Wind Power and Fault Clearance

Final Report

Elforsk rapport 10:99

Johnny Vikesjö, Lars Messing, Gothia Power

April 2011

Wind Power and Fault Clearance

Final Report

Elforsk rapport 10:99

Johnny Vikesjö, Lars Messing, Gothia Power April 2011

Preface

The increased penetration of wind power will increase the impact of wind power on the grid and thereby increase the importance of a clear guidance concerning the requirements on the protection system of the wind power units and the grid protection in connection to wind power units.

In order to obtain guidelines for design of protection systems in a rational manner a project V-310, “Power Fault Clearence” has been conducted within the Vindforsk III programme. The project was split in two parts. The first report from the project (Elforsk report 10:52) includes a survey of present praxis for fault protection for wind power installations. In this second and final report from the project, guidelines for design of protection systems are given.

Vindforsk III is funded by ABB, Arise wind power , AQ System, E.ON Elnät, E.ON Vind Sverige, EnergiNorge, Falkenberg Energi, Fortum, Fred. Olsen Renewables, Gothia Vind, Göteborg Energi, HS Kraft, Jämtkraft, Karlstads Energi, Luleå Energi, Mälarenergi, o2, Rabbalshede Kraft, Skellefteå Kraft, Statkraft, Stena Renewable, Svenska Kraftnät, Tekniska Verken i Linköping, Triventus, Wallenstam, Varberg Energi, Vattenfall Vindkraft, Vestas Northern Europe, Öresundskraft and the Swedish Energy Agency.

Comments on the work and the report have been given by a reference group with the following members;

Kjell Gustafsson, Statkraft

John Kemmlert, Svenska Kraftnät

Johan Öckerman, Vattenfall

Ulf Thomasson, Fortum

Anton Dahlgren, E.ON

Anders Pettersson, Skellefteå Kraft

Matz Tapper, Svensk Energi

Söhnke Schierloh, Enercon

Kjell Persson, Arise Elnät AB

Stockholm April 2011

Anders Björck

Programme manager Vindforsk III

Elforsk AB

Sammanfattning

Den ökade andelen vindkraft i kraftnätet ökar vindkraftens påverkan på kraftnätet vilket gör det allt viktigare att ha en tydlig vägledning angående kraven på både felbortkopplingssystemen i vindkraftverken och på felbortkoppling i nät som ansluter till vindkraft.

Felbortkopplingssystemet ska uppfylla anslutningskraven för kraftnätet, som bestäms av nätoperatörerna och nätägarna, likväl som de generella säkerhetskraven såsom; personsäkerhet, driftsäkerhet och ekonomisk försäkring, dvs ett skydd mot de ekonomiska förluster som fel kan ge upphov till.

Vindforsk har utsett Gothia Power AB att utföra studien angående felbortkoppling vid vindkraftsinstallationer. Studien är uppdelad i två delar;

Del 1; Den första delen av studien behandlade nuvarande praxis för felbortkoppling. Legala krav, krav på drifttillgänglighet och personlig säkerhet studerades. Förslag på felbortkopplingskrav för vindkraftverk och för anslutande nät formuleras. I huvudsak kan "normala" felbortkopplingskrav beträffande snabbhet, selektivitet och redundans även användas för skydd i anslutning till vindkraftapplikationer.

Del 2; Den andra delen av projektet syftar till att ta fram ett vägledande dokument angående konstruktion av felbortkopplingssystem i anslutning till vindkraft.

Denna rapport behandlar huvudsakligen del 2 av projektet.

Huvudsaklig fokus har lagts på felbortkoppling i elnätet som ansluter vindkraftverk. Angående interna fel och kritiska driftfall i vindkraftverket, ges en kort överblick av rimliga skyddsfunktioner.

Ett antal kritiska felfall har identifierats och diskuterats:

- Icke detekterad önätsdrift och återinkoppling. Det finns ofta en viss risk att önätsdrift inte detekteras, d v s då önätet har aktiv och reaktiv effektbalans. I dessa fall rekommenderas att använda kontrollerad återinkoppling i närheten av vindkraftgenerering.
- Oönskad frånkoppling av felfri ledning vid fel på annan anläggning i nätet. Detta kan ske för ledningar som ansluter generering. Kortslutningsskydd med riktad funktion rekommenderas i dessa fall.
- Risk för utebliven ledningsskyddsfunktion. Felströmsinmatning från ansluten generering till en felbehäftad ledning påverkar felströmmen genom utgående fack i matande station. Detta problem uppstår troligen endast för mycket långa ledningar med stor felströmsinmatning nära den matande stationen.
- Felbortkoppling av samlingsskenekortslutning i matande station. Den normalt använda skyddsfunktionen med blockeringskopplat överströmsskydd på matande transformator måste modifieras om någon ledning har ansluten generering som matar in felström. Två alternativ att lösa detta problem anges; användning av ljusbågsvakt och/eller användning av riktade kortslutningsskydd i de fack som ansluter ledningar med generering.

Påverkan på felströmmen från vindkraftverk behandlas. Felströmmen från de nya typerna av generatorsystem; DFIG (Doubly Fed Induction Generator) och generatorer anslutna via fulleffektomriktare, skiljer sig från felströmmen från konventionella synkrongeneratorer. Detta innebär att konventionell felströmsberäkning inte kommer att ge korrekt resultat. I många applikationer är inverkan försumbar, dock inte alltid.

Tre olika typer av skyddskraftapplikationer har studerats:

- Skydd där ett fåtal enstaka vindkraftverk ansluts till en normal distributionsledning
- Skydd där en liten vindkraftpark ansluts till en ledning i ett normalt distributionssystem
- Skydd där en vindkraftpark är direkt ansluten till regionnät eller stamnät

Kortslutningar och jordfel har studerats vid olika felpunkter; i vindkraftverket, på ledning i distributionsnätet/uppsamlingsnätet, och i det anslutande regionnätet/stamnätet. För dessa fel beskrivs olika skyddsalternativ. Även skydd för avvikande spänning och frekvens behandlas.

Sammanfattningsvis ges riktlinjer för val av skydd för olika objekt:

- Skydd i fack som ansluter **distributionsledning** med ansluten vindkraftgenerering
- Skydd i vindkraftverk som är ansluten till **distributionsledning**
- Skydd i fack för ledning i **uppsamlingsnätet för en vindkraftpark**
- Skydd i vindkraftverk som är ansluten till **uppsamlingsnätet för en vindkraftpark**
- Transformatorskydd i matande station

Beroende på olika betingelser anges riktlinjer för val av skydd (kapitel 9). Generella krav för de olika skydden anges.

Summary

The increased penetration of wind power will increase the impact of wind power on the grid and thereby increase the importance of a clear guidance concerning the requirements on the protection system of the wind power units and the grid protection in connection to wind power units.

The protection system should be able to satisfy the grid connection requirements, set by the TSO (Transmission System Operator) and the grid owners, as well as the general safety and security requirements, such as; personal safety, operational security and economic insurance, i.e. an insurance against economic losses.

Vindforsk has appointed Gothia Power AB to perform a study concerning the fault clearance function in connection to wind power installations. The study is divided into two parts;

Part 1: The first stage of the project handled the present praxis for the protection, including investigation of legal requirements, operational requirement and personal safety requirement applicable to wind power applications. Proposals for protection requirement for wind power units and the connecting grid are given. Basically "normal" fault clearance requirements regarding speed, selectivity and redundancy can be used also in applications in connection to wind power.

Part 2: The second part of the project results in a guideline for design of protection systems in connection to wind power.

In this report mainly part 2 is covered.

The main focus is given to clearance of faults in the grid connecting the wind power plants. Regarding internal faults and critical operation states within the wind power plant, a short discussion of feasible protection functions is given.

Some critical fault cases in the grid have been identified and discussed:

- Undetected islanding and failure of reclosing. There can be a risk of undetected island operation. In such cases it is recommended to use controlled autoreclosing in the vicinity of wind power generation.
- Unwanted disconnection of a healthy feeder in case of a fault occurring elsewhere in the network. This can occur in a feeder bay connecting generation. Directional short circuit protection is proposed in these cases.
- Prevention of feeder protection function. Fault current infeed from connected generation along a feeder will influence the fault current through the feeding bay. This problem occurs probably only for very long feeders with large infeed close to the feeding substation.
- Clearance of busbar faults in the feeding substation. Normally used blocked overcurrent protection of busbars must be modified in case of fault current infeed from any feeder. Two solutions are possible: use of arc detection protection and/or directional short circuit protection in bays connecting feeders with generation.

The impact of fault current infeed from wind generator systems at grid faults is discussed. Fault currents from the new types of generator systems; DFIG

(Doubly Fed Induction Generator) and full power converter connected generator, differ from conventional synchronous generators. It is therefore concluded that conventional fault calculations will not give correct fault current levels. In many applications this error is negligible, but not always.

Three different types of wind power applications are studied:

- Protection with a limited number of wind power units connected to a distribution feeder
- Protection with a small wind farm connected one feeder in a distribution system
- Protection of a wind farm connected to the sub-transmission or transmission system

Short circuits and earth faults are studied for different fault locations: in the wind power plant, on a feeder in the distribution/collection grid and in the connecting subtransmission/transmission grid. For these faults different kind of protections are discussed. Also protection for deviating voltage and frequency are discussed.

As conclusion, guidelines are given for the choice of protection of different objects:

- Protection in a substation bay connected to a **distribution grid** containing wind power
- Protection in a wind power unit connected to a **distribution grid**
- Protection at the substation bay connected to a **wind farm collection grid**
- Protection in a wind power unit connected to a **wind farm collection grid**
- Substation transformer protection

Depending on the different conditions, guidelines for selection of protection is given (Section 9). General requirement for the protection is presented.

Content

Abbreviations

DFIG;	Doubly fed induction generator
EMF;	Electromotoric force
HV;	High voltage
IEC;	International Electrotechnical Commission
LV;	Low voltage
MV;	Medium voltage
ROCOF;	Rate Of Change Of Frequency
TSO;	Transmission System Operator

1 Background

This report is the second project report of the Vindforsk project V-310: "Wind Power and Fault Clearance" [1]. The first project report described the present design and safety requirements for the fault clearance systems for wind farms and the interconnected grid. In this project report a protection concept is developed based on the requirements in the first report as well as an investigation of commonly identified problems relating to the protection of wind power and its connecting grid.

The requirements, as given in part 1 of the project, are shortly described as:

A general requirement for protection systems is that all protection functions shall have redundancy if lack of the personal safety and operational security not can be considered to be negligible. The fault clearance shall be selective as far as possible.

The normal praxis for fault clearance in the Swedish transmission grid (400 kV and 220 kV systems) fulfils the realistic requirements of fault clearance in connection to wind power.

The normal praxis for fault clearance in the Swedish sub-transmission grid (40 - 130 kV systems) fulfils the realistic requirements of fault clearance in connection to wind power.

In the distribution grids where solitary wind turbines are connected requirements are given for fast fault clearance of short circuits: within 1.0 s, at normal fault clearance and within 1.5 s at back-up fault clearance. The clearance of phase to earth faults follows the requirement given by regulations (ELSÄK-FS 2008:1). Although the fact that the requirements are quite strait forward, there might be difficulties for fulfilment.

In the collection grids of wind farms requirement are given for fast fault clearance of short circuits: within 1.0 s, at normal fault clearance and within 1.5 s at back-up fault clearance. The clearance of phase to earth faults follows the requirement given by regulations (ELSÄK-FS 2008:1). If a collection grid is built without overhead lines it is not required to automatically clear earth faults.

In wind power plants (turbines) the protection shall enable back-up fault clearance of short circuits and earth faults close to the plant (where line protection does not give full redundancy). Internal short circuits/earth faults shall be cleared. Protections shall be selective to grid protections. Unnormal operating conditions, that can cause damage to the plant, shall be detected and the plant shall be tripped before the occurrence of damage or other severe consequences. The protection shall be coordinated with the internal fault ride through facility of the wind power plant. Island operation shall be detected.

The documentation of the protection system in the grid and on the wind turbine is needed to enable the following: Review of the construction; Spare parts management; Maintenance planning; functioning and commissioning testing. Required documents are described.

It shall be noted that the present requirements can be slightly changed in the future. In the ongoing activity to formulate “Requirements for Grid Connection Applicable to all Generators” within ENTSO-E a working draft is available [8]. The fault ride through requirements might be stricter for some wind power plants in the future. Otherwise no other requirements on the fault clearance are dealt with in this stage.

In the revision of AMP, ”Anslutning av mindre produktionsanläggningar till elnätet” [6] and ASP, ”Anslutning av större produktionsanläggningar till elnätet” (not yet completed) there are no new requirements on the fault clearance formulated.

2 Problem discussion

The purpose of this report is to be a guideline for protection of wind farms and their connecting grid. The ambition has been to produce a guideline that can be used in the most common applications for wind power and provide guidance for some more problematic cases.

The most common applications for protection system in connection to wind power have been categorized based on both the size of the wind farm and on the type of grid connection, i.e. transmission grid, subtransmission grid or the distribution grid. It is common praxis that single wind power units, or small groups of wind power units, are connected to the distribution grid while middle sized or large wind farms normally are connected to the subtransmission or transmission grid.

There are primarily two wind power generator concepts that dominate today. The first concept is the DFIG (doubly fed induction generator) [1] where the rotor of the asynchronous generator is connected to the grid via a power converter while the stator is directly connected to the grid. The second power generator concept is a full power converter concept where the generator (asynchronous or synchronous) is connected to the grid via a full power converter. The wind power units for these two concepts will behave differently during grid faults and will for that reason be treated separately.

A commonly identified problem within all distributed generation, such as wind farms, is anti-islanding protection. The term anti-islanding refers to the ability to detect island operation. An undetected island operation can lead to a number of problems with fulfilling the safety requirements and will for that reason be discussed in this report.

Another important factor is how the system earthing of wind farms connected to the subtransmission grid should be made. The system earthing of the wind farm has a large impact on the earth fault currents and thereby also a large impact on the ability to detect earth faults. The concept of system earthing will be discussed in general terms and recommendations will be given for system earthing of wind farms connected to the subtransmission grid.

There are a number of cases where the common concept of protection will be insufficient to satisfy the requirements on personal safety, operational security and/or economical insurance. These cases are discussed in the report and recommendations for the protection system selection and design are made in these cases for the different applications.

To summarize, this report shall result in a proposal of a protection concept that shall satisfy the personal safety, operational security and economical insurance requirements on the protection system of a wind farm and its interconnected grid for the most common applications. The report shall also give recommendations and some guidance related to some more problematic protection cases for wind farms.

3 Methodology

The development of the protection concept has been based on the following four stages

- First, the requirements and current practice for the protection system of wind farms and their connection grid were investigated in the first project report.
- Second, a number of general application cases for the protection system in connection to wind power were determined.
- Third, a number of problematic cases concerning protection systems in connection to wind farms were identified by performing a literature study.
- Fourth, the different application cases and problematic cases were investigated with the purpose to develop a protection concept for each case that fulfills the requirements on the protection system.

4 Critical fault cases

In this section, four cases are discussed where the wind power may affect the protection system.

- Undetected islanding and failure of reclosing
- Unwanted disconnection of healthy feeder
- Prevention of feeder protection operation
- Busbar short circuit in the feeding substation

4.1 Undetected islanding and failure of reclosing

Island operation of a grid can occur with or without any primary shunt fault in the grid. Below islanding with a fault is discussed. This can be classified as failure of fault clearance.

Autoreclosing is an important function to minimize interruption time of customers after line faults. This feature is used on overhead lines where the majority of faults are of a temporary nature. When the line is tripped the arcing fault is extinguished and the line can be re-energized for continued operation. In connection to wind power, it is essential that autoreclosing is made so that the energization at reclosing, either to the non faulted system or to a permanent fault, does not give dangerous stress to the wind power unit.

If a feeder is disconnected due to a fault on the line, the wind power unit may remain connected and continue to energize the area. This fault case is illustrated in Figure 1. When the feeder tries to reclose the line the fault current might still remain leading to failure of reclosing. The current from a small wind power unit is often too small to trip the overcurrent protection in the wind power unit connection point. If also the change in voltage and frequency is too small for tripping of the frequency and voltage relays, the wind power unit will remain connected and feed the fault current, at least for some time. The undetected island operation may implicate voltage quality problems, failure of reclosing, faults that without the provision of fault current from the wind power unit would have been temporary might become permanent, equipment might be damaged (due to out of phase reclosing transients) leading to increased unavailability and expensive repairs.

The undetected island, which also can occur during non-faulted operation, may also constitute a risk for personnel security. For this reason the wind power unit should always disconnect at island operation and specially before any reclosing is made. Due to this it is sometimes recommended that the fast autoreclosing function should be turned off or equipped with voltage blocking facility. Some grid owners in Sweden have deactivated the fast reclosing attempt of distribution feeders connection distributed generation. However, a too long time for autoreclosing might implicate degraded voltage quality and higher unavailability. Hence, it can be argued that a reasonable fast autoreclosing should be used.

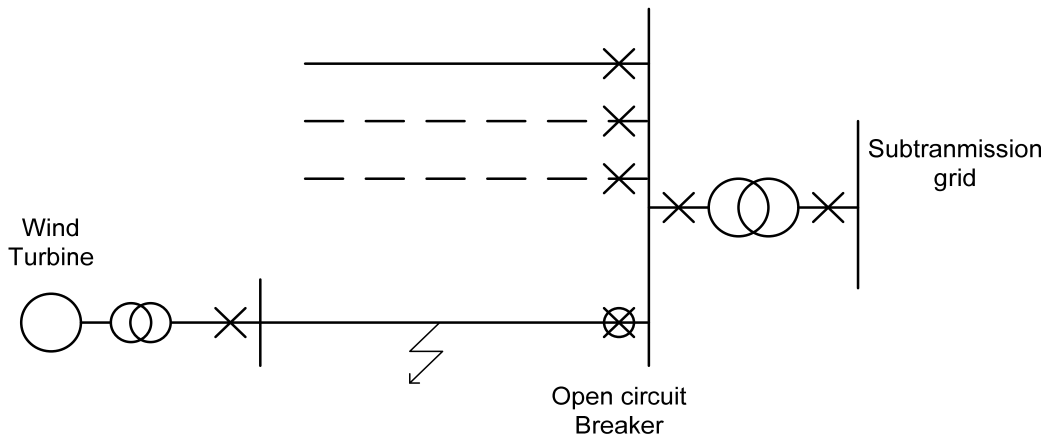

Figure 1; Fault on a feeder and undetected islanding

Autoreclosing for a feeder connecting wind power should be controlled which could be made with one of the following methods

- Voltage blocking; the feeder circuit breaker is allowed to reclose only if the line side voltage is zero.
- Synchrocheck; the feeder circuit breaker is allowed to reclose only if the voltage level, frequency difference and phase angle difference over the circuit breaker is smaller than set levels
- Delayed reclosing; the dead time of the line is made so long that all generators connected to the feeder have been disconnected before the reclosing.

In transmission and subtransmission grids that connect wind power, should the use of autoreclosing be adapted to avoid dangerous situations for the wind power units. This must be treated individually depending on the subtransmission/transmission grid structure in connection to distributed generation.

Dangerous situations for the wind power plants are mainly reclosing in phase opposition causing electrical and mechanical stress. If there is a risk of this situation, for example if the wind power is connected via radial connection, any of the above described methods should be used,

4.2 Unwanted disconnection of a healthy feeder

If there is a fault on an adjacent feeder, see Figure 2, should only the feeder with the fault be disconnected and the other lines should remain connected. What instead might happen is that the connected wind power unit(s) start to feed the fault on the adjacent line and that the fault current is large enough to cause tripping of the relay for the wind power connected feeder. This case is more likely if the fault is located near the substation and if the fault is a symmetric 3-phase fault. A directional relay could be an efficient way to avoid this problem. Another way to deal with the problem might be to use appropriate setting of the relays (relay coordination). But delayed tripping might be impossible due to thermal limit constraints. The cost aspect of the different protection alternatives will in practice normally have a large impact on the final choice of protection concept.

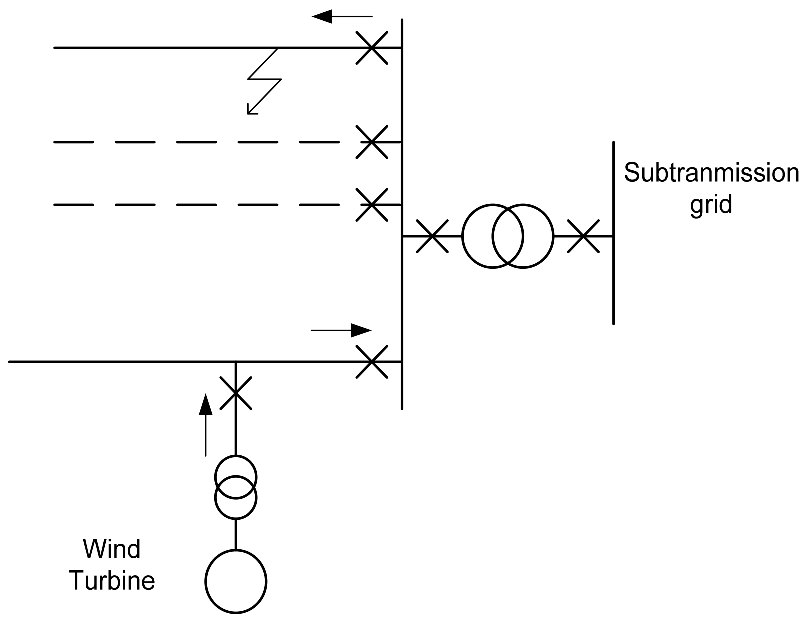

Figure 2; Risk for unwanted disconnection of a healthy feeder

4.3 Prevention of feeder protection operation

In case of a short circuit fault near the far end of a wind power unit feeder, there is a possibility that the wind power unit will decrease the fault current measured by the feeder protection relay and thereby prevent the fault clearing. This case is illustrated in Figure 3 and is most likely when; the fault occurs near the end of a long feeder (> 10 km), the wind power unit is located close to the main feeding end of the cable and if the fault has a high resistance. To evaluate this risk fault calculations should be made. In case of a single wind power unit, the influence on the feeder protection is, in most cases, limited. A way to deal with the problem is to lower the pickup current of the relay; however, this will also increase the risk of disconnection of a healthy feeder.

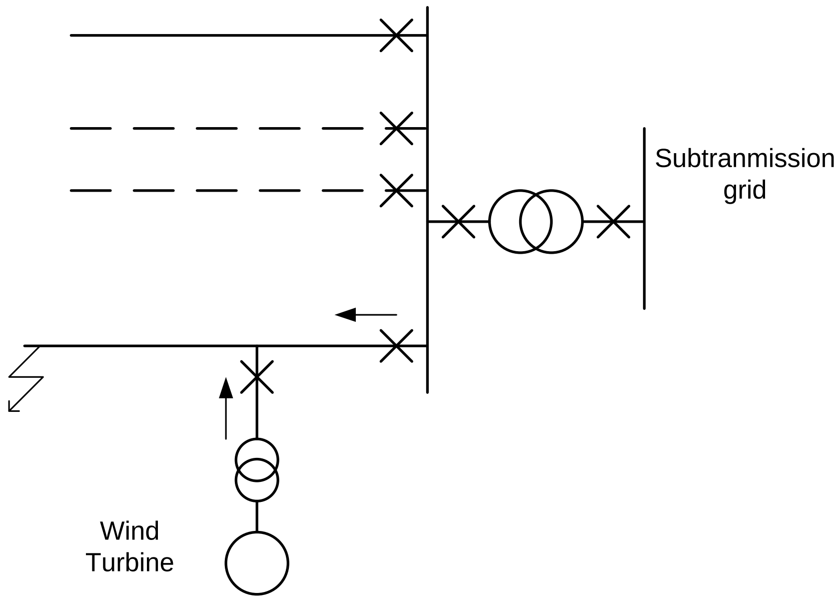

Figure 3; Prevention of feeder protection operation

4.4 Busbar short circuit in the feeding substation

The fault is illustrated in Figure 4.

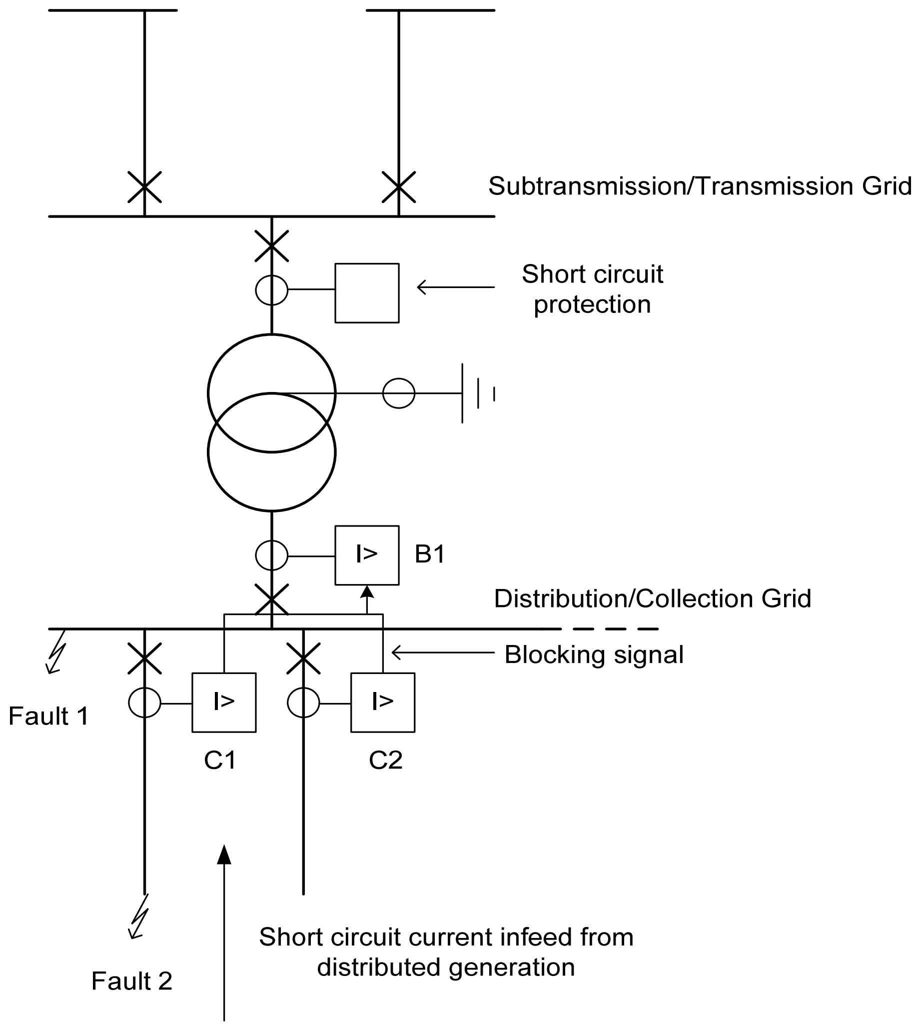

Figure 4; Busbar short circuit

It is essential that a busbar fault is cleared as fast as possible as the short circuit current might be large. A commonly used protection principle is a blocking scheme as shown in Figure 4. When the short circuit (Fault 1) occurs the overcurrent protection B1 at the low voltage side of the transformer will pick-up. After a short delay this protection will trip and clear the fault current fed from the external grid. To assure selectivity the fast trip from B1 must be prevented for short circuits on the outgoing feeders (Fault 2). This is done by blocking of the overcurrent protection B1 from start of the feeder short circuit protections C1, C2…. If distributed generation (wind power or others) are connected to the feeders there is a risk that a short circuit protection on any of the outgoing feeders will start in case of a busbar short circuit and thus block protection B1. This is not acceptable as the fault clearance time can be unacceptable long.

To achieve an acceptable protection function the following alternatives are feasible;

- Arc detection protection is used in the MV substation thus enabling very fast disconnection of arcing faults at busbar short circuits. The drawback of this is that non-arcing faults are not detected. This can be the case at switch in to a forgotten earthing device after maintenance work.
- In the blocking system described above the problem can be solved by using directional short circuit protections on outgoing feeders having connected generation. The setting calculations for the outgoing feeders will show if directional protections are required.

Independent of the protection design used for the detection and trip of the busbar short circuits, all circuit breakers connecting fault current contribution to the busbar short circuit shall be tripped.

4.5 Example calculation of prevention of feeder protection operation

If a wind power unit is connected to the distribution line it might limit the fault current measured by the relay at the beginning of the distribution line which might prevent tripping, see Figure 5.

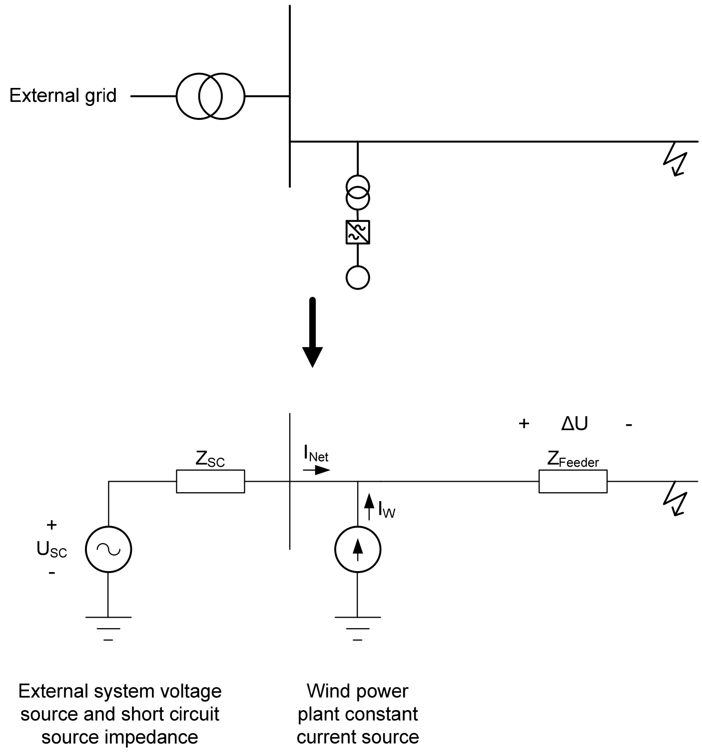

Figure 5; Equivalent of a fault on a distribution feeder where the measured fault current I_{Net} is reduced by the current I_w from the wind power unit.

The external system is modeled as a voltage source U_{SC} and a short circuit source impedance Z_{SC}. The wind power unit is modeled as a constant current source feeding the current I_W. The feeder impedance is Z_{Feeder}. The voltage drop over the feeder is ΔU .

The fault current from the external system can be formulated as;

$$I_{Net} = \frac{U_{SC} - \Delta U}{Z_{SC}}$$

This gives;

$$I_{Net} = \frac{U_{SC} - (I_{Net} + I_W) \cdot Z_{Feeder}}{Z_{SC}}$$

Giving;

$$I_{Net} \cdot (Z_{SC} + Z_{Feeder}) = U_{SC} - I_W \cdot Z_{Feeder}$$

And

$$I_{Net} = \frac{U_{SC} - I_W \cdot Z_{Feeder}}{Z_{SC} + Z_{Feeder}} = \frac{U_{SC}}{Z_{SC} + Z_{Feeder}} - I_W \frac{Z_{Feeder}}{Z_{SC} + Z_{Feeder}}$$

For a single 2 MW wind power unit connected to a 25 km 10 kV distribution feeder will the 3-phase short circuit current in the feeder bay decrease as shown in Figure 6, where the +-marked curve shows the current without the wind power unit in operation and the x-marked curve shows the current with the wind power unit in operation.

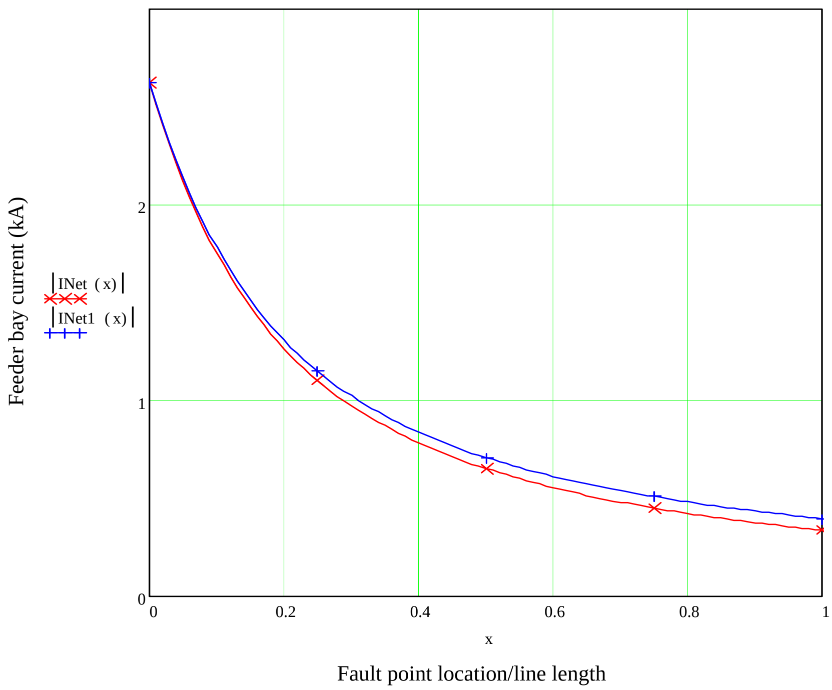

Figure 6; Distribution bay current at short circuit in the feeder

One conclusion is that a single wind power unit, connected to a distribution feeder, in most cases will have negligible influence on the feeder bay phase overcurrent protection. Therefore the normal procedures should be used for the distribution bay phase overcurrent protection.

If more than one wind power plant is connected to the feeder the influence on the fault current at the distribution bay will be greater. It is however assumed that the number of large generator plant connected to one feeder is limited. Calculations in each case are recommended.

5 Faults in wind power units

This section contains a discussion of symmetrical 3-phase short circuits at the terminal of a generator and at the grid side interface of the wind power unit converter.

A visualization of different possible fault locations for the synchronous generator with full power converter is shown in Figure 7. The short circuits can be divided in short circuits that occur within the generator, the full power converter or in the transformer and in short circuit faults that occur in the connections between these devices. This section has been concentrated on the discussion of symmetrical 3-phase faults on the lines between these devices.

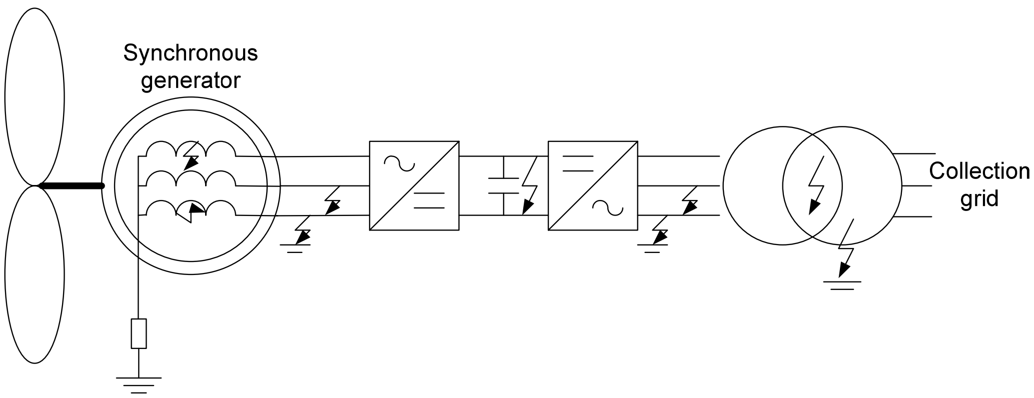

Figure 7; Possible fault locations in a wind power unit with a synchronous generator and full power converter.

Figure 8 shows possible fault locations for a wind power unit with a doubly fed induction generator.

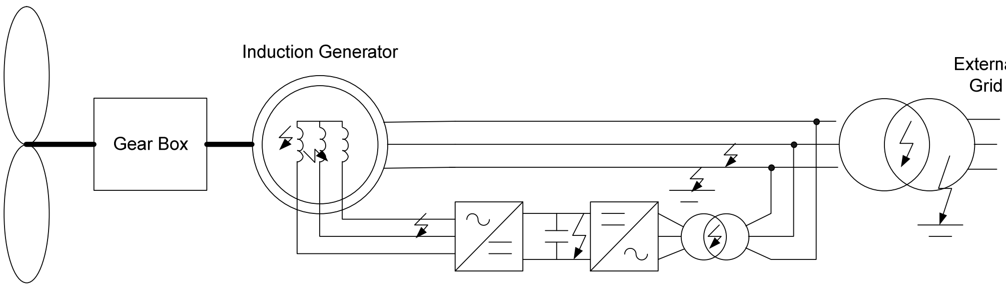

Figure 8; Possible fault locations in a DFIG wind power unit.

5.1 Symmetrical 3-phase fault on the generator terminals

5.1.1 Synchronous generator

If a 3-phase short circuit occurs at the generator terminal the voltage at the terminal will drop to zero. This will give rise to a high current due to the high potential difference between the generator EMF and the zero potential at the fault location. The fault current [2] for a three phase short circuit consists of one aperiodic current component (dc-component) that depends on the angle of the voltage phase angle at the time the short circuit occurs and a damped sinusoidal current component.

$$\mathrm{I(t)} = \mathrm{I(t)}_{\mathrm{aperiodic}} + \mathrm{I(t)}_{\mathrm{dampedsinusoidal}}$$

Where

$$\mathrm{I(t)}_{\mathrm{damped\,sinusoidal}} = E\left(\left(\frac{1}{x''_d} - \frac{1}{x'_d}\right)e^{-\frac{t}{T''_d}} + \left(\frac{1}{x'_d} - \frac{1}{x_d}\right)e^{-\frac{t}{T'_d}} + \frac{1}{x_d}\right)\cos(\omega t + \lambda)$$

$$\mathrm{I(t)}_{\mathrm{aperiodic}} = -\frac{E}{X''_d} e^{-\frac{t}{T_a}} \cos(\lambda)$$

The meaning of the different variables is given below

E =pre-fault internal voltage

x''_d =subtransient reactance

x'_d =transient reactance

x_d =synchronous reactance

T''_d =subtransient time constant

T'_d =transient time constant

T_d =aperiodic time constant

λ = angle of the phase at time zero

ω = system angular velocity

The resulting fault current together with its two components is plotted in Figure 9. The initial subtransient fault current for a synchronous generator is normally in the range of 4-7 times the generator rated current.

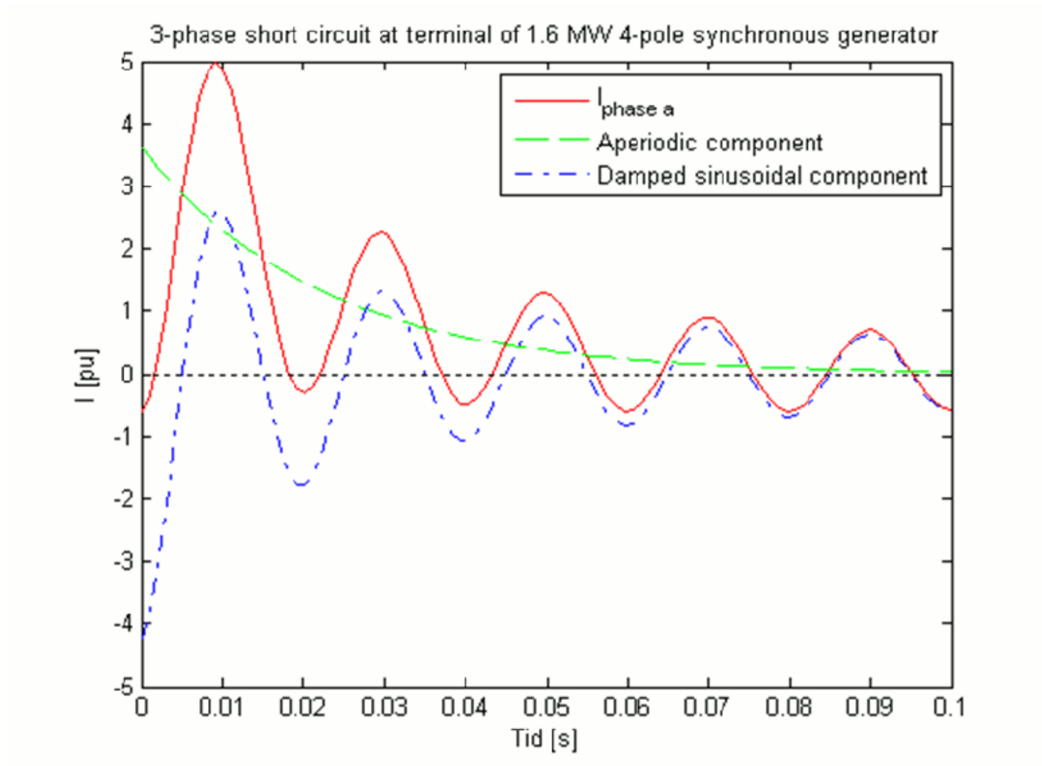

Figure 9; Subtransient and transient current after a 3-phase fault at the terminal of a synchronous generator

5.1.2 Induction generator

The fault current for a symmetrical 3-phase short circuit at the generator terminal of an induction generator is similar to the fault current from a synchronous generator [3]. The fault current is initially only limited by the sub-transient reactance x_d'' and the duration of the subtransient is dependent on the subtransient time constant T_d'' which in turn is largely dependent on the characteristics of the damper windings. When a stable point has been achieved the fault current will instead be limited by the transient reactance x_d' which will diminish depending on the transient constant T_d'. The final steady state fault current will be determined by the electromotive force EMF and the synchronous reactance x_d.

The 3-phase short circuit of an induction generator can mathematically be described in a similar way as the short circuit for the synchronous generator but with $1/x_d$ left out. However, due to difficulties to determine data the damped sinusoidal component is often reduced to just giving the possible peak values

$$\mathrm{I(t)} = \mathrm{I(t)}_{\mathrm{aperiodic}} + \mathrm{I(t)}_{\mathrm{dampedsinusoidal}}$$

Where

$$I(t)_{dampedsinusoidal} = \frac{E}{X''_d}\cos(\omega t + \lambda)e^{-\frac{t}{T''_d}}$$

$$I(t)_{aperiodic} = \frac{E}{X''_d}\cos(\lambda)e^{-\frac{t}{T_a}}$$

An example of the short circuit characteristics is shown in Figure 10. The initial sub-transient fault current for an induction generator is normally in the range of 4-7 times the generators rated current.

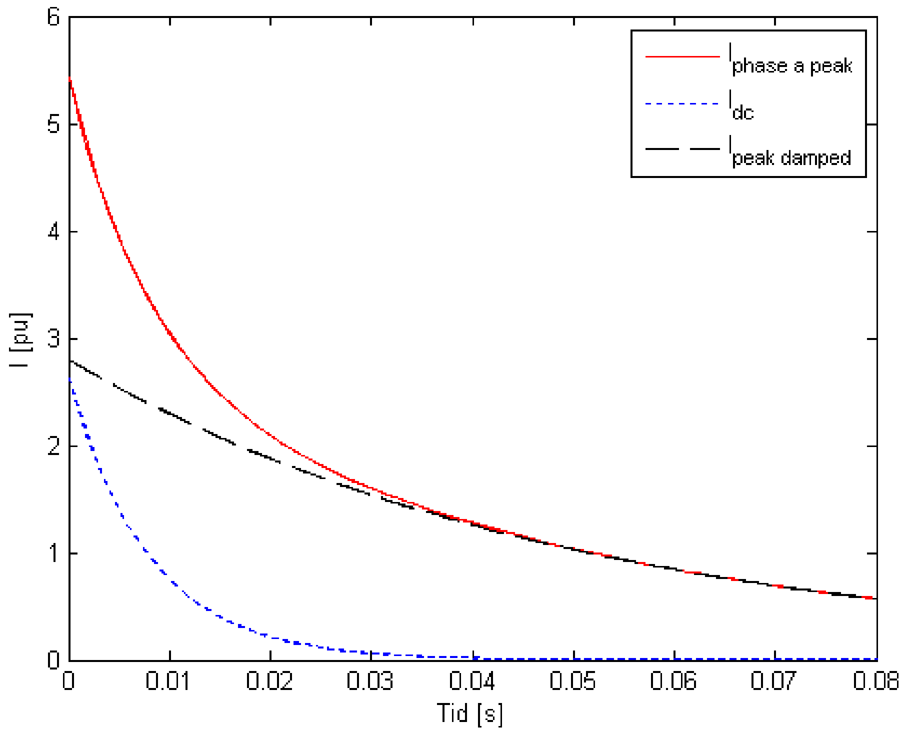

Figure 10; Fault current in one phase and its components for a symmetric 3-phase short circuit at the terminal of an induction generator

5.2 Symmetrical 3-phase fault on the LV side of the transformer

In this section, a 3-phase fault on the LV side of the transformer for both a DFIG and a wind power unit with full power converter is analyzed.

5.2.1 DFIG

Figure 11 shows the fault current. Since the stator in a DFIG is directly connected to the grid, the subtransient behavior will be similar to the case of a 3-phase fault at the generator terminal of an induction generator without a connected partial converter. However, after that the current has dropped to about 1 to 1.5 times the rated current, can the fault current be controlled to keep this level if it is set to provide fault current. Hence, the DFIG will, after the initial transient act as a constant current source giving out either a full fault current in the range of 1-1.5 times rated current or feeding out zero current.

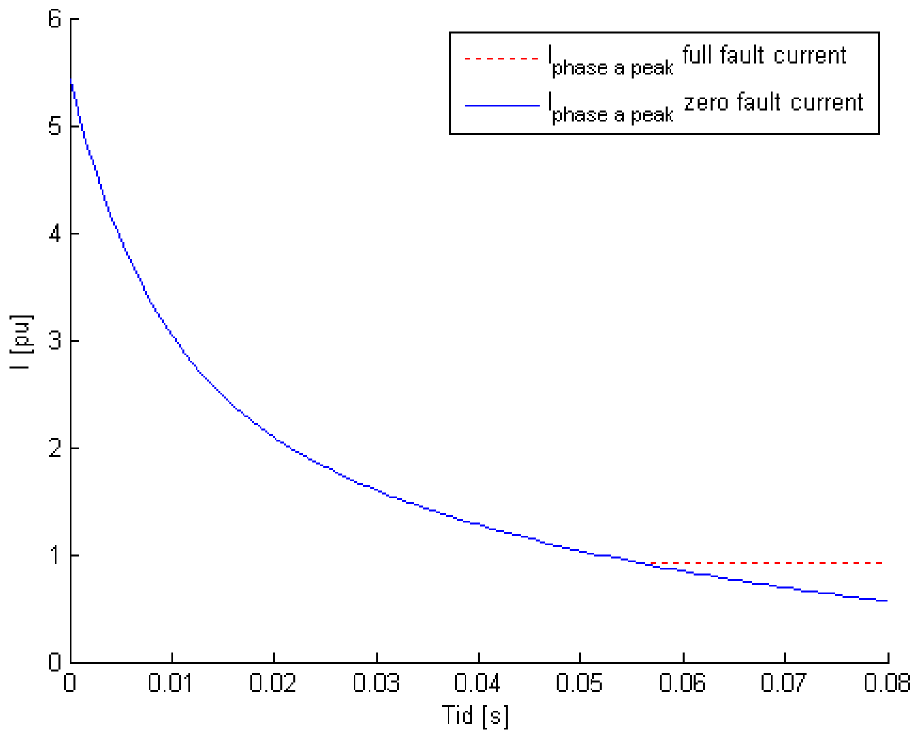

Figure 11; Fault current in one phase and its components for a symmetric 3-phase short circuit at the terminal of an induction generator

5.2.2 Full power converter interface

For a synchronous generator a with full power converter no part of the generator is directly connected to the grid and the full power converter has the ability to control the output voltage, frequency and reactive current. Hence, a wind power unit with a full power converter could be assumed to act as a constant current source for faults on the grid side of the converter. The converters are normally controlled to either feed out zero current during grid faults or to feed out full fault current, which could be slightly above the rated current (1 to 1.5 times I-rated), see Figure 12.

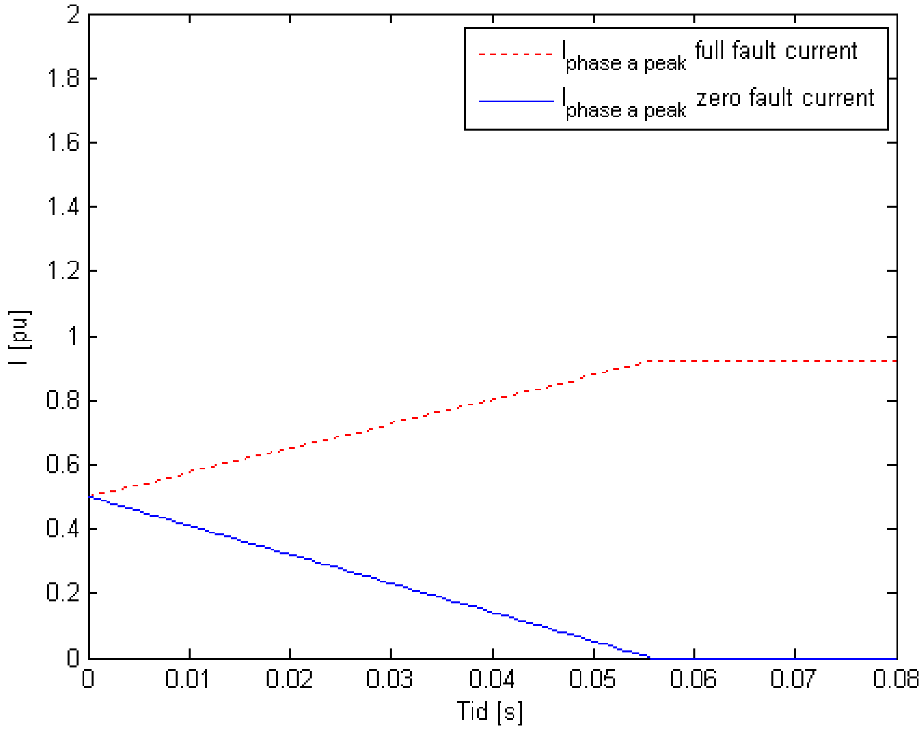

Figure 12; Example of possible fault current outfeed for a 3-phase fault at the terminal of full power converter

5.3 Protection functions within the wind power unit

The protection functions for faults and other critical events within the unit are normally handled internally by the wind generation system. Below is a short survey of phenomena to consider:

- Generator stator short circuit: normally to be tripped as fast as possible
- Generator stator earth fault: normally to be tripped as fast as possible
- Converter short circuit: normally to be tripped as fast as possible
- Converter earth fault: normally to be tripped as fast as possible
- Transformer short circuit: normally to be tripped as fast as possible
- Transformer earth fault: normally to be tripped as fast as possible
- Generator negative sequence current (asymmetric current): to be tripped before critical thermal stress of the generator
- Generator thermal overload: to be tripped before critical thermal stress of the generator
- Reverse power: action depending of the plant ability to withstand some reverse power
- Over/under voltage: action depending of plant ability and power system requirements
- Over/under frequency: action depending of plant ability and power system requirements

The degree of redundancy in the fault clearance system is to a large extent based on an economic evaluation between risk and investment. An often used principle is the N-1 criterion, saying that a fault shall be cleared even if one component in the fault clearance system is out of order.

6 Protection with a limited number of wind power units connected to a distribution feeder

This section presents application examples for faults in the wind power unit and faults on the distribution line.

Characteristic for distribution lines are that they operate at a lower voltage than sub-transmission and transmission lines, they are usually radial and they have usually loads connected all along the line, not just at the end of the line. It is also common that the distribution grid is connected to the feeding power system in one point only.

An example of the protection of a single wind power unit connected to a radial feeder in the distribution system is shown in Figure 13. Fault locations 1-3 are discussed in the following text.

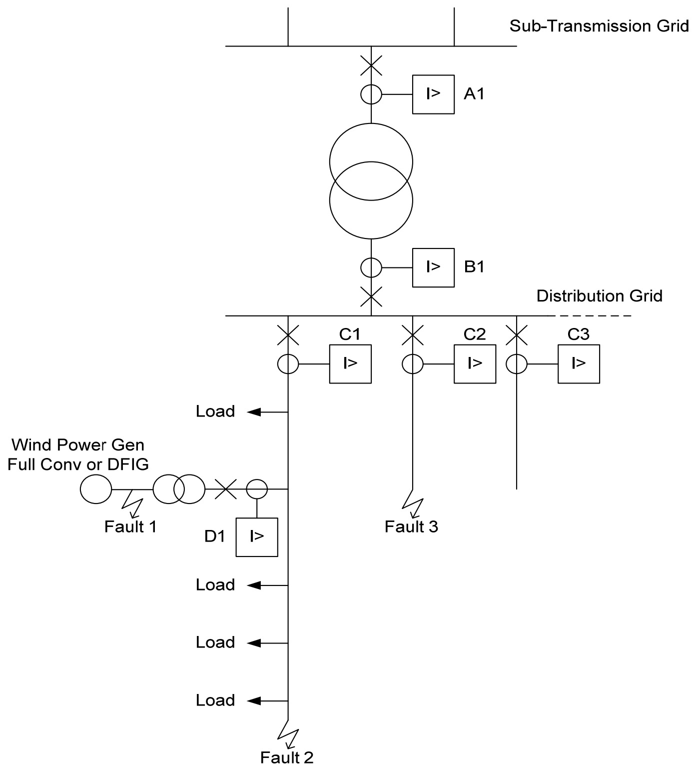

Figure 13; Application example, Single wind power unit connected to a distribution feeder

6.1 Short circuit in the wind power unit

"Fault 1" in Figure 13 illustrates a short circuit fault in the wind power unit. All short circuits within the wind power unit shall normally be detected and tripped by the fault clearance system within the plant. There should, however, be a possibility for back-up fault clearance of internal short circuits, preferably in the wind power unit such that the entire radial does not need to be disconnected if the primary protection in the wind power unit fails to clear the short circuit.

6.1.1 Protection at wind power unit circuit breaker

The back-up protection can be realized by a local non-directional phase over-current protection at the high voltage side of the unit transformer or by the feeder bay short circuit protection (in Figure 13 indicated as a phase over-current protection).

Coordination of the settings shall be done considering internal protections in the wind generator system. If protection D1 exists, the following can serve as a guideline for the setting of the phase over-current protection;

The current level setting may be chosen within the interval;

$$1.2 \cdot \frac{I_{load\max}}{k} \leq I_{pick-up} \leq 0.7 \cdot I_{sc\min}$$

k is the reset ratio of overcurrent protection, I_{scmin} is the minimum fault current at the HV-side of the transformer at LV-side short circuit and $I_{load\ max}$ is the maximum load current measured by protection D1 at non-faulted cases.

The time delay of the protection must be coordinated with the short circuit protection C1 in the distribution bay of the feeder connecting the plant. It is desirable to have as short time delay as possible for protection D1.

6.2 Short circuit on the feeder connecting the plant

This fault is illustrated as "Fault 2" in Figure 13. This fault shall be disconnected at the bay in the substation connecting the feeder as well as at all wind power units connected to the faulted feeder.

6.2.1 Protection at the distribution bay

In the distribution bay (C1) the following protection functions may be used

- Non-directional phase overcurrent protection
- Directional phase overcurrent protection
- Impedance protection with quadrilateral impedance characteristic;

Non-directional phase overcurrent protection

The phase overcurrent protection can be used to detect and clear the short circuit if the fault current is large enough. This must be checked by means of fault current calculation and analysis of the largest load current through the bay. The setting of the protection of the distribution lines should be done so that

1. The pick-up current should be set low enough to detect line end faults but also high enough to carry expected loads without tripping.
2. The delay time of the relays should be short enough to minimize arc flash but also long enough to ensure coordination with downstream protections.
3. The setting $I_{pick\text{-}up}$ (smallest current for trip) can be set so the following is fulfilled;

$$1.2 \cdot \frac{I_{\max}}{k} \leq I_{pick-up} \leq 0.7 \cdot I_{sc\min}$$

Where

I_{max} is the largest load current through the bay,

k is the reset ratio of overcurrent protection and

I_{scmin} is the smallest calculated short circuit current measured by the phase overcurrent protection at 2-phase short circuit on the feeder. There might also be a requirement that the phase overcurrent protection shall serve as back-up protection for short circuits in the wind power plant. The short circuit current at a 2-phase short circuit at the low voltage side of the plant transformer should be calculated and might be used as I_{scmin}.

$I_{pick\text{-}up}$ should be higher than the maximum expected load current that the line is expected to carry. Most faults on power lines can be detected by phase overcurrent relays because the fault currents are normally much higher than the load current.

Directional phase overcurrent protection

If I_{max} is so large that the above described equation cannot be fulfilled. A solution can be to use directional phase overcurrent protection in the bay.

Underimpedance protection

The underimpedance protection with quadrilateral impedance characteristic can increase the possibilities to detect and clear short circuits having low fault current levels, for example, faults on the low voltage side of the unit transformers in the wind power generator systems. The underimpedance protection has the ability to detect faults within a preset distance that is estimated by the calculated impedance.

The under impedance protection uses the measured voltage and current to calculate the impedance. In case of a fault, the measured impedance will decrease and if the impedance gets inside the set impedance characteristic the relay will send a trip signal to the circuit breaker. The apparent impedance is equivalent to the distance between the protection and the fault point, given in Ω/phase. The impedance protection shall have at least two zones. The impedance characteristic for both zones shall have quadrilateral shape with separate reactance and resistance settings. The zones shall have definite time delay.

There are some advantages by using underimpedance protection, compared to phase overcurrent protection;

The reach of the protection zone is independent of the fault type and operation state of the power system.

The impedance characteristic can be made so that the sensitivity is high for fault currents and low for load currents (Figure 14).

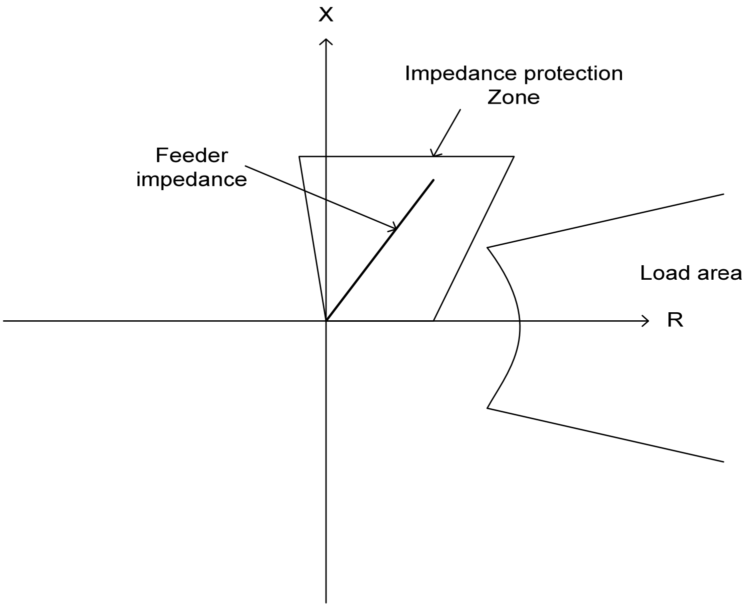

Figure 14; Example of impedance protection characteristic

The need for impedance protection has to be determined case by case. It must be checked that the smallest current for fault detection is large enough to detect all faults to be cleared. This limit is in the range 10 - 30 % of the rated current of the underimpedance protection.

Current differential protection

The current differential relay works by comparing the current coming in and the current going out from a protected zone. The protection relay requires current measurement in all points of the line with power input and output and is for this reason not realistic to apply on a normal distribution feeder, as the system is designed today. There is also a requirement on high performance communication channels.

6.2.2 Protection in the wind power unit

The feeder short circuit ("Fault 2" in Figure 13) shall be detected in the wind power unit. The current from the plant will probably be unaffected by the fault location. This current will also be limited to a maximum value close to the rated current of the plant. The first conclusion is that phase overcurrent protection cannot be used as short circuit protection for external faults.

The undervoltage protection in the power plant will probably detect the short circuits on the feeder connecting the wind power unit. There is, however, a difficulty to distinguish between short circuits on the feeder and faults at other points in the external network. Hence, the undervoltage protection must be set with a trip delay to realize selectivity. This time delay might be long which may implicate a long fault time that could be unacceptable from a personal security point of view. The undervoltage protection settings must not interfere with fault ride through capabilities or requirements on continuous operation at 90 % voltage, according to regulations in SvKFS 2005:2 [7].

After the feeder bay protection C1 has tripped there will probably be unbalance in active and/or reactive power leading to a significant change of voltage and frequency in the island network. In that case will the over/under voltage and/or over/under frequency protections trip the plant. Hence, the over/under frequency and voltage relays will in most cases be sufficient for clearance of short circuit fault, on the connecting feeder, if appropriate time delays are used. The under/over frequency protection settings must not interfere with the requirements in SvKFS 2005:2 [7] where it is stated that the plants shall remain in operation if the frequency is within the range 47,5 – 52 Hz.

6.3 Short circuit on other feeders in the distribution grid

This fault (“Fault 3” as shown in Figure 13) shall be disconnected at the bay (C2) in the substation connecting the faulted feeder and at all wind power plants connected to the faulted feeder. There will be fault current fed from the wind power plant causing reverse fault current measured by protection C1. This current is limited by the current capacity from the wind power plant, which is in the same range as the rated current. For a single wind power plant this current is not large enough to give an unwanted trip, as the current setting must be set to allow the normally generated current in the reverse direction.

6.4 Earth fault on the feeder connecting the plant

The distribution networks are supposed to have high impedance system earthing. This is necessary to fulfill Swedish security requirements. The structure of the distribution system with earth fault protection is shown in Figure 15.

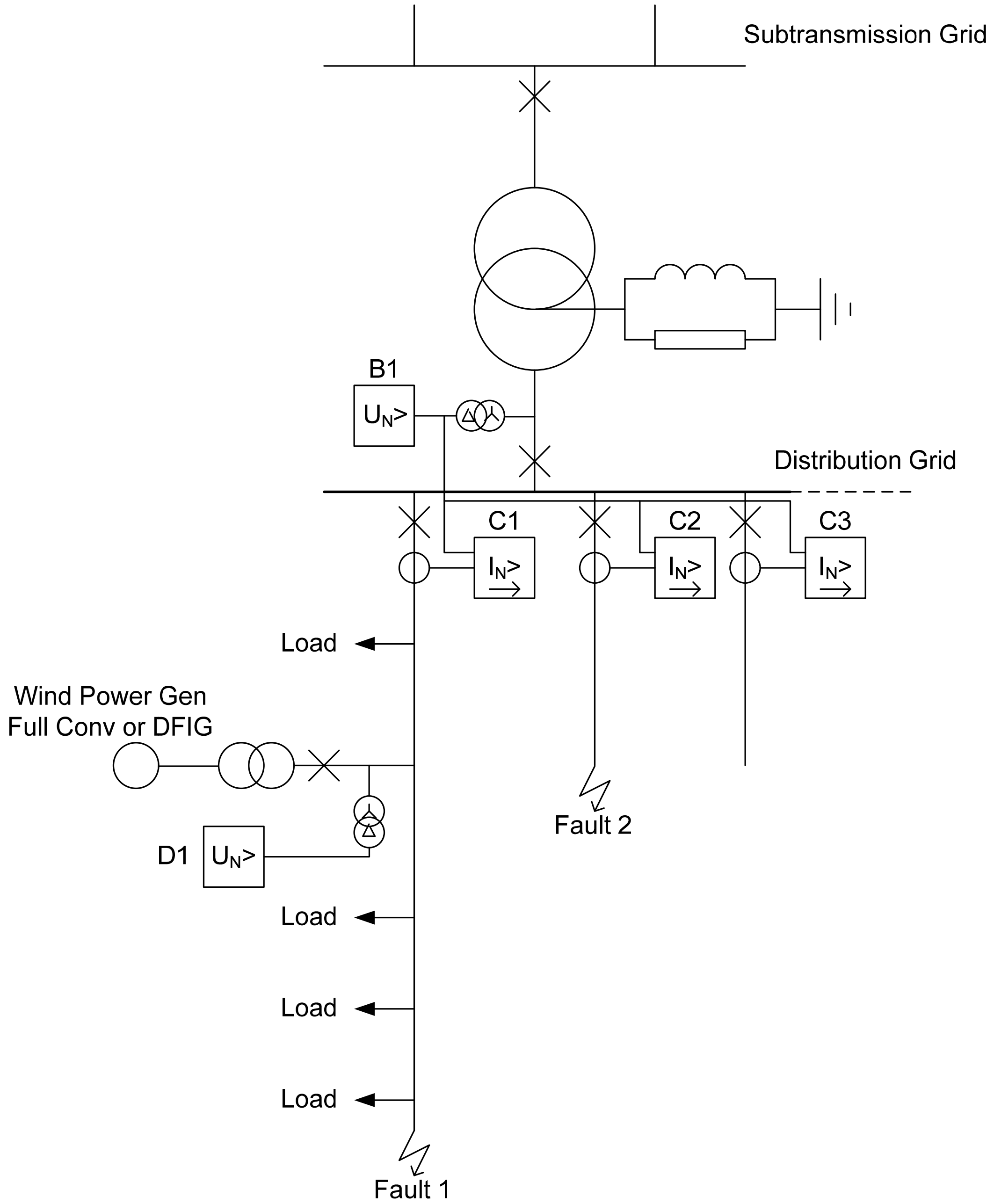

Figure 15; Distribution network with proposed earth fault protection

The earth fault current is fed via the system capacitance to earth and via the neutral point equipment (Petersen coil and neutral point resistor).

6.4.1 Earth fault protection in the substation

The earth fault protection in the substation feeding the distribution feeders can be made in a traditional way, even if wind power units are connected to the feeders. The earth fault protection can consist of:

- Directional earth fault current protection in each feeder bay. If the system has a neutral point resistor the protection will measure the active component (in phase with the zero sequence voltage) of the earth fault current out on the feeder. In some cases the capacitive earth fault current from the non-faulted feeders are used.
- Zero sequence voltage protection, fed from an open delta connected voltage transformer group, either on the transformer low voltage side busbar or on the transformer low voltage side bay. This protection will detect all earth faults in the distribution network and will therefore serve as back-up protection for the feeder earth fault protections. The protection will also serve as main protection for earth faults on the busbar or in the low voltage winding of the transformer.

The earth fault current magnitude is independent of the fault location. This means that the earth fault protection cannot use current dependent time grading of the protections to get selectivity. Instead simple time based selectivity is normally used where the most remote protections, in the radial network, have the shortest time delay.

In case of an earth fault (Fault 1) as shown in Figure 15 we have the following sequence;

At t = 0 the earth fault occurs and earth fault current will flow to the fault point. The faulted feeder bay earth fault current protection will pick-up and start its timer.

At t = t1, often about 1.0 s, the earth fault current protection will trip and the faulted feeder will be disconnected from the rest of the network.

At t> t1 the faulted feeder is energized from the connected wind power plant. The magnitude of the earth fault current is now dependent on the capacitance between the feeder phases and earth (zero sequence capacitance). This current can be quite small but it is not allowed to continue the operation with a sustained earth fault. In this situation there are two different scenarios;

There will be a large active and/or reactive power un-balance for the faulted feeder. The consequence will be deviations in frequency (due to active power un-balance) or in voltage (due to reactive power un-balance). Under/over frequency protection and/or under/over voltage protections will detect this situation and initiate disconnection of the wind power plant. According to the safety regulations trip must occur within 5 s. There is a risk that the un-balance is so small that the time to reach the trip level of under/over frequency protection will be longer than 5 s.

There might be active and reactive power balance for the faulted feeder. The voltage and frequency protections will not be activated. Thus there is an island operation with a sustained earth fault, which is not acceptable. The wind power units have to be disconnected.

If it cannot be proved that power balance is impossible, two different solutions are proposed, where the first is recommended;

1. A residual voltage (zero sequence voltage) protection is applied on the high voltage side of the unit transformer of the wind power plant. This protection can be fed from an open delta connected three phase voltage transformer group or from a voltage transformer in the high voltage transformer neutral point, if it exists. The protection must have a time delay longer than the feeder earth fault protections.
2. A transfer trip is sent from the earth fault protection for the bay feeding the faulted feeder. In this alternative a fast and reliable telecommunication link from the feeding substation to the wind power plants is required.

A special case that can occur is the following; a high resistive earth fault occurs at fault point 1. Initially both the feeder protection C1 and the residual overvoltage protection D1 starts. After a short delay protection C1 trips the line. The earth fault is now fed from the wind power plant and the residual voltage, fed to protection D1, will be changed as the zero sequence system impedance change. If the capacitive fault current from the feeder itself is large, the zero sequence voltage will decrease after the trip from C1. In this moment there is a risk that protection D1 will cease.

The zero sequence voltage at resistive earth faults in a high impedance earthed system can be calculated as;

$$U_0 = \frac{U_{ph-ea}}{1 + \frac{3 \cdot R_f}{Z_0}}$$

Where U_{ph-ea} is the normal phase to earth voltage,

R_f is the resistance to earth in the fault point and

Z_0 is the zero sequence impedance of the system

If the Petersen coil is well tuned Z_0 can be considered to be equal to 3 times the resistance of the neutral point resistor ($3R_N$).

Assume that the rated current of the neutral point resistor is 10 A and that the faulted feeder will generate 20 A at a non-resistance earth fault. Before the trip of the feeder Z_0 will be;

$$Z_0 = 3R_N = 3 \cdot \frac{U_{ph-ea}}{10}$$

After trip of the feeder Z_0 will be;

$$Z_0 = -jX_c = -j3 \cdot \frac{U_{ph-ea}}{20}$$

Figure 16 shows the zero sequence voltage (U_0/U_{ph}) as a function of the fault resistance as measured by protection D1. The curve marked by x shows the situation before the trip at C1 (where the total capacitive current is compensated) and the curve marked + shows the situation after the trip.

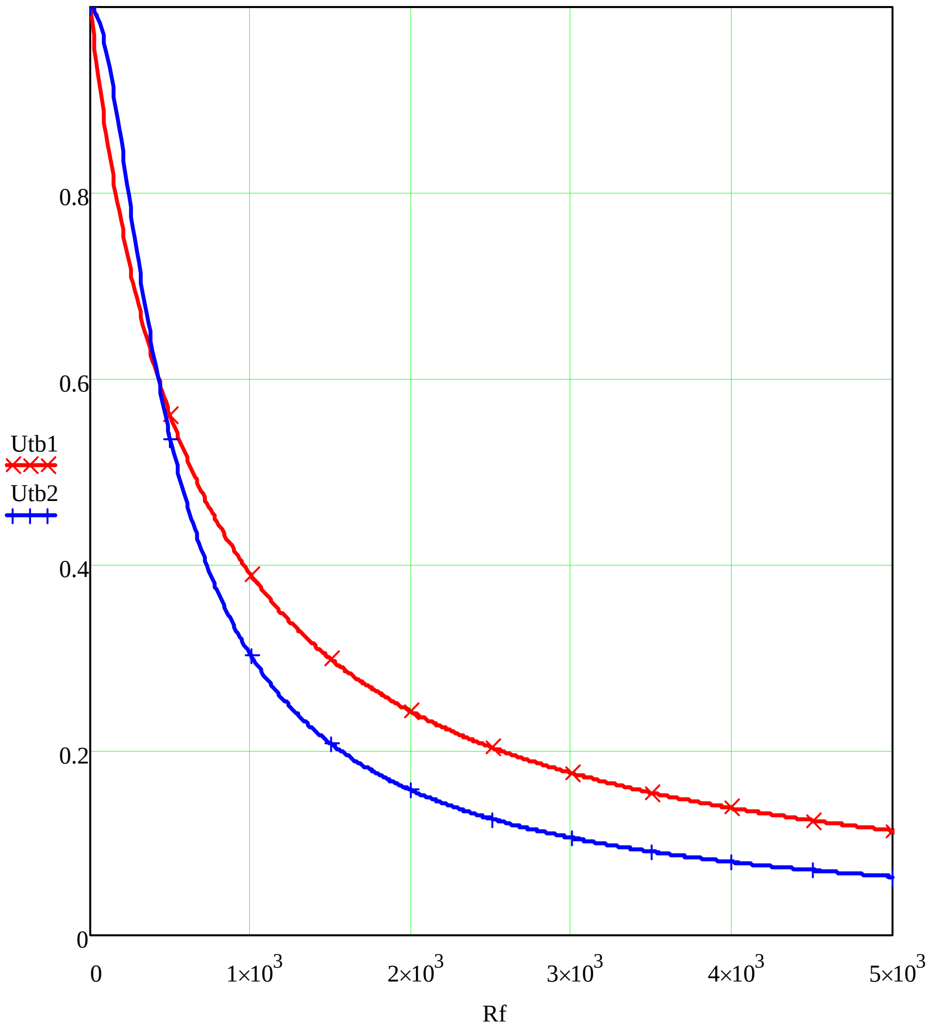

Figure 16; U_0 / U_{ph} as a function of R_f R_f at connected and disconnected feeder

If this situation cannot be accepted the following can be done;

- Distributed compensation of the capacitive earth fault current is done on the feeder. This is done by connecting local Petersen coils to the high voltage side neutrals of distribution transformers. The vector group of the distribution transformer must allow connection of the Petersen coil.
- Using zero sequence protection in D1 with two different levels and time dependent logic to switch between the function levels (made in some applications at Vattenfall)

Distributed compensation is recommended as it will give further advantages concerning earth fault current limitation and earth fault detection.

6.5 Overvoltage

The overvoltage protection at the wind power units should detect any overvoltage on the high voltage side of the turbine transformer. The overvoltage relay shall measure the phase-to-phase voltage as the phase to earth voltage will get a high value during earth faults where the overvoltage protection shall not operate.

The voltage level of the overvoltage protection shall be set to prevent equipment damages caused by the overvoltage stress. One important factor is the overexcitation of the unit transformer that can occur at overvoltage. The limitation stated by the manufacturer should be the basis for setting. The transformer standard, IEC 60076-1, states that a transformer should be in continuous service without damage if the volt per hertz is below 1.05 per unit.

The voltage for customers shall have a deviation of maximum ±10 % from nominal.

It is proposed to have overvoltage protection in two steps;

- Step 1 with a high set voltage level; about 125 % of nominal voltage and a trip time of 0 – 0.5 s.
- Step 2 with a low set voltage level; about 110 % of nominal voltage and a trip time of 2 – 5 s.

6.6 Undervoltage

This protection function shall detect operational states where low voltage can give damage to the generating unit or to the connected customers. The undervoltage protection can also serve as a simple short circuit back-up protection. The undervoltage relay shall measure the phase to phase voltage.

The regulation SvKFS 2005:2 [7] gives strict requirements for operation at low voltage situations.

The low voltage setting shall be less or equal to the lowest operation voltage of the grid. This is normally 90 % of the nominal voltage.

The time delay has to be coordinated to short circuit protections in the system. In the distribution system there is a risk that the fault clearance time for short circuits can be up to several seconds. A maximum value is estimated to 2.5 s, but this should be analyzed for each network.

Proposed setting is; 85 % of nominal voltage with adapted time delay to assure selectivity.

6.7 Over/under frequency protection

This protection is required for each wind power generating unit. This protection can be a part of the wind power generating unit internal protection system. The over/under frequency protection may also constitute a part of the anti islanding protection. The pickup level should be made so that the wind power unit is not disconnected for the stated normal frequency variations on the grid. It is required to set the pickup level for the overfrequency protection to ≥52 Hz and the underfrequency pickup level to ≤47.5 Hz. A short time delay is recommended.

7 Protection with a small wind farm connected one feeder in a distribution system

This section presents application examples for faults in the wind farm power unit and faults on the distribution line.

Characteristic for distribution system connecting a small wind farm, is that it operates at a lower voltage than the subtransmission or transmission systems. The system has a radial structure. The wind farm feeder normally has no load connected, while the distribution feeders have loads connected all along the line, not just at the end of the line. It is also common that the distribution grid that is connected to the feeding power system in one point only.

In this system the wind farm feeder disturbances can influence the customers connected to the other feeders.

An example of the protection of a wind farm connected to a radial feeder in the distribution system is shown in Figure 17. Fault locations 1-3 are discussed in the following text. The protection system for this application will in many aspects have similar conditions and solutions as for the feeder with limited number of wind power units. Therefore will the descriptions below to some extent be similar to what is written in chapter 6.

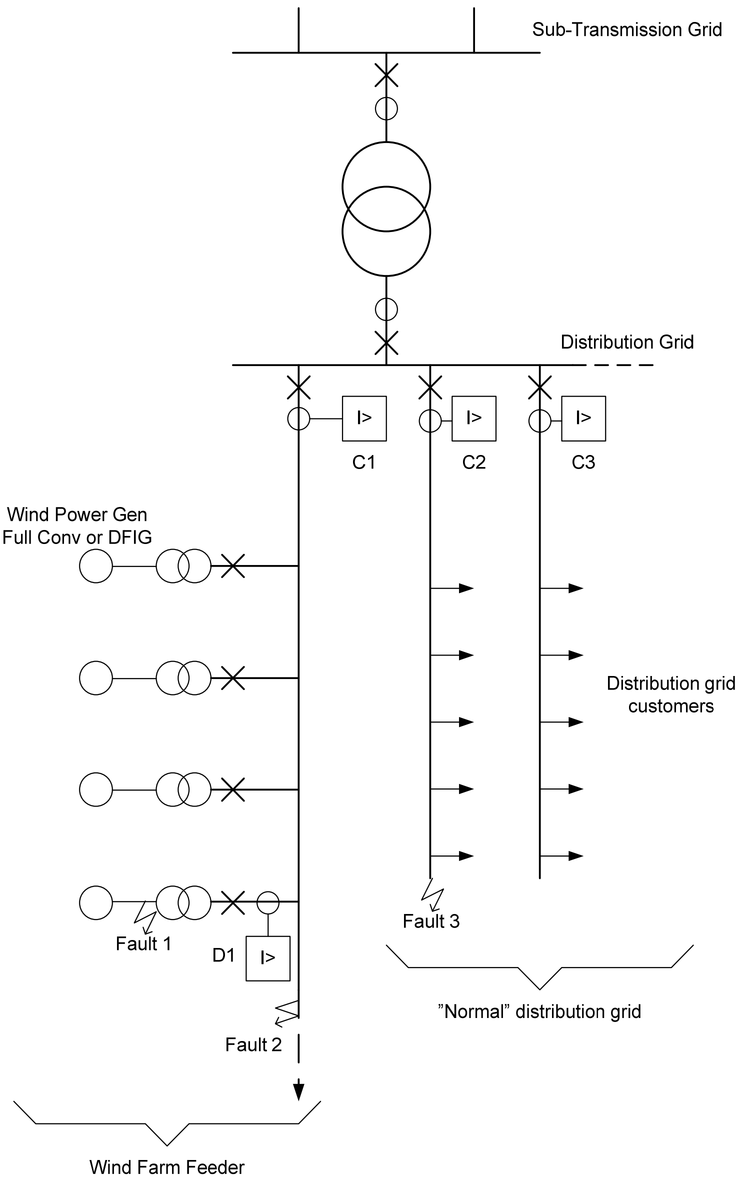

Figure 17; Application example, Small wind farm connected to a distribution system

7.1 Short circuit in a wind power unit

"Fault 1" in Figure 17 illustrates a short circuit fault in one of the wind power units. All short circuits within the wind power unit shall normally be detected and tripped by the fault clearance system within the plant. There should, however, be a possibility for back-up fault clearance of the internal short circuits, preferably in the wind power unit such that the entire radial does not need to be disconnected if the primary protection in the wind power unit fails to clear the short circuit.

7.1.1 Protection at wind power unit high voltage side

The back-up protection can be realized by a local non-directional phase over-current protection at the high voltage side of the unit transformer or by the feeder bay short circuit protection (in Figure 17 indicated as a phase over-current protection).

Coordination of the settings shall be done considering internal protections in the wind generator system. If protection D1 exists, then the following can serve as a guideline for the setting of the phase overcurrent protection;

The current level setting may be chosen within the interval;

$$1.2 \cdot \frac{I_{load\max}}{k} \leq I_{pick-up} \leq 0.7 \cdot I_{sc\min}$$

k is the reset ratio of overcurrent protection, I_{scmin} is the minimum fault current at the HV-side of the transformer at LV-side short circuit and $I_{load\ max}$ is the maximum load current measured by protection D1 at non-faulted cases.

The time delay of the protection must be coordinated to the short circuit protection C1 in the distribution bay of the feeder connecting the plant. It is desirable to have as short time delay as possible for protection D1.

7.2 Short circuit on the feeder connecting the plant

This fault is illustrated as "Fault 2" in Figure 17. This fault shall be disconnected at the bay in the substation connecting the feeder as well as at all wind power units connected to the faulted feeder.

7.2.1 Protections at distribution bay

In the distribution bay (C1) the following protection functions may be used

- Non-directional phase overcurrent protection
- Directional phase overcurrent protection
- Impedance protection with quadrilateral impedance characteristic;

Phase overcurrent protection

The phase overcurrent protection can be used to detect and clear the short circuit if the fault current is large enough. This must be checked by means of fault current calculation and analysis of the largest load current through the bay. The setting of the protection of the distribution lines should be done so that:

1. The pick-up current should be set low enough to detect line end faults but also high enough to carry expected loads without tripping.
2. The delay time of the relays should be short enough to minimize arc flash but also long enough to ensure coordination with downstream protections.

The setting $I_{pick-up}$ (smallest current for trip) can be set to fulfill:

$$1.2 \cdot \frac{I_{\max}}{k} \leq I_{pick-up} \leq 0.7 \cdot I_{sc\min}$$

Where

I_{max} is the largest load current through the bay,

k is the reset ratio of overcurrent protection and

I_{scmin} is the smallest calculated short circuit current measured by the phase overcurrent protection at a 2-phase short circuit on the feeder. There might also be a requirement that the phase overcurrent protection shall serve as back-up protection for short circuits in the wind power plant. The short circuit current at a 2-phase short circuit at the low voltage side of the plant transformer should be calculated and might be used as I_{scmin}.

$I_{pick\text{-}up}$ should be higher than the maximum expected load current that the line is expected to carry. Most faults on power lines can be detected by phase overcurrent relays because the fault currents are normally higher than the load currents.

It should be noticed that the sum of the fault current infeed from all the wind power plant at fault 2 shown in Figure 17, might influence the current in the feeding substation bay C1 significantly. This should be analyzed as shown in section 0.

Directional phase overcurrent protection

If I_{max} I_{max} is so large that the above described equation cannot be fulfilled an alternative solution must be found. A solution can be to use directional phase overcurrent protection in the bay. This enables a current setting smaller than the totally generated current from the wind farm connected to the feeder.

Underimpedance protection

The underimpedance protection with quadrilateral impedance characteristic can increase the possibilities to detect and clear short circuits having low fault current levels, for example, faults on the low voltage side of unit transformers in the wind power generator systems. The underimpedance protection has the ability to detect faults within a preset distance that is estimated by the calculated impedance.

The underimpedance protection uses the measured voltage and current to calculate the impedance. In case of a fault, the measured impedance will decrease and if the impedance gets inside the set impedance characteristic the relay will send a trip signal to the circuit breaker. The apparent impedance is equivalent to the distance between the protection and the fault point, given in Ω/phase. The impedance protection shall have at least two zones. The impedance characteristic for both zones shall have quadrilateral shape with separate reactance and resistance settings. The zones shall have definite time delay.

There are some advantages by using underimpedance protection, compared to phase overcurrent protection;

- The reach of the protection zone is independent of the fault type and the operation state of the power system.
- The impedance characteristic can be set so that the sensitivity is high for fault currents and low for load currents (Figure 18).

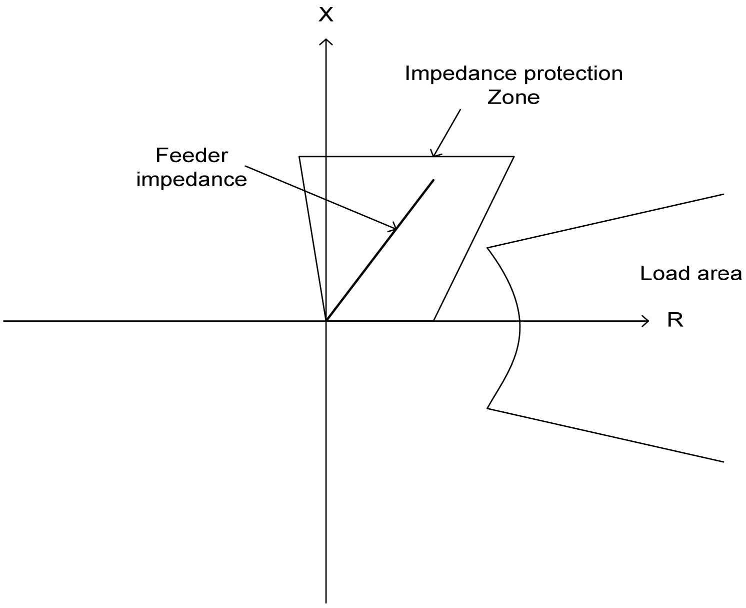

Figure 18; Example of impedance protection characteristic

The need for impedance protection has to be determined case by case. It must be checked that the smallest current for fault detection is large enough to detect all faults to be cleared. This limit is in the range 10 - 30 % of the protection rated current.

Current differential protection

The current differential relay works by comparing the current coming in and the current going out from a protected zone. The protection relay requires current measurement in all points of the line with power input or output and is for this reason not realistic to apply on a normal distribution feeder, as the system is designed today. There is also a requirement on high performance communication channels.

7.2.2 Protection in wind power unit

The feeder short circuit ("Fault 2" in Figure 17) shall be detected by protection in the wind power unit. This fault current contribution, from the wind power unit, is limited to a maximum value close to the rated current of the plant. The first conclusion is that phase overcurrent protection cannot be used as short circuit protection for external faults.

The undervoltage protection in the power plant will probably detect the short circuits on the feeder connecting the wind power unit. There is, however, a difficulty to distinguish between short circuits on the feeder and faults on other points in the external network. Hence, the undervoltage protection must be set with a trip delay to realize selectivity. This time delay might be long which may implicate a long fault time that could be unacceptable from a personal security point of view.

The undervoltage protection settings must not interfere with fault ride through capabilities or requirements on continuous operation at 90 % voltage, according to regulations in SvKFS 2005:2 [7].

After the feeder bay trip (protection C1) there will probably be an unbalance in active and/or reactive power, leading to a significant change of voltage and frequency in the island network. In that case the over/under voltage and/or over/under frequency protections will trip the plant. Hence, the over/under frequency and voltage relays will in most cases be sufficient for clearance of short circuit fault if appropriate time delays are used.

7.3 Short circuit on other feeders in the distribution grid

This fault ("Fault 3" as shown in Figure 17) shall be disconnected at the bay (C2) in the substation connecting the faulted feeder and at all wind power plants connected to the faulted feeder. There will be fault current fed from the wind power plant causing a reverse fault current measured by protection C1. This current is limited by the current capacity from the wind power plants, which is in the same range as the rated current. For a number of wind power plants this current is normally not large enough to give unwanted trip, as the current setting must be set to allow the normally generated current in the reverse direction. If the fault current fed from each of the connected wind power plants is larger than the rated current, there might be a risk of unwanted trip. In some cases it is said that the fault current from a wind turbine can reach over 120 % of the rated current.

7.4 Earth fault on the feeder connecting the plant

The distribution networks are supposed to have high impedance system earthing. This is necessary to fulfill Swedish electricity safety regulations [4]. The structure of the distribution system with earth fault protections is shown in Figure 19.

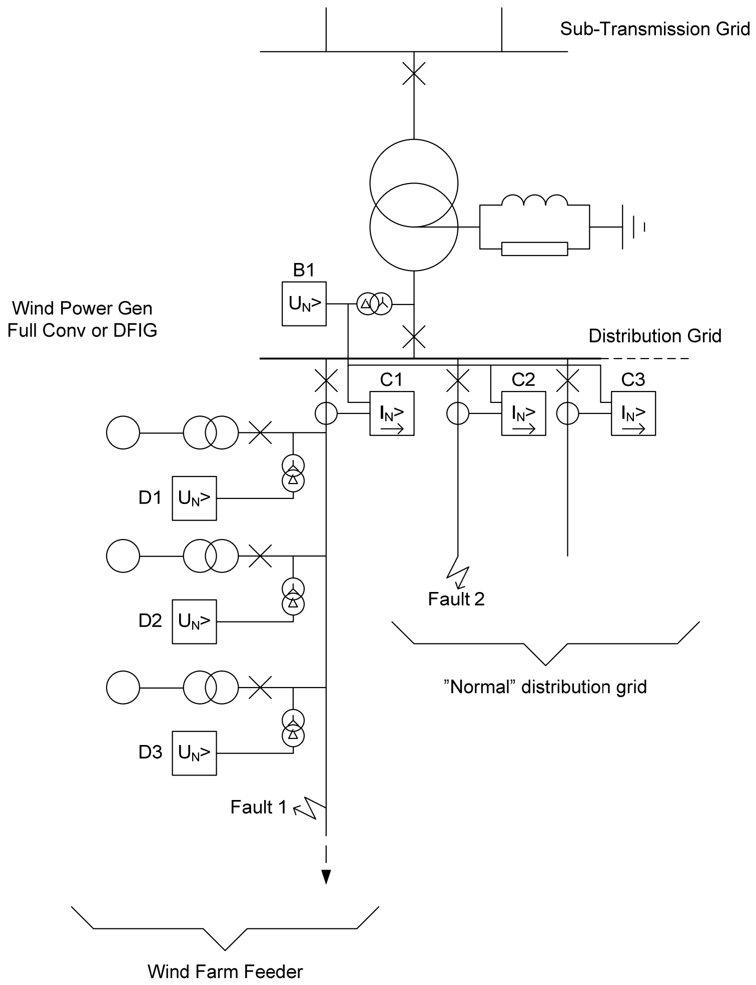

Figure 19; Distribution network with a wind farm feeder, with proposed earth fault protections

The earth fault current is fed via the system capacitance to earth and via the neutral point equipment (Petersen coil and neutral point resistor).

7.4.1 Earth fault protection in the substation

The earth fault protection in the substation feeding the distribution feeders can be made in traditional way, even if wind power units are connected to the feeders. The earth fault protection can consist of;

- Directional earth fault current protection in each feeder bay. If the system has a neutral point resistor the protection will measure the active component (in phase with the zero sequence voltage) of the earth fault current out on the feeder. In some cases the capacitive earth fault current from the non-faulted feeders are used.
- Zero sequence voltage protection, fed from an open delta connected voltage transformer group, either on the transformer low voltage side busbar or on the transformer low voltage side bay. This protection will

detect all earth faults in the distribution network and will therefore serve as back-up protection for the feeder earth fault protections. The protection will also serve as the main protection for earth faults on the busbar or in the low voltage winding of the transformer.

The earth fault current magnitude is independent of the fault location. This means that the earth fault protection cannot use current dependent time grading of the protections to get selectivity. Instead, simple time based selectivity is normally used where the most remote protections, in the radial network, have the shortest time delay.

In case of an earth fault ("Fault 1") as shown in Figure 19 we have the following sequence;

At t = 0 the earth fault occurs and earth fault current will flow to the fault point. The faulted feeder bay earth fault current protection will pick-up and start its timer.

At t = t1, often about 1.0 s, the earth fault current protection will trip and the faulted feeder will be disconnected from the rest of the network.

At t> t1 the faulted feeder is energized from the connected wind power plant. The magnitude of the earth fault current is now dependent on the capacitance between the feeder phases and earth (zero sequence capacitance). This current can be quite small but it is not allowed to continue the operation with sustained earth fault. In this situation there are two different scenarios:

1. There will be a large active and/or reactive power un-balance for the faulted feeder. The consequence will be deviations in frequency (due to active power un-balance) or in voltage (due to reactive power un-balance). Under/over frequency protections and/or under/over voltage protections will detect this situation and initiate disconnection of the wind power plant. According the safety regulations trip must occur within 5 s. There is a risk that the un-balance is so small that the time to reach the trip level of under/over frequency protection will be longer than 5 s. If no load is connected to the feeder the risk is very small.
2. There might be active and reactive power balance for the faulted feeder. The voltage and frequency protections will not be activated. Thus there is an island operation with a sustained earth fault, which is not acceptable. The wind power units have to be disconnected.

If it cannot be proved that power balance is impossible, two different solutions are proposed, where the first is recommended:

1. A residual voltage (zero sequence voltage) protection is applied on the high voltage side of the unit transformer of the wind power plant. This protection can be fed from an open delta connected three phase voltage transformer group or from a voltage transformer in the high voltage transformer neutral point, if it exists. The protection must have a time delay longer than the feeder earth fault protections.
2. A transfer trip is sent from the earth fault protection for the bay feeding the faulted feeder. In this alternative a fast and reliable telecommunication link from the feeding substation to the wind power plants is required.

A special case that can occur is the following; a high resistive earth fault occurs at fault point 1. Initially both the feeder protection C1 the residual overvoltage protections D1, D2,… starts. After a short delay protection C1 trips the line. The earth fault is now fed from the wind power plant and the residual voltage, fed to protection D1, will be changed as the zero sequence system impedance change. If the capacitive fault current from the feeder itself is large, the zero sequence voltage will decrease after the trip from C1. In this moment there is a risk that protection D1 will cease.

The zero sequence voltage at resistive earth faults in a high impedance earthed system can be calculated as:

$$U_0 = \frac{U_{ph-ea}}{1 + \frac{3 \cdot R_f}{Z_0}}$$

Where $U_{ph\text{-}ea}$ is the normal phase to earth voltage,

R_f is the resistance to earth in the fault point and

Z_0 is the zero sequence impedance of the system

If the Petersen coil is well tuned Z_0 can be considered to be equal to 3 times the resistance of the neutral point resistor ($3R_N$).

Assume that the rated current of the neutral point resistor is 10 A and that the faulted feeder will generate 20 A at a solid earth fault. Before the trip of the feeder, the impedance Z_0 will be.

$$Z_0 = 3R_N = 3 \cdot \frac{U_{ph-ea}}{10}$$

After the trip of the feeder, the impedance Z_0 will be;

$$Z_0 = -jX_c = j3 \cdot \frac{U_{ph-ea}}{20}$$

Figure 20 shows the zero sequence voltage (U_0/U_{ph}) as a function of the fault resistance as measured by protection D1. The curve marked by x shows the situation before the trip at C1 and the curve marked + shows the situation after the trip.

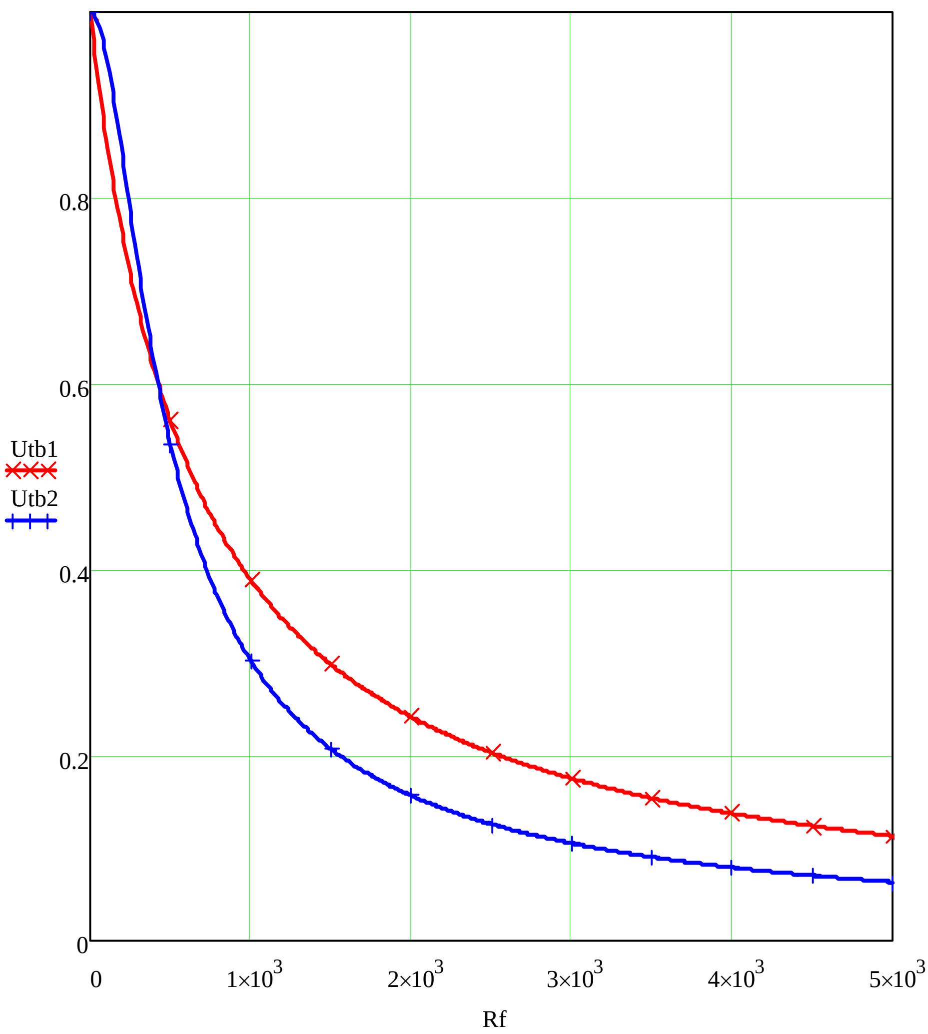

Figure 20 U_0 / U_{ph} as a function of R_f at connected and disconnected feeder

If this situation cannot be accepted the following can be done:

- Distributed compensation of the capacitive earth fault current along the feeder. This is done by connecting local Petersen coils to the high voltage side neutrals of distribution transformers.
- Using zero sequence protection in D1 with two different levels and time dependent logic to switch between the function levels (made in some applications at Vattenfall)

The first alternative is recommended as it will give further advantages concerning earth fault current limitation and earth fault detection.

7.5 Overvoltage

The overvoltage protection at the wind power units should detect overvoltage at the high voltage side of the turbine transformer. The overvoltage relay shall measure the phase-to-phase voltage as the phase to earth voltage will get a high value during earth faults where the overvoltage protection shall not operate.

The voltage level of the overvoltage protection shall be set to prevent equipment damages caused by the overvoltage stress. One important factor is the overexcitation of the unit transformer that can occur at overvoltage. The limitation stated by the manufacturer should be the basis for the setting. The transformer standard, IEC 60076-1, states that a transformer should be in continuous service without damage if the volt per hertz is below 1.05 per unit.

The voltage for customers shall have a deviation of maximum 10 % from the nominal.

It is proposed to have overvoltage protection in two steps;

- Step 1 with a high set voltage level; about 125 % of nominal voltage and a trip time of 0 – 0.5 s.
- Step 2 with a low set voltage level; about 110 % of nominal voltage and a trip time of 2 – 5 s.

7.6 Undervoltage

This protection function shall detect operational states where low voltage can give damage to the generating unit or to the connected customers. The undervoltage protection can also serve as a simple short circuit back-up protection. The undervoltage relay shall measure the phase-to-phase voltage.

The regulation SvKFS 2005:2 gives strict requirements for operation at low voltage situations.

The low voltage setting shall be less or equal to the lowest operation voltage of the grid. This is normally 90 % of the nominal voltage.

The time delay has to be coordinated to short circuit protections in the system. In the distribution system there is a risk that the fault clearance time for short circuits can be up to several seconds. A maximum value is estimated to 2.5 s, but this should be analyzed for each network.

The proposed setting is 85 % of the nominal voltage with an adapted time delay to assure selectivity.

7.7 Over/under frequency protection

This protection is required for each wind power generating unit. This protection can be a part of the wind power generating unit internal protection system. The over/under frequency protection may also constitute a part of the anti islanding protection. The pickup level should be made so that the wind power unit is not disconnected for the stated normal frequency variations on the grid. It is required to set the pickup level for the overfrequency protection to ≥52 Hz and the underfrequency pickup level to ≤47.5 Hz. A short trip delay is recommended.

8 Protection of a wind farm connected to the subtransmission or transmission system

In this section different fault scenarios are identified for a wind farm connected through a collection grid and a step up transformer to either the subtransmission or transmission grid.

Characteristic for the collection grid is

- The wind power units are connected to a network (collection grid) that only contains power production sources and negligible load.
- For large wind farms the length of the cable can become rather long which may give high capacitive currents.
- The numbers of breakers on the radial are most commonly minimized so that there is one breaker in the substation bay where the radial is connected and one breaker for each wind farm, i.e. the whole radial must be disconnected if there is a fault on the radial.
- If a radial is disconnected due to a fault on the cable, a rather large amount of power production could be lost in one instance.
- Characteristic for short circuit faults in cables compared to faults in overhead lines is a lower fault frequency, a larger share of faults that are permanent and a longer repair time for faults, hence the automatic reclosing will not provide benefits.
- Common voltage levels for the collection grid are 20 kV and 30 kV both for wind farms on shore and for offshore wind farms.

The Swedish subtransmission system has nominal voltages between 40 kV to 130 kV while the nominal voltage levels for the transmission grid are 220 kV and 400 kV. Wind farms connected to the transmission system are generally of larger size than wind farms connected to the subtransmission system. Due to the larger size, a trip of a wind farm, connected to the transmission grid, will in general have a larger impact on the grid stability compared to a smaller wind farm connected to the subtransmission system. Hence, a better and more expensive protection system could be motivated.

The most common principle of a collection grid is shown in Figure 21 where the wind power generators are connected to radial feeders of the collection grid. This alternative is quite similar to a common distribution system except that there is no load connected.

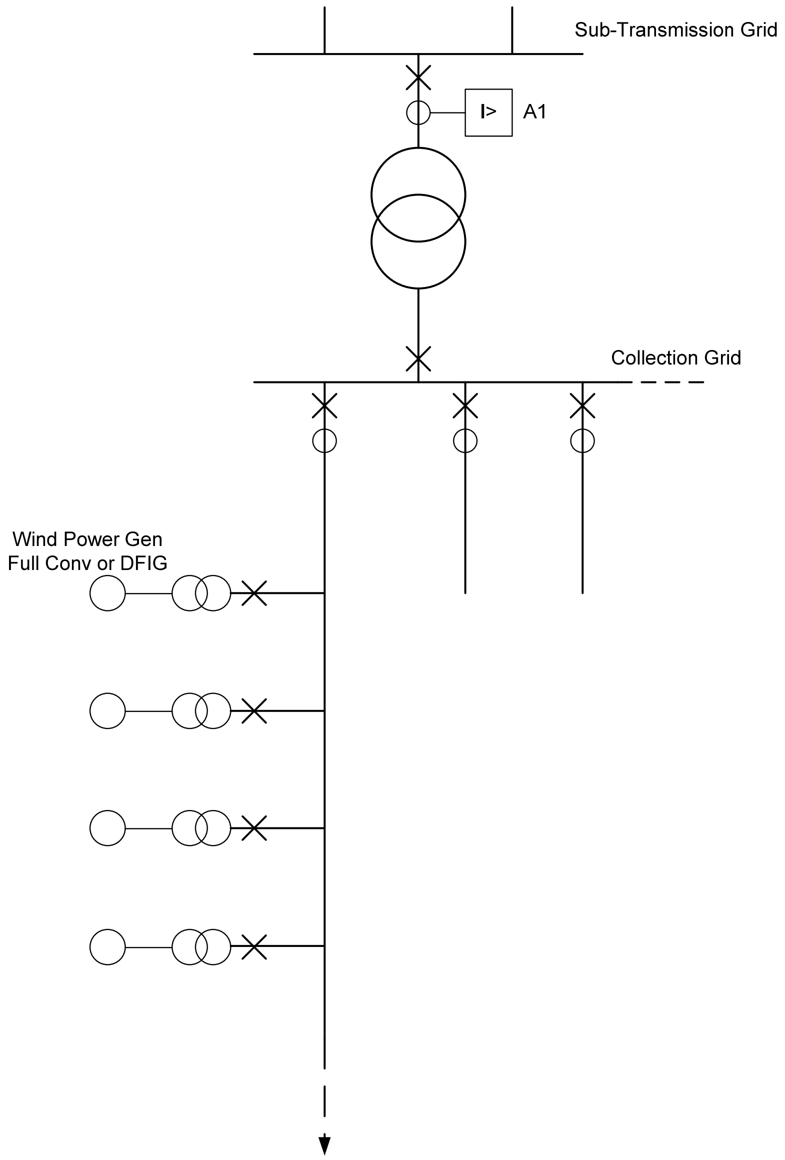

Figure 21; Collection grid with radial feeders

An alternative that gives better availability is shown in Figure 22. In this case it is possible to take one cable between two wind power units out of service without any loss of generation. With sufficient fault clearance system also cable fault can be cleared without disconnection of any generation.

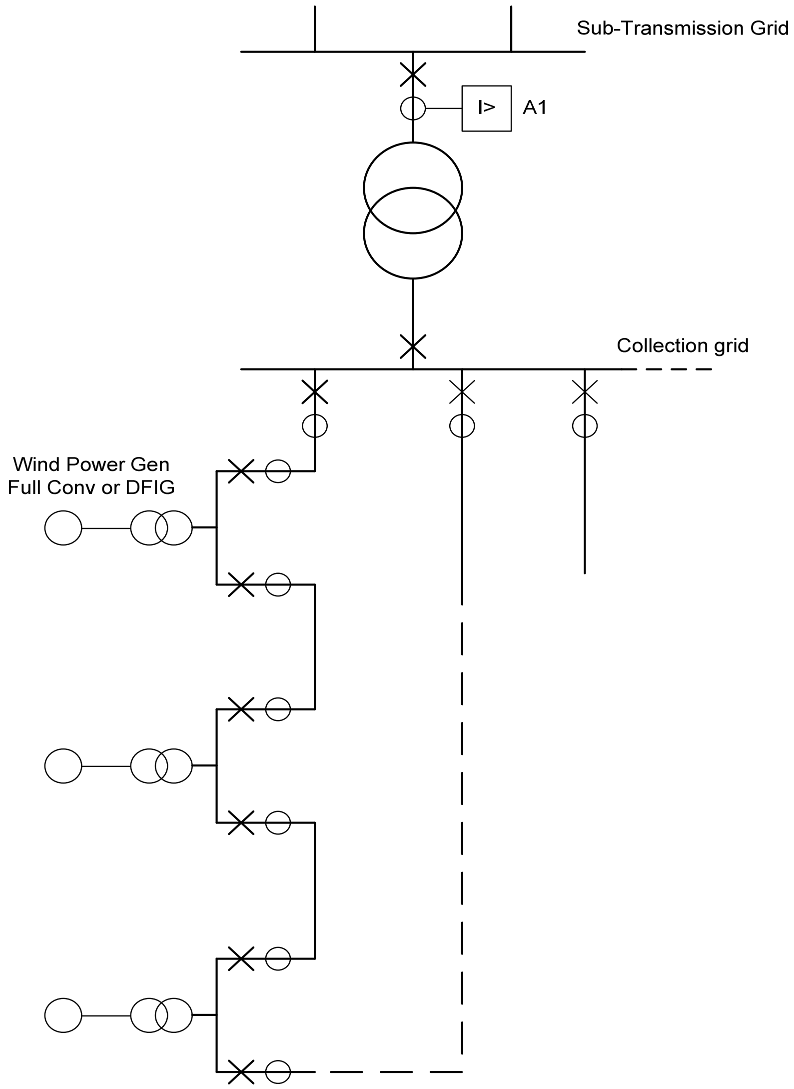

Figure 22; Collection grid with meshed structure

8.1 Short circuit in the wind power unit

Short circuits within the wind power unit shall be detected and tripped by the fault clearance system within the plant and there should be a possibility for back-up fault clearance of the internal short circuits in the unit. This back-up protection can be realized by a local phase over-current protection or high voltage fuses at the high voltage side of the unit transformer or by the feeder bay short circuit protection.

8.2 Short circuit on the cable feeder in the collection grid

This fault shall be disconnected at the bay in the substation connecting the feeder as well as at all wind power units connected to the faulted feeder, if the collection grid have radial feeder as shown in Figure 21.

8.2.1 Protections at collection grid bay in the substation

In the distribution bay the following protection functions may be used

- Non-directional phase overcurrent protection
- Directional phase overcurrent protection
- Impedance protection with quadrilateral impedance characteristic;

Non-directional phase overcurrent protection

The phase overcurrent can be used to detect and clear the short circuit if the fault current is large enough. This must be checked by means of fault current the calculation and analysis of largest load current through the bay. The setting of the protection of the collection grid lines should be done so that:

1. The pick-up current should be set low enough to detect line end faults but also high enough to carry expected load current without tripping.
2. The delay time of the relays should be short enough to minimize arc flash but also long enough to ensure coordination with downstream protections (wind unit short circuit protection).

The setting $I_{pick\text{-}up}$ (smallest current for trip) can be made so the following is fulfilled;

$$1.2 \cdot \frac{I_{\max}}{k} \leq I_{pick-up} \leq 0.7 \cdot I_{sc\min}$$

Where;

I_{max} is the largest load current through the bay,

k is the reset ratio of overcurrent protection and

I_{scmin} is the smallest calculated short circuit current measured by the phase overcurrent protection at a 2-phase short circuit on the feeder. There might also be a requirement that the phase overcurrent protection shall serve as back-up protection for short circuits in the wind power plant. The short circuit current at a 2-phase short circuit at the low voltage side of the wind power unit transformer, should be calculated and might be used as I_{scmin}.

$I_{pick\text{-}up}$ should be higher than the maximum expected load current that the line is expected to carry. Most faults on power lines can be detected by phase overcurrent relays because the fault currents are normally higher than the load current.

Directional phase overcurrent protection

If I_{max} is so large that the above described equation cannot be fulfilled a solution can be to use directional phase overcurrent protection in the bay.

Underimpedance protection

The underimpedance protection with quadrilateral impedance characteristic can increase the possibilities to detect and clear short circuits having low fault current levels, for example, faults on the low voltage side of unit transformers in the wind power generator systems. The underimpedance protection has the ability to detect faults within a preset distance that is estimated by the calculated impedance.

The underimpedance protection uses the measured voltage and current to calculate the impedance. In case of a fault, the measured impedance will decrease and if the impedance gets inside the set impedance characteristic the relay will send a trip signal to the circuit breaker. The apparent impedance is equivalent to the distance between the protection and the fault point, given in Ω/phase. The impedance protection shall have at least two zones. The impedance characteristic for both zones shall have quadrilateral shape with separate reactance and resistance settings. The zones shall have definite time delay.

There are some advantages by using under impedance protection, compared to phase overcurrent protection:

- The reach of the protection zone is independent of fault type and operation state of the power system.
- The impedance characteristic can be made so that the sensitivity is high for fault currents and low for load currents, se Figure 23.

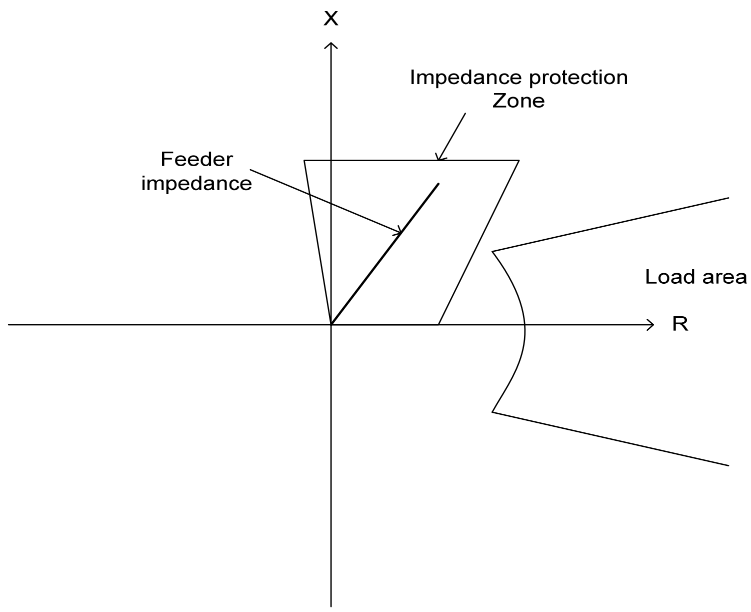

Figure 23; Example of impedance protection characteristic

The need for impedance protection has to be determined case by case.

8.2.2 Current differential protection alternative

The current differential relay works by comparing the currents coming in and the currents going out from a protected zone. The protection relay requires current measurement in all points of the line with power input or output and is for this reason not realistic to apply on a radial cable feeder in the collection grid.

If the collection grid has a meshed structure as shown in Figure 22 the differential protection can provide fast and selective clearance of cable faults. It is assumed that communication is available between the generating units, also for other reasons than protection, such as control and supervision.

8.2.3 Protection in wind power units

The current from the wind power unit will under normal conditions limit the maximum magnitude of the current to about 1.2 to 1.5 times the rated current which is close to the normal load current. This implies that the phase overcurrent protection cannot be used as short circuit protection for external faults. Two possible protection solutions are:

- Undervoltage protection trips due to undervoltage caused by unbalance in reactive power. The undervoltage protection must be set with a time delay to achieve selectivity between faults on the feeder and faults on other points of the system. This might implicate long fault times that may be unacceptable from a personal security point of view.
- The over/under frequency protection trips caused by unbalance in active power. After the feeder bay protection C1 have tripped there will most likely be an unbalance in active and/or reactive power, since only production sources are connected, leading to a significant change of voltage and frequency in the island network. In such case will the over/under frequency and over/under voltage relays in most cases be sufficient for clearance of short circuit fault.

8.3 Short circuit on a subtransmission/transmission line

This fault shall be cleared by opening the circuit breakers in both ends of the line. From part 1 of this report [1] the following requirements are recommended:

Short circuits on the subtransmission line interconnected with the wind farm shall be cleared within 130 ms, at normal fault clearance and within 500 ms at back-up fault clearance. Transmission line short circuits shall be cleared within 130 ms at normal fault clearance and within 250 ms at back-up fault clearance.

8.3.1 Short circuit protection at transmission or subtransmission line bays

The normal fault clearance system with distance protection and/or differential protection can be used. In some cases simple overcurrent protections are acceptable. This must however be investigated for the individual cases so that the requirements are fulfilled.

8.3.2 Short circuit protection in the HV transformer bay connecting the wind farm

In case of a short circuit in the transmission or subtransmission system there might be fault current fed from the wind farm generators. The connection can be seen in Figure 24.

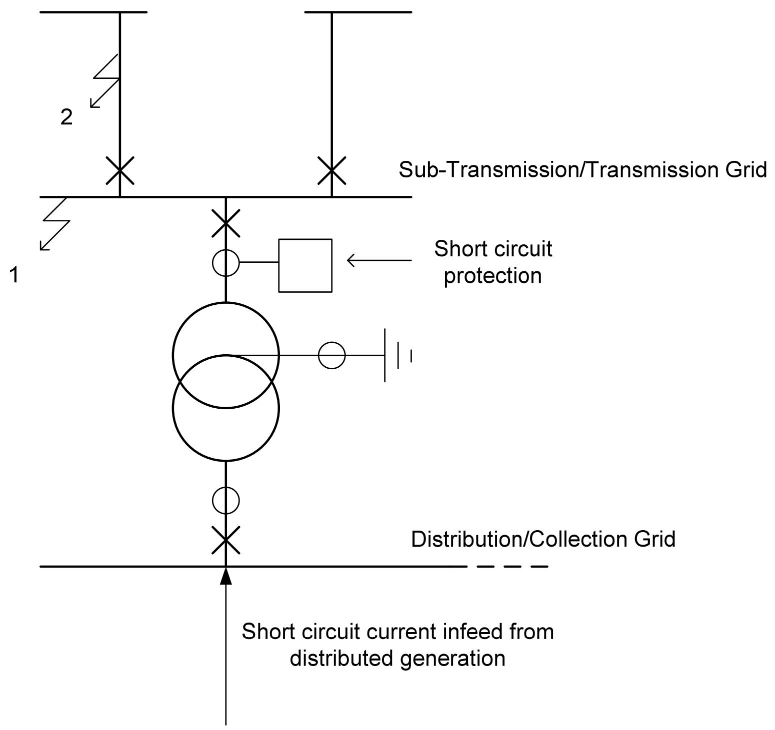

Figure 24; Transformer connecting wind farm collection grid to the power system

On the HV-side of the transformer there is normally a phase overcurrent protection applied. The short circuit protection can be applied on the low voltage side of the transformer. The phase overcurrent protection can probably not distinguish between load current and the current at the fault 1 and 2 shown in Figure 24. It is therefore recommended to use an underimpedance protection in this case.

8.3.3 Short circuit protection at wind power unit

When the main feeder to the wind farm is disconnected, the wind farm will form an island separated from the main grid. Two scenarios are possible

- The island contains only production sources and no load. Hence, the over/under voltage or over/under frequency relays will disconnect the wind power units due to the changes in voltage or frequency caused by production and consumption unbalance for reactive or active power.
- The island contains both production sources and loads that could be in active and reactive power balance when the islanding occurs. In this case it can take a long time before the over/under voltage and/or over/under frequency protections trips, i.e. it may take a long time until the frequency and voltage change enough to pass the pickup level of the relays.

For the first scenario, no additional protection to the normally required over/under frequency and over/under voltage protection is required to detect the island condition.

For the second scenario an intertrip signal is sent direct from the substation bay to all the wind power units in the wind farm, this alternative require communication links to all wind power units.

Another alternative is to use a ROCOF relay as a fast detection of short circuits in the local system that has become an island after trip of the connection to the external grid. The ROCOF is recommended to be set higher than 0.5 Hz/s and with a minimum time delay of 0.5 s to avoid false tripping.

8.4 Earth fault on the collection grid cable

Feeder earth faults shall be signaled or cleared within 2 s, at normal fault clearance and within 5 s at back-up fault clearance if the collection grid includes overhead lines and the earth fault current is limited according to the Swedish electricity safety regulations (starkströmsföreskrifterna) [4]. If medium size neutral point resistance (Ir in the range 100 – 500 A) is used, it is reasonable that fault clearance shall be achieved within 0.5 s irrespective if the system includes overhead lines or not. If the earth fault current is significantly reduced after trip that disconnects the high current neutral point resistor a longer delay (up to 5 s) of wind power plants feeding the fault, can be accepted.

This requires disconnection at the substation bay and at all wind power units connected to the faulted feeder. In case of a collection grid with cables only it is not required to trip earth faults. To avoid severe cable damages at earth faults it is however recommended to disconnect the earth faults also in this case.

The choice of earth fault protection in the collection grid bay is not affected by the presence of wind power generation connected to the collection grid feeders and normal procedures should be followed. Earth fault protection at the wind power unit connections must however be installed.

8.4.1 Earth fault protection at substation bays

In the design of the short circuit protection to be used for a collection grid (wind farm) feeder bay, the following shall be investigated:

1. If the collection grid has a radial structure it is recommended to use residual overcurrent protection in the outgoing bays as shown in Figure 25. The protection can have directional or non-directional function, depending on the system earthing method.

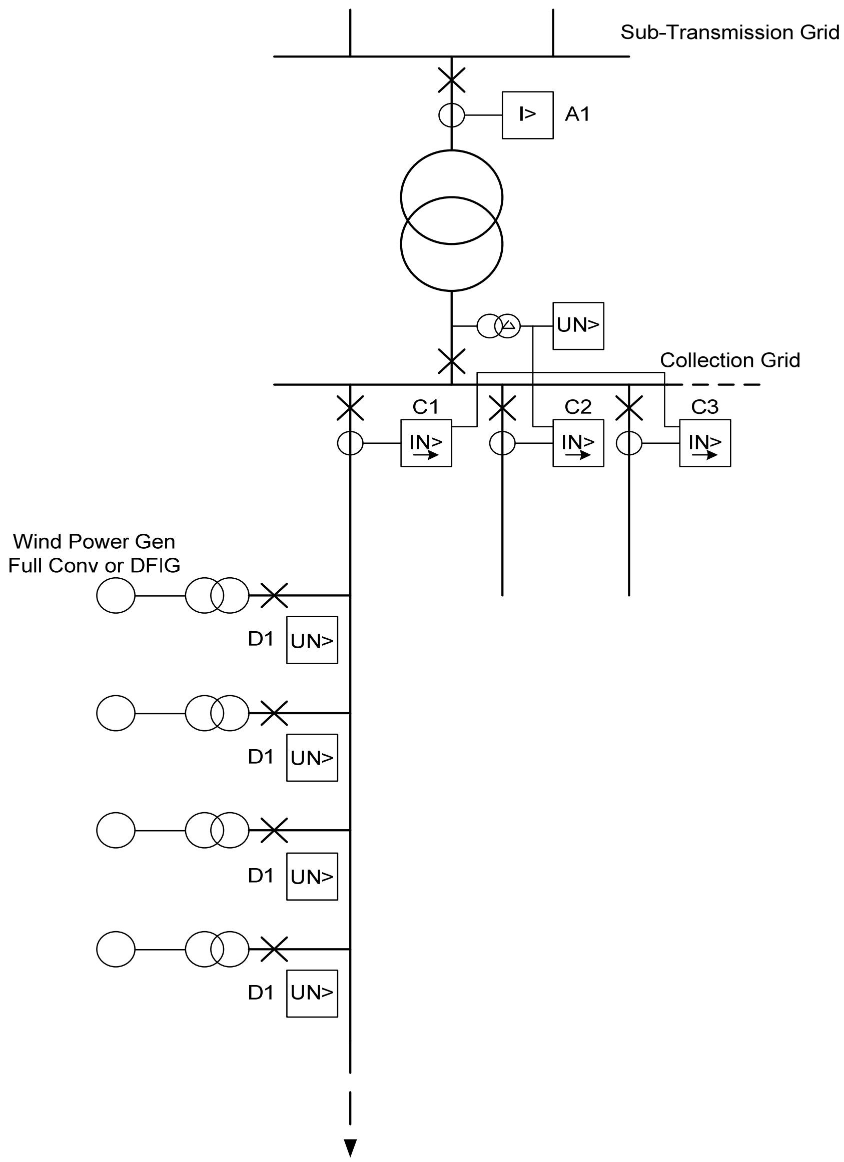

Figure 25; Collection grid with radial feeders, alternative 1

2. In case the collection grid has a meshed structure, it is recommended to use an earth fault protection system based on directional earth fault current protection with a communication scheme as shown in Figure 26.

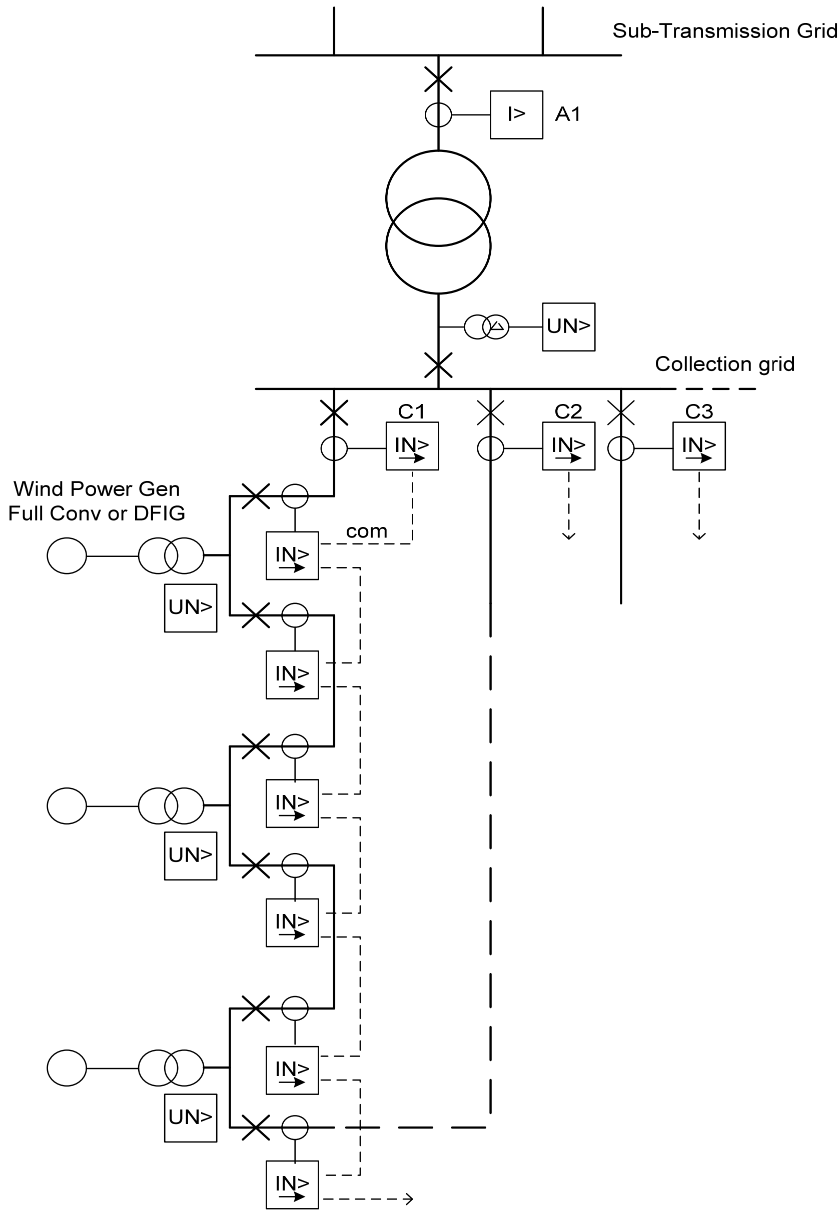

Figure 26; Meshed collection grid

8.5 Overvoltage

The pickup level of the overvoltage protection shall be set such that an equipment damage caused by overvoltage stress is prevented. Both the wind power units and the substation bay shall have overvoltage protection. The pickup level for the first step must not to be set lower than the values given by Svenska Kraftnät in SvKFS 2005:2 [7], see Table 1.

Table 1; Requirements from Svenska Kraftnät given in SvKFS 2005:2

	Frequency region	Voltage region	Time	Power reduction
(< 25 MW)	51.0-52.0	90-105%	> 30 min	Reduced
Operation ranges	49.0-51.0	90-105%	continuous	
	47.5-49.0	90-105%	> 30 min	< 5% reduction
(> 25 MW)	51.0-52.0	95-105%	> 30 min	Reduced
Operation ranges	49.0-51.0	105-110%	> 60 min	Normal
	49.0-51.0	90-105%	continuous	Normal
	49.7-51.0	85-90%	> 60 min	< 10% reduction
	49.7-51.0	105-110%	> 30 min	< 10% reduction
	47.5-49.0	95-105%	> 30 min	< 5% reduction
	47.5-49.7	90-110%	> 10 min	-

8.5.1 Overvoltage protection at substation bays

The overvoltage relay shall measure the phase-to-phase voltage as the phase to earth voltage will get a high value during earth-fault where the overvoltage protection shall not operate.

One important factor is the over-excitation of the unit transformer that can occur at overvoltage. The limitation stated by the manufacturer should be the basis for setting. The transformer standard, IEC 60076-1, states that a transformer should be in continuous service without damage if the volt per hertz is below 1.05 per unit. To fulfill the requirements stated in SvKFS 2005:2 if might be necessary to specify transformers with higher overexcitation capability than stated in the standard.

The voltage for customers shall have a deviation of maximum ±10 % from nominal.

It is proposed to have overvoltage protection in two steps;

- Step 1 with a high set voltage level; about 125 % of nominal voltage and a trip time of 0 – 0.5 s.
- Step 2 with a low set voltage level; about 110 % of nominal voltage and a trip time of 2 – 5 s.

8.6 Earth fault on the subtransmission/transmission line connecting the plant

Earth faults on the transmission line shall be disconnected at both ends of the faulted line. If the faulted line is the only connection between the wind farm and the main grid then the wind farm will form an island together with eventual other loads and production sources. The island operation needs to be detected and all production sources, such as the wind power units, shall disconnect before eventual automatic reclosing on the subtransmission/transmission line attempts to reconnect the line.

8.6.1 Earth fault protection at substation transmission or subtransmission line bays

The normal fault clearance system with distance protection, differential protection and/or residual overcurrent protection can be used.

8.6.2 Earth fault protection in the HV transformer bay connecting the wind farm

In case of an earth fault in the transmission or subtransmission system there might be fault current fed from the wind farm generators. The situation is shown in Figure 27.

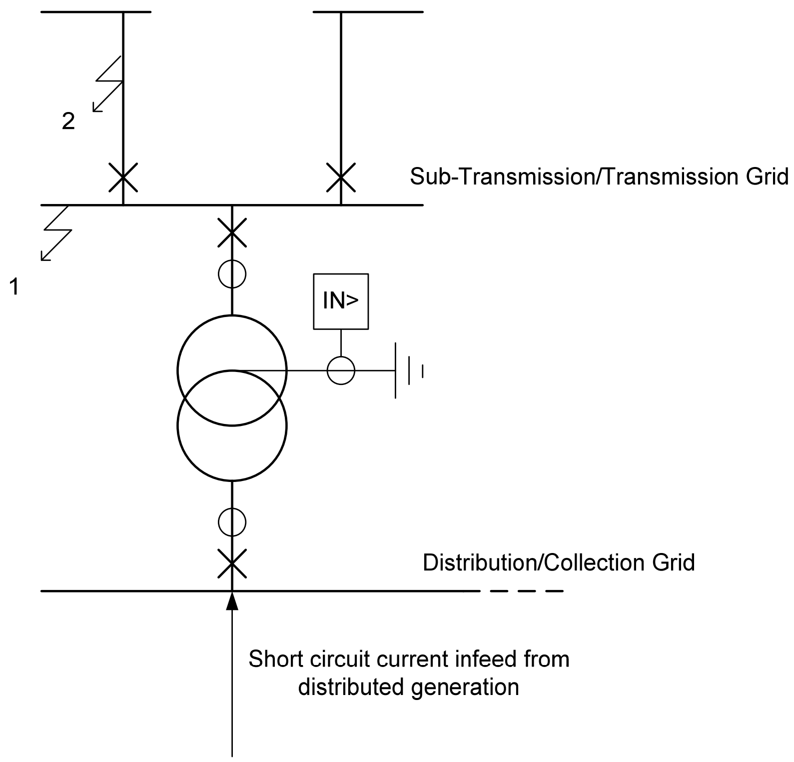

Figure 27; Transformer connecting wind farm collection grid to the power system

On the HV-side neutral point of the transformer there is normally an overcurrent protection applied. This overcurrent protection normally has one step with a long time delay (2.0 s) and a very sensitive current setting. As the wind farm can provide short circuit power (positive and negatives sequence) there is a need to add a high current step with a trip time less than 0.5 s in order to fulfill requirements.

If the connected subtransmission system has high impedance system earthing (in Sweden 40 – 70 kV systems) a relatively fast residual overvoltage protection on the HV-side of the transformer is required.

8.6.3 Earth fault protection at wind power unit

When a subtransmission/transmission line is disconnected there might be a possibility that the wind farm will form an island together with other loads connected to the substation. If no other loads or a negligible load is connected to the substation, the frequency and voltage protections at each wind power unit in the wind farm will trip.

If a balanced condition can occur, then a ROCOF relay could be used or an intertripping signal could be sent through a communication link to each wind power unit. The ROCOF is recommended to be set higher than 0.5 Hz/s and with a minimum time delay of 0.5 s to avoid false tripping.

8.7 Undervoltage protection

This protection function shall detect operational states where low voltage can give damages to the generating unit or to the connected electricity customers. The undervoltage protection can also serve as a simple short circuit back-up protection. The undervoltage relay shall measure the phase to phase voltage.

The undervoltage protection must be set to fulfill the requirements from Svenska Kraftnät [7] given in Table 1. Also the fault ride through requirements given in Figure 28 and Figure 29 must be fulfilled. Hence, the undervoltage relay must to not disconnect for undervoltages with shorter duration than 0.25 s. The time delay has to be coordinated to short circuit protections in the system. Proposed setting is; 85 % of nominal voltage with adapted time delay to assure selectivity.

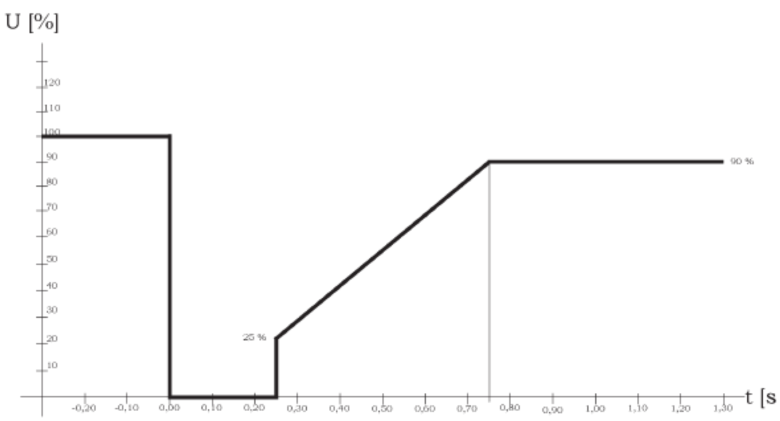

Figure 28; Undervoltage profile requirements from SvKFS 2005:2 for wind farms larger than 100 MW

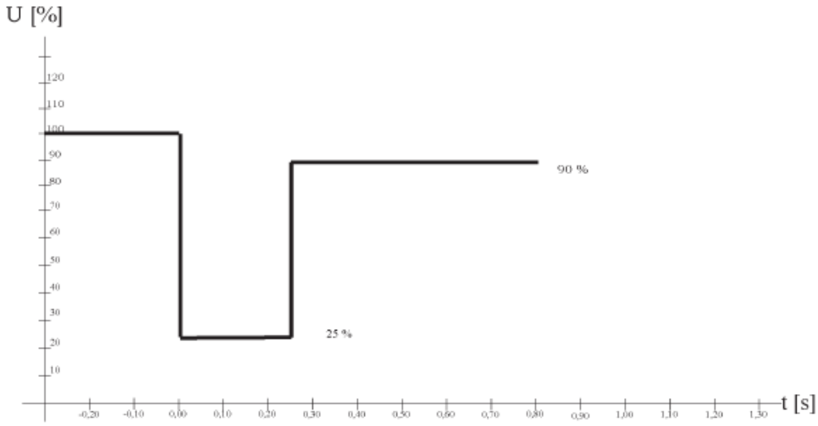

Figure 29; Undervoltage profile requirements from SvKFS 2005:2 for wind farms smaller than 100 MW

8.8 Over/under frequency protection

This protection is required for each wind power generating unit and can be a part of the wind power generating unit internal protection system. It is, however, normally required by the grid owners that external protections are installed. In such a case must both the internal protection in the wind power unit and external protections be set to fulfill the requirements given in Table 1 Disconnection can be made if the frequency is below 47.5 Hz or higher than 52 Hz.

9 Proposed protection concept

9.1 Protection in a substation bay connected to a distribution grid containing wind power

In the decision of which type of **short circuit protection** that should be used for a distribution feeder bay connecting wind power, the following shall be investigated;

- The maximum load current out on the feeder, where the connected wind power production is zero; $I_{load,max}$
- The minimum short circuit current through the bay at feeder short circuit; $I_{sc,min}$. This current can be calculated by applying a two phase short circuit at the most remote point on the feeder. In this calculation should the production connected to the feeder be maximized, the short circuit power from the external network should be minimized and any abnormal switching state should be considered.
- The current through the bay in case of a short circuit at the low voltage side of the wind power unit transformer; I_{scwin}
- The maximum total fault current from the feeder connected power generators at remote short circuit (on another feeder in the distribution network); I_{win}

Below is described how the choice of feeder short circuit protection can be made:

Non-directional phase overcurrent protection

The following shall be fulfilled;

- $I_{sc,\min} > 1.2 \cdot I_{load,\max}$ All feeder faults must be detected without risk of unwanted trip due to maximum load current. The infeed from connected generating plants will affect the current through the bay.
- $I_{sc,win} > 1.2 \cdot I_{load,\max}$ The feeder short circuit protection shall if possible serve as back-up protection for unit transformer short circuits.
- $I_{win} < I_{sc,\min}$ The feeder short circuit protection shall not trip for faults on other feeders.

The non-directional overcurrent protection shall have at least two steps;

- A low current step with the possibility to set different time delay characteristics; IEC Normal Inverse, IEC Very Inverse, IEC Extremely

Inverse, RI Inverse and definite time delay. This step is normally set as sensitive as possible without risking unwanted trip.

- A high current step with definite time delay. This step is normally set to a high current and 0 s delay.

Directional phase overcurrent protection

The following shall be fulfilled;

- $I_{sc,\min} > 1.2 \cdot I_{load,\max}$ All feeder faults must be detected without risk of unwanted trip due to maximum load current. The infeed from connected generating plants will affect the current through the bay.
- $I_{sc,win} > 1.2 \cdot I_{load,\max}$ The feeder short circuit protection shall if possible serve as back-up protection for unit transformer short circuits.

- The directional protection eliminates the risk of unwanted trip due to fault current or normal load current in the reverse direction.

The directional overcurrent protection shall have at least two steps;

- A low current step with the possibility to set different time delay characteristics; IEC Normal Inverse, IEC Very Inverse, IEC Extremely Inverse, RI Inverse and definite time delay. This step is normally set as sensitive as possible without risking unwanted trip.

- A high current step with definite time delay. This step is normally set to a high current and 0 s delay.

Impedance protection with quadrilateral impedance characteristic;

- This alternative can increase the possibilities to detect and clear short circuits having low fault current level, for example faults on the low voltage side of unit transformers in the wind power generator systems.

- The impedance protection shall have at least two zones. The impedance characteristic for both zones shall have quadrilateral shape with separate reactance and resistance settings. The zones shall have definite time delay.

The following factors have to be checked before the choice of **earth fault protection**;

System earthing method; Isolated, Petersen coil earthing, Resistance earthing

- Capacitive earth fault current for every feeder at a solid earth fault (Rf = 0) I_{c1}, I_{c2}, … I_{cn}

- Total capacitive earth fault current at a solid earth fault $I_{ctot}I_{ctot}$
- Earth fault current from the neutral point resistor at zero resistance earth fault (if existing) I_{RN}
- Are there overhead lines in the distribution system

The choice of earth fault protection is not affected by the presence of wind power generation connected to the distribution feeders. Normal procedures should be followed.

Earth fault protection at the wind power plant connections must however be installed.

The following alternatives for the distribution bay earth fault protection are available;

Non-directional residual overcurrent protection can be used if the following is fulfilled:

- $I_{RN}(R_{fault} = required) > \max\lfloor I_{ci}(R_{fault} = 0)\rfloor_{i=1,n}$ where the required fault resistance sensitivity is stated in national regulations (starkströmsföreskrifterna) [4].

In distribution systems without overhead lines it can be acceptable to use a neutral point resistor giving larger earth fault currents (in the range 100 – 500 A). The very high sensitivity is not required in such system. In such a case the non-directional residual overcurrent protection can be used.

Directional residual overcurrent protection;

Can be used if the following are fulfilled;

- Neutral point resistor gives sufficient resistive earth fault current for acceptable fault detection. This has to be checked by means of network calculation. Alternatively can the system be operated without any Petersen coil and neutral point resistor. In such a case shall the directional earth fault protections measure the capacitive earth fault current from the non-faulted feeders.
- The directional residual overcurrent protection shall have at least one step; One low current step with definite time delay.

The directional phase overcurrent protection shall use zero sequence voltage as directional angle reference for the directional function. Normally, the resistive part of the residual current (in phase with the zero sequence voltage) is measured. It shall however be possible to have measurement of the capacitive component of the residual current. (Settable characteristic phase angle).

The directional phase overcurrent protection shall have sensitivity as stated by the regulations; 3000 or 5000 Ω detection and fault clearance if overhead lines exist in the distribution system. If there are only underground cables in the distribution system, no sensitivity requirements are stated.

Table 2 shows a summary of the proposed protections in the substation bay for different fault conditions.

Table 2; Proposed protections in the substation bay for short circuits and earth faults on a distribution line.

Fault	Protection	Conditions to be fulfilled
Short circuit on a distribution line	Non-directional overcurrent	$I_{sc,\min} > 1.2 \cdot I_{load\max}$ $I_{sc,win} > 1.2 \cdot I_{load\max}$ $I_{win} < I_{sc,\min}$
	Directional overcurrent	$I_{sc,\min} > 1.2 \cdot I_{load\max}$ $I_{sc,win} > 1.2 \cdot I_{load\max}$
	Impedance protection with quadrilateral impedance characteristics	
Earth fault on a distribution line	Directional earth fault protection	Earth fault current large enough for acceptable detection.
	Non-Directional earth fault protection	The capacitive earth fault current in the feeder is less than the fault current from the neutral point resistor at zero resistance earth fault

Table 3 shows the required functions or application areas for the recommended protections for phase to phase faults and earth faults. The table also contains setting recommendations.

Table 3; Required functions, application areas and settings for phase overcurrent protection, earth fault protection, directional earth fault protection and zero sequence voltage protection.

Protection	Required functions or application areas	Settings
Non-directional overcurrent	Two steps; One low current step One high current step	Require calculations of fault currents As sensitive as possible without risking unwanted trips 0 s delay
Directional overcurrent	Two steps; One low current step One high current step	Require calculations of fault currents As sensitive as possible without risking unwanted trips 0 s delay
Impedance protection with quadrilateral impedance characteristics	Two zones quadrilateral shape separate reactance and resistance settings definite time delay	Require calculations of impedance during normal conditions and fault conditions
Non-directional earth fault protection	Earth fault current from the neutral point resistor, at solid earth fault, larger than the capacitive earth fault current for the feeder at solid earth fault. Sensitivity requirements must be fulfilled.	Require calculations
Directional earth fault protection	Neutral point resistor gives sufficient resistive earth fault current for acceptable fault detection. If no Petersen coil or neutral point resistor	Require calculations

Protection	Required functions or application areas	Settings
	→ capacitive current measurement	
Zero sequence voltage	Open delta connected voltage transformer group on - Distribution grid busbar - MV side of the HV/MV substation transformer	

Table 4 shows the required functions or application areas for the over/under voltage and over/under frequency protections. The table also contains short setting recommendations.

Table 4; Required functions, application areas and settings for over / under voltage protection and over / under frequency protection.

Protection	Required functions / application areas	Settings
Overvoltage	Shall detect overvoltage at HV side of the wind power unit transformer Two steps High set voltage Low set voltage	~125% of nominal voltage. Trip time 0 - 0.5 s 110% of nominal voltage Trip time 2 - 5 s
Undervoltage	Coordinated with short circuit protections.	Pickup level not to be set above the lowest operation voltage of the grid Set to 85% recommended Time delayed to assure selectivity and fulfillment of fault ride through requirement Max 2.5 s trip time
Overfrequency		≥52 Hz, 0,5 s delay
Underfrequency		≤47.5 Hz, 0,5 s delay

9.2 Protection in a wind power unit connected to a distribution grid

Table 5 shows a summary of the proposed protections in the substation bay for different faults. A non-directional overcurrent protection may be used as short circuit protection. The overcurrent protection will, however, be insufficient as protection for external faults, since the fault current amplitude will be limited close to the amplitude of the rated current. Hence, as protection for external short circuit the wind power unit protection system have to rely on over/under frequency and over/under voltage protections. However, if faster fault clearance is required then a ROCOF relay is recommended. Another possibility is to send an intertripping signal from the substation bay directly to the wind power unit but this require a fast and reliable communication link.

Table 5; Proposed protections and conditions to be fulfilled in the substation bay for short circuits in wind power unit and on distribution line. Earth fault on distribution line and anti islanding protection.

Fault	Protection	Conditions to be fulfilled
Short circuit in the wind power unit	Non-directional overcurrent	$I_{sc,\min} > 1.2 \cdot I_{load\max}$
	Directional overcurrent	$I_{sc,\min} < 1.2 \cdot I_{load\max}$
Short circuit on distribution line	Over/Undervoltage	
	Over/under frequency ROCOF (only in special cases)	Protection concept depends on possibility of balance in active and reactive power
Earth fault on distribution line	Zero sequence voltage	
	Over/under frequency ROCOF (only in special cases)	Protection concept depends on possibility of balance in active and reactive power.
Island operation detection	Over/under frequency and over/undervoltage	Low or negligible probability that active and reactive power is in balance island operation
	Over/under frequency, Over/under voltage ROCOF (only in special cases)	The probability that active and reactive power is in balance island operation is not negligible.
	Intertripping from substation bay	

Table 6 shows the required functions or application areas for the protections for phase to phase faults and earth faults. The table also contains setting recommendations.

Table 6; Required functions, application areas and settings for phase overcurrent protection, earth fault protection, directional earth fault protection and zero sequence voltage protection.

Protection	**Required functions / application areas**	**Settings**
Non-directional overcurrent	Two steps One low current step One high current step	Require calculations of fault currents As sensitive as possible without risking unwanted trips 0 s delay
Directional overcurrent	Two steps One low current step One high current step	Require calculations of fault currents. As sensitive as possible without risking unwanted trips 0 s delay
Zero sequence voltage	Open delta connected voltage transformer group on MV side of the unit transformer or connected to a voltage transformer at the MV neutral point of the unit transformer	

Table 7 shows the required functions or application areas for; the over/under voltage, over/under frequency, and the anti islanding protection options. The table also contains short setting recommendations.

Table 7; Required functions, application areas and settings for over / under voltage protection and over / under frequency.

Protection	**Required functions / application areas**	**Settings**
Overvoltage	Shall detect overvoltage at HV side of the wind power unit transformer. Two steps High set voltage Low set voltage	 ~125% of nominal voltage. Trip time 0 - 0.5 s 110% of nominal voltage Trip time 2 - 5 s
Undervoltage	Coordinated with short circuit protections.	Pickup level not to be set above the lowest operation voltage of the grid Set to 85% recommended Time delayed to assure selectivity and fulfillment of fault ride through requirement Max 2.5 s trip time
Overfrequency		≥52 Hz, 0.5 s delay
Underfrequency		≤47.5 Hz, 0.5 s delay
ROCOF	Must measure absolute value of df/dt	≥0.5 Hz/s with ≥0.5 s delay recommended
Intertripping from substation bay	High speed reliable communication link	

9.3 Protection in the substation bay connected to a collection grid

In the decision of which type of **short circuit protection** that should be used for a collection grid (wind farm) feeder bay, the following shall be investigated;

- The maximum load current out on the feeder, when the connected wind power production is zero; $I_{load,max}$ (normally quite small)
- The minimum short circuit current through the bay at feeder short circuit; $I_{sc,min}$. This current can be calculated by applying a two phase short circuit at the most remote point of the feeder. In this calculation should the production connected to the feeder be maximized, the short circuit power from the external network should be minimized and any abnormal switching state should be considered.
- The current through the bay in case of a short circuit at the low voltage side of the wind power unit transformer; I_{scwin}
- The maximum total fault current from the feeder connected power generators at remote short circuit (on another feeder in the distribution network); I_{win}
- The structure of the collection grid: alternatives 1 and 2 as shown in Figure 30 and Figure 31.

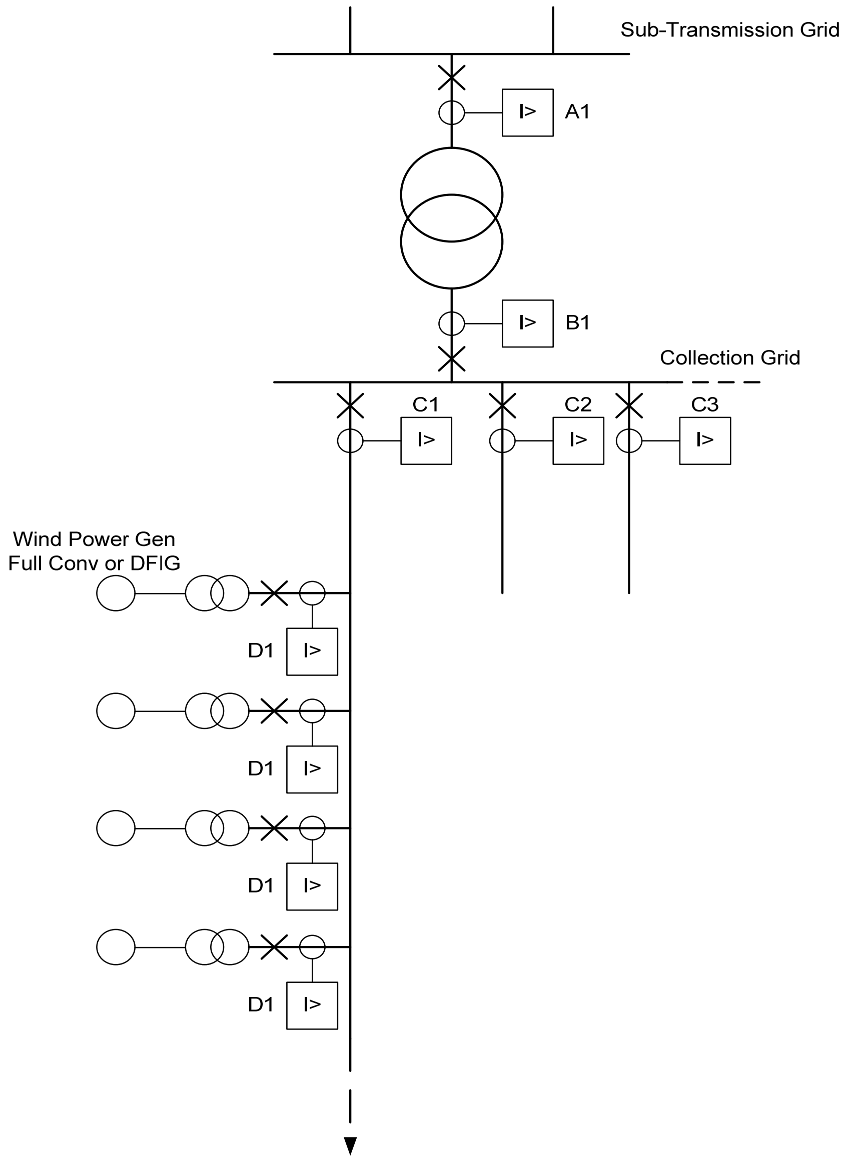

Figure 30; Collection grid with radial feeders, alternative 1

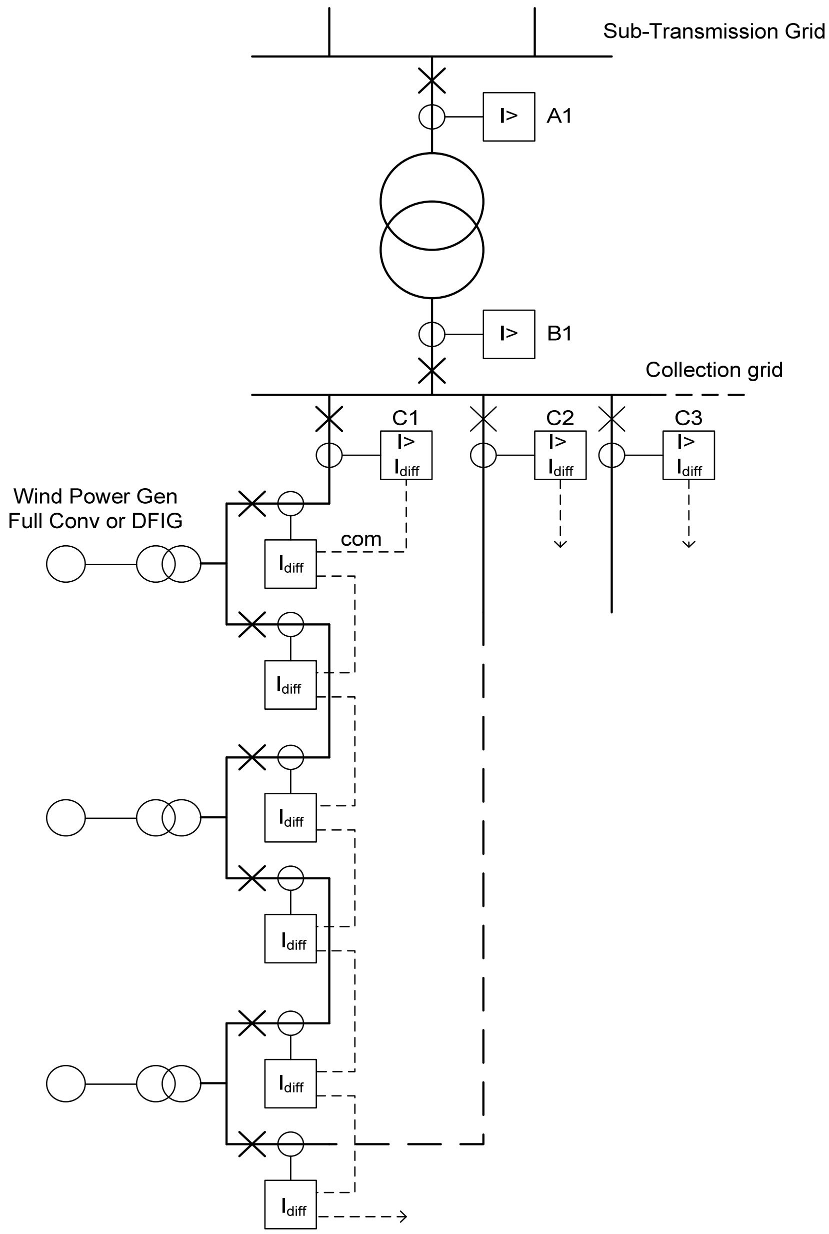

Figure 31; Meshed collection grid, alternative 2

How the choice of feeder short circuit protection can be made is described below.

Non-directional phase overcurrent protection can be used if the following is fulfilled:

- $I_{sc,\min} > 1.2 \cdot I_{load,\max}$ All feeder faults must be detected without risk of unwanted trip due to maximum load current. The infeed from connected generating plants will affect the current through the bay.
- $I_{sc,win} > 1.2 \cdot I_{load,\max}$ The feeder short circuit protection shall if possible serve as back-up protection for unit transformer short circuits.
- $I_{win} < I_{sc,\min}$ The feeder short circuit protection shall not trip for faults on other feeders. Normally this criterion cannot be fulfilled as the fault current fed from the generators are in the same range as the normal operation generated current.

The non-directional overcurrent protection shall have at least two steps;

- A low current step with the possibility to set different time delay characteristics; IEC Normal Inverse, IEC Very Inverse, IEC Extremely Inverse, RI Inverse and definite time delay. This step is normally set as sensitive as possible without risking unwanted trip.
- A high current step with definite time delay. This step is normally set to a high current and 0 s delay.

Directional phase overcurrent protection can be used if the following is fulfilled:

- $I_{sc,\min} > 1.2 \cdot I_{load,\max}$ All feeder faults must be detected without risk of unwanted trip due to maximum load current. The infeed from connected generating plants will affect the current through the bay.
- $I_{sc,win} > 1.2 \cdot I_{load,\max}$ The feeder short circuit protection shall if possible serve as back-up protection for unit transformer short circuits.

The directional protection eliminates the risk of unwanted trip due to fault current or normal load current in the reverse direction.

The directional overcurrent protection shall have at least two steps;

- A low current step with the possibility to set different time delay characteristics; IEC Normal Inverse, IEC Very Inverse, IEC Extremely Inverse, RI Inverse and definite time delay. This step is normally set as sensitive as possible without risking unwanted trip.
- A high current step with definite time delay. This step is normally set to a high current and 0 s delay.

Impedance protection with quadrilateral impedance characteristic

This alternative can increase the possibilities to detect and clear short circuits having low fault current level, for example faults on the low voltage side of unit transformers in the wind power generator systems.

The impedance protection shall have at least two zones. The impedance characteristic for both zones shall have quadrilateral shape with separate reactance and resistance settings. The zones shall have definite time delay.

Line differential current protection

This alternative can be used in alternative 2, where a group of wind generator systems are connected to a loop feeder configuration. This alternative gives the following advantages;

- Very high sensitivity of feeder short circuit detection as the differential protection can be set to a current level below the load current level.
- Absolute selectivity
- Fast fault clearance, normally instantaneous trip
- One feeder short circuit will not give any generator trips.

In this application the line differential protection for each feeder section, together with an overcurrent or underimpedance protection in the sub-station bay, gives a reliable and secure protection system.

- The line differential protection shall have bias current stabilization characteristic.
- Observe that communication with sufficient capacity and speed is required.

9.3.1 Earth fault protection

In the decision of which type of **earth fault protection** that should be used for a collection grid (wind farm) feeder bay, the following shall be investigated;

- System earthing method; Isolated, Petersen coil earthing, Resistance earthing
- Capacitive earth fault current for every feeder at solid earth fault I_{c1}, I_{c2}, … I_{cn}
- Total capacitive earth fault current at solid earth fault I_{ctot}
- Earth fault current from the neutral point resistor at zero resistance earth fault (if existing) I_{RN}
- Are there overhead lines in the distribution system
- The structure of the collection grid; alternatives 1 and 2 in Figure 32 and Figure 33.

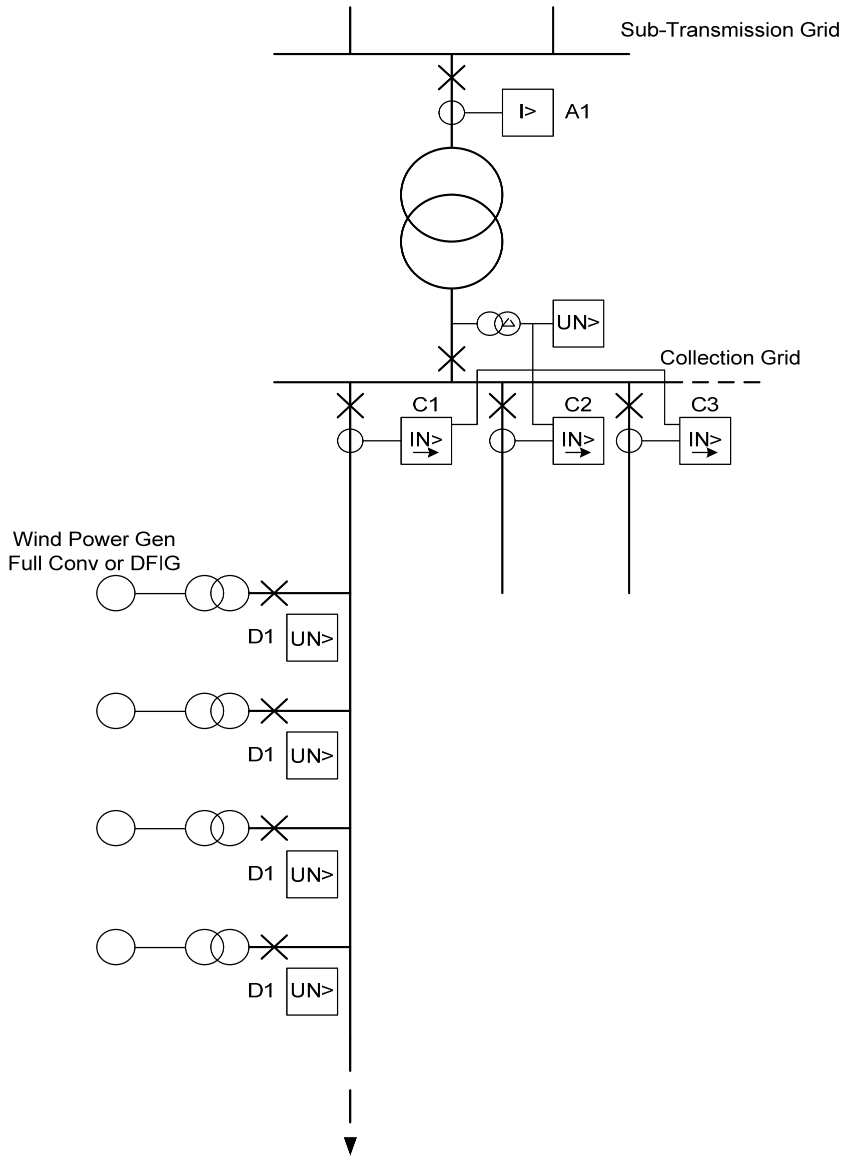

Figure 32; Collection grid with radial feeders, alternative 1

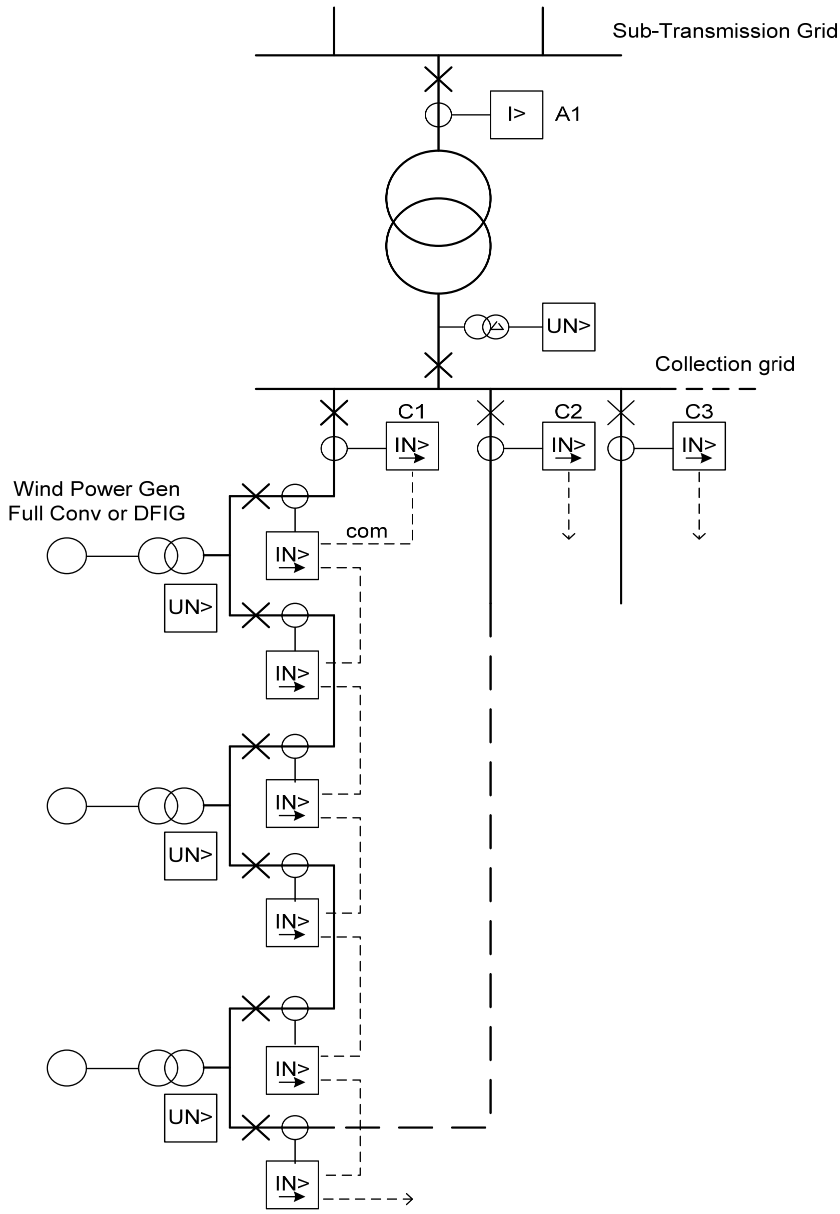

Figure 33; Meshed collection grid, alternative 2

In the collection grid bay the choice of earth fault protection is not affected of the presence of wind power generation connected to the distribution feeders. Normal procedures should be followed. Earth fault protection at the wind power plant connections must however be installed.

The following alternatives for the distribution bay earth fault protection are available, for **radial feeders** in the collection grid as shown in Figure 32.

Non-directional residual overcurrent protection can be used if the following are fulfilled:

$I_{RN}(R_{fault} = required) > \max\lfloor I_{ci}(R_{fault} = 0)\rfloor_{i=1,n}$ where the required fault resistance sensitivity is stated in national regulations (starkströmsföreskrifterna) [4].

In distribution systems without overhead lines it can be acceptable to use a neutral point resistor giving larger earth fault currents (in the range 200 – 500 A). The very high sensitivity is not required in such system. In such a case the non-directional residual overcurrent protection can be used.

Directional residual overcurrent protection can be used if the following are fulfilled:

- Neutral point resistor gives sufficient resistive earth fault current for acceptable fault detection. This has to be checked by means of network calculations. Alternatively can the system be operated without any Petersen coil and neutral point resistor. In such a case shall the directional earth fault protections measure the capacitive earth fault current from the non-faulted feeders.
- The directional residual overcurrent protection shall have at least one step; One low current step with definite time delay.

The directional residual overcurrent protection shall use zero sequence voltage as directional angle reference for the directional function. Normally the resistive part of the residual current (in phase with the zero sequence voltage) is measured. It shall however be possible to have measurement of the capacitive component of the residual current. (Settable characteristic phase angle)

The directional residual overcurrent shall have sensitivity as stated by regulations; 3000 or 5000 Ω detection and fault clearance if overhead lines exist in the distribution system. If there are only underground cables in the distribution system no sensitivity requirements are stated.

The following alternatives for the distribution bay earth fault protection are available, for the **meshed collection grid** shown in Figure 33;

Directional residual overcurrent protection and residual overvoltage protection with communication scheme;

Can be used if the following are fulfilled;

- Neutral point resistor gives sufficient resistive earth fault current for acceptable fault detection. This has to be checked by means of network calculations. Alternatively can the system be operated without any Petersen coil and neutral point resistor. In such a case shall the directional earth fault protections measure the capacitive earth fault current from the non-faulted feeders.

The directional residual overcurrent protection shall have at least two steps;

- One low current forward step with definite time delay used for trip with communication blocking from remote line end

- One low current reversal step used for communication blocking of the protection in the remote line end.

The residual overvoltage function is used to release the residual overcurrent function and as a back-up function. In the wind power generator connections this step shall trip the whole unit.

- The directional residual overcurrent protection shall use zero sequence voltage as directional angle reference for the directional function. Normally the resistive part of the residual current (in phase with the zero sequence voltage) is measured. It shall however be possible to have measurement of the capacitive component of the residual current. Settable characteristic phase angle

The directional residual overcurrent protection shall have sensitivity as stated by regulations; 3000 or 5000 Ω detection and fault clearance if overhead lines exist in the distribution system. If there are only earth cables in the distribution system no sensitivity requirements are stated.

In order to achieve selectivity for the directional earth fault protections the communication based logic is used. The principle is described as shown in Figure 34.

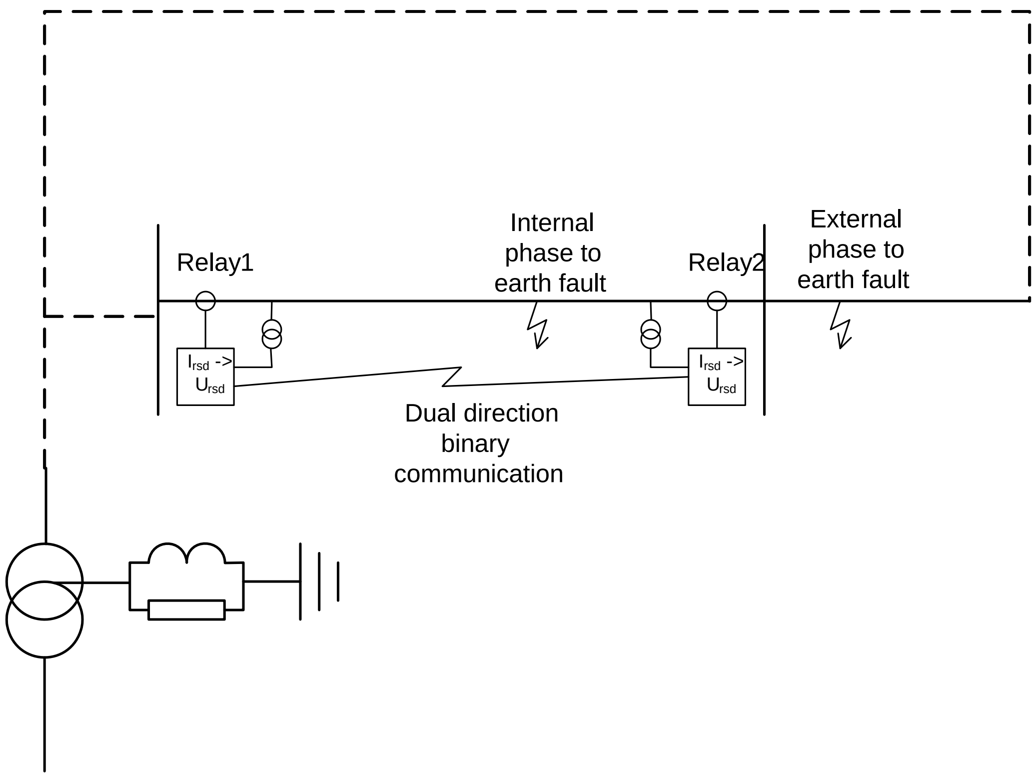

Figure 34, Principle of the earth fault protection communication system

A logical diagram showing the principle is presented in Figure 35.

The earth fault directional protection has two directional functions in each line end.

In case of internal fault at a feeder the forward looking step will be activated in at least one end. When one line end has tripped the fault will be fed via the other line end and the forward step in this end will trip and finally clear the fault.

In case of an external fault the reverse function will be activate at one of the line ends. This will send a signal to block trip at the other line end.

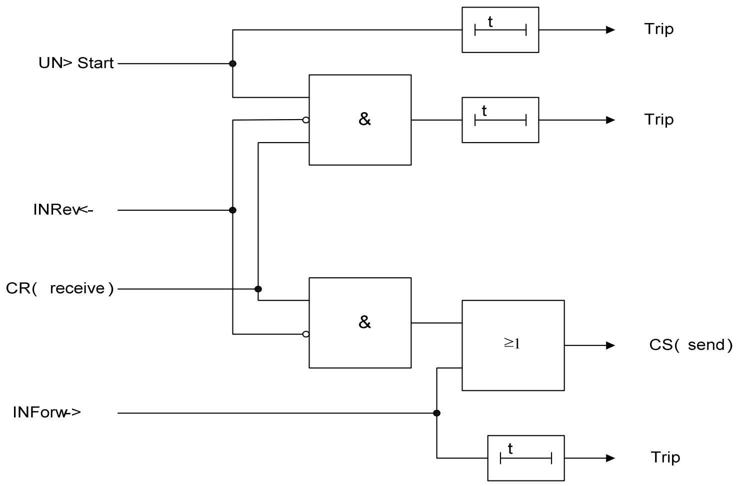

Figure 35; Logical diagram of the earth fault communication aided protection

Table 8 shows a summary of the proposed protections in the substation bay for different fault conditions.

Table 8; Summary of the proposed protections in the substation bay for short circuits in wind power units and on feeders and for earth fault on feeders.

Fault	Protection	Conditions to be fulfilled
Short circuit on collection grid line	Non-directional overcurrent	$I_{sc,\min} > 1.2 \cdot I_{load\max}$ $I_{sc,win} > 1.2 \cdot I_{load\max}$ $I_{win} < I_{sc,\min}$
	Directional overcurrent	$I_{sc,\min} > 1.2 \cdot I_{load\max}$ $I_{sc,win} > 1.2 \cdot I_{load\max}$
	Impedance protection with quadrilateral impedance	

Fault	**Protection**	**Conditions to be fulfilled**
	characteristics	
	Line differential protection	
Earth fault on distribution line	Non-Directional earth fault protection	The capacitive earth fault current in the feeder is less than the fault current from the neutral point resistor at zero resistance earth fault
	Directional earth fault protection	Earth fault current large enough for acceptable detection.

Table 9 shows the required functions or application areas for the recommended protections for phase-to-phase faults and earth faults. The table also contains short setting recommendations.

Table 9; Required functions, application areas and settings for phase overcurrent protection, earth fault protection, directional earth fault protection and zero sequence voltage protection.

Protection	Required functions or application areas	Settings
Non-directional overcurrent	Two steps; One low current step One high current step	Require calculations of fault currents. As sensitive as possible without risking unwanted trips 0 s delay
Directional overcurrent	Two steps; One low current step One high current step	Require calculations of fault currents. As sensitive as possible without risking unwanted trips 0 s delay
Impedance protection with quadrilateral impedance characteristics	Two zones with; quadrilateral shape separate reactance and resistance settings; definite time delay	Require calculations of impedance during normal conditions and fault conditions.
Line differential protection	High speed reliable communication link Bias current stabilization characteristics	
Non-directional earth fault protection	Earth fault current from the neutral point resistor, at zero resistance earth fault, larger than the capacitive earth fault current for the feeder at zero resistance earth fault.	Require calculations.
Directional earth fault protection	Neutral point resistor gives sufficient resistive earth fault current for acceptable fault detection. If no Petersen coil or neutral point resistor → capacitive current measurement	Require calculations.

Table 10 shows the required functions or application areas for the over/under voltage and over/under frequency protections. The table also contains setting recommendations.

Table 10; Required functions, application areas and settings for over / under voltage protection and over / under frequency protection.

Protection	Required functions / application areas	Settings
Overvoltage	Shall detect overvoltage at HV side of the wind power unit transformer. Two steps High set voltage Low set voltage	 ~125% of nominal voltage. Trip time 0 - 0.5 s 110% of nominal voltage Trip time 2 - 5 s
Undervoltage	Coordinated with short circuit protections.	Pickup level not to be set above the lowest operation voltage of the grid Set to 85% recommended Time delayed to assure selectivity and fulfillment of fault ride through requirement Max 2.5 s trip time
Over frequency		≥52 Hz, 0.5 s
Under frequency		≤47.5 Hz, 0.5 s

9.4 Protection in a wind power unit connected to a collection grid

Table 11 shows a summary of the proposed protections in the wind power unit for different faults. A non-directional overcurrent protection may be used as short circuit protection. The overcurrent protection will, however, be insufficient as protection for external faults, since the fault current will be limited to amplitude close to the rated current. Hence, as protection for external short circuit the wind power unit protection system have to rely on over/under frequency and over/under voltage protections. However, if faster fault clearance is required then a ROCOF relay can be used.

A good alternative to the ROCOF protection is to send and intertripping signal from the substation bay, but this require a fast and reliable communication link. The substation bay shall also have over/under frequency and over/under voltage protection.

Table 11; Summary of the proposed protections in the substation bay for short circuits protection, earth fault protection and anti islanding.

Fault	**Protection**	**Conditions to be fulfilled**
Short circuit in the wind power unit	Non-directional overcurrent	$I_{sc,\min} > 1.2 \cdot I_{load\max}$
	Directional overcurrent	$I_{sc,\min} < 1.2 \cdot I_{load\max}$
Short circuit on distribution line	Over/Undervoltage	
	Over/under frequency ROCOF (only in special cases)	Protection concept depends on possibility of balance in active and reactive power
Earth fault on distribution line	Zero sequence voltage	
	Over/under frequency ROCOF (only in special cases)	Protection concept depends on possibility of balance in active and reactive power.
Island operation detection	Over/under frequency and over/undervoltage	Low or negligible probability that active and reactive power is in balance island operation
	Over/under frequency, Over/under voltage ROCOF (only in special cases)	The probability that active and reactive power is in balance island operation is not negligible.
	Intertripping from substation bay	

Table 12 shows the required functions or application areas for the protections for phase to phase faults and earth faults. The table also contains setting recommendations.

Table 12; Required functions, application areas and settings for overcurrent protection and zero sequence voltage protection.

Protection	**Required functions / application areas**	**Settings**
Non-directional overcurrent	Two steps; One low current step One high current step	Require calculations of fault currents. As sensitive as possible without risking unwanted trips 0 s delay
Directional overcurrent	Two steps; One low current step One high current step	Require calculations of fault currents. As sensitive as possible without risking unwanted trips 0 s delay
Zero sequence voltage	Open delta connected voltage transformer group.	

Table 13 shows the required functions or application areas for the over/under voltage, over/under frequency and ROCOF protections. The table also contains setting recommendations.

Table 13; Required functions, application areas and settings for over / under voltage protection and over / under frequency protection.

Protection	Required functions / application areas	Settings
Over voltage	Shall detect overvoltage at HV side of the wind power unit transformer. Two steps High set voltage Low set voltage	 ~125% of nominal voltage. Trip time 0 - 0.5 s 110% of nominal voltage Trip time 2 - 5 s
Under voltage	Coordinated with short circuit protections.	Pickup level not to be set above the lowest operation voltage of the grid Set to 85% recommended Time delayed to assure selectivity and fulfillment of fault ride through requirement Max 2.5 s trip time
Over frequency		≥52 Hz, 0.5 s
Under frequency		≤47.5 Hz, 0.5 s
ROCOF	Must measure absolute value of df/dt	≥0.5 Hz/s with ≥0.5 s delay recommended
Intertripping from substation bay	High speed reliable communication link	

9.5 Substation transformer protection

The transformer connecting a distribution system or a wind power collection network to the rest of the system might change protection design compared to standard solutions.

It is assumed that the "normal" set of transformer **short circuit protection** include the following;

- Transformer differential protection
- HV-side phase overcurrent protection
- LV-side phase overcurrent protection

Due to the fact that fault current can be fed from the distribution/collection network it might be necessary to modify the protection system. The situation is shown in Figure 36.

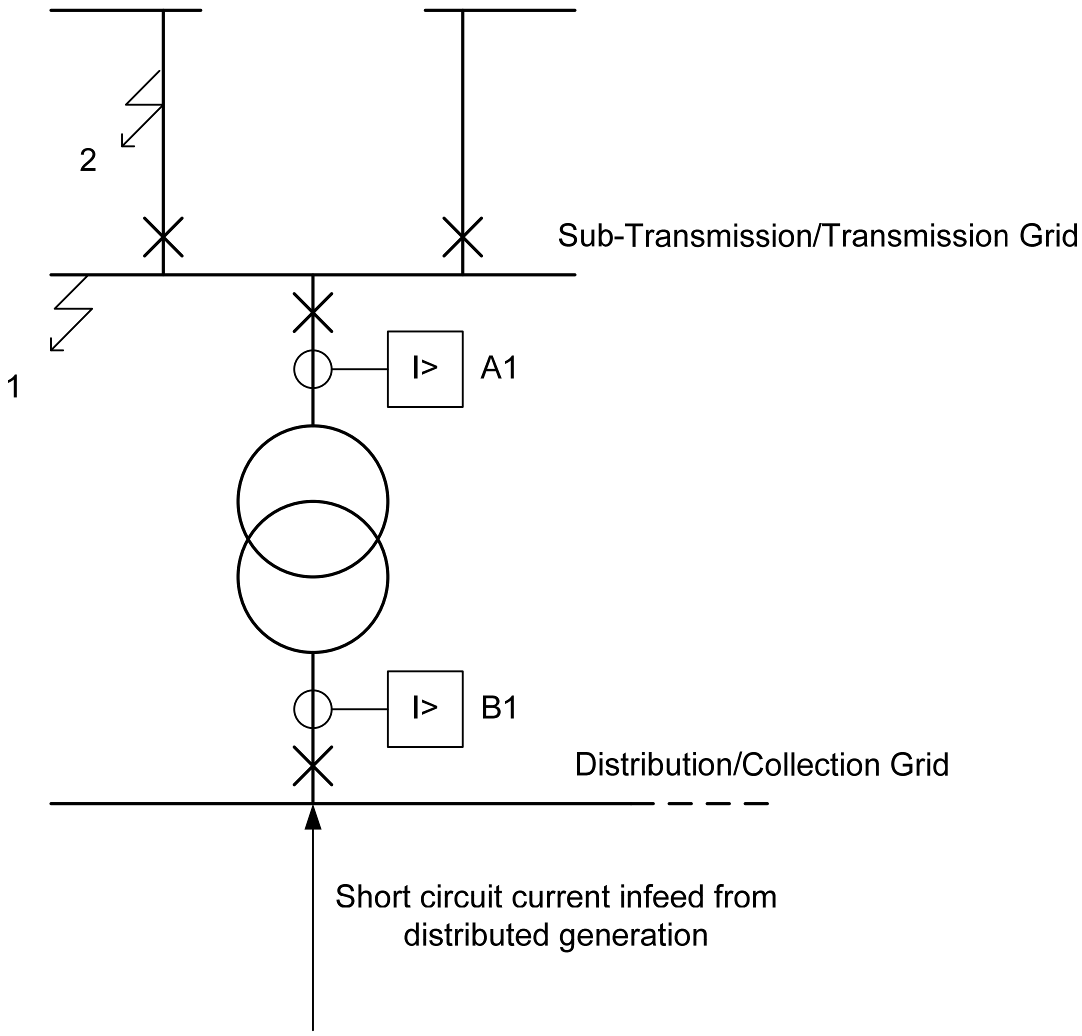

Figure 36; Short circuit current fed through the transformer to the subtransmission / transmission network

In case of a short circuit at fault point 1 the protection A1 shall operate and trip the transformer. In case of short circuit at fault point 2 the line protection shall operate and trip the line. The transformer protection shall serve as back-up short circuit protection if the line protection does not have local redundancy.

There is a probability that the normally used transformer phase overcurrent protection has a current setting so that the short circuits cannot be detected and tripped. In most cases will the islanding of the distribution/collection network be detected and the generators will be tripped. There is however a risk that the fault duration will be unacceptable long. Therefore it is recommended to use an underimpedance protection at the HV-side of the transformer.

Underimpedance protection with quadrilateral impedance characteristic can be used if the following is fulfilled:

- The impedance protection shall have at least two zones. The impedance characteristic for both zones shall have quadrilateral shape with separate reactance and resistance settings. The zones shall have definite time delay.

It is assumed that the "normal" set of transformer **earth fault** protection include the following;

- HV-side neutral point (residual) overcurrent protection (if the winding is directly earthed)
- HV-side neutral point (residual) overvoltage protection (if the winding is not directly earthed)
- LV-side neutral point (residual) overvoltage protection

Earth fault current can be fed from the transformer as the distribution/collection network feed short circuit power (positive and negative sequence). It might be necessary to modify the protection system compared to normal standard. The situation is shown in Figure 37.

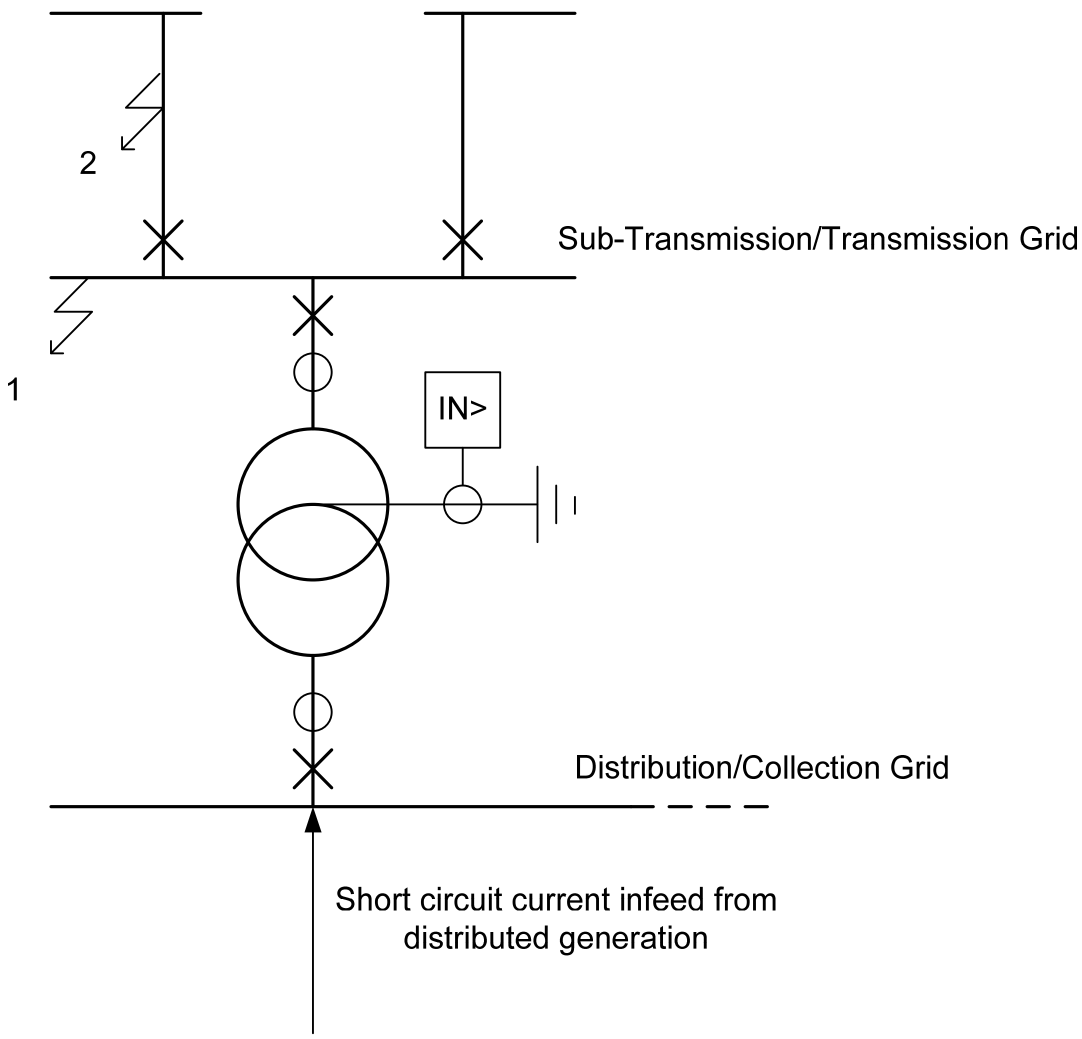

Figure 37; Earth fault current fed from the transformer to the subtransmission / transmission network

In case of an earth fault at fault point 1 the neutral point earth fault protection shall operate and trip the transformer. In case of fault point 2 shall the line protection normally operate and trip the line. The transformer protection shall serve as a back-up earth protection if the line protection does not have local redundancy.

Often the neutral point overcurrent protection only has one step with a relative long trip time (2.0 s). In this application it is suggested to introduce a fast high current step with short time delay (0.4 s). The current setting of this protection must be co-ordinated with the sub-transmission/transmission line earth fault protections.

10 Future work

This study has provided a number of application examples for protection of wind farms and its connected grid. However, there are in this report a number of cases where no general absolute protection setting recommendation can be made since the settings are dependent on the characteristics of the individual grid. In such cases must calculations be made for the specific protection and grid. Coordination must also be made with the other protections. To provide guideline material for wind power owners and facilitate the relay coordination communication between grid owners and wind farm owners a future work that includes guidelines for the calculations of the protection setting parameters is recommended.

The methods for fault calculation in networks having generation with DFIG generator systems or generators connected via full power converters should be studied further.

Appendix 1- System Earthing

The system earthing is the way the transformer and the generator neutral points are connected to earth. The system earthing has a large impact on the properties of earth faults and thereby also on the ability to detect earth faults. The system earthing methods can be categorized either as an effective system earthing or as a high impedance system earthing. The choice between these earthing methods is normally made as it always has been made, according to practice. It is common that different system earthing concepts are used on different voltage levels.

Effective system earthing (solid earthing)
In effectively earthed systems, some or all of the transformer and generator Y-winding neutrals are directly connected to the station earth. It is mainly used in systems with a rated voltage above 110 kV and in low voltage (LV) systems, including LV generator systems. In effectively earthed distribution systems the earth fault currents are large, in the same range as the short circuit currents. This will cause some disadvantages;

- The large earth fault current can give arcs that may cause fire.
- Large earth fault currents will cause potential rise in the point of the earth fault. The consequence can be large touch voltages and step voltages which may pose a risk for personal injuries, see Figure 38 and Figure 39.
- For generator systems having effective earthing will the earth fault current result in stator damages very quickly, thus will rapid fault clearance be of great importance.

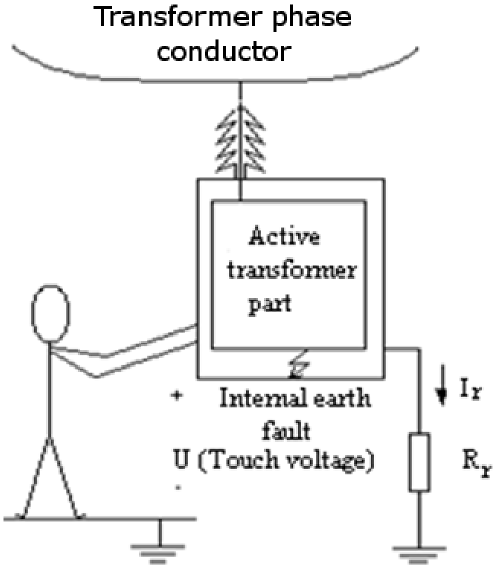

Figure 38; Example of touch voltage at phase to earth fault

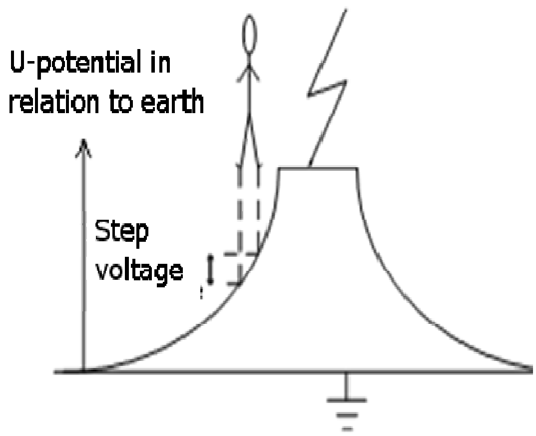

Figure 39; Example of step voltage at phase to earth fault

There are also some advantages by using effective system earthing;
The voltage rise of the non-faulted phases, at phase to earth fault is limited compared to the high impedance earthed systems. This gives less insulation requirement, especially at the highest system voltages.

- The high earth fault current can be used as effective detection of earth faults.
- Simple residual overcurrent protections are often sufficient as earth fault protection.

High impedance system earthing
In high impedance earthed systems, no transformer or generator neutrals are directly connected to the station earth. There are three main principles for high impedance system earthing;

- isolated neutral system,
- resistance earthed system
- reactance (resonance) earthed system

Isolated neutral system
The isolated neutral system is not intentionally earthed, except for high impedance connections for protection or measurement purposes. The principle structure of this system is shown in Figure 40.

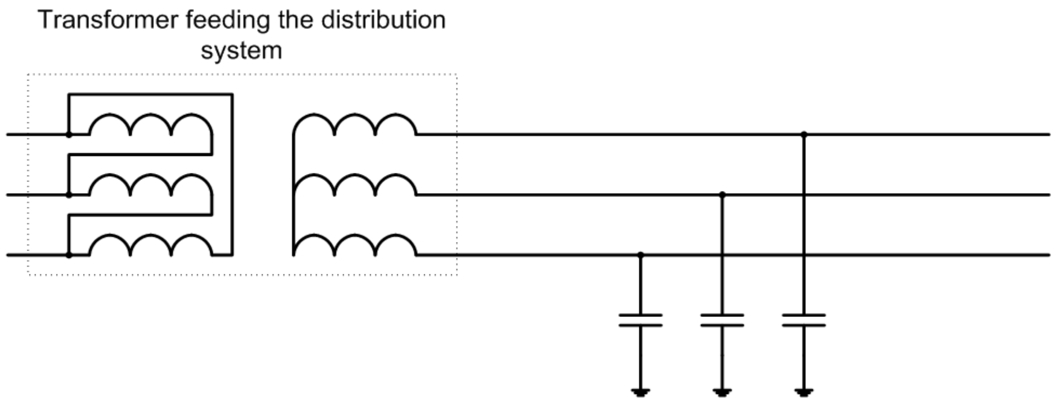

Figure 40; Isolated distribution system

This alternative can be used in systems with limited capacitive earth fault currents. The neutral point is often connected to earth via a voltage transformer or a surge arrester. The impedance of such apparatus is, however, large enough to not give any noticeable effects on the system earthing.

System with neutral point resistor

In this system earthing method a resistor is connected between the neutral point and earth. The principle structure of this system is shown in Figure 41.

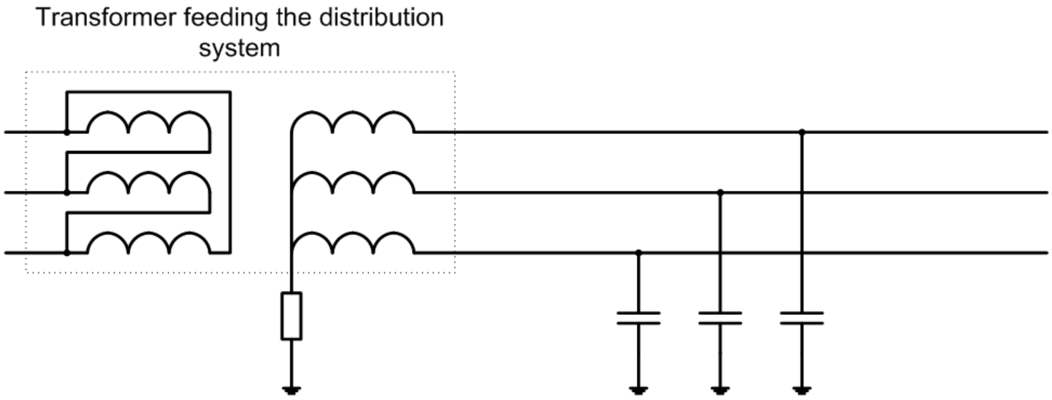

Figure 41; System with resistance earthing (neutral point resistor)

This alternative is used in small systems in order to achieve sufficient coupling to earth of the system, and thus avoiding overvoltages emanating from the high voltage system. One advantage with this system is that the neutral point resistor gives a well-defined earth fault current that can be used by the residual current earth fault protection.

This earthing system is also normally used for conventional generators (synchronous machines), where the resistor will give an earth fault current in the range 5 – 20 A.

An alternative is to use a neutral point resistor that gives larger earth fault currents; in the range 100 – 300 A. The system characteristics will be the following;

- In case of low a resistive earth fault the touch voltage/step voltage will be large. This means that the earth fault must be cleared within 0.5 s.
- Residual non-directional overcurrent protection can be used as earth fault protection in the outgoing MV bays.
- In case of an earth fault in a three phase cable there is a risk that the large earth fault current will cause a short circuit and thus lead to severe cable damages.
- The risk of transient overvoltages in the system will be reduced compared to the case with high impedance earthing.

The alternative with this medium sized neutral point resistance earthing can be attractive in collection grid of wind farms, not connecting any other customers. It must however be observed that the large current might give a higher potential rise at the single wind power plant thus giving corresponding potential rise to the generator low voltage system. The earthing system at each site must therefore be thoroughly designed. It must however be observed that the large current might give higher potential rise at the single wind power plant thus giving corresponding potential rise to the generator low voltage system. The earthing system at each site must therefore be thoroughly designed.

System with neutral point reactor (Petersen coil)
In this system earthing method a reactance is connected between the neutral point and earth. The principle structure of this system is shown in Figure 42.

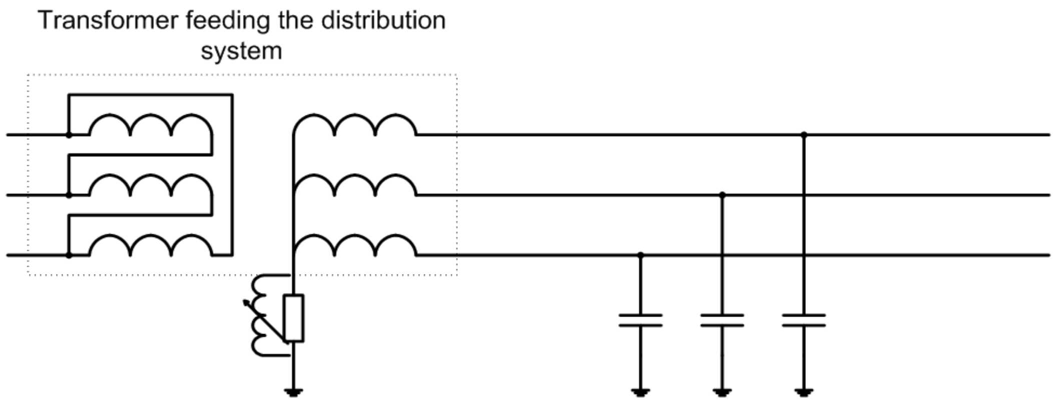

Figure 42; System with reactance earthing (Petersen coil)

The neutral point reactor will give an earth fault current in phase opposition to the capacitive earth fault current. The resulting earth fault current will therefore be reduced. If the fault is an arcing fault the reduction of the current in the fault point can enable self-extinguishing of the fault. Medium voltage distribution systems normally have reactance earthing. Wind farm collection grids should have this kind of earthing if it includes overhead lines. In other cases it could be possible to use resistance earthing with relatively high earth fault current.

- To give a well-defined earth fault current, that can be measured by a residual current earth fault protection, it is common that a resistor is connected in parallel with the neutral point reactor.

Requirements on impedance system earthing
The following requirements should be considered in the choice of high impedance system earthing;

- The total earth fault current must be limited so that the voltage rise of equipment, subjected to the earth fault, is limited to acceptable values. Such values are sometimes stated in safety regulations.
- In case of no earth fault clearance, the earth fault current must be limited so that the thermal stress of equipment (earthing equipment etc.) does not exceed the thermal capability of the equipment. It is normal practice, in some high impedance earthed systems, to continue the operation even if an earth fault has occurred. This might be the case in wind farm collection cable grids.
- The earth fault voltages (zero sequence voltages) and currents (zero sequence currents) shall reach values, for all faults to be detected, so that the fault clearance can have acceptable selectivity and sensitivity.

The system earthing must be chosen so that the coupling to earth is large enough to avoid capacitive coupled overvoltages (in feeding transformers) from feeding MV/HV networks. This is of utmost importance for generator systems.

Earthing recommendations for MV systems
For very small MV systems, with a small capacitance to earth it is recommended to use resistance earthing, i.e. a resistor is connected to the neutral point of the transformer feeding the MV system. This resistor will cause an effective coupling of the system to earth and thus prevent high voltage rise of the whole distribution system. This will ensure that there will be a well-defined resistive earth fault current (in phase with the residual voltage) so that earth fault current protection can be used.

For MV systems with only one or two feeders from the feeding transformer station it is recommended to use resistive earthing, with or without a parallel Petersen coil. This will assure a well-defined resistive earth fault current (in phase with the residual voltage) out on the faulted feeder. The phase to earth fault can therefore be detected by residual current protection, measuring the resistive earth fault current.

For MV systems in areas with high earth resistivity and/or very large capacitive earth fault current, it is recommended to use reactance earthing (Petersen coil system earthing). Especially networks with cable lines can have large capacitive earth fault current. Reactance earthing is used to reduce the earth fault current, and thus the voltage rise of equipment subjected to the earth fault. It is also recommended that a neutral point resistor is connected in parallel with the neutral point reactor.

For MV systems with moderate capacitive earth fault currents (in the range 5 – 20 A), and more than two feeders that contribute to the capacitive earth fault current, it can be considered to operate the network isolated (without apparatus between the transformer neutral and earth). Before this decision is taken investigations must be made to ensure an acceptable earth fault protection function. This alternative is recommended for distribution systems in Sweden, also when wind power is connected.

For MV systems where there are moderate requirements on the sensitivity of the earth fault protection resistance earthing of the transformer neutral, with a resistor giving an earth fault current in the range several hundreds of amperes can be used. The advantage with this system is that a non-directional earth fault current protection can be used as feeder earth fault protection. This alternative is acceptable for collection networks with no other electricity customers connected.

Zero sequence equivalent of transformers
In the power systems several voltage systems are connected to each other via power transformers. When earth faults occur this will give zero sequence voltages and currents. It is of utmost importance for the protection system how the zero sequence quantities will propagate between the power systems. Therefore the following can be stated for power transformers, depending on the type of winding connections.

Yy-connected Power Transformer

The Yy connected transformer is shown in Figure 43. The zero sequence equivalent of the Yy connected transformer is shown in Figure 44.

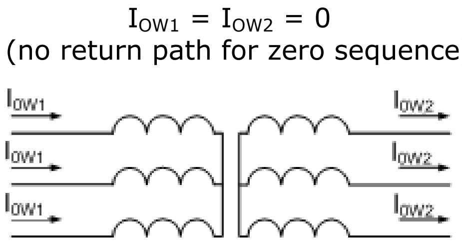

Figure 43; Yy-connected power transformer

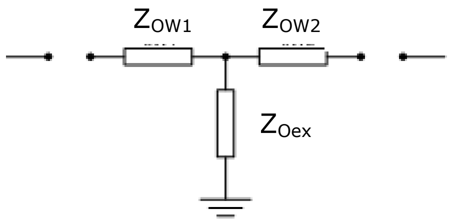

Figure 44; Zero sequence equivalent for a Yy-connected power transformer

It is obvious that zero sequence current cannot exist in the Yy-connected transformer. This means that zero sequence voltage and current cannot be transformed over the transformer.

YNy-connected Power Transformer

The YNy connected transformer is shown in Figure 45 and its zero sequence equivalent is shown in Figure 46.

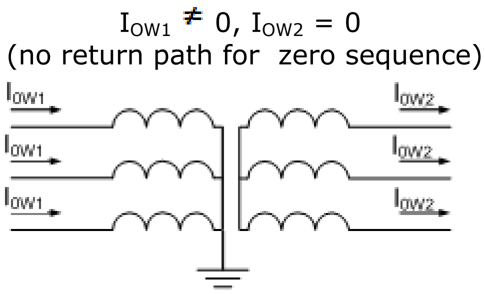

Figure 45; YNy-connected power transformer

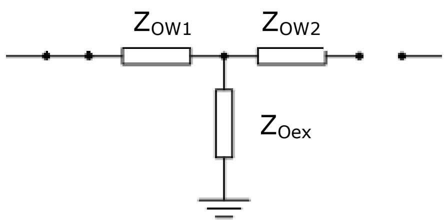

Figure 46; Zero sequence equivalent for the YNy-connected power transformer

Zero sequence voltage and current cannot be transformed over the transformer.

In case of earth fault on the same transformer side as winding 1 there will be zero sequence current flow in winding 1. The zero sequence impedance of this winding is mainly given by the zero sequence excitation impedance of the transformer (Z_{0exc}). This impedance is larger than the short circuit impedance of the transformer and will be dependent on the core design. For a five leg transformer core the zero sequence excitation impedance will be very large. For a three leg transformer core the zero sequence excitation impedance will be in the range 50 – 100 % of the transformer rated impedance.

YNyn-connected Power Transformer

The connection of an YNyn transformer is shown in Figure 47 and its zero sequence equivalent is shown in Figure 48.

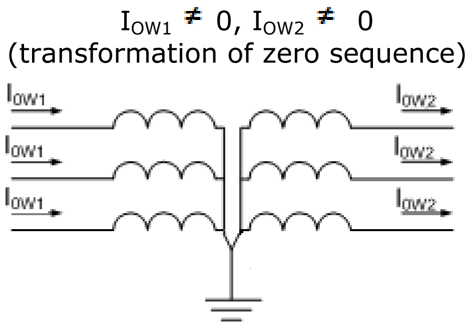

Figure 47; YNyn-connected power transformer

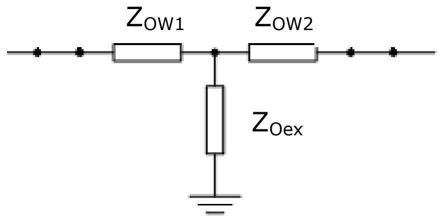

Figure 48; Zero sequence equivalent for the YNyn-connected power transformer

The zero sequence current can be transformed from winding 1 to winding 2 and vice versa. The zero sequence impedance between the winding 1 and winding 2 sides is equal to $Z_{0w1} + Z_{0w2}$.

The transformation of zero sequence currents from one voltage level to another can normally not be accepted. The reasons for this are that;

- the total earth fault current in one system will be influenced by the other system, thus giving difficulty to reduce the earth fault current by means of Petersen coil tuning.
- there will also be a risk of earth fault current protection trip in one system when an earth fault occurs in the other system.

YNd-connected Power Transformer

The connection of an YNd transformer is shown in Figure 49 and its zero sequence equivalent is shown in Figure 50.

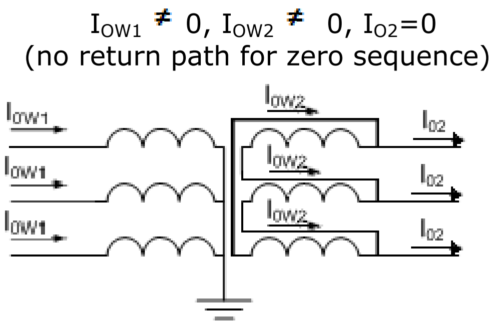

Figure 49; YNd-connected power transformer

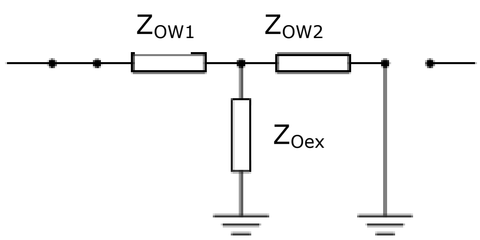

Figure 50; Zero sequence equivalent for the YNd-connected power transformer

Zero sequence current can flow in winding 1 (I_{0w1}) which will cause a circulating current in the d-connected winding 2. There will, however, not be any zero sequence current and voltage transformed to the winding 2 side. Hence, zero sequence voltage and current cannot be transformed over the transformer.

The zero sequence impedance seen from winding 1 side is equal to Z_{0w1} + Z_{0w2} as the delta-connected winding 2 will practically short circuit the zero sequence excitation impedance. The zero sequence impedance is approximately equal to the positive sequence impedance of the transformer.

Yd-connected Power Transformer

The connection of a Yd transformer is shown in Figure 51 and its zero sequence equivalent is shown in Figure 52.

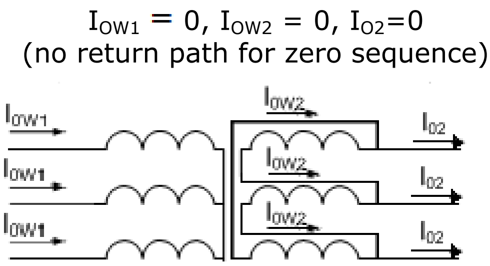

Figure 51; Yd-connected power transformer

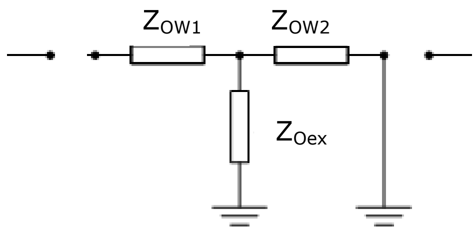

Figure 52; Zero sequence equivalent for the Yd-connected power transformer

It is obvious that zero sequence current cannot exist in the Yd-connected transformer. Hence, zero sequence voltage and current cannot be transformed over the transformer.

Unit transformer of the wind power unit

The unit transformers in wind power units are assumed to have Dyn connected windings (D connected high voltage side winding). This means that zero sequence voltage and current cannot be transformed from one side of the transformer to the other side. In case of an earth fault on the low voltage side, the earth fault current, fed via the transformer, will be in the same range as the short circuit current. In case of an earth fault on the high voltage side of the transformer no zero sequence current will be fed from the transformer. This earth fault will be energized (positive and negative sequence current) from the generator via the transformer.

HV/MV-transformers connecting distribution systems with wind power units

The distribution system can be connected via the transformer to either a high impedance earthed system or to an effectively earthed system.

In the first alternative is the distribution system (6 – 20 kV) connected via the transformer to a high impedance earthed subtransmission system (40 - 70 kV). The winding connection is dependent of the utility standard which can be:

1. Yyn-connected transformer, where the MV distribution winding normally connects a Petersen coil and a parallel neutral point resistor. No zero sequence voltage or current can be transformed from one side to the other side.
2. YNyn-connected transformer, where the MV distribution winding normally connects a Petersen coil and a parallel neutral point resistor. The HV winding neutral can be connected to earth via neutral point equipment (Petersen coil and/or neutral point resistor). In this case there is a risk of zero sequence transformation through the transformer. The consequences of this must be analyzed case by case.
3. Yd-connected transformers, where the neutral point equipment (Petersen coil and neutral point resistor) often is connected to a separate Z-connected earthing transformer. No zero sequence voltage and current can be transformed from one side to the other side of the transformer.

In the second alternative the distribution system (6 – 20 kV) is connected via the transformer to an effectively earthed transmission or subtransmission system (130 – 400 kV). The winding connection is dependent on the utility standard which can be:

1. Yyn-connected transformer, where the MV distribution winding normally connect a Petersen coil and a parallel neutral point resistor. The HV-side winding has isolated neutral point. No zero sequence voltage or current can be transformed from one side to the other side.
2. YNyn-connected transformer, where the MV distribution winding normally connects a Petersen coil and a parallel neutral point resistor. The HV-side winding has a directly earthed neutral point. With this connection type of the transformer windings there will be zero sequence voltage and current transformation between the voltage levels of the transformer. This coupling between the voltage levels is also dependent of the MV-side system earthing. The consequences of this must be analyzed from case to case.
3. Yd-connected transformer, where the neutral point equipment (Petersen coil and neutral point resistor) often is connected to a separate Z-connected earthing transformer. No zero sequence voltage or current can be transformed from one side to the other side of the transformer.
4. YNd-connected transformer, where the HV-side winding has a directly earthed neutral point. Often the neutral point equipment (Petersen coil and neutral point resistor) is connected to a separate Z-connected earthing transformer. No zero sequence voltage or current can be transformed from one side to the other side of the transformer. The transformer can however feed zero sequence current to high voltage side earth faults.

HV/MV-transformers connecting collection systems for wind farms

There are two alternatives for these transformers that depend on which voltage level the collection grid is connected to via the transformer and the system earthing of the connected grid.

In the first alternative the collection grid is (often 30 kV) connected via the transformer to a high impedance earthed subtransmission system (40 - 70 kV). The winding connection is independent of the utility standard as it is assumed that no load will be connected to the collection grid. The transformer winding connection could be:

1. Yyn-connected transformer, where the MV collection grid winding normally connects a Petersen coil and/or a neutral point resistor. Note that no zero sequence voltage or current can be transformed from one side to the other side.
2. Yd-connected transformer, where it is common that the neutral point equipment (Petersen coil and/or neutral point resistor) is connected to a separate Z-connected earthing transformer. Note that no zero sequence voltage or current can be transformed from one side to the other side of the transformer.

In the second alternative the collection grid is (often 30 kV) connected via the transformer to an effectively earthed transmission or sub-transmission system (130 – 400 kV). The winding connection is dependent on the utility standard which can be:

1. Yyn-connected transformer, where the MV collection grid winding normally connects a Petersen coil and/or a neutral point resistor. The HV-side winding has isolated neutral point. No zero sequence voltage or current can be transformed from one side to the other side. One risk with this transformer type is the consequences of earth faults on the high voltage side. If all lines to the substation are tripped in the remote line end but the fault is energized from the transformer having generation on the MV-side, no current based protection can detect the fault. There is also a risk that the phase to earth voltage of 'healthy' phases will be larger than the largest voltage for equipment (for the transformer winding, etc.).
2. YNyn-connected transformer, where the MV collection grid winding normally connects a Petersen coil and/or a neutral point resistor. The HV-side winding has a directly earthed neutral point. With this connection type of the transformer windings there will be zero sequence voltage and current transformation between the voltage levels of the transformer. This coupling between the voltage levels is also dependent of the MV-side system earthing.
3. Yd-connected transformer, where the neutral point equipment (Petersen coil and/or neutral point resistor) often is connected to a separate Z-connected earthing transformer. No zero sequence voltage or current can be transformed from one side to the other side of the transformer. One risk with this transformer type is the consequences of earth faults on the high voltage side. If all lines to the substation are tripped in the remote line end but the fault is energized from the

transformer having generation on the MV side, no current based protection can detect the fault. There is also a risk that the phase to earth voltage of "healthy" phases will be larger than the largest voltage for equipment (for the transformer winding, etc.).

4. YNd-connected transformer. The HV-side winding has a directly earthed neutral point. Often the neutral point equipment (Petersen coil and/or neutral point resistor) is connected to a separate Z-connected earthing transformer. No zero sequence voltage or current can be transformed from one side to the other side of the transformer. The transformer can however feed zero sequence current to high voltage side earth faults.

Summary of transformer zero sequence options

Table 14 shows a summary of the transformer winding connections, the zero sequence transformation and the zero sequence impedance. The zero sequence properties must be considered in design and setting of earth fault protection systems.

Table 14; Summary of the transformer winding type influence on zero sequence impedance

Winding connection type	Zero sequence transformation between windings / zero seq series imp.	Zero sequence impedance, Seen from Winding 1	Zero sequence impedance, Seen from Winding 2	Applications
Dyn	No/Not Appl	∞	Low ≈ pos. seq. series imp.	Gen unit transf. (HV/MV sub-station transf.)
Yyn	No/Not Appl.	∞	Medium/high dep. on core type	HV/MV sub-station transf.
YNyn	Yes/≈ pos. seq. series imp.	Dep on W2 system zero seq imp.	Dep on W1 system zero seq imp.	HV/MV sub-station transf.
YNd	No/Not Appl.	≈ pos. seq. series imp.	∞	HV/MV sub-station transf.
Yd	No/Not Appl.	≈ pos. seq. series imp.	∞	HV/MV sub-station transf.

Appendix 2 - Islanding detection

An island in a power system will exist if a portion of a power system is disconnected from the remainder of the system, but remains energized by a power source connected to the separated grid. Islanding could be either intentional or unintentional. Intentional islanding requires that the power source has the ability to operate the isolated island in a stable way. Many of the distributed generation sources do not have this ability and the unintentional islanding can in such cases lead to safety hazards to utility service personnel, cause damage to high voltage apparatus due to deviating voltage and/or frequency and worsen power quality. Detection of unintentional islanding is therefore essential and has been regarded as one of the most challenging issues within the area of distributed generation. There are three common concepts for islanding detection protection;

- Passive islanding detection methods
- Active islanding detection methods
- Communication based islanding detection methods.

Passive islanding detection methods

The first concept is referred to as "passive anti-islanding methods" where only locally available electrical quantities are measured, such as voltage and frequency. The idea is that the normally installed over/under frequency and over/under voltage relays in the wind power unit should be able to detect the island operation. This can in many cases be sufficient, however, the passive methods have the disadvantage of large non-detection areas where the change in frequency and voltage caused by the islanding is not large enough to pass the pickup levels of the frequency or voltage relays. To reduce these non-detection areas relays have been developed that measure how fast the electrical quantity change. The ROCOF (Rate Of Change Of Frequency) is a relay based on this principle that measures the absolute value of the frequency change. The ROCOF relay are today one of the most commonly used islanding detection protection that have been implemented when the over/under voltage and over/under frequency not have been considered to be sufficient. The main benefit of ROCOF detection is that island detection will be made faster compared to the over/under voltage and over/under frequency detection. However, the island operation will be undetected by the ROCOF if the production and consumption in the island is in balance when the islanding occurs.

Active islanding detection methods

The second concept is referred to as "active islanding detection methods" that actively tries to manipulate the local electrical quantities such as the frequency, the voltage or the delivered power at the wind power unit connection point. A problem with the active methods is that the manipulation causes poorer voltage quality by, for example, introducing more harmonics in the system. Active methods are often constructed for converter based system and many of them cannot be implemented in wind power units without converters.

Communication based islanding detection methods

The third concept is communication based methods. These methods can be more effective than passive methods that just use local information. The communication methods have, however, been considered expensive and is for that reason not used for smaller wind power units.

Examples of communication based principles are;

- Voltage phase angle monitoring where the phase angle at the wind power unit is compared to the phase angle at remote points in the power system.
- Direct intertrip of wind power units from the substation connecting feeder with the wind power units. The intertrip can alternatively be sent from system wide protections with ability to detect island operation.

Intentional islanding

Under some circumstances there can be reasons to allow intentional island operation. This could increase the voltage sag performance of a distribution feeder. The way in which intentional islanding operation shall be used is not simple and it might be necessary to determine case by case. To be able to perform an intentional islanding it is necessary to have sufficient voltage and frequency regulation capabilities on the grid. Due to the unpredictable nature of the wind as a power source it is rather complicated to use island operation solely based on wind farms as a power source. Hence, for intentional islanding it is preferable to use wind power in combination with a power source with better regulation capabilities such as, for example, a hydro power plant.

Discussion of ROCOF setting

The ROCOF shall be set so that the relay do not give unwanted trip for other frequency disturbances such as trip of large generators in, for example, hydro power plants or nuclear plants. In ASP [5] it is recommended to set the ROCOF to 0.1 Hz/s. It has however been observed that this is too sensitive. There have been a number of unwanted operations and trips of wind power units in connection to "normal" frequency disturbances. Some statistics from real events in the Nordel system during one year is shown in Figure 53. The statistic is based on collected data from continues measurements. The measured values are taken from output of ABB phasor measurement unit

RES521. The frequency time derivative is calculated in a time window of maximum 150 ms. This value is in line with the operation of most df/dt protections. The values in Figure 53 therefore gives a reasonable accuracy of the rated of change of frequency at production disconnection in the Nordel system. The measurements are made remote from the primary disturbance and thus having minor influence from transients.

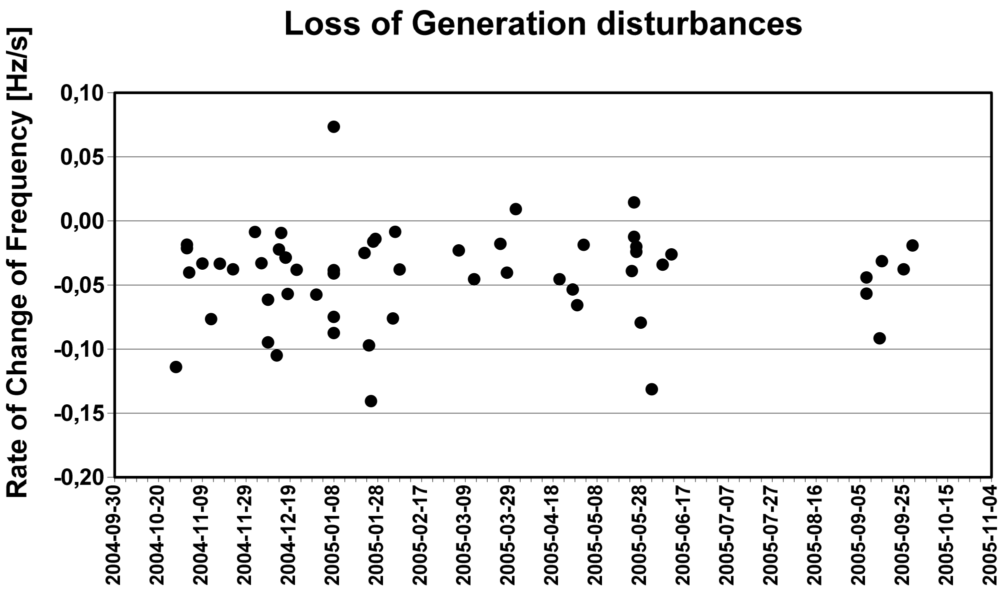

Figure 53; Rate of change of frequency at loss of generation in the Nordel system during one year

It can be concluded from these observations that a setting level of 0.1 Hz/s is not sufficient to prevent unwanted trip of wind power units. It is proposed to use a setting ≥ 0.5 Hz/s to avoid unwanted trip from the ROCOF protection. A time delay of at least 0.5 s is needed for selectivity in case of network faults.

Calculated example of frequency change after the loss of a large power plant in the Nordel system

This example is given to perform a sanity check of the measured frequency changes given in Figure 53. The rate of change of frequency can be approximated as

$$\frac{df}{dt} = -\frac{P_{LOAD} \cdot f_r - P_{OUT} \cdot f_r}{2HP_r}$$

Where

P_{Load} = load in MW at rated frequency

P_{out} = output of generating plant MW

P_r = rated capacity of generating plant in MW

H = inertia constant of generating plant in MWs/MVA

f_r = rated frequency

The load and consumption of power is under normal grid conditions in balance and varies significantly depending on the time of the year, the day of the week and the time of the day. An example for the power production variations during a week in the Nordel system is given in Figure 54. We will use the low peak value of 28 0000 MW and a high peak value of 50 000 MW in this example and assume that a large nuclear power station of 1 400 MW is tripped. It is assumed that the capacity of the connected power is 70 000 MW. An average system inertia of 4 MWs/MVA is further assumed and a frequency of 50 Hz. With this assumption the change of frequency df/dt will be about -0.12 Hz/s in the high production peak case and about -0.20 Hz/s in the low production peak case.

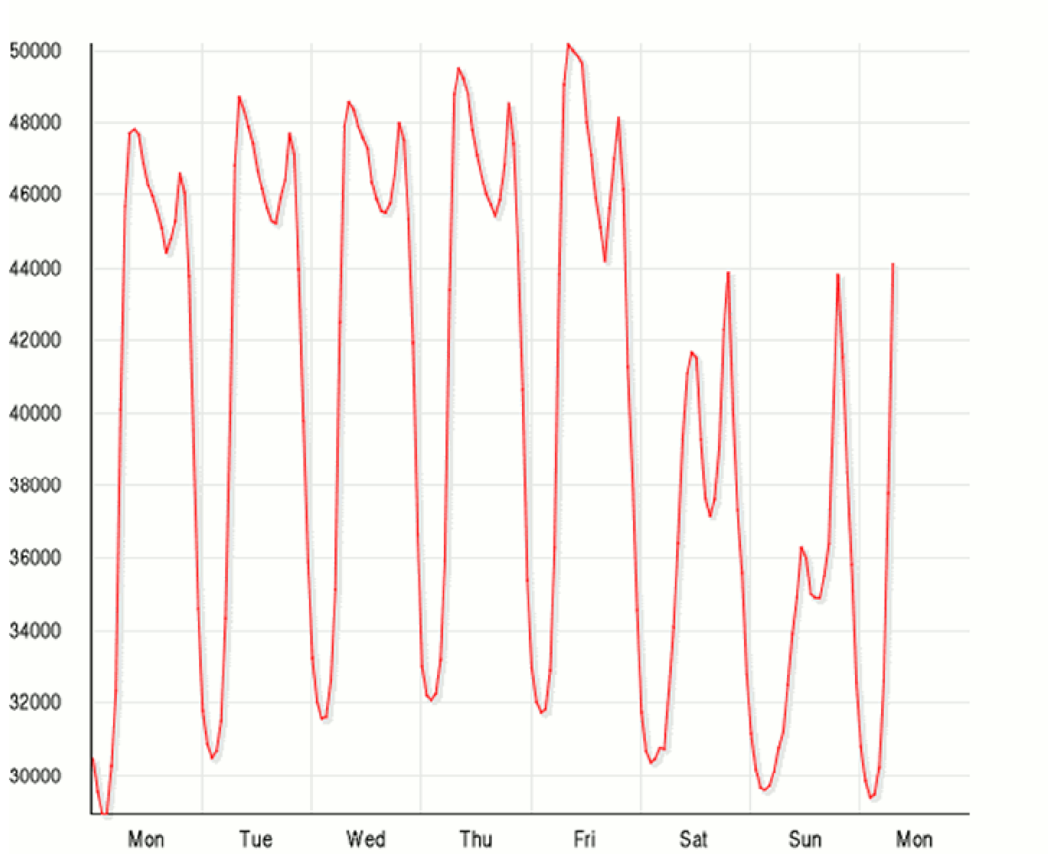

Figure 54; Power production variation example during one week in the Nordel System. Power production is given in MWh/h.

One problem with the DFIG and the full power converter wind power units is that they today are assumed to provide about 0 MWs/MVA and can lower the total inertia of the system. As an example, if today's Nordel system again is assumed to have an average inertia of 4 MWs/MVA and that 20% of the produced power in this system is replaced by wind power. Then the new average inertia would become

$$4 \cdot 0.8 + 0 \cdot 0.2 = 3.2 MWs / MVA$$

With a system inertia of 3.2 MWs/MVA instead of 4 MWs/MVA the calculated frequency change when a production source of 1 400 MW is tripped is increased to -0.26 Hz/s during low peak and -0.15 Hz/s during high peak.

This can be compared to a sever critical event in the Nordel system, if a disturbance occurs where more than one big generating plant is disconnected, compare to the 2003 disturbance. It can be reasonable to recommend at least 0.5 Hz/s setting of ROCOF protection.

Hence, there is a risk that an increased wind power penetration in the power system will reduce the total inertia of the system and thereby reduce the stability of the system during connection and disconnection of loads and production sources. This scenario is not likely to be accepted, which makes it likely that the requirements on the wind power units to provide inertia will increase with increasing wind power penetration.

Calculated example of undetectable zone and backup zone for ROCOF

This calculated example is given to show under which conditions a ROCOF is beneficial as well as to show for which conditions the ROCOF only will serve as a backup protection or be unable to detect the island operation.

To illustrate an example, an 800 kW 1MVA generator with an inertia constant *H* of 1.2 s operating at 600 kW when the loss of the grid supply occurs is assumed. Figure 55 shows how df/dt is changed depending on the deviation between the consumed power and the produced power. The red zone (---) in the diagram indicates when the change of frequency is less than 0.3 Hz/s, which will be undetected by the ROCOF relay. In this example will the ROCOF trip in 0.3 s if the consumed power deviates more than 11.5 kW which corresponds to only 1.5 percent of the rated output. Hence, there is a high probability that the ROCOF relay will trip if an island condition occurs for the considered example. Even if this balance would exist when the islanding occurs it is highly unlikely that the balance will remain due to the normal variance in produced and consumed power. The grey dotted lines (-- --) indicate the ranges where the rate of change of frequency is large enough to pass the pickup level for the over/under frequency relays for a delay time of 0.3 s. Note that the zone that the ROCOF relay will trip before the over/under frequency relay is quite large. This example indicates that the ROCOF can provide faster detection of island operation than the over/under frequency protection if there is “close to” active power balance. The ROCOF relays will, if there is a low probability of balance in consumed and active power, provide few benefits while it will be a potential source to false tripping. Hence, it is recommended to not install ROCOF relays, if it can be identified that island operation will give significant power unbalance.

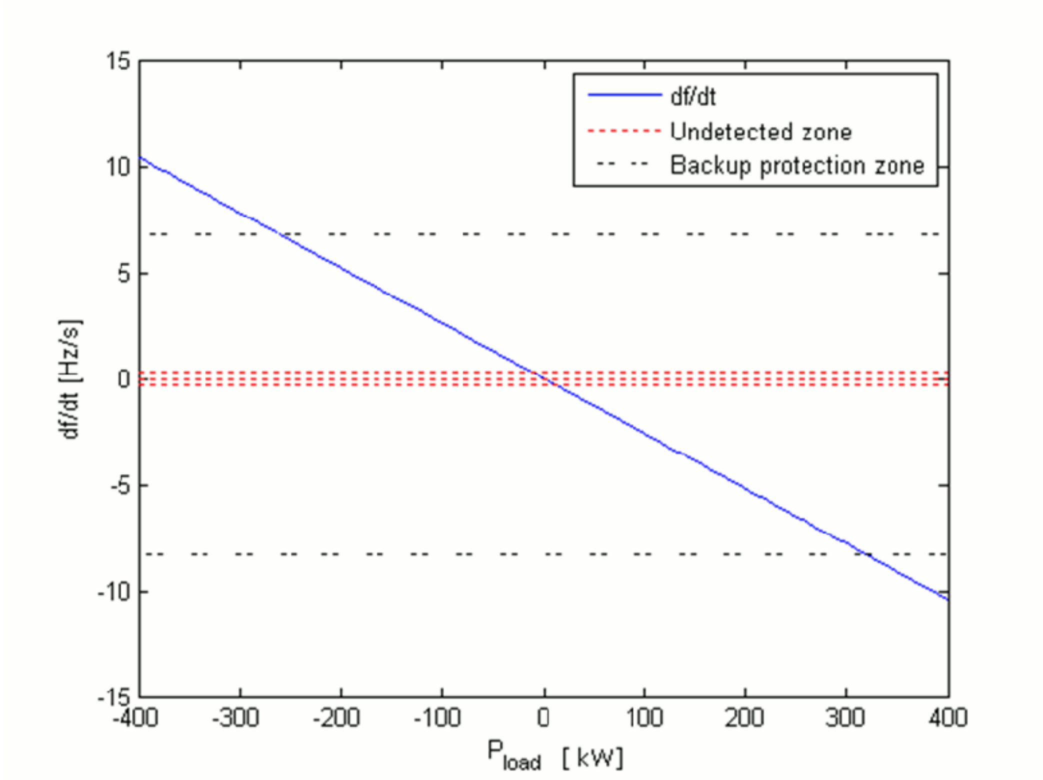

Figure 55; Example of undetected zone and backup zone for ROCOF

References

[1] Messing L, Vikesjö J (2010). *Wind Power and Fault Clearance, Part 1-Requirements, ELFORSK report 10:52. August* 2010.

[2] Jenkins N, Ekanayke J.B & Strbac G. (2010). *Distributed Generation*. IET Renewable Energy Series 1.

[3] Jenkins et al. (2000). Embedded Generation. The Institution of Electrical Engineers, London, United Kingdom.

[4] ELSÄK-FS 2008:1, Elsäkerhetsverkets föreskrifter och allmänna råd om hur elektriska starkströmsanläggningar ska vara utförda (Swedish electric safety regulations)

[5] ASP, Anslutning av större produktionsanläggningar till elnätet, ELFORSK Rapport 06:79

[6] AMP, Anslutning av mindre produktionsanläggningar till elnätet, utgåva 3, Svensk Energi 2010

[7] Svenska Kraftnät (2005), *Affärsverket Svenska Kraftnäts föreskrifter och allmänna råd om driftsäkerhetsteknisk utformning av produktionsanläggningar*, SvKFS 2005:2, dec. 2005, www.svk.se

[8] ENTSO-E, Working Draft: ”Requirements for Grid Connection Applicable to all Generator”, 20.10.2010

ELFORSK

SVENSKA ELFÖRETAGENS FORSKNINGS- OCH UTVECKLINGS - ELFORSK - AB

Elforsk AB, 101 53 Stockholm. Besöksadress: Olof Palmes Gata 31
Telefon: 08-677 25 30, Telefax: 08-677 25 35
www.elforsk.se