that it gives a natural spread of the knowledge. Education, done mainly by universities, provided another natural platform for spreading of the knowledge. Both academic publishing and education provide academics with experience in spreading knowledge, which can be used for spreading through other channels as well.

Not all the further research items mentioned in this section are suitable for research at universities. However, to allow for spreading and open discussion of the knowledge it is recommended that some of the work is performed at universities. Collaboration between industry and university will obviously remain essential.

8 Concluding remarks

The work presented in this report confirms that voltage-dip transients occur in association with voltage dips due to faults in transmission systems. Oscillations at beginning and ending of voltage dips were mentioned before, but this work is the first systematic study on the subject.

It has also been shown, in this report, that those transients propagate from the transmission grid to the terminals of auxiliary equipment. Due to resonances, amplification of the amplitude of the oscillations may occur.

The voltage-dip transients, at the equipment terminals, may adversely affect auxiliary equipment, including causing tripping of the equipment.

Some of the specific things to look out for, related to voltage-dip transients and auxiliary equipment, are:

- The replacement of overhead lines by cables, or the addition of new cables to the transmission grid, will impact the properties of the voltage-dip transients.
- Resonant frequencies of the auxiliary grid are affected by the impedance of the equipment connected to this grid. Changes in that equipment will change the resonant frequency and possibly the properties of the voltage-dip transients at the equipment terminals.
- The immunity of modern power-electronics equipment against voltage-dip transients is largely unknown.

The next steps, to be taken to avoid future interference due to voltage-dip transients, include permanent measurements, realistic simulations as well as further studies and research by different stakeholders.

9 References

- [1] M. F. McGranaghan, D. R. Mueller, M. J. Samotyj, Voltage sags in industrial systems, IEEE Transactions on Industry Applications, vol. 29, no. 2, pp. 397-403, March-April 1993.
- [2] J. Lamoree, D. Mueller, P. Vinett, W. Jones, M. Samotyj, Voltage sag analysis case studies, IEEE Transactions on Industry Applications, vol. 30, no. 4, pp. 1083-1089, July-Aug. 1994.
- [3] C. L. Becnel, Maintaining process continuity during voltage dips, IEEE Transactions on Industry Applications, vol. 18, no. 4, pp. 324-328, July 1982.
- [4] L. Conrad, K. Little, C. Grigg, Predicting and preventing problems associated with remote fault-clearing voltage dips, IEEE Transactions on Industry Applications, vol. 27, no. 1, pp. 167-172, Jan.-Feb. 1991.
- [5] M. H. J. Bollen, Understanding power quality, voltage sags and interruptions, Wiley / IEEE Press, 2000.
- [6] IEEE recommended practice for evaluating electric power system compatibility with electronic process equipment, IEEE Std 1346-1998.
- [7] L. E. Conrad, M. H. J. Bollen, Voltage sag coordination for reliable plant operation, IEEE Transactions on Industry Applications, vol. 33, no. 6, pp. 1459-1464, Nov.-Dec. 1997.
- [8] IEEE recommended practice for the design of reliable industrial and commercial power systems (Gold Book), IEEE Std 493-1997 [IEEE Gold Book], vol., no., pp.1-464, 31 Aug. 1998.
- [9] C. Becker et al., Proposed chapter 9 for predicting voltage sags (dips) in revision to IEEE Std 493, the Gold Book, IEEE Transactions on Industry Applications, vol. 30, no. 3, pp. 805-821, May-June 1994.
- [10] IEC 61000-4-30, Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques - Power quality measurement methods.
- [11] IEEE Guide for Voltage Sag Indices, IEEE Std 1564-2014, vol., no., pp.1-59, 20 June 2014.
- [12] D. D. Sabin and M. H. J. Bollen, Overview of IEEE Std 1564-2014 Guide for Voltage Sag Indices, 16th International Conference on Harmonics and Quality of Power (ICHQP), Bucharest, Romania, 2014, pp. 497-501.
- [13] Voltage Dip Immunity of Equipment and Installations, CIGRE Technical Brochure 412, 2010.
- [14] <https://www.semi.org/en>
- [15] SEMI F47 - Specification for Semiconductor Processing Equipment Voltage Sag Immunity, <https://store-us.semi.org/products>.
- [16] IEC 61000-4-11, Electromagnetic compatibility (EMC) - Part 4-11: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests for equipment with input current up to 16 A per phase.
- [17] IEC 61000-4-34, Electromagnetic compatibility (EMC) - Part 4-34: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests for equipment with mains current more than 16 A per phase.

- [18] IEEE 1668, Trial-use recommended practice for voltage sag and short interruption ride-through testing for end-use electrical equipment rated less than 1000 V.
- [19] Y. Wang, A. Bagheri, M. H. J. Bollen, X.-Y. Xiao, Single-event characteristics for voltage dips in three-phase systems, *IEEE Transactions on Power Delivery*, vol. 32, no. 2, pp. 832-840, April 2017.
- [20] Y. Wang, M. H. J. Bollen and X.-Y. Xiao, Calculation of the phase-angle-jump for voltage dips in three-phase systems, *IEEE Transactions on Power Delivery*, vol. 30, no. 1, pp. 480-487, Feb. 2015.
- [21] CIGRE Working Group 34.01, Reliable fault clearing and back-up protection, CIGRE Technical Brochure 140, 1999.
- [22] J. Matevosyan, T. Ackermann, L. Söder, S. Bolik, Comparison of international regulations for connection of wind turbines to the network, *Nordic Wind Energy Conference*, 2004.
- [23] Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators (Text with EEA relevance), EUR-LEX Document 32016R0631, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:JOL_2016_112_R_0001#d1e1386-1-1.
- [24] M. H. J. Bollen, L. D. Zhang, Analysis of voltage tolerance of AC adjustable-speed drives for three-phase balanced and unbalanced sags, *IEEE Transactions on Industry Applications*, vol. 36, no. 3, pp. 904-910, May-June 2000.
- [25] M.H.J. Bollen, G. Olguin, M. Martins, Voltage dips at the terminals of wind power installations. *Wind energy*, 8(3), 307-318, 2005.
- [26] E. Gomez-Lazaro, J. A. Fuentes, A. Molina-Garcia, M. Canas-Carreton, "Characterization and visualization of voltage dips in wind power installations, *IEEE Transactions on Power Delivery*, vol. 24, no. 4, pp. 2071-2078, Oct. 2009.
- [27] J. LÓpez, E. Gubía, P. Sanchis, X. Roboam and L. Marroyo, "Wind turbines based on doubly fed induction generator under asymmetrical voltage dips," in *IEEE Transactions on Energy Conversion*, vol. 23, no. 1, pp. 321-330, March 2008.
- [28] R.A. de Oliveira, M.H.J. Bollen, Magnification of transients at the voltage dips starting and its impacts on DFIG-based wind power plants. *Electric Power Systems Research*, 211, 108244, 2022.
- [29] R.A. de Oliveira, M.H.J. Bollen, Impact of voltage dips originated in the transmission grid on EV charging stations, 2022 20th International Conference on Harmonics & Quality of Power (ICHQP), May 2022.
- [30] R. Boeira, R., Ribeiro, R.C. Leborgne, R.A. de Oliveira, propagation of voltage dips in a mixed DFIG-PMSG wind power plant, 2021 IEEE PES Innovative Smart Grid Technologies Conference-Latin America (ISGT Latin America) September 2021.
- [31] R.A. de Oliveira, M.H.J. Bollen, Susceptibility of large wind power plants to voltage disturbances—Recommendations to stakeholders. *Journal of Modern Power Systems and Clean Energy*, 10(2), 416-429, 2021.
- [32] R.A. de Oliveira, M.H.J. Bollen, Dynamic behaviour of wind turbines when submitted to distinctly characterized voltage dips, *CIGRE*, 2021.
- [33] R.A. de Oliveira, C. Chen, M.H.J. Bollen, R.C. Leborgne, Comparative Analysis of Transformer-Energizing and Fault-Caused Voltage Dips on the Dynamic Behavior of DFIG-Based Wind Turbines. 2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe) (pp. 589-593).

- [34] R.A. de Oliveira, C. Chen, M.H. Bollen, R.C. Leborgne, Short-term distortion and protection operation in DFIG-based wind parks during voltage dips, 2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe) (pp. 819-823).
- [35] Math H.J. Bollen, Irene Y.H. Gu, Signal processing of power quality disturbances, Wiley / IEEE Press, 2006.
- [36] CSNI Draft Report, Defence in depth of electrical systems and grid interaction, Final DIDEYSYS Task Group Report
- [37] Lena Max, Johan Olson, Andreas Petersson, Impact on nuclear power plant operation of a changing generation mix, Energiforsk Rapport 2021:835.
- [38] The CSNI Working Group on Electrical Power Systems (WGELEC), technical report on: advancing the robustness of electrical power systems of nuclear power plants, August 2019.
- [39] Robustness of electrical systems of nuclear power plants in light of the Fukushima Daiichi accident (ROBELSYS), Workshop, April 2014.
- [40] E. Styvaktakis, M. H. J. Bollen and I. Y. H. Gu, Expert system for classification and analysis of power system events, IEEE Transactions on Power Delivery, vol. 17, no. 2, pp. 423-428, April 2002.
- [41] E. Styvaktakis, Automating power quality analysis, Doctoral dissertation, Chalmers University of Technology, Sweden, 2002.
- [42] E. Styvaktakis, M. H. J. Bollen, Signatures of voltage dips: transformer saturation and multistage dips, IEEE Transactions on Power Delivery, vol. 18, no. 1, pp. 265-270, Jan. 2003.
- [43] M. H. J. Bollen, Voltage recovery after unbalanced and balanced voltage dips in three-phase systems, IEEE Transactions on Power Delivery, vol. 18, no. 4, pp. 1376-1381, Oct. 2003.
- [44] J. Liang, K. Zhu, Transient characteristics analysis of shunt capacitor asynchronous energizing, IEEE Transactions on Power Delivery, vol. 35, no. 5, pp. 2186-2195, Oct. 2020.
- [45] B. Bhargava, A. H. Khan, A. F. Imece, J. DiPietro, Effectiveness of pre-insertion inductors for mitigating remote overvoltages due to shunt capacitor energization, IEEE Transactions on Power Delivery, vol. 8, no. 3, pp. 1226-1238, July 1993.
- [46] H. Khalilnezhad, M. Popov, L. van der Sluis, J. P. W. de Jong, N. Nenadovic, J. A. Bos, Assessment of line energization transients when increasing cable length in 380 KV power grids, 2016 IEEE International Conference on Power System Technology (POWERCON), Wollongong, NSW, Australia, 2016
- [47] M. Bollen, S. Mousavi-Gargari, Harmonic resonances due to transmission cables. In International Conference on Innovation for Secure and Efficient Transmission Grids, CIGRE Belgium Conference, 2014.
- [48] O. Lennerhag, M.H.J. Bollen, Power system impacts of decreasing resonance frequencies. 18th International Conference on Harmonics and Quality of Power (ICHQP), 2018.
- [49] K. Jansen, B. van Hulst, C. Engelbrecht, P. Heslen, K. Velitsikakis and C. Lakenbrink, "Resonances due to long HVAC offshore cable connections: studies to verify the immunity of Dutch transmission network," IEEE Eindhoven PowerTech, Eindhoven, Netherlands, 2015.

- [50] O. Lennerhag, G. Sundberg, R. Rogersten, S. Råström, Towards an impedance-based criterion for efficient analysis of resonant overvoltages in the Swedish transmission system, 20th International Conference on Harmonics & Quality of Power (ICHQP), Naples, Italy, 2022
- [51] J. Lundquist, O. Lennerhag, "Minimum voltage-current characteristic for calculating surge arrester energy dissipation in temporary overvoltage conditions, IEEE Transactions on Power Delivery, vol. 37, no. 3, pp. 2268-2274, June 2022.
- [52] O. Lennerhag, J. Lundquist, M. H. J. Bollen, Temporary detuning of cablified transmission grids for mitigation of resonant overvoltages, IEEE Transactions on Power Delivery, vol. 37, no. 2, pp. 1050-1057, April 2022.
- [53] A. Kalyuzhny, Switching capacitor bank back-to-back to underground cables, IEEE Transactions on Power Delivery, vol. 28, no. 2, pp. 1128-1137, April 2013.
- [54] T. Suwanasri, S. Wattanawongpitak and C. Suwanasri, "Multi-step back-to-back capacitor bank switching in a 115 kV substation, ECTI-CON2010: The 2010 ECTI International Confernce on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, Chiang Mai, Thailand, 2010, pp. 459-463.
- [55] A. Greenwood, Electrical transients in power systems, Wiley, 1991
- [56] Reinhold Rüdenberg, Elektrische Schaltvorgänge und verwandte Störungserscheinungen in Starkstromanlagen, Springer, 1926.
- [57] Reinhold Rüdenberg, Transient performance of electric power systems, phenomena in lumped networks, McGraw-Hill, 1950.
- [58] L. Van der Sluis, Transients in power systems, John Wiley & Sons, 2001.
- [59] David F. Peelo, Current interruption transients calculation, John Wiley & Sons, 2020.
- [60] R. Smeets., L. van der Sluis, M. Kapetanovic, D.F. Peelo, A. Janssen, Switching in electrical transmission and distribution systems. John Wiley & Sons, 2015.
- [61] R.A. Adams, S.W. Middlekauf, E.H. Camm, J.A. McGee. Solving customer power quality problems due to voltage magnification, IEEE Transactions on Power Delivery, 13(4):1515–1520, October 1998.
- [62] E.P. Dick, D. Fisher, R. Marttila, C. Mulkins, Point-on-wave capacitor switching and adjustable-speed drives. IEEE Transactions on Power Delivery, 11(3):1367–1372, July 1996.
- [63] A.A. Girgis, C.M. Fallon, J.C.P. Rubino, R.C. Catoe. Harmonics and transient overvoltages due to capacitor switching. IEEE Transactions on Industry Applications, 29(6):1184–1188, November/December 1993.
- [64] C.E. McCoy, B.L. Floryancic. Characteristics and measurement of capacitor switching atmedium voltage distribution level. IEEE Transactions on Industry Applications, 30(6):1480–1489, November/December 1994.
- [65] M.F. McGranaghan, T.E. Grebe, G. Hensley, M. Samotyj, T. Singh. Impact of utility-switched capacitors on customer systems - II: Adjustable-speed drive concerns. IEEE Transactions on Power Delivery, 6(4):1623–1628, October 1991.
- [66] V.E.Wagner, J.P. Staniak, T.L. Orloff. Utility capacitor switching and adjustable-speed drives, IEEE Transactions on Industry Applications 27, no. 4 (1991): 645-651.
- [67] M. F. McGranaghan, R. M. Zavadil, G. Hensley, T. Singh, M. Samotyj, Impact of utility switched capacitors on customer systems-magnification at low voltage

- capacitors, IEEE Transactions on Power Delivery, vol. 7, no. 2, pp. 862-868, April 1992.
- [68] C. Li, On capacitor switching transient immunity of inverter-based renewable generations, IEEE Transactions on Power Delivery, vol. 30, no. 5, pp. 2339-2345, Oct. 2015.
- [69] R. A. de Oliveira and M. H. J. Bollen, Susceptibility of large wind power plants to voltage disturbances — recommendations to stakeholders, Journal of Modern Power Systems and Clean Energy, vol. 10, no. 2, pp. 416-429, March 2022.
- [70] Power quality in Fingrid's 110 kV grid", Fingrid, 2015.
- [71] Matti Lahtinen, personal communication, 6 August 2001,
- [72] Power quality indices and objectives, CIGRE Technical Brochure 261, 2004.
- [73] 7th CEER-ECRB Benchmarking report on the quality of electricity and gas supply, CEER Ref: C22-EQS-103-03, 2022.
- [74] Roozbeh Torkzadeh, Analysis of voltage dips in future networks - an assessment for the energy transition impacts on severe voltage dips in the Dutch electric grid, Doctoral thesis, Eindhoven University of Technology, The Netherlands, 2024.
- [75] R. A. de Oliveira, R. S. Salles, S. K. Rönnerberg, M. P. de Carli, R. C. Leborgne, Harmonic anomalies due to geomagnetically induced currents as a potential cause of protection mal-trips at the south Atlantic anomaly area, IEEE Transactions on Power Delivery, vol. 39, no. 2, pp. 1124-1136, April 2024.
- [76] R. A. de Oliveira, A. Malfoy, S. K. Rönnerberg, Deep anomaly detection of voltage waveform distortion in the transmission grid due to geomagnetically induced currents, IEEE Transactions on Instrumentation and Measurement, vol. 73, pp. 1-12, 2024, Art no. 2509212.
- [77] Craig J Rodger, Mark A. Clilverd, Daniel H. Mac Manus, Ian Martin, Michael Dalzell, James B. Brundell, Tim Divett, Geomagnetically induced currents and harmonic distortion: Storm-time observations from New Zealand, Space Weather 18, no. 3 (2020).
- [78] IEC 61000-4-13, Electromagnetic compatibility (EMC) - Part 4-13: Testing and measurement techniques - Harmonics and interharmonics including mains signalling at a.c. power port, low frequency immunity tests.
- [79] S.K. Rönnerberg, at al., On waveform distortion in the frequency range of 2 kHz–150 kHz— Review and research challenges. Electric Power Systems Research, 150, 1-10, 2017.
- [80] Sarah Rönnerberg, Emission and interaction from domestic installations in the low voltage electricity network, up to 150 kHz, Doctoral Thesis, Luleå University of Technology, Skellefteå, Sweden, 2013
- [81] Tatiano Busatto, On waveform distortion in modern low-voltage installations with multiple nonlinear devices, Doctoral Thesis, Luleå University of Technology, Skellefteå, Sweden, 2020
- [82] Vineetha Ravindran, Time-varying waveform distortion in low voltage networks, Doctoral Thesis, Luleå University of Technology, Skellefteå, Sweden, 2021
- [83] Selcuk Sakar, Modelling and interference analysis of ac-dc converters for immunity to voltage disturbances up to 150 kHz, Doctoral Thesis, Luleå University of Technology, Skellefteå, Sweden, 2021.

- [84] Angela Espin Delgado, Propagation of supraharmonics in low-voltage networks, doctoral thesis, Luleå University of Technology, 2022.
- [85] Jil Sutaria, On the supraharmonics in single-phase and three-phase installations, Doctoral Thesis, Luleå University of Technology, Skellefteå, Sweden, 2023.
- [86] D.T. Rizy, E. W. Gunther, M. F. McGranaghan, Transient and harmonic voltages associated with automated capacitor switching on distribution systems, IEEE transactions on power systems 2, no. 3 (1987): 713-723.
- [87] T.A. Bellei, R. P. O'leary, E. H. Camm. Evaluating capacitor-switching devices for preventing nuisance tripping of adjustable-speed drives due to voltage magnification. IEEE Transactions on Power Delivery 11, no. 3 (1996): 1373-1378.
- [88] M.H.J. Bollen, Fainan Hassan. Integration of distributed generation in the power system. John Wiley & sons, 2011.
- [89] Föreskrift EIFS 2023:3. Energimarknadsinspektionens föreskrifter och allmänna råd om krav som ska vara uppfyllda för att överföringen av el ska vara av god kvalitet.
- [90] IEC 60034, Rotating electrical machines.
- [91] P.A. Crossley, P. G. McLaren. Distance protection based on travelling waves, IEEE Transactions on Power Apparatus and Systems, 9 (1983): 2971-2983.
- [92] Mathias Bollen, On travelling-wave-based protection of high-voltage networks." Doctoral thesis, Eindhoven, The Netherlands, 1989.
- [93] Roger A, de Oliveira, Math H.J. Bollen, Magnification of transients at the voltage dips starting and its impacts on DFIG-based wind power plants, Electric Power Systems Research 211 (2022): 108244.
- [94] Naser Nakhodchi, Math H.J. Bollen, Tatiano Busatto. Transfer of harmonics in distribution networks. IEEE Transactions on Power Delivery 37, no. 3 (2021): 1617-1626.
- [95] Jan Meyer, Robert Stiegler, Peter Schegner, Ingolf Röder, Andreas Belger. Harmonic resonances in residential low-voltage networks caused by consumer electronics. CIRED-Open Access Proceedings Journal 2017, no. 1 (2017): 672-676.
- [96] Tatiano Busatto, Math Bollen, Sarah Rönnberg, Photovoltaics and Harmonics in Low-Voltage Networks, Energiforsk Rapport 2018:473.
- [97] Math Bollen, Naser Nakhodchi, Övertoner i lågspänningsnät, Energiforsk Rapport 2023:973.
- [98] Daphne Schwanz, On transfer functions for power quality studies in wind power and solar PV plants, doctoral dissertation, Luleå University of Technology, Skellefteå, 2019.
- [99] Daphne Schwanz, Math Bollen, Sarah Rönnberg, Obalans från enfasanslutna solpaneler, Energiforsk Rapport 2015:130.
- [100] Tatiano Bussatto, On waveform distortion in modern low-voltage installations with multiple nonlinear devices, doctoral dissertation, Luleå University of Technology, Skellefteå, 2020.
- [101] Tatiano Bussatto, Math Bollen, Sarah Rönnberg, Photovoltaics and Harmonics in Low-Voltage Networks, Energiforsk Rapport 2018:473.
- [102] Naser Nakhochi, On harmonics in low-voltage networks, doctoral dissertation, doctoral dissertation, Luleå University of Technology, 2023.
- [103] Math Bollen, Naser Nakhodchi, Övertoner i lågspänningsnät, Energiforsk Rapport 2023:973.

- [104] Angela Espin Delgado, Propagation of supraharmonics in low-voltage networks, doctoral dissertation, Luleå University of Technology, Skellefteå, 2022.
- [105] Math Bollen, Överspänning från enfasanslutna solpaneler, Energiforsk Rapport 2018:506.
- [106] Enock Mulenga, On the hosting capacity of distribution networks for solar power, doctoral dissertation, Luleå University of Technology, Skellefteå, 2021
- [107] Guidelines of Good Practice for the implementation and use of voltage quality monitoring for regulatory purposes, CEER Reference C12-EQS-51-03, 2012.
- [108] Guidelines for power quality monitoring - Measurement locations, processing and presentation of data, CIGRE Technical Brochure 596, 2014.
- [109] Power quality and EMC issues with future electricity networks, CIRED Technical Brochure 719, 2018.
- [110] EN 50160, Voltage characteristics of electricity supplied by public electricity networks.
- [111] Fractional factorial design, Wikipedia.
- [112] Roger Alves de Oliveira, Applications of unsupervised deep learning for analysing time-varying power quality big data, doctoral thesis Luleå University of Technology, Skellefteå, 2023.
- [113] Ankita Benjamin, Sachin Kumar Jain, A review of literature on effects of harmonics on protective relays, 2018 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia) (2018): 407-412.
- [114] Hossein Farzin, Mehdi Monadi, Mahmud Fotuhi-Firuzabad, Mehdi Savaghebi. A reliability model for overcurrent relays considering harmonic-related malfunctions, International Journal of Electrical Power & Energy Systems 131 (2021): 107093.
- [115] Roger Alves de Oliveira, Rafael S. Salles, Sarah K. Rönnberg, Miguel P. de Carli, Roberto Chouhy Leborgne, Harmonic Anomalies due to Geomagnetically Induced Currents as a Potential Cause of Protection Mal-Trips at the South Atlantic Anomaly Area, IEEE Transactions on Power Delivery (2024).
- [116] E. Styvaktakis, M.H.J. Bollen, I.Y.H. Gu, Transformer saturation after a voltage dip, IEEE Power Engineering Review, April 2000, pp.62-64.
- [117] Math H.J Bollen, Irene Yu-Hua Gu. On the analysis of voltage and current transients in three-phase power systems, IEEE Transactions on Power Delivery 22, no. 2 (2007): 1194-1201.
- [118] Network modelling for harmonic studies, CIGRE Technical Brochure 766, 2019.

VOLTAGE DIP TRANSIENTS AND AUXILIARY EQUIPMENT IN NUCLEAR POWER STATIONS

Voltage-dip transients, oscillations at the beginning and ending of voltage dips, occur due to faults in the transmission system. They propagate to the terminals of auxiliary equipment and may have a negative impact on the performance of that equipment. There is limited knowledge on origin, propagation, and impact of voltage-dip transients. Further work is needed to ensure that voltage-dip transients will not endanger the reliability of auxiliary equipment in nuclear power plants. Voltage-dip transients deserve much more attention than they have received before.

A new step in energy research

The research company Energiforsk initiates, coordinates, and conducts energy research and analyses, as well as communicates knowledge in favor of a robust and sustainable energy system. We are a politically neutral limited company that reinvests our profit in more research. Our owners are industry organisations Swedenergy and the Swedish Gas Association, the Swedish TSO Svenska kraftnät, and the gas and energy company Nordion Energi.

