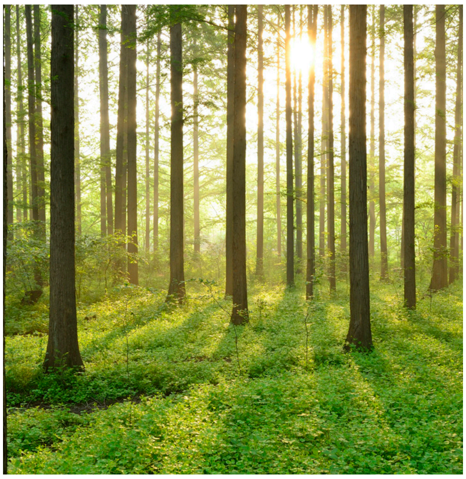
# EFFECTIVE VOLTAGE CONTROL AND OPERATIONAL COORDINATION OF REGIONAL REACTIVE POWER RESOURCES

REPORT 2020:692



NUCLEAR

GRID INTERFERENCE ON NUCLEAR POWER PLANT OPERATIONS

Energiforsk

# Effective voltage control and operational coordination of regional reactive power resources

## Case Study of western part of SE3 area

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# Foreword

**To have an effective, stable and safe operation of a nuclear power plant, technical operational conditions in the connecting power system need to be within defined operational security- and stability ranges. A sufficient operational security is crucial for power producers, so they can operate in a production environment that is technically acceptable.**

In the southern part of Sweden, the permanent shutdown of nuclear power plants, changing demand behaviour and introduction of an increasing amount of renewable power production are affecting the voltage control and access to/need of, reactive power in the area. Co-ordination and smart dispatch of the available reactive power resources is important. It is not effective to transfer reactive power over long distances. Hence, the reactive power management, and, accordingly, control of the power system voltage, needs to be dealt with on a regional level.

A case study has been performed of the western part of SE3 using data from Ringhals NPP and Svenska kraftnät. It was performed by Solvina, with senior consultants Magnus Lenasson and Simon Rohlén. The project is part of the Grid Interference on Nuclear power plant Operations, GINO, program that is financed by The Swedish Radiation Safety Authority, Svenska Kraftnät, Vattenfall, Uniper/Sydkraft Nuclear, Fortum, Skellefteå Kraft and Karlstads Energi.

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

# Sammanfattning

**Idag har Ringhals kärnkraftverk (hädanefter benämnt ”Ringhals”) en stor påverkan på upprätthållningen av spänningen i det närliggande området (västra delen av elområde SE3) med en stor reaktiv effektkapacitet för både produktion och absorption. I och med avvecklingen av Ringhals 1 och 2 påverkas den reaktiva effektkapaciteten och spänningskontrollen i området. Denna rapport undersöker hur situationen har varit historiskt avseende spänningsnivåer, effektflöden och shuntanslutningar, samt hur situationen kan förändras i framtiden och vilka åtgärder som kan förbättra situationen.**

Inom projektet samlas data in från både Ringhals och Svk angående de reaktiva resurserna i området samt driftsinstruktioner och rutiner. Historiska mätningar av spänningsnivåer, lastvinklar, shuntanslutningar och effektflöden samlas in från Svk. Uppgifterna behandlas och analyseras för att hitta viktiga egenskaper för spänningskontrollen i området, hur situationen kan förändras i framtiden och vilka åtgärder som kan förbättra spänningskontrollen.

Ringhals har en viktig roll i att upprätthålla spänningen i området med en total reaktiv kapacitet på cirka 1300 Mvar (före avveckling). Ringhals magnetiseringssystem går normalt i så kallat spänningsregleringsläge. Förändring av generatorspänningen kan göras av Ringhals efter önskemål från Svk. Detta görs genom att ändra börvärdet för generatorspänningen. Utan manuell interaktion ökar den reaktiva kraftproduktionen automatiskt när nätspänningen minskar, och tvärtom, för att hålla generatorspänningen konstant.

Svk driver under den undersökta tidsperioden för denna rapport ett antal mekaniskt omkopplade shuntar i området tillsammans med en SVC (som numera är avvecklad). Shuntarna styrs under normala förhållanden manuellt från Svk:s kontrollrum.

När det gäller kärnkraftssäkerhet är det av stor betydelse för Ringhals att externt nät upprätthåller spänningskvaliteten i alla anläggningstillstånd (till exempel normaldrift och driftsstopp).

Det kan ses i mätdata att Ringhals reaktiva effektförmåga används i hög grad under flera tillfällen. Under högspänningssituationer observeras att även med alla anslutna reaktorer måste Ringhals absorbera reaktiv effekt. Detta belyser att området under låg belastning har ett behov av reaktiv kraftabsorption.

Vid flera tillfällen har det varit hög reaktiv kraftexport från Ringhals med anslutna närliggande reaktorer i nätet och vice versa. Detta indikerar att styrningen av reaktorerna kan förbättras med avseende på spänningskontroll och reaktiv effektöverföring till eller från Ringhals.

Med avvecklingen av Ringhals 1 och 2 kommer en proportionellt stor del av den reaktiva effektförmågan och spänningskontrollen i området att gå förlorad. Den framtida idrifttagningen av en STATCOM i Stenkullen och Sydvästlänken kommer

säkerligen att bidra till att förbättra dessa aspekter. På grund av situationens komplexitet (med förändrade kraftflöden och nätegenskaper) kan det emellertid inte dras några slutsatser i denna rapport om dessa åtgärder är tillräckliga för att upprätthålla stabil och pålitlig spänningskontroll i framtiden.

# Summary

**Today Ringhals nuclear power plant (hereinafter referred to as "Ringhals") plays a major role in maintaining the voltage in the nearby area (west part of electricity price area SE3) with a great reactive power capacity of both production and absorption. With the decommissioning of Ringhals 1 and 2 the reactive power capacity and voltage control will be affected. This report investigates how the situation has been historically with regards to voltage levels, power flow and shunt connections; how the situation may change in the future and which measures may improve the situation.**

Within the project, data is gathered from both Ringhals and Svenska kraftnät (SvK) regarding the reactive resources in the area as well as operational routines. Historical measurements of voltage levels, load angles, shunt connections and power flow are gathered from Svk. The data is processed and analyzed to find key characteristics regarding the voltage control in the area, how it may change in the future and which measures that may improve the voltage control.

Ringhals has a major role in maintaining the voltage in the area with a total reactive capacity of approximately 1300 Mvar (before decommissioning). Ringhals Automatic Voltage Regulators (AVRs) are normally in voltage control mode. A change of generator voltage can be done by Ringhals, if requested by Svk. This is done by changing the generator voltage setpoint. Without manual interaction the reactive power production increases automatically when the grid voltage decreases, and vice versa, in order to keep the generator voltage constant.

During the time period which has been investigated in this report Svk operated a number of mechanically switched shunts in the area together with one SVC (which now is decommissioned). The shunts are during normal conditions controlled manually from Svk's control room.

With regards to nuclear safety, it is of great importance for Ringhals that the external network maintains the voltage quality at all plant states (for example normal operation and outage).

It can be seen in the measurement data that Ringhals' reactive power capability is used to a high degree during several occasions. During high voltage situations it is observed that, even with all reactors connected, Ringhals absorbs a high value of reactive power. This highlights that, during low load situations, the area has a high demand of reactive power absorption.

On several occasions there has been high reactive power export from Ringhals with nearby reactors connected and vice versa. This indicates that the control of the reactors may be improved with regards to voltage control and reactive power transfer to or from Ringhals.

With the decommissioning of Ringhals 1 and 2 a proportionally big part of the reactive power capability and voltage control in the area will be lost. The future

commissioning of a STATCOM at Stenkullen and the South-West link will certainly help to improve these aspects. However, due to the complexity of the situation (with changing power flows and grid characteristics) it cannot be concluded in this report if these measures are sufficient to maintain stable and reliable voltage control in the future.

# List of content





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# 1 Part A – Background and System Information

## 1.1 AIM OF REPORT

This report aims at explaining both the physical reality and the operational routines of the voltage control in the transmission system in the west part of SE3 area which is located around Ringhals nuclear power plant. Capabilities, strategies and routines will be explained and different cases, normal as well as extreme ones, will be visualized. The main benefit of the report will be increased understanding of the parties involved and the different aspects they should consider taking into account. Any findings of suboptimal use of reactive resources will be stated and explained. A general methodology for similar projects will also be presented.

## 1.2 METHOD

The methodology used for this report can be summarized in three steps: data gathering, data processing and analysis.

*Data gathering*

Measurements of voltage and power from 2015 to 2019 was gathered from Ringhals. From these historical measurements some instances with either low/high voltage or low/high reactive power were detected. Measurement data containing shunt connections, voltage levels, load angle and power flow for the west part of SE3 for the days with these detected instances was gathered from Svk.

In addition to the measurement data, technical data and operational routines were gathered from both Svk and Ringhals.

*Data processing*

From the technical data the reactive resources in the area were summarized and presented together with a description of key technical characteristics.

In the obtained measurement data shunt connections/disconnections, power flows, voltage levels and load angles are presented for several time instances during the entire day. For each day, the specific time instance that most clearly highlights the low/high voltage or low/high reactive power situation of the day was chosen to be used in the visualization. Along with the visualizations, descriptions of relevant findings from the measurement data are presented to help explain the situations.

*Analysis*

The processed data is analyzed by investigating how efficiently the reactive resources has been utilized as well as how much of Ringhals reactive capability that has been used.

Predictions on the effect that future changes in the area will have on the voltage control is based upon theoretical analysis in combination from findings from the gathered data.

## 1.3 DELIMITATIONS

This report will not include any major simulation study but instead visualize and explain the collected data. Regarding possible future changes in the system only known examples are considered, such as the south west link, the STATCOM in Stenkullen and the decommissioning of Ringhals unit 1 and 2.

Regarding different reactive resources, only their ability to provide reactive power and voltage control is regarded. Other aspects such as contribution to inertia are outside the scope of this report.

## 1.4 THEORETICAL BACKGROUND

In this section, a theoretical background that is helpful in order to understand later parts of the report is presented.

### 1.4.1 Voltage and power flows

Voltage control is an important task for all transmission system operators (TSOs) and should be treated as an important factor to guarantee efficient and reliable system operation. Appropriate voltage control in the system leads to better voltage stability and minimized reactive power flows in the grid. The latter is important because it is beneficial to transfer the reactive power in the grid over as short distances as possible. This is to minimize transmission losses and manage any voltage control issues locally to an as high degree as possible.

Although voltage control often is reduced to only relate to reactive power balance in the system, voltage control is also related to the active power flow in the system.

To illustrate the relation between voltage, active power and reactive power in the grid, consider the simple circuit in Figure 1.

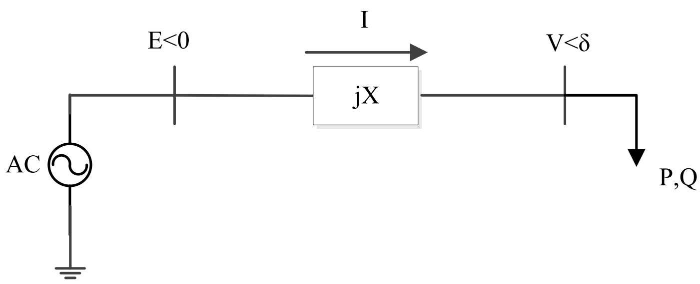


**Figure 1. Simple circuit represents a large system connected by a lossless transmission line to a load bus.**

In Figure 1, a large system connected by a lossless transmission line to a load bus is illustrated. The voltage, active and reactive powers are related to each other in this simple system according to Equation 1, where V is the load bus voltage, X is the line reactance, E is the sending end voltage and P and Q are the active and reactive powers delivered to the load bus, respectively.

$$V = \sqrt{-XQ + \frac{E^2}{2} \pm \sqrt{\frac{E^4}{4} - X^2P^2 - E^2XQ}} \tag{1}$$

To visually illustrate the relationship between voltage, active and reactive powers, the PV curves for different power factor angles ( $\phi$ ) are plotted in Figure 2 while E=100 kV and X=100 Ω (the figure illustrates the relationship for a 100 kV system, the principle is the same for a 400 kV system).

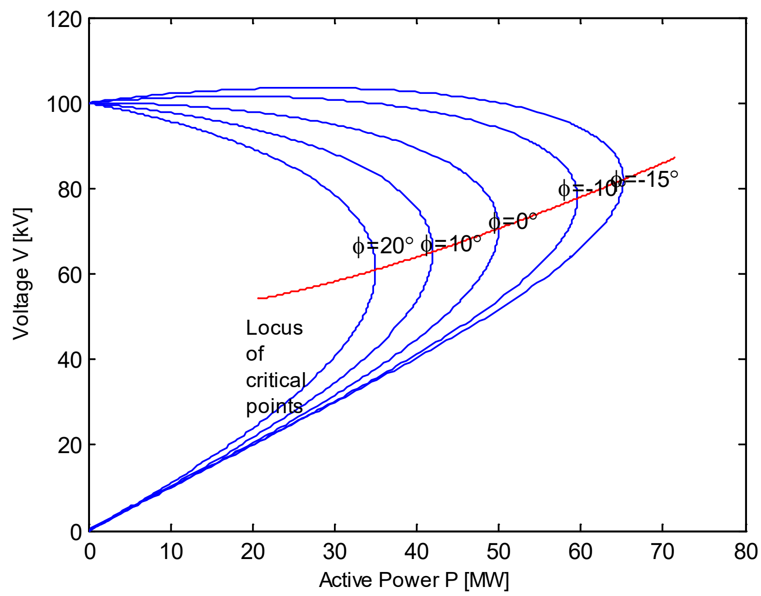


**Figure 2. PV curves for different power factor angles; P+jQ=S( $\cos\phi$ + $j\sin\phi$ ).**

As shown in Figure 2, the voltage drops as the line power increases and finally it collapses when it crosses the red line. For a given amount of active power, the reactive power is a key factor which strongly impacts the voltage stability margin. Moreover, there are two voltage levels, high and low, corresponding to a given amount of active power. The power system operates at high voltage levels to reduce losses in the system and to have a high safety margin to the critical stability point.

As mentioned above, for a given amount of active power, there is a direct link between voltage stability and reactive power flow in the system. As the reactive power cannot be transmitted over long distances efficiently, and since it is not desirable to do so, the voltage control issue is treated as a local problem which is to be managed mainly using the available local reactive resources in the grid [1].

Synchronous generators are traditionally the most used equipment to control the voltage within a specific area. In combination with synchronous generators, shunt reactors and capacitors are traditional reactive resources which are used to regulate the reactive power balance and improve the voltage control in the system. They are relatively economical, easy, and quick to install in the power systems. Shunt reactors are used to absorb reactive power and lower the voltage while shunt capacitors are used to inject reactive power and boost the voltage. With a fixed nominal capacity of the reactive shunts for a specific area, the approach to control them is important and needs to be appropriately treated by the TSO [1].

### 1.4.2 Strong and weak buses

As mentioned previously, the intention is to mainly manage any voltage control issues by utilizing the locally available reactive resources. This means that for a low voltage scenario at a bus, the intention is to utilize any locally available reactive resources to inject reactive power and for the high voltage scenario, absorb excess reactive power. Injecting and absorbing the reactive power leads to increasing and decreasing of the voltage level in the nearby area. How much the voltage level changes for a specific bus when a local reactive resource is connected or disconnected depends on how strong or weak that bus is in the system. If a bus in a system is strong, then it basically means that connection or disconnection of reactive resources at the nearby area has a smaller impact on the voltage at that bus. In other words, it can be said that the voltage stiffness is high. On the other hand, if a bus in a system is weak, then the connection or disconnection of reactive resources at the nearby area has a larger impact on the voltage, thus the voltage stiffness is low.

One indicator to show how strong or weak a bus is in the system, is the short circuit capacity of the bus. A high short circuit capacity indicates a stronger bus and a low short circuit capacity indicates a weaker bus. The short circuit capacity levels at the different buses in a system can be investigated in order to find out which of them are weaker from a voltage stability perspective. Other analysis methods, like modal analysis, can be used for analysis in order to find weak points in the system [1].

In traditional power systems it is mainly the synchronous generators within a specific area that determines the network strength at that area (often related to specific buses). When the number of the synchronous machines are lowered a new assessment of the strength of the system buses may be needed to get a better understanding of the new situation.

### 1.4.3 Reactive resources

To maintain a stable voltage in the power system the right amount of reactive power is required. Reactive power is mainly consumed by induction motors, transformers and loaded lines. Lines that are lightly loaded, as well as cables, produce reactive power due to their capacitive elements.

Reactive power is hard to transmit over long distances since it entails large currents which in themselves increase the line consumption of reactive power. On the other hand, the production of reactive power does not require any prime mover like the production of active power. Because of these two prerequisites it is desired and often possible to place the reactive production close to the consumption.

To cater for this need of reactive power there is a number of different types of reactive production resources. These are:

- Mechanically switched shunts (reactors and capacitor banks)
- Thyristor switched shunts (SVC's)

- Transistor switched components (STATCOM's, VSC-HVDC links, inverter-connected production)
- Synchronous generators (for active power production or as synchronous condensers)

Some of the components are part of the transmission system, some are part of connected regional distribution systems and some belong to independent power producers. A rough visualization of where different components appear in the power system is seen in Figure 3.

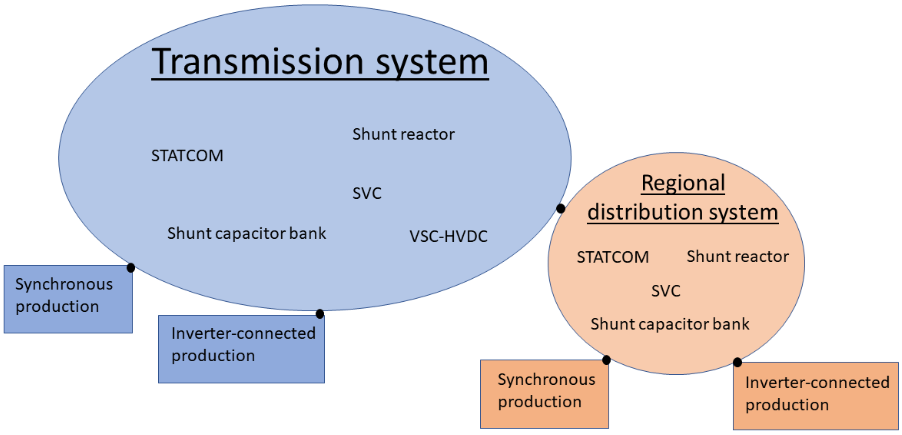


**Figure 3. Different reactive resources and their place in the power system**

### *Mechanically switched shunts*

The mechanically switched shunts, shunt capacitor banks and shunt reactors, cannot be used for stepless voltage control, they are simply turned on or off. When switched on, the shunt reactors consume reactive power (they are inductive) whereas the capacitor banks produce reactive power (they are capacitive). The reactive power they produce or consume is roughly constant at normal voltage levels, but it depends squarely on the voltage so their support might drastically change during stressed voltage situations. Since they are only switched on or off, the switching causes step changes in the voltage.

### *Transistor based components*

Transistor based components like STATCOM's and VSC-HVDC links are very good for stepless voltage control due to the very fast switching of the transistors. VSC-HVDC is primarily built to transfer large amounts of active power or to connect non-synchronous areas. Their location will therefore be based on their primary use, and their voltage control support might not be in the optimal spot in the power system. They do however normally come with large reactive capabilities ensuring good support for quite large areas of the power system. The STATCOM's have voltage control as their primary use and are therefore placed in the location in most need of voltage control support. They are however expensive and therefore not well suited for supplying bulk reactive power. Mechanically switched shunts for bulk supply and STATCOM's for fine controlling is therefore a sensible combination.

*Thyristor switched shunts*

SVC's consist of several smaller shunts (normally some capacitive and some inductive). The capacitive shunts are switched in and out by thyristors and the inductive is controlled stepless through a reactor. The switching is controlled by a voltage controller. The SVC behavior is something in between a STATCOM and a mechanically switched shunt. It is actively controlled, but not as fast as a STATCOM. The voltage steps from the switching are visible but much smaller than the ones from mechanically switched shunts.

*Inverter connected production*

Modern wind farms are to a high extent connected to the grid through inverters enabling the turbines to run at different speeds for different winds. These inverters are transistor based and thus in possession of the prerequisites for good voltage control support. They are however primarily installed for conveying active power from generators to the grid. Thus, their reactive capabilities and practical ability to participate in voltage control are highly dependent grid codes, grid code compliance verification and technical design choices for the individual wind farms.

*Synchronous machines*

Synchronous machines directly (synchronously) connected to the grid is primarily found in conventional power production units such as hydro power plants, thermal power plants and gas turbine power plants. They can also be used as synchronous condensers. Then no prime mover is required, and they can be placed where the voltage control need is the highest.

The synchronous machines are the classical base of the voltage control in the power system with their large reactive capabilities and their ability to provide stepless voltage control. An AVR controls the excitation of the synchronous machine, high excitation means high production of reactive power and thus higher voltage at the generator terminals, low excitation means high reactive absorption and thus lower voltage at the generator terminals.

### 1.4.4 Voltage control modes

The AVR of a synchronous machine can normally be run in three different modes:

- Voltage control (U control): The excitation is adjusted to keep the generator voltage at a specific setpoint, the reactive power will vary depending on the conditions in the surrounding grid. If a generator operates with a constant active power production and in voltage control with a fixed voltage set point, then the reactive power exchange at the connection point will vary almost linearly based on the network voltage. The linear slope will be due to the step-up transformer impedance.

- Reactive power control (Q control): The excitation is adjusted to keep the reactive power export at a specific setpoint. The generator voltage will vary depending on conditions in the surrounding grid.
- Power factor control (cos φ control): The excitation is adjusted to keep the relation between the active and the reactive power at a specific setpoint. The generator voltage will vary depending on the conditions in the surrounding grid. The reactive power will change when the active power changes, but otherwise remain constant.

As for the benefits for the power system the mode voltage control has similarities with the benefits of a STATCOM or VSC-HVDC link, i.e. active control of the voltage towards a specific setpoint. The two other modes have more similarities with the benefits of mechanically switched shunts, i.e. with the right settings they contribute to maintaining the reactive capacity in the system, but they do not add any active control of the generator voltage.

### 1.4.5 Consequences of high or low voltage or reactive power

It is an important task for the TSOs to keep the voltage within acceptable limits since if the voltage gets too high it can have an negative impact on equipment (especially the insulation of apparatus and cables), it may cause overexcitation of transformers and might lead to over voltage protection reaction. High voltage also increases the corona losses and can cause plant and personal injury.

If the voltage gets too low several problems may occur. A low voltage scenario might lead to component protection reacting (HVDC-converters, generators etc.), higher transmission losses, and reduces transmission capacity. Low voltage may also cause stability issues, especially during stressed conditions if cascading outages occurs. Then the distance relays protection might be trigged because of the low voltage and typically high current. This may in worst cases lead to propagating outages and possibly total system blackout. This is, for an example, what happened during the 2003 Swedish/Danish blackout [1].

Too much reactive power production from a specific synchronous generating unit causes heating problem for the rotor windings and if the extra reactive power production continues for a long-time the Over Excitation Limiter (OEL) reacts. This scenario is more probable if the voltage level is low at the nearby area and the generating unit must inject a large amount of the reactive power to the surrounding area to boost the voltage. Moreover, if the voltage at the surrounding area is too high and if the generating unit is absorbing the reactive power, this degrades the generating unit fault ride through capability because of the weaker electromagnetic coupling of the synchronous machine. Less fault ride through capability is potentially dangerous for the system integrity since it increases the chances of a generator getting disconnected during a fault. If one unit gets disconnected by its protection, there is a potential risk of cascading outages and total system collapse.  So, it is critical to regulate the reactive power balance and accordingly the voltage levels within the acceptable tolerance bands.

## 1.5 TECHNICAL DESCRIPTION WEST PART OF SE3

The following section describes the main technical aspects that influences voltage control in the area.

### 1.5.1 Description of the area

The transmission system in the west of Sweden is characterized by Ringhals, being the largest power station in the Nordic countries, the city of Gothenburg, being a significant load center, and by the HVDC connection Kontiskan to Jutland. See a key map in Figure 4.

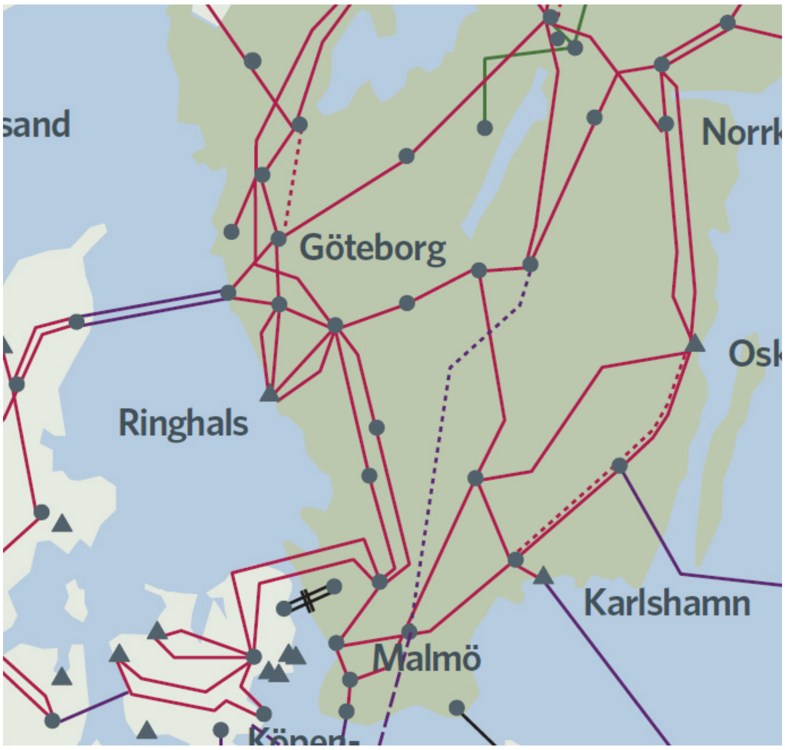


**Figure 4. Key map over transmission system in Southern Sweden. Dotted lines represent connections not yet in operation. Purple lines represent HVDC connections.**

Ringhals is currently connected to the transmission system stations Strömma and Horred with two lines to each station. Two Ringhals units are connected to Strömma and two units are connected to Horred. The different units are not connected to each other at the Ringhals 400 kV stations. The voltage on the 400 kV side of the step-up transformers can thus be different for all four units.

### 1.5.2 Reactive resources

The mechanically and thyristor switched shunts in the transmission system in the west part of SE3 which has been connected in the investigated time period can be seen in Table 1. The ones named Kontiskan are in place to offset the nonlinear reactive consumption of the HVDC-classic connection Kontiskan.

**Table 1. List of reactive shunts in the transmission system in the area around the west part of SE3. If the commissioning year is blank the exact year of commissioning is unknown and if the decommissioning year is blank the unit is still in operation as of the date of this report.**

| Station | Shunt | Size (negative value means reactive consumption) | Reference voltage | Commissioning year | Decommissioning year |
|---|---|---|---|---|---|
| Kilanda | X1 | -200 Mvar | 400 kV | 1999 | |
| Kontiskan 1 (XT30) | ZK10 | -66 Mvar | 420 kV | | |
| Kontiskan 1 (XT30) | ZK11 | -66 Mvar | 420 kV | | |
| Kontiskan 1 (XT30) | ZK12 | -45 Mvar | 420 kV | | |
| Kontiskan 2 (XT20) | EK1 | 56,2 Mvar | 145 kV | | |
| Kontiskan 2 (XT20) | EK2 | 56,2 Mvar | 145 kV | | |
| Kontiskan 2 (XT20) | ZK3 | -56,2 Mvar | 145 kV | | |
| Kontiskan 2 (XT20) | ZK5 | -11 Mvar | 145 kV | | |
| Strömma | EK1 | 150 Mvar | 400 kV | 2018 | |
| Strömma | X1 | -165 Mvar | 420 kV | 2012 | |
| Stenkullen SVC | | -200 to 200 Mvar | | | 2019 |
| Tenhult | X1 | -150 Mvar | 400 kV | 2006 | |

Currently there is no transistor based reactive resource connected to the transmission system in the Ringhals area. There is a planned installation of a STATCOM at the station at Stenkullen during year 2020 which will replace the current SVC. The STATCOM will have a capacity of approximately ±200 Mvar. The HVDC connection ”South-West link” is under construction and will at completion bring voltage control ability to both end stations, Barkeryd and Hurva. The South-West link will add approximately ±300-450 Mvar in capacity per converter with two converters per station. They are geographically at some distance from Ringhals but will due to their large reactive capability, have an impact on the voltage control in the entire southern Sweden.

### 1.5.3 Ringhals reactive capability

Ringhals’ different units are obligated according to [2] to be able to produce reactive power equivalent to 1/3 of the maximum continuous active power as well as being able to reduce the reactive power production to 0. These values are valid between 90 % to 105 % of nominal voltage (corresponding nominal generator voltage on the voltage on the high voltage side of the step-up transformer). The exact technical capability is different between the different units and may be changing with time due to component and control system changes (for example a change in excitation system). It is however always at the lowest according to what the grid code demands and therefore these capability values are suitable to be used. In a voltage collapse situation with low voltages, although it is not required by Ringhals, the generators can support the power system with the actual maximum reactive power of the generators. Hence, the decommissioning of Ringhals 1 and 2 does not only decrease the steady state obligated reactive power resources, but also the maximum dynamic resources. In Table 2 the different units' maximum generator active power and the reactive power that they are obligated to be able to produce according to the grid code is presented.

**Table 2. Active and reactive power at Ringhals.**

| Unit | Maximum active power [3] | Reactive power according to [2] |
|---|---|---|
| **Ringhals 1** | 881 MW | 294 Mvar |
| **Ringhals 2** | 852 MW | 284 Mvar |
| **Ringhals 3** | 1063 MW | 354 Mvar |
| **Ringhals 4** | 1103 MW | 368 Mvar |

All four units combined are obligated to be able to produce a total reactive power of 0-1300 Mvar. Ringhals 2 was decommissioned 2019-12-31, which lowered the total reactive power to 1016 Mvar. Ringhals 1 is planned to be decommissioned 2020-12-31. After the decommissioning of Ringhals 1 and 2 the total maximum reactive power of Ringhals will be reduced to 722 Mvar.

Given a constant active power, Figure 5 and Figure 6 below show an visualization of the dependence between generator voltage, external grid voltage and reactive power for a specific operational condition and transformer voltage ration. It also shows which margins are held at different operating positions. The figures are for Ringhals 2 which is decommissioned, but the principle applies to all units. The box describes the limits of what is possible to drive the unit within, with respect to the allowable voltage in the auxiliary power system (the limits on each side) and with regard to maximum and minimum excitation (the limits upwards and downwards).There are active and reactive power losses in the step-up transformer and the auxiliary system which varies depending on the operational conditions. This means that one cannot directly compare the values at the connection point with the generator output. The intent of the figures is to give an understanding of interaction between the grid at the connection point and the generator unit.

Figure 5 and Figure 6 contain the following information:

- Generator reactive power (Y-axis dotted black lines)
- Generator voltage (X-axis dotted black lines)
- Grid reactive power at connection point (horizontal/tilted solid black lines)
- Grid voltage at the connection point (vertical/tilted solid blue lines)
- Maximum stator current limit (solid green line)
- Over/under excitation limits (thick solid black lines)
- Maximum and minimum allowed voltage for the auxiliary systems (magenta lines)

Somewhere in the chart there is an optimum for each unit where it should be operated with regards to losses, stability margins and vibrations.

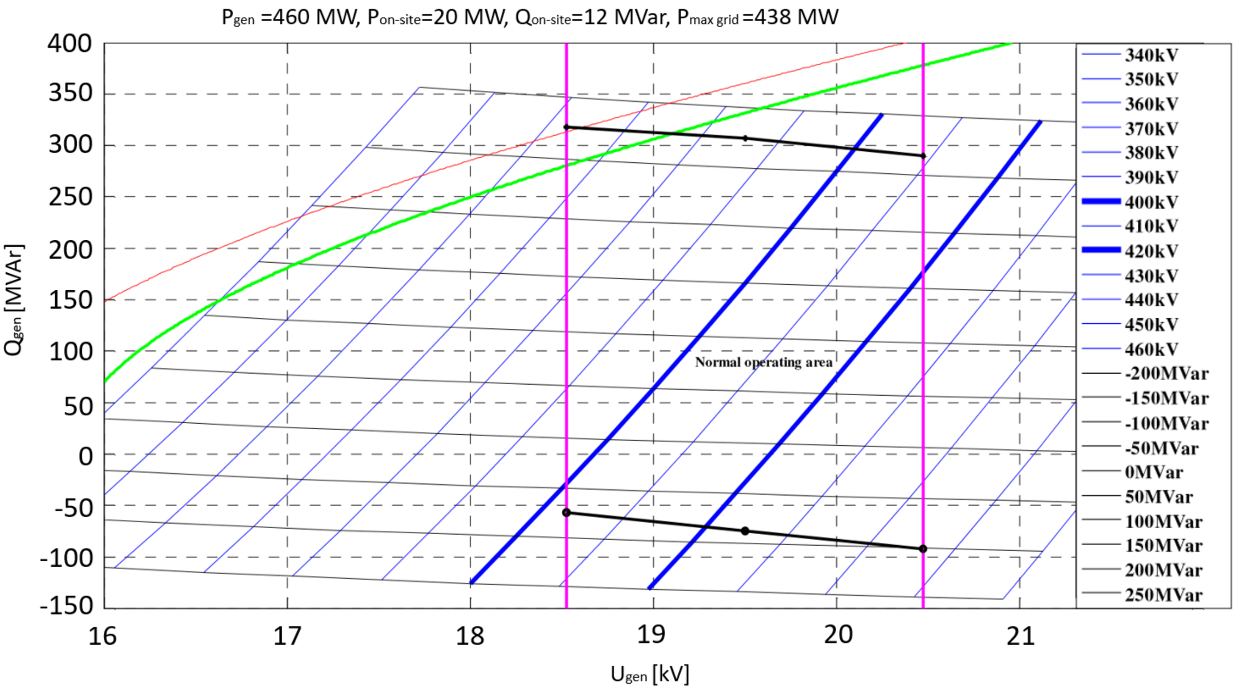


**Figure 5. Dependence between reactive power, generator voltage and grid voltage at a constant active power [5].**

In Figure 6, the red arrows describe the behavior when the generator is in voltage control mode (which is the control mode solely used by Ringhals). It can be seen how the reactive power changes when the grid voltage changes for a specific generator voltage. When the grid voltage increases the reactive power production decreases and vice versa while the generator voltage remains constant until limit levels are reached. For low grid voltages the generator voltage follows the upper limits, first the field current limiter (black line) and then the stator current limiter (green line). For high grid voltages the generator voltage follows the lower limits which is the under-excitation limiter (black line).

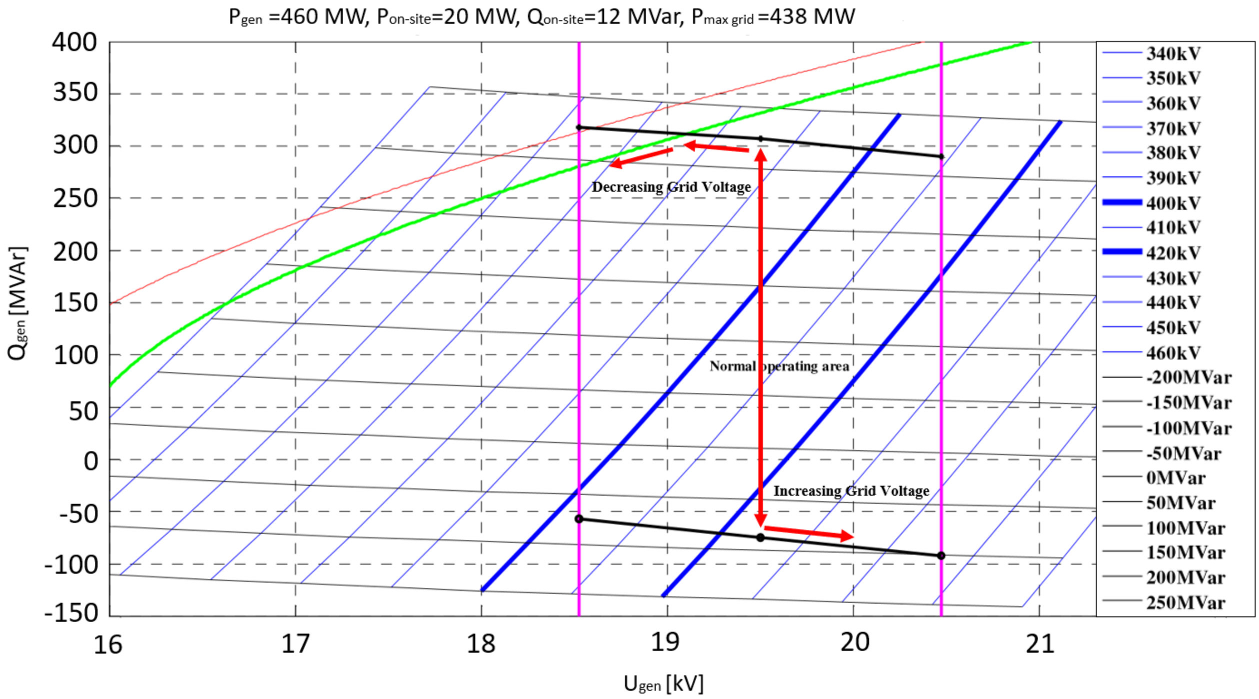


**Figure 6. Same as Figure 5 but with red arrows added to illustrate how changes in grid voltage effects the operation point when in voltage control mode [5].**

Ringhals has no monitoring of the voltage further out in the grid than in the 400 kV switchyard at the power plant. Ringhals also has no insight into other voltage control measures that SvK performs in the network.

### 1.5.4 Grid voltage design demands for Ringhals

In [2] demands of the grid voltage levels which Ringhals must be designed to operate at is stated. According to [2] Ringhals must be designed to operate continuously at 90-105 % grid voltage with full power production as well as for at least one hour with slightly reduced production at 85-110 % grid voltage. There is also transition rules in [2] that accepts lower capability for existing power plants.

## 1.6 OPERATIONAL DESCRIPTION RINGHALS AREA

This section describes the operational routines of SvK and Ringhals with regards to voltage control in the nearby area of Ringhals.

### 1.6.1 Operational routines and instructions Svenska Kraftnät

According to [4] the transmission network shall normally be operated between 400 kV to 415 kV. The network requirements are related to the connection points and the generator performance and stability margins are related to the generator output (and generator bus).

The voltage at Ringhals is usually at the higher end of this range and has at several times been over 415 kV. Measurement data shows that the voltage at several occasions has been above 420 kV, see Figure 7 and Figure 8 (the range of the graph is limited to 420 kV and therefore exactly how much higher than 420 kV cannot be seen). Typically, high voltage in the area occurs during low loading situations (nights during summers being a typical scenario for high voltage).

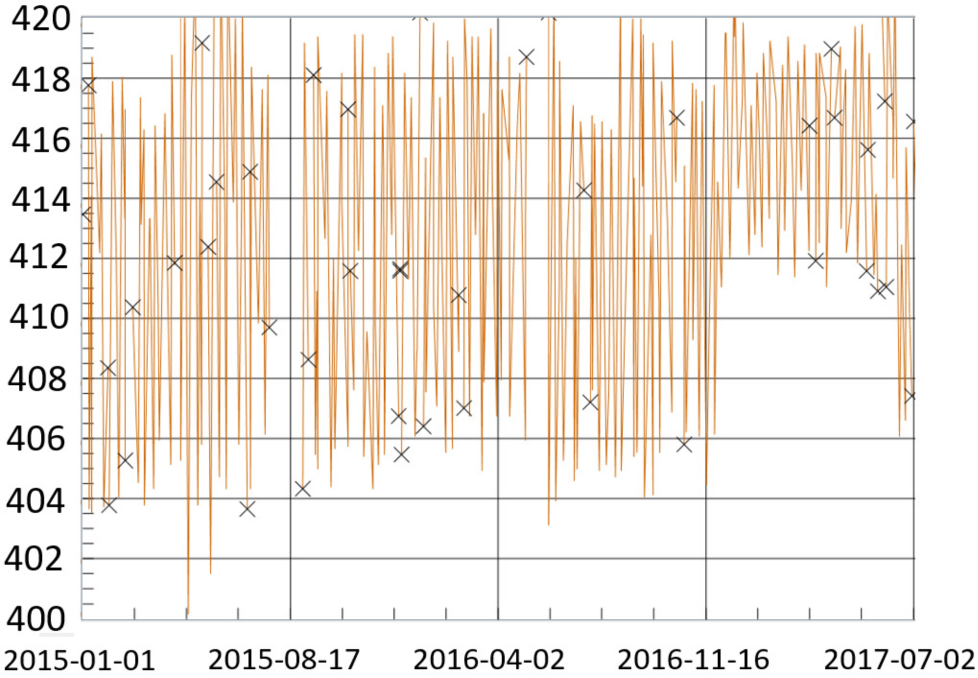


**Figure 7. Voltage at Ringhals 2 2015-2017 (minutely measurement) [6].**

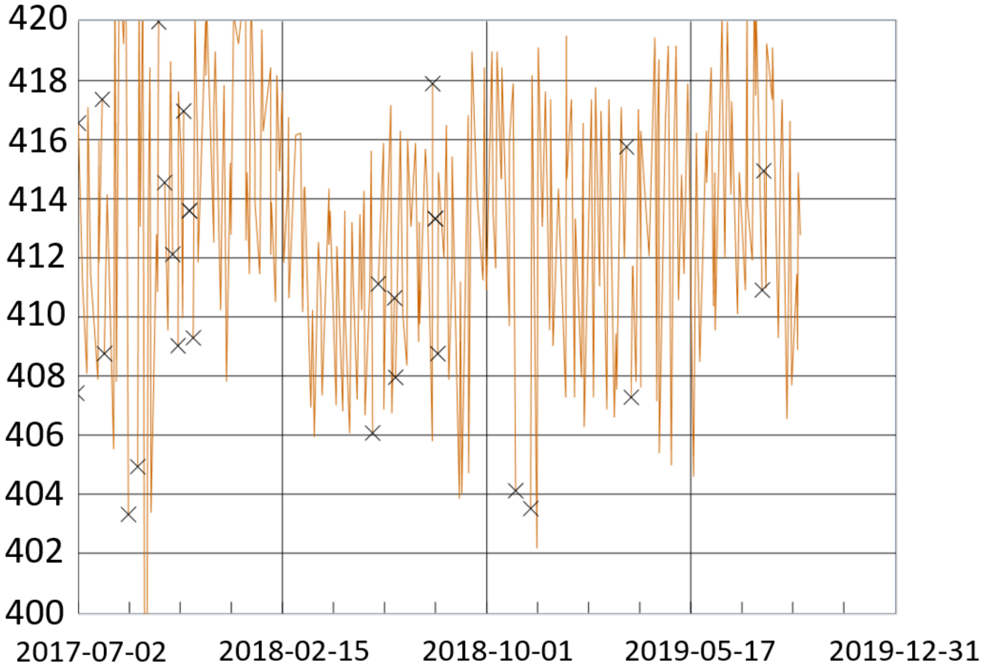


**Figure 8. Voltage at Ringhals 2 2017-2019 (minutely measurement) [6].**

In Figure 5 it can be seen that a lack of coordination between the grid and the plant in concern of reactive resources, can result in the plant absorbing reactive power from the grid when the voltage reaches high levels. According to [2] it is not mandatory for the plant to absorb reactive power. The limit in grid voltage which a unit can be operate at without reactive power absorption is different for each unit and is also dependent on the step-up transformer.

SvK controls the voltage according to [4]. The following actions are available to SvK to maintain a desirable voltage.

To increase voltage:

1. Connect, for the reason of voltage control, disconnected lines after agreement with the on-duty engineer
2. Disconnect shunt reactors
3. Order a decrease of reactive power output from the transmission grid to about zero
4. Connect shunt capacitors connected to the transmission grid
5. Order infeed of reactive power at connection points up to the established requirement, inform the on-duty engineer
6. Increase reactive production from synchronous condensers and adjust the reactive power output from SVCs to maximum, inform the on-duty engineer

To decrease voltage:

1. Decrease reactive production from synchronous condensers and adjust the reactive power output from SVCs to zero
2. Order a decrease of reactive power input to the transmission grid to about zero
3. Order output of reactive power at connection points up to the established requirement, inform the on-duty engineer
4. Disconnect shunt capacitors connected to the transmission grid
5. Connect shunt reactors
6. Operate synchronous condenser in under-excited mode and adjust SVCs to minimum, inform the on-duty engineer
7. Disconnect lines in agreement with the on-duty engineer

*Reactive resources control*

During normal grid conditions the control of the reactive resources in the area are done manually from Svk’s control room except for the SVC at Stenkullen. The routines for when action is taken are based on the voltage levels in the area.

As a safety feature (for example in cases where connection between a station and the control room is lost or when actions are required within seconds) all mechanically switched shunts are equipped with an extreme voltage automatic switching function. During extreme voltage conditions the extreme voltage automatic switching function is activated, and the shunt is either connected or disconnected (usually with a small time delay).

The reactive power production/absorption of SVCs are automatically controlled based upon the voltage at the connection point. The exact characteristics of the control varies for different types of SVC. In general, the injected/absorbed reactive power changes proportionally with a decreased/increased in voltage within the working range of the SVC.

*Ringhals control*

When SvK cannot regulate the voltage and have sufficient margins in the area, with its own or the distribution networks' reactive resources, they can contact Ringhals. They then ask for a certain voltage increase/decrease and it is up to Ringhals to decide whether they can deliver this increase/decrease or not. The increase/decrease itself is carried out as a setpoint change for the voltage control, which results in a changed reactive exchange to achieve the new voltage setpoint.

Ringhals always operates its connected generators in voltage control mode. This means that they maintain a certain voltage on the generator busbars and the reactive exchange becomes what is physically required to maintain the desired voltage.

*Distribution Grid control*

Distribution grids that connects to the transmission grid is obligated to maintain certain reactive power exchanges at their connection points. In practice this in not always fulfilled. In some parts of southern Sweden distribution grids exports high volumes of reactive power to the transmission grid. This situation has been prevalent for a long time since the transmission grid historically has been able to absorb the reactive power from the distribution grids without issues.

With changing grid configuration, it is now of interest for SvK to address the agreements between distribution grids and transmission grid regarding reactive power transfer. This will also be addressed with the implementation of new EU-grid codes.

When Svk cannot control the voltage with sufficient margins with their own reactive resources they contact distribution network owners and ask them to change their reactive power exchange. Whether the distribution grid owners can or cannot aid with this is highly dependent on their ability to ask power suppliers, who are connected to the distribution grid, to change their reactive power exchange.

### 1.6.2 Operational routines and instructions at Ringhals

All units at Ringhals are operated in voltage control mode. The voltage is controlled with regards to the terminal voltage of the generators. It remains constant for a constant generator voltage setpoint value, with exception of dynamic transient occurrences that may affect the voltage or when interaction of any limiter may hinder the generator voltage from being held equal to the setpoint. With voltage control mode operation, the reactive power production/consumption of the generators are dependent on the voltage of the grid.

With regards to the auxiliary grid at Ringhals, generator voltage from 95 % to 105 % is acceptable. However, the setpoint value for generator voltage is usually in the range of 97 % to 103 % of nominal generator voltage [6].

The current agreement between Ringhals and Svk states that Ringhals' voltage control should be controlled in agreement between Ringhals and SvK. As of now no such written agreement is formally known. Regarding voltage control at Ringhals, changes in generator voltage setpoint is made by operators at Ringhals after requests from SvK. After changes in setpoint has been made the value remains at the given value until a new request from SvK is received. After a unit has been offline it will have the setpoint value which it had during synchronization when it goes online again, until a request for change has been received.

# 2 Part B – Visualizations & Analysis

This chapter presents visualizations of different cases with either high voltage levels, normal voltage levels with inefficient reactive resource use or high reactive power exchange between Ringhals and the grid together with a brief description of interesting findings from each case. A discussion of the interdependence between Ringhals and the grid regarding voltage levels and reactive power flow is presented. Finally, a discussion of how these aspects may change in the future with the decommissioning processes of Ringhals and the commissioning of the STATCOM at Stenkullen and the South-West link is presented.

## 2.1 POWER FLOWS AND VOLTAGES

This section presents results from analyzed network data. Voltage levels, load angles and power flows for the area of interest is presented for the following occasions:

- 2017-08-23 – High voltage levels
- 2017-08-27 – High voltage levels
- 2017-09-15 – Normal voltage case with suboptimal coordination
- 2018-01-10 – High reactive power export from Ringhals
- 2018-01-20 – High reactive power export from Ringhals
- 2018-02-09 – High reactive power export from Ringhals
- 2018-11-04 – High reactive power absorption by Ringhals

A more detailed explanation of the data and a discussion regarding the accuracy is given in section 2.1.1. The values include voltage and angle for each station, power flows on each line and connections of the various reactive resources. The capacitor at Strömma was commissioned after the investigated dates and it is therefore excluded in the illustrations.

The specific time instance of the day for which the data is present has been chosen based upon how well it illustrates the high/low voltage or high reactive power production/absorption situation of the day.

The reactive power of the reactive resources is always presented as the rated reactive power of the unit. In reality, the reactive power changes with changing voltage. However, the change is relatively small and is neglected in this report.

Each occasion is presented together with a brief description of any shunt actions made before and after the specific time as well as findings of interest.

### 2.1.1 Data verification

All values presented are taken directly from the network data obtained from Svk. In the obtained network data, some of the values are measurement values and some are estimates from a tool that automatically estimates the values for which there are no measurements. Which values that are measurements and which are estimates are unknown. There may therefore be inaccuracies in the presented values.

In order to verify that the inaccuracies in the data isn't of such a severe degree that the data gives a misrepresentative picture of the network conditions on the analyzed occasions, a comparison between the estimate data and a separate set of measurement data has been made. The separate measurement data has been obtained from Svk and consists of:

- Hourly measurement of the reactive power (Mvarh) transfer between the four Ringhals units and the grid.
- Average voltage measurements on an hourly basis for Breared, Horred, Lindome, Stenkullen and Uddebo from 2016-01-01 to 2019-04-04.

*Reactive power comparison*

The measurement data presents hourly reactive power (Mvarh) compared to the reactive power (Mvar) in the estimate data, therefore it is not to be expected that the data matches perfectly. However, a comparison can be made to assess the accuracy of the estimate data. In the comparison between the estimate data and the measurement data it can be seen that estimated data of reactive power exchange between Ringhals and the grid is accurate to a degree which is sufficient for the premise of this report when compared to the measured reactive energy exchange. In Figure 9 the difference between the measured hourly reactive power exchange (Mvarh) and the estimated reactive power (Mvar) can be seen for Ringhals 4 for 2018-01-10. The difference seen in Figure 9 is typical for all the compared cases, which the exception for the case on 2017-08-23 (see later in this section for an explanation).

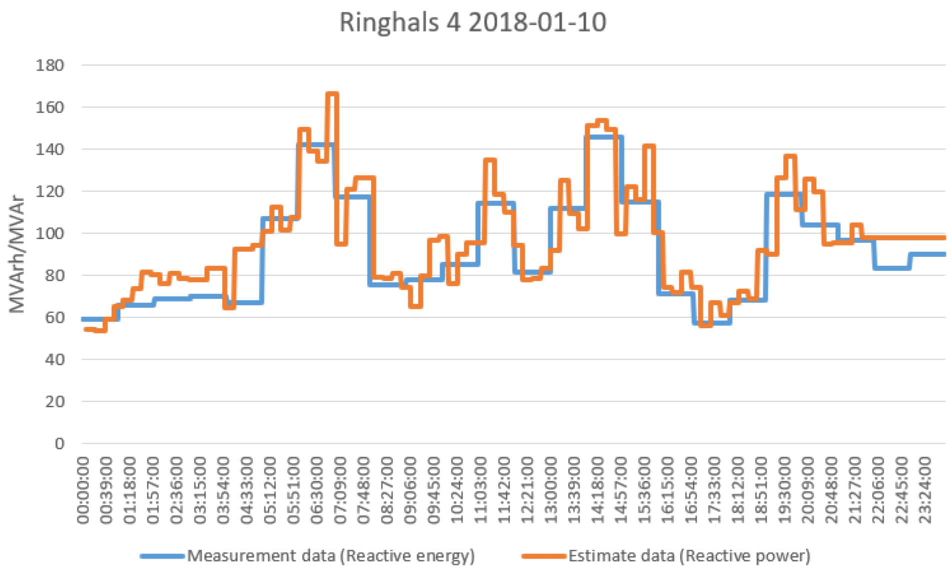


**Figure 9. Comparison between measurement data and estimate data for the reactive power exchange between Ringhals 4 and the grid.**

Since the reactive power between Ringhals and the grid is accurate in the compared data, it is predicted that reactive power in the rest of the analyzed area is accurate to a degree which is sufficient for this report. This is further motivated by the fact that the reactive power exchange between Ringhals and the grid is the reactive power exchange of highest interest for this report and therefore has the highest need for accuracy.

*Voltage comparison*

The measurement data presents the hourly average voltage which similarly to the reactive power data cannot be expected to fully match the estimate data which presents the current voltage for the busses for each point in time. It can however be used to give an indication of the accuracy of the estimate data. The comparison showed that the voltage in the estimate data matched the measured average voltages to a sufficiently high degree during the occasions which are presented in the report. However, it can be seen that there may be deviations of up to ±5 kV during some instances. The reason for this can either be due to the difference between data types (one being an average and one being the voltage for specific time instances), inaccuracies in the estimate data or a combination of both. In Figure 10 the difference between the measured average voltage and the estimated voltage at Breared can be seen for the case on 2017-09-15. The difference seen in Figure 10 is typical for all the compared cases, with exception for the case on 2017-08-23 (see later in this section for an explanation).

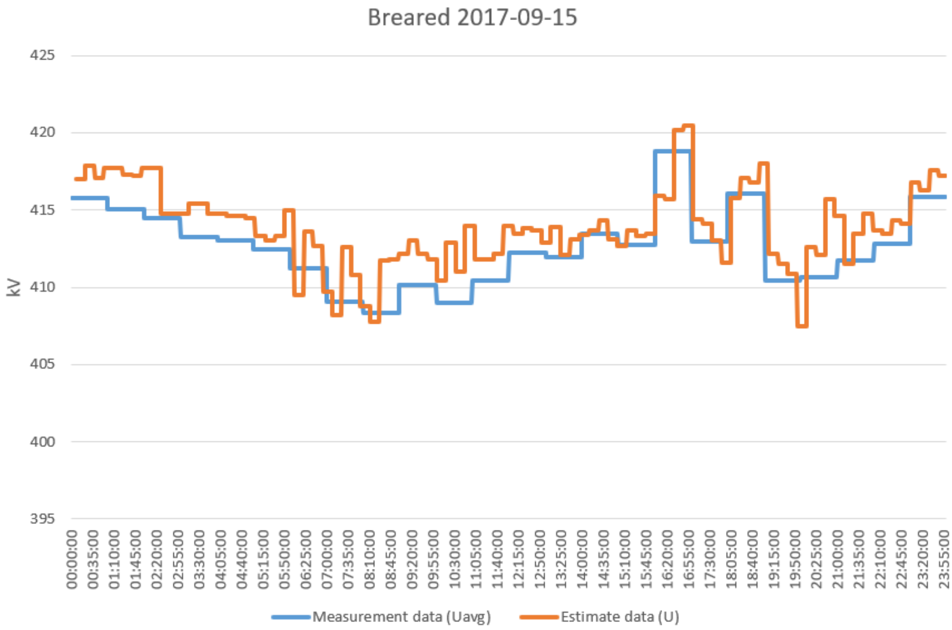


**Figure 10. Comparison between measurement data and estimate data for voltage at Breared 2017-09-15.**

Similar to the reactive power comparison it is predicted that voltages in the rest of the analyzed area is accurate to a degree which is sufficient for this report since the voltages are sufficiently accurate in the compared cases.

*2017-08-23 Data deviation*

When comparing both the reactive power and the voltages for the case on 2017-08-23 it can be seen that there is a large difference between the measurement and the estimate data from approximately 09:00 to 16:30. See Figure 11 for the voltage at Horred, the same deviation can be seen in all voltage and reactive power data.

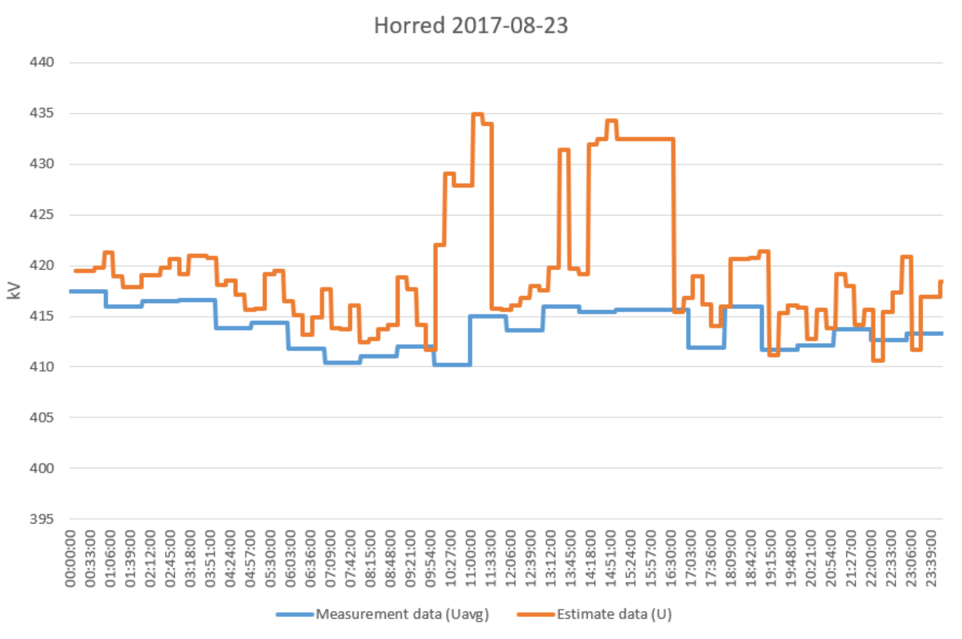


**Figure 11. Comparison between measurement data and estimate data for voltage at Horred 2017-08-23.**

When analyzing the measurement data, it can be seen that the average voltages are high (above 415 kV) during the majority of the day and that Ringhals is absorbing reactive power. Therefore, the case is still of interest for analysis. Even though the time for the analyzed case is after this large difference due to the large size of the difference it is concluded that estimate values for this case cannot be used. The visualization will only show measurement data for this case.

*Verification summary*

In the comparison it is seen that the majority of the estimate data is correct with a few exceptions. There is a slight tendency for the estimate data to present voltages that are either to high (typically +2-3 kV and sometimes up to +5 kV) when the measured data indicates voltages are high (above or near 415 kV) and vice versa for low voltages. This should be remembered when reading the remainder of this report. However, as previously stated the analysis and the conclusions are still seen as valid.

### 2.1.2 High voltage cases

Two different cases which have been selected due to high voltages are presented. Both of them occurred in august 2017. The load during this period is low, which is typical for summer periods. Low load can typically lead to high voltages, see section 1.3.1 for explanation.

*High voltage on 2017-08-23*

In Figure 12 voltage levels, reactive power flow and active power flow are presented for the area on the 23rd of August 2017 23:00. As stated previously this case presents the limited measurement data instead of the estimate data.

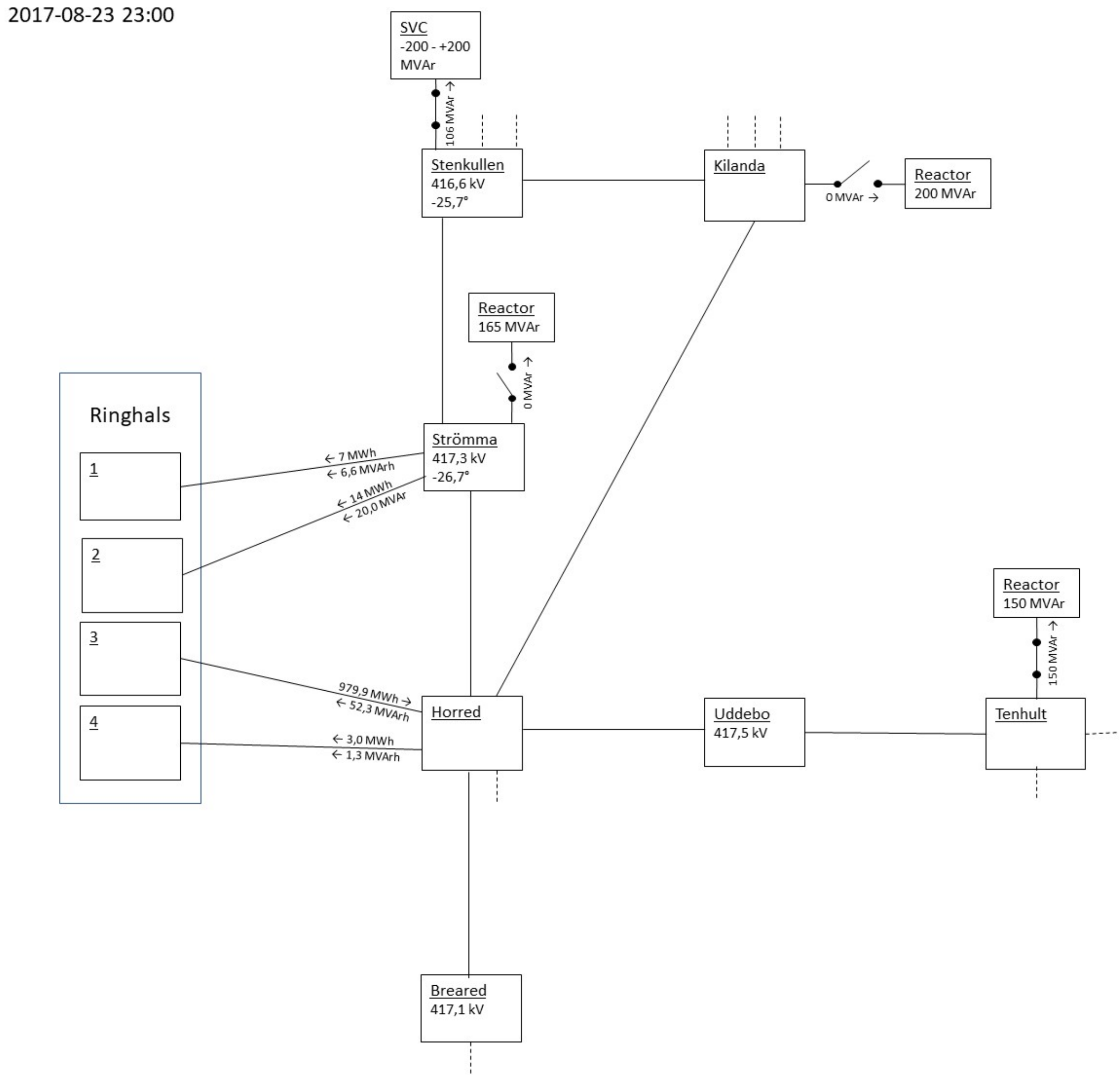


**Figure 12. Power flow, voltage levels and load angle for the investigated area. 2017-08-23 11:05**

As shown in the figure, the average voltages at 23:00 are high at all the stations where data is presented and most likely in the adjacent stations as well. Ringhals unit 3 absorbs reactive power. The other units in Ringhals are not in operation. It can be seen that the reactive resources at Strömma and Kilanda are disconnected where it could have been beneficial to have them connected to lower the voltage and reduce the reactive power absorption of Ringhals 3. It was also found that during the night at around 01:00 to 03:00 all the reactors were connected and Ringhals was still absorbing approximately 50 Mvarh per hour. This indicates that during low loading situations the area needs Ringhals to absorb reactive power even when all reactive resources are connected.

*2017-08-27*

In Figure 13 voltage levels, load angle, reactive power flow and active power flow are presented for the area on the 27th of August 2017 11:16.

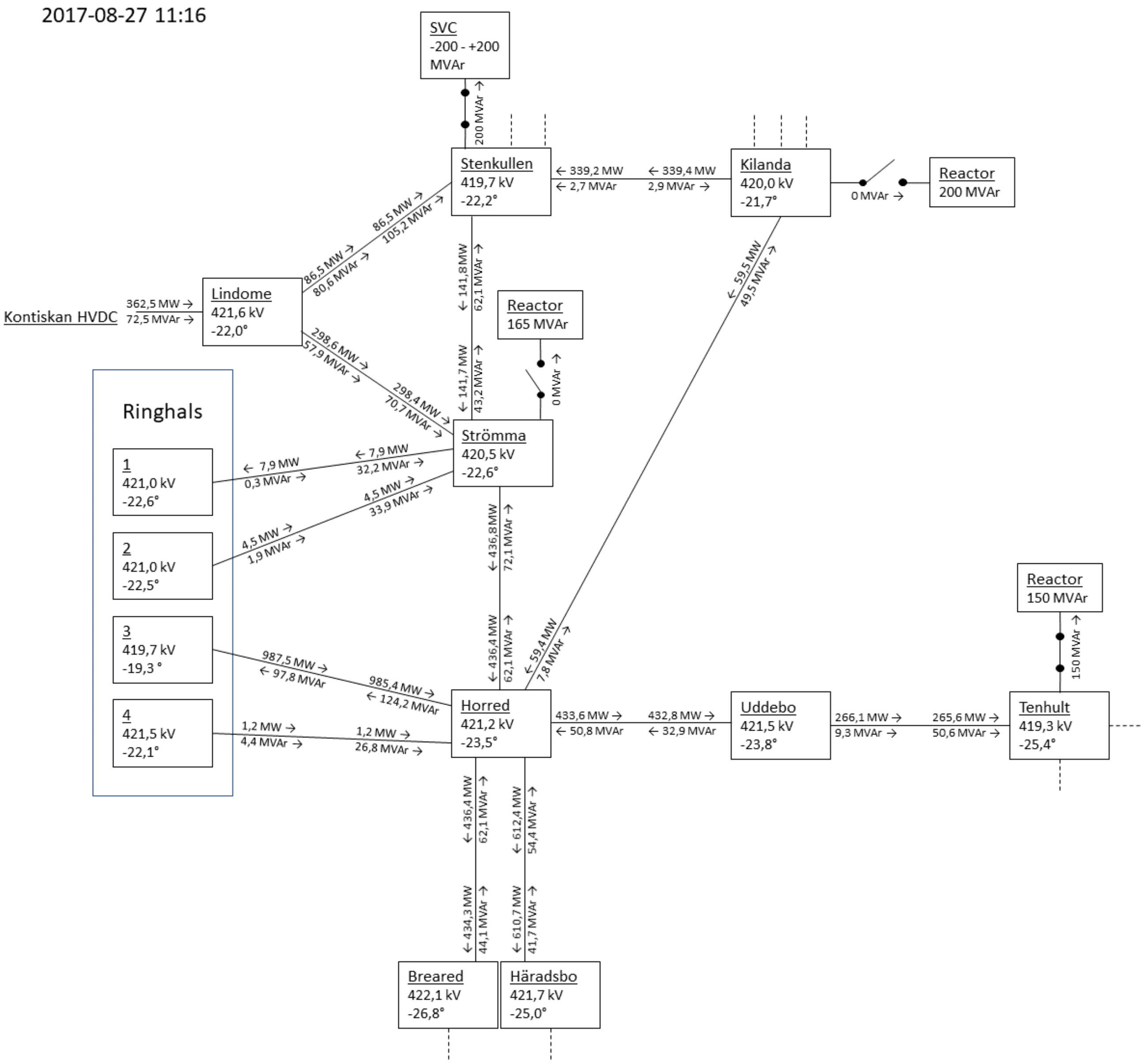


**Figure 13. Power flow, voltage levels and load angle for the investigated area. 2017-08-27 11:16**

Prior to the presented moment the Kilanda reactor is disconnected at 10:27. Prior to the disconnection the voltage at Kilanda is approximately 415 kV which is at the higher end of the acceptable voltage range.

As shown in the figure, the voltages at 11:16 are again high at the whole region and also for the Ringhals units. The reactor in Tenhult is connected to lower the voltage. Ringhals unit 3 absorbs reactive power. The reactor in Strömma is not connected.

At this occasion it could have been beneficial to connect the reactor at Strömma to decrease the voltage and the reactive power absorption of Ringhals 3.

### 2.1.3 Normal voltage case with suboptimal coordination

In Figure 14 voltage levels, load angle, reactive power flow and active power flow are presented for the area on the 15th of September 2017 08:12.

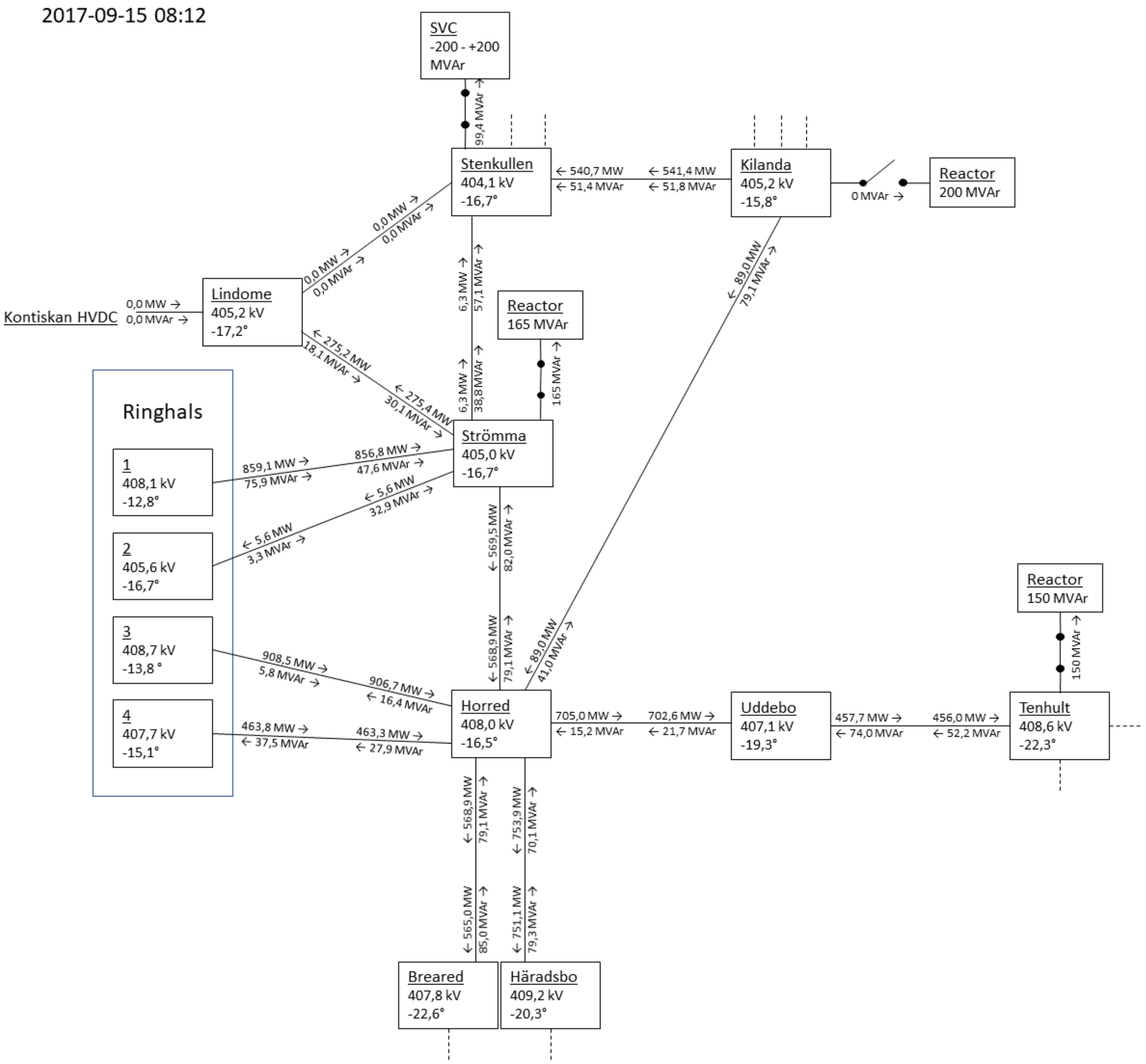


**Figure 14. Power flow, voltage levels and load angle for the investigated area. 2017-09-15 08:12**

Prior to the presented moment the Kilanda reactor is disconnected at 06:07 due to low voltage (405 kV at Kilanda station).

As shown in the figure, the voltages at 08:12 are low to normal in the entire region but still within acceptable limits. It can be seen that all reactors in the area except at Kilanda is connected, which may be the reason for the voltages that are low or at the low end of the normal range.

It could have been beneficial to increase the voltage by disconnecting reactors. Since Ringhals is the main power producer in the area it would be most beneficial to start with disconnection of reactors close to Ringhals, Strömma would be the first choice then followed by changing the setpoint of the SVC at Stenkullen.

### 2.1.4 High reactive power export from Ringhals cases

Three different cases with high reactive power export from Ringhals are presented, all of them occurred in winter season of 2018. The load during this period is high, which is typical for winter periods.

*2018-01-10*

In Figure 15 voltage levels, load angle, reactive power flow and active power flow are presented for the area on the 10th of January 2018 14:34.

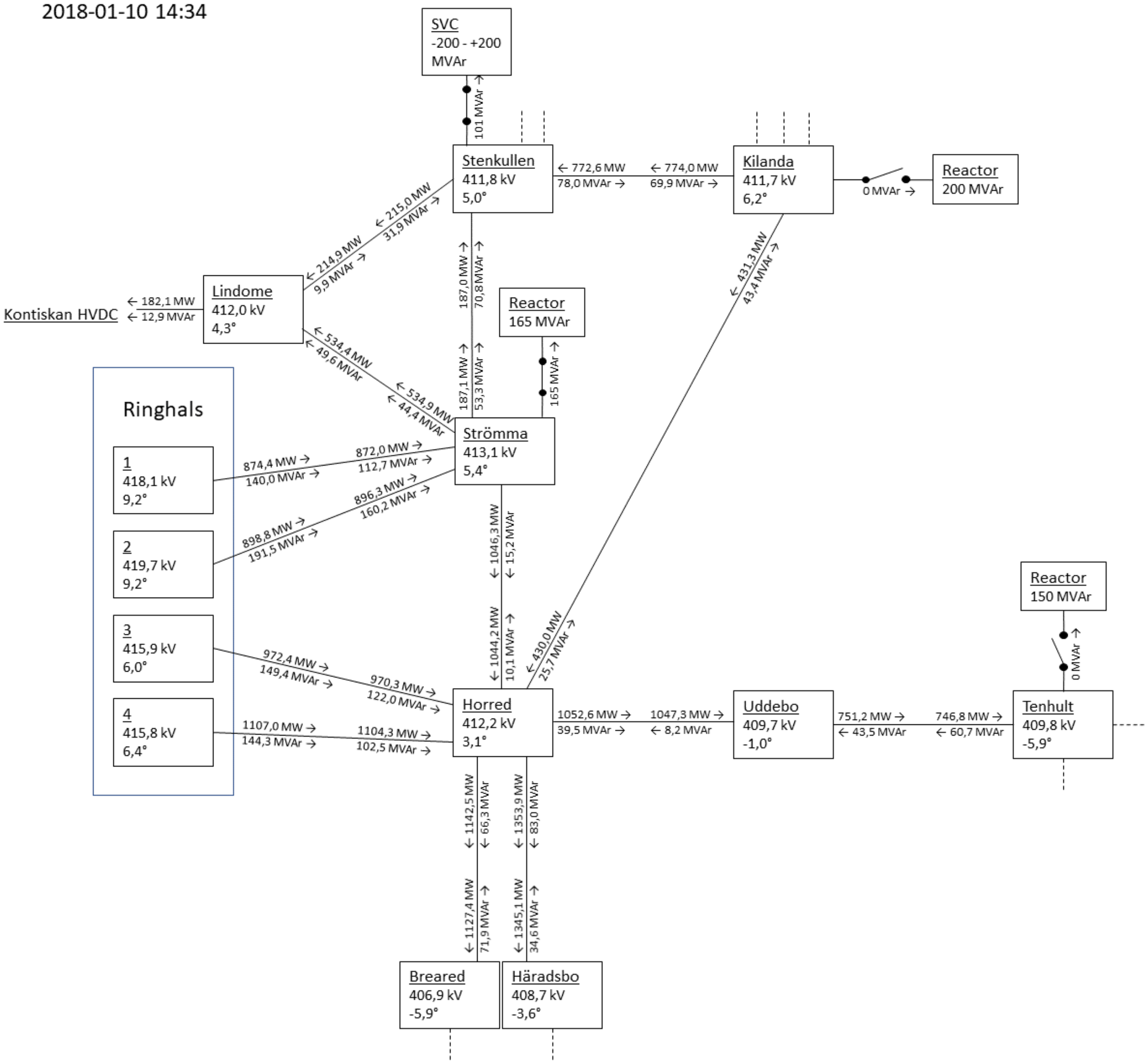


**Figure 15. Power flow, voltage levels and load angle for the investigated area. 2018-01-10 14:34**

At this moment the voltages at the Ringhals units are high compared to stations in the nearby area and since the units are heavily loaded, the Ringhals units produce a high amount of the reactive power.

To lower the reactive power production at Ringhals the nearby voltages are increased by disconnection of the Strömma reactor a few minutes after the presented instance. The reactive power export of Ringhals is still fairly high after this action (in total approximately 400 Mvar).

In this case there is a high reactive power consumption in the area and even with all reactors in the area disconnected, Ringhals is still exporting a great amount of reactive power. A final action to address this, which is not yet implemented, is to change setting of the SVC at Stenkullen. The reactive power absorption by the SVC could have been lowered to increase the voltage at the nearby area and lower the reactive power production at the Ringhals.

*2018-01-20*

In Figure 16 voltage levels, load angle, reactive power flow and active power flow are presented for the area on the 20th of January 2018 09:01.

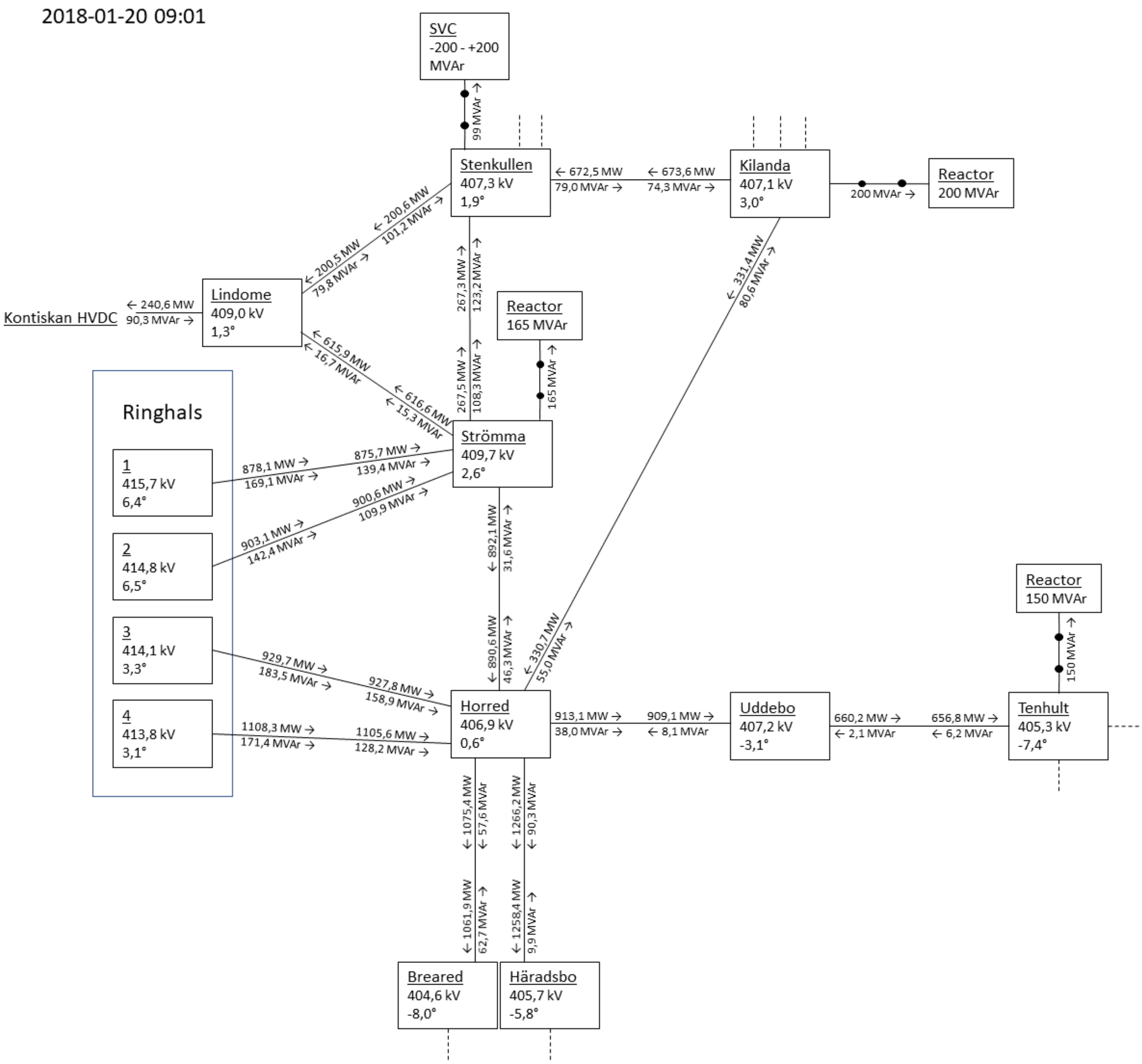


**Figure 16. Power flow, voltage levels and load angle for the investigated area. 2018-01-20 09:01**

As can be seen in Figure 16 there is a high reactive power export from Ringhals to the nearby area. To lower this the reactors at Strömma, Kilanda and Tenhult are disconnected in the minutes following 09:01. This only marginally increases the voltages in the nearby area due to high loading. The reactive power export from Ringhals is therefore also only marginally decreased (approximately 500 Mvar after disconnection of reactors). The SVC at Stenkullen could be used to lower its reactive power absorption (even possibly produce reactive power) to decrease the reactive power export from Ringhals, this could however increase the voltage levels in the area too much.



Energiforsk

The situation at this moment is similar to the one at 2018-01-20 in that there is a high load situation with high reactive power consumption in the area and even with all reactors disconnected there is a high reactive power export from Ringhals. This highlight that there is a high demand of reactive power in the area during high load situations.

*2018-02-09*

In Figure 17 voltage levels, load angle, reactive power flow and active power flow are presented for the area on the 9th of February 2018 07:44.

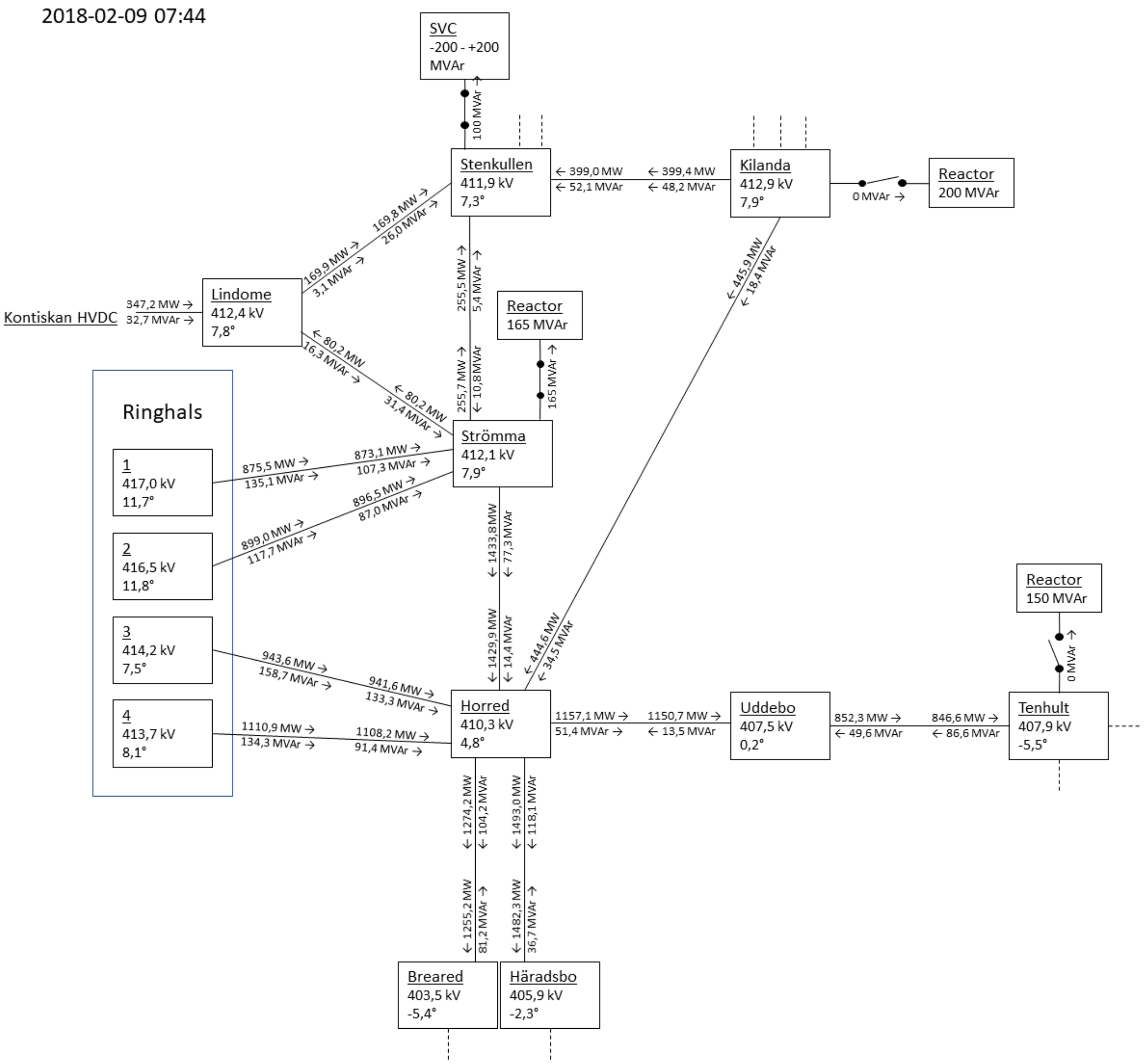


**Figure 17. Power flow, voltage levels and load angle for the investigated area. 2018-02-09 07:44**



Energiforsk

As can be seen in Figure 17, there is a high reactive power export from Ringhals. It can be observed that the voltage levels are lowest in the southern parts of the area (Breared and Häradsbo). No connection/disconnection of reactors occurred during the day.

In order to obtain a more desirable operation the Strömma reactor could have been disconnected to increase the voltage levels in the area and lower the reactive power export from Ringhals.

### 2.1.5 High reactive power absorption by Ringhals cases

In Figure 18 voltage levels, load angle, reactive power flow and active power flow are presented for the area on the 4th of November 2018 23:13.

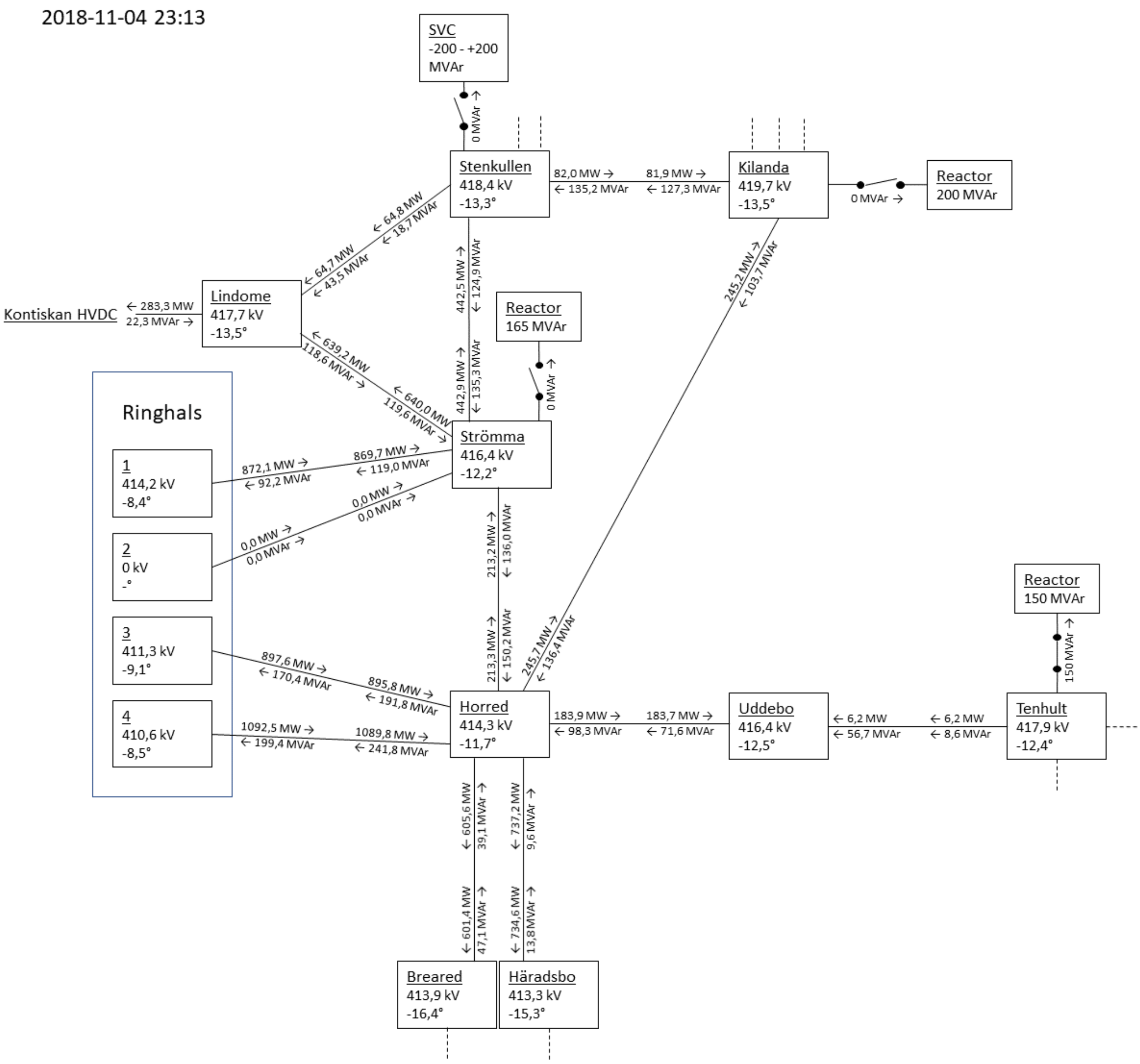


**Figure 18. Power flow, voltage levels and load angle for the investigated area. 2018-11-04 23:13**



Energiforsk

In Figure 18, it can be seen that Ringhals is absorbing a high value of reactive power, this is because the voltage levels at Ringhals is lower than at Horred and Strömma. A few minutes after this moment the reactor at Strömma is connected which lowers the voltage level at Strömma and decreases the reactive power absorption of Ringhals. The main decrease in absorption is seen at Ringhals 1. Ringhals 3 and Ringhals 4 are still absorbing reactive power at levels similar to the ones before the connection of the Strömma reactor.

The reactive power absorption of Ringhals 1 remains for approximately three hours after the connection of the Strömma reactor (until 2019-11-05 02:00). At this time the voltage level at Strömma has decreased to 404 kV (possibly due to changes in load in the area) which is the main factor for the change in reactive power. The reactive power absorption of Ringhals 3 and 4 remains stable until 2019-11-05 10:00. At this point two influencing events have occurred. The voltage levels in the area starts to decrease at 05:00 (most likely due to an increase in active power consumption in the area). At approximately at 06:00 the reactors at Tenhult and Strömma are disconnected to increase the voltage and it can be seen that this momentarily increases the voltage. But with the increase in active power consumption the voltage continues to decrease. This is reflected in the reactive power absorption by Ringhals; the absorption decreases as the voltage decreases followed by a small increase with the disconnection of the reactors. At approximately 07:00 the voltage levels at all of the connected generators at Ringhals (unit 2 is disconnected) is increased. This change influences the reactive power exchange between Ringhals and the transmission grid. Ringhals 1 is producing reactive power in the range of 70-120 Mvar. Ringhals 3 and Ringhals 4 still absorbs a small amount of reactive power but the amount is reduced. This helps to increase the voltage levels in the area as well.

This case highlights the influence of active power consumption on the voltage in the area and how the reactive power exchange is influenced by the voltage difference between Ringhals and the grid. It can clearly be seen how the change in generator voltage influences the reactive power production of the generators at Ringhals.

## 2.2 ADDITIONAL HISTORICAL DATA

In addition to the more detailed data presented in section 2.1, this section presents some information regarding the frequency of high reactive power production, high reactive power absorption and high voltage measured at Ringhals. It should be noted that the sampling time for these values are much longer (which means that short spikes will be missed) than for the previous presented values in section 2.1. Therefore, the values presented in this section may differ from values presented in section 2.1, which have a higher sampling rate.

### 2.2.1 High reactive power export

During the years 2015 to 2019, reactive production has been higher than 560 Mvar from Ringhals (all units) at approximately 10 occasions. The highest observed value during 2015-2019 is 675 Mvar on January 20, 2018. Generally, high reactive power is more often noted during the winter season.

### 2.2.2 High reactive power absorption

During the years 2015 to 2019, the reactive power has been below -400 Mvar about 15 times. In November 2018, the reactive power was below -500 Mvar twice. Generally, most occasions with low reactive power are noted during the summer.

### 2.2.3 High voltage

During the years 2015 to 2019 at approximately 50 occasions at least one of the units measured a voltage above 420 kV.

## 2.3 INTERDEPENDENCE BETWEEN RINGHALS AND ADJACENT STATIONS

This section presents some of the key findings from the processed data. It should be noted that the conclusions are based solely on the analyzed data and may not be true for other scenarios. The finding may however indicate broad issues and phenomena.

Both high voltage cases have in common that there are high voltages in the area and that Ringhals is absorbing reactive power. The reactors in Strömma and Kilanda are both offline for both occasions which indicates inefficient use of the resources. Connection of the reactors (primarily the reactor in Strömma) would have reduced the reactive power absorption of Ringhals. During the high voltage situation on 23rd of August 2017 it can be observed that even with all reactors connected and with the SVC absorbing approximately 100 Mvar, Ringhals still had to absorb reactive power. From a voltage stability perspective this is not an optimal situation.

From the case of the 4th of November 2018 with high reactive power absorption at Ringhals the effect of loading in the area has on voltage can be seen. The following increase of the voltage at the generator terminals at Ringhals improves the situation by increasing the voltage at Ringhals and lowering the reactive power absorption.

On several occasions there has been high reactive power export from Ringhals with nearby reactors connected and vice versa. This indicates that the control of the reactors may be improved with regards to reactive power transfer to/from Ringhals and voltage control. Since all shunt connection/disconnection control is done manually by Svk instantaneous response to undesirable states of operation is unrealistic. With more attention to the difference in voltage levels between Ringhals/Strömma and Ringhals/Horred the reactive resources could have been more efficiently used and some of these situations could have been avoided.

The exact voltage levels when Ringhals starts to absorb reactive power varies for each unit, generator voltage setpoint, unit transformer and power production. However, as a rule of thumb, extra attention should be paid when the voltage levels at Horred or Strömma is higher than corresponding Ringhals units.

The SVC at Stenkullen is in the obtained data either disconnected or working in the range of absorbing between 100 Mvar and 200 Mvar. At some occasions it is observed that reactive power is absorbed by the SVC even when the voltage at Stenkullen station is low (on 2017-08-26 09:51 the SVC is absorbing 100 Mvar with a voltage of 403 kV at the station and on 2017-08-27 23:27 the SVC is absorbing 160 Mvar with a voltage of 399 kV at the station). During instances like these it could have been desirable for the SVC to be supplying rather than absorbing reactive power to help with increasing the voltage. It should be noted that the SVC now is decommissioned.

## 2.4 SITUATION WITHOUT RINGHALS 1 AND 2

With the commenced decommissioning of Ringhals 2, and the plan to decommission Ringhals 1, concerns are raised about difficulties to control the voltage in the area. The traditional and main measure to control the voltage is based on utilizing synchronous machines and when the Ringhals units are decommissioned there will probably be a lack of reactive resources in the area. The total reactive power capacity of Ringhals units 1 and 2 is around 600 Mvar. A loss of reactive power capacity of this size could have effects (especially during high load situations) that cannot be neglected.

Apart from this reactive power capacity loss, when the Ringhals units 1 and 2 are decommissioned, the power flow in the grid will be reshaped and the short circuit capacity will be reduced. With this, more detailed static and dynamic simulation studies are required to anticipate more accurately what will happen in the system in terms of the voltage control. This is particularly important as we know that voltage control issue mainly occurs in the central and southern part of Sweden. So, the absence of the Ringhals units 1 and 2 would probably need more attention to be given with detailed simulation studies.

There are plans to compensate for the loss of the synchronous machines of Ringhals 1 and 2 with regards to their impact on voltage control and reactive power capability. Namely the STATCOM at Stenkullen and the South-West link [7].

### 2.4.1 With addition of STATCOM at Stenkullen

One direct measure to improve the voltage control and reactive power capacity in the area is the STATCOM which is being installed at Stenkullen to replace the current SVC. Installation of the STATCOM at Stenkullen station could potentially be a great resource to improve the reactive power balance and voltage control in the area. However, the magnitude of effect it will have on the voltage control in the area greatly depends on the control of the STATCOM.

### 2.4.2 With addition of South-West Link at Barkeryd and Hurva

The South-West link is being installed mainly with active power transfer in focus but the VSC-converters at the stations can potentially provide a great addition to the voltage control in the areas near the stations. The greatest impact will be seen close to the stations. The impact may be seen near Ringhals area as well. It is most likely that the effect from the Barkeryd stations will have a more prominent effect at Ringhals than the Hurva station due to the distance being closer. The effect should be further investigated as the voltage control is mainly a problem to be solved locally. Since the South-West link station is a bit far from the area being investigated, the effects on the area are hard to predict without more detailed studies.

### 2.4.3 Additional factors and potential beneficial additions

In addition to the STATCOM at Stenkullen and the South-West link one approach that could be considered to improve the future situation with regards to reactive power capacity is to consider installing shunts at the stations Strömma or Horred.

A rough prediction is that shunt capacitors with around 300-400 Mvar in total reactive power capacity at either the Strömma or Horred substation could be beneficial. This might compensate for the loss of the reactive power from Ringhals units 1 and 2. This will help during high loading situations and could help to avoid low voltage situations. These situations should be prioritized as typically low voltage, and not high voltage, is the main problem during voltage collapse events. However, as stated more detailed studies are needed to know which measures are needed.

Although the addition of reactive shunts might help to manage the lack of the reactive power resources within the area with the loss of Ringhals 1 and 2. It cannot compensate for the reduction in short circuit capacity. This is important as when the short circuit capacity is decreased with the decommissioning of Ringhals units 1 and 2, the nearby buses will be more sensitive to reactive power changes. It will then be even more difficult to predict the effects that new reactive resources will have on the voltage stability in the area.

The connection of inverter-based generation (wind, solar etc.) in the area in the future will also contribute with regards to voltage control and reactive power capacity. This is since the inverter-based generation have the capability to contribute with reactive power and to some extent to the short circuit capacity levels. It is therefore beneficial to know the details and specifications for the installed inverter-based generation (if there are any) to have a better overall picture of the future situation.

# 3 Part C – General Methodology

A general methodology that could be implemented if a similar study with the topic of voltage control in an area is to be performed is presented in this chapter. The content of this chapter is similar to the method for the studies performed in this report, described in section 1.2, but with a broader, more general, perspective with the core elements highlighted. The methodology presented in this chapter is aimed for a study with the intent to analyse the voltage control in a specified area and the reactive power exchange between a large power plant and the grid. Additionally, the study is assumed to also give an understanding of the interaction between the plant and the grid and how it could change with a potential decommissioning of the plant.

*Scope*

The scope of the project is assumed to be similar to the one for this report where the role the plant has in voltage control in the area, the coordination of reactive resources in the area and how it could change in the future is to be studied.

Since voltage control, voltage stability and reactive power exchange are local issues the area around the plant which is to be studied should be limited to a degree where only the most relevant buses are included. This is highly dependent on the project specific conditions. Nearby buses with influencing components such as HVDC-converters, large synchronous generators or reactive resources should be included.

*Data gathering*

The data that is recommended to gather is dependent on the scope of the project and may most likely need project specific adaptation. However, the following information regarding technical specifications and operational routines should provide a starting point for the project:

- Plant active power and obligated reactive power capability
- Plant voltage control modes and setpoint control
- Reactive resources in the area and control scheme for them
- The TSO´s voltage control routines

If historical data is to be analysed with the intent to investigate how voltage and reactive power has behaved historically, a select number of occasions should be chosen to narrow down the amount of data. If historical voltage measurements from the plant or the adjacent buses can be obtained, points in time with either high or low voltage may be found and be selected for further analysis. The following data should be gathered (preferably as accurate measurements as possible with a high sample rate):

- Voltage at each bus
- Reactive power flows between the plant and the grid
- Reactive resource connections/disconnections

If predictions of how the situation may change in the future is to be performed, information regarding any major changes should, if possible, be obtained. Changes of relevance may be commissioning/decommissioning/rework of power plants, reactive resources or major loads or changes in grid topology.

*Data processing*

Technical specifications and operational routines should be summarized, and the historical data investigated with the aim to understand the role the plant has in the area with regards to voltage control and how well the reactive resources are utilized. The process for this step varies for each project and needs to be adapted accordingly.

*Data analysis*

If inefficient use of reactive resources is found the cause for this should, if possible, be found and presented together with possible solutions based upon theoretical analysis. The role the plant has in the area can be analysed by investigating how active the plant is in voltage control and how much of its reactive power capability is being used. The coordination between the plant and the TSO should be investigated. Regarding future situations, predictions should be based upon theoretical analysis and if more detailed predictions are wanted more detailed studies should be performed with a more extensive data gathering.

# 4 Part D – Conclusions, Observations and Suggestions

The conclusions, observations and suggestions presented in this chapter are solely based on the processed data and therefore the accuracy may be limited. However, the data processed should have been sufficient to make broad conclusions and to highlight some potential issues.

*Decommissioning of Ringhals 1 and 2*

Currently, the control room at Ringhals 1 is the first point of contact for Svk, and they then distribute information to other units regarding increase / decrease in voltage. This order will need to be changed with the closure of Ringhals 1 and 2. Ringhals 3 and 4 will then also be connected to different network stations, unlike now when Ringhals 1 and 2 are connected to Strömma and Ringhals 3 and 4 are connected to Horred.

With only two units in operation at Ringhals, the likelihood that all units are out of operation at the same time increases. The probability of this is greatest during the outage period (which typically occurs in the summer). Svk must then have sufficient reactive power capacity in the network to keep the voltage without the help of Ringhals. Svk is obligated according to [8] to ensure secure production conditions for Ringhals. With regards to nuclear safety, it is of great importance for Ringhals that external networks maintain the voltage quality even during shutdowns (such as outage periods).

*Shunt control*

In the processed data there has on several occasions been found that reactors have been either connected when it would have been more efficient to have them disconnected and vice versa. An improvement in control of these reactive resources either with implementation of more automatic control or updated routines for operators could be an improvement. Both for the current situation but maybe even more so after the decommissioning of Ringhals. This is since with the decommissioning there will be less voltage control in the immediate area near Ringhals, and thus the system may be more vulnerable to inefficient reactive shunts control. A potential case where this could pose an issue is if the Strömma reactor is connected during high load situation (potentially similar to the situation at the studied case on 2018-02-09) with only one or two of Ringhals units connected. Then the Ringhals generator may be operating close to the field current limit and thus the voltage control margin could be low.

*Distribution grid reactive power injection*

It is known that connected distribution grids on some occasions inject reactive power above the levels which they should. This has a negative impact on the voltage control in the area since the reactive power exchange between Svk's grid and the distribution grid cannot be directly controlled by Svk. To improve this, the contract between the distribution grids and Svk should be revised and maybe more importantly the compliance with the requirements should be ensured.

*Reactive power capacity*

From the processed data it is observed that there on some occasions are high demands of both reactive power production and absorption from Ringhals with all reactive resources in the grid already utilized. This raises the question if there is enough reactive power capability in the area when the decommissioning of Ringhals has commenced. We know that Ringhals, with all four units active, has the capacity to supply up to at least 1300 Mvar (1016 Mvar without Ringhals 2), and even though it is not formally demanded of Ringhals, absorption up to almost 500 Mvar has been seen in the data. This will in steps be decreased with the decommissioning of unit 1 and 2. We know that the STATCOM at Stenkullen and the South-west link will add some reactive capability in the area. Since neither Stenkullen or the stations of the South-West link (Hurva and Barkeryd) are in the close proximity to Ringhals it is uncertain how much of the added capacity can be assigned to fill the capacity gap that will occur after the decommissioning. From the information that is the basis for this report it is uncertain if this added capacity will be enough. Further studies are recommended to investigate the potential capacity issue that may occur to see how the capacity changes for each step of the decommissioning and which additional resources that may be needed.

*Voltage control*

Aside from the capacity issue, the control capability needs to be addressed as well. Today Ringhals plays a great part in maintaining stable voltage in the region and with the decommissioning of Ringhals this will be reduced. The mechanically switched reactive resources in the area do not have the capability to replace Ringhals voltage control capability due to the inherent nature of mechanically switched shunts. The addition of the STATCOM at Stenkullen and the South-West link will influence the voltage control in the area after commissioning. It is evident that these additions will be positive for the voltage control in the area but without more detailed simulations and analysis this report cannot confirm whether these additions will be enough. The complexity of the situation is not purely related to the loss of Ringhals voltage control capability but also to the fact that the short circuit capacity will be affected with each step of the decommissioning along with reshaped power flows. The change in short circuit capacity will make the nearby busses weaker, meaning that they will become more vulnerable from a voltage stability point of view. As stated, no conclusions whether the problems with voltage control and stability will occur can be made. Rather it should be highlighted that this is a complex issue that may cause problems and that more detailed studies are recommended if more thorough answers are wanted.

*Communication between Svk and Ringhals*

Exact information of the conditions that are needed for Ringhals to be at an optimal operational point with regards to efficiency and stability is not presented in this report, but it should be safe to say that it should be close to nominal generator voltage with an voltage at the connection points at Horred and Strömma within the acceptable range. Therefore, it is of interest that extreme conditions with high or low reactive power from Ringhals are avoided with satisfactory voltage control. As of today, Ringhals changes the setpoint of the generator voltage only when asked to do so by Svk which is not done frequently. It could be beneficial if the information of which conditions that are most suitable for Ringhals efficiency and if Ringhals can be more active in the voltage control are investigated and presented to Svk. This could make Svk's operators more equipped to utilize Ringhals from a voltage control perspective and also to make sure that Ringhals is operating at beneficial conditions. In order to avoid reactive power absorption of Ringhals it could be beneficial if the units where operated at a higher generator voltage setpoint during low load situations. This could be reached with a more optimized coordination between reactive resources in grid and plant reactive resources along with potential installation of new reactors. A more detailed study to investigate the pros and cons of operating the units at a higher setpoint versus the effects of operating the units at lower excitation levels could be of interest.

# 5 References


[1] R. Safari: "Control of voltage and damping in bulk power systems" Division of Industrial Electrical Engineering and Automation, Faculty of Engineering, Lund University, Sweden, rev.1, Jan. 2018.

[2] Svenska kraftnät, "Affärsverket svenska kraftnäts föreskrifter och allmänna råd om driftsäkerhetsteknisk utformning av produktionsanläggningar", SvKFS2005:2, 2005

[3] Vattenfall AB, "Ringhals produktion och driftläge", accessed 2019-09-03 <https://group.vattenfall.com/se/var-verksamhet/ringhals/produktion>

[4] Svenska kraftnät, "Driftinstruktion D042"

[5] Ringhals AB, "Using QV-Curves in visualizing interaction between the grid and on-site power voltage, at power operation", Sep. 2016

[6] Ringhals AB

[7] Svenska kraftnät, "Systemutvecklingsplan 2020-2029", accessed 2020-08-26 <https://www.svk.se/siteassets/om-oss/rapporter/2019/systemutvecklingsplan2020-2029.pdf>

[8] SFS 1997:857. Ellagen. Stockholm: Infrastrukturdepartementet.

# EFFECTIVE VOLTAGE CONTROL AND OPERATIONAL COORDINATION OF REGIONAL REACTIVE POWER RESOURCES

Today Ringhals nuclear power plant plays a major role in maintaining the voltage in the nearby area with a great reactive power capacity of both production and absorption. With the decommissioning of Ringhals 1 and 2 the reactive power capacity and voltage control will be affected.

This report investigates how the situation has been historically with regards to voltage levels, power flow and shunt connections; how the situation may change in the future and which measures may improve the situation.

Data is gathered from both Ringhals and Svenska kraftnät regarding the reactive resources in the area as well as operational routines. It can be seen in the measurement data that Ringhals' reactive power capability is used to a high degree during several occasions. During high voltage situations it is observed that, even with all reactors connected, Ringhals absorbs a high value of reactive power. This highlights that, during low load situations, the area has a high demand of reactive power absorption.

On several occasions there has been high reactive power export from Ringhals with nearby reactors connected and vice versa. This indicates that the control of the reactors may be improved with regards to voltage control and reactive power transfer to or from Ringhals. The future commissioning of a STATCOM at Stenkullen and the South-West link will certainly help to improve these aspects. However, due to the complexity of the situation it cannot be concluded in this report if these measures are sufficient to maintain stable and reliable voltage control in the future.

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