The Swedish Transmission System Operator's Perspective on Planning Series-Compensated Network Sections Containing Wind Power Plants

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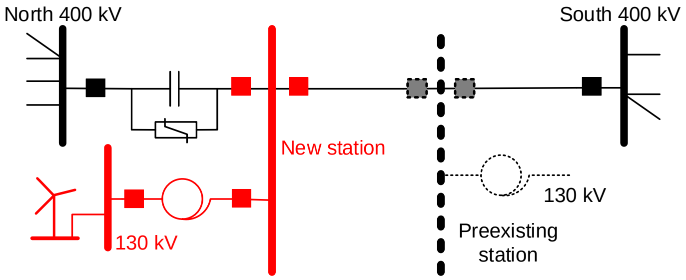
***Abstract*—The rapid proliferation of wind power plants has generated an increasing demand to modify the series-compensated network sections in Sweden. Moreover, the network planning must consider factors such as the expected load increase and series-capacitor refurbishments or renewal. This work discusses the Swedish transmission system operator's perspective on planning series-compensated network sections containing wind power plants, providing in-depth summaries of essential studies conducted using frequency domain- and electromagnetic transient tools. Such studies include transient overvoltages, temporary overvoltages, and subsynchronous oscillation studies. However, the initial planning that determines the series capacitor's design parameters is also covered to capture the entire system design chain. The initial planning consists of steady-state calculations, phasor-based transient simulations, and relay protection considerations, such as current inversion. Finally, this work thoroughly discusses how the study results are incorporated into the series capacitor design specification to achieve the best possible system solution.**

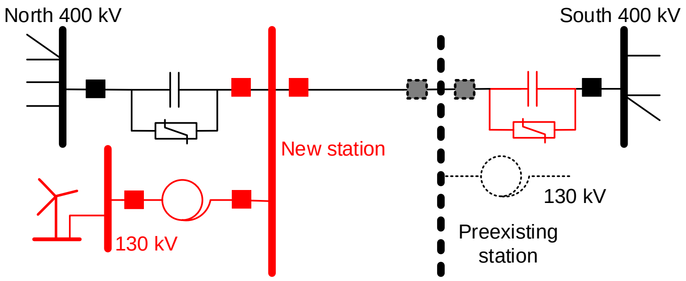
***Keywords*—Capacitor, Ferroresonance, Overvoltages, Resonance, Subsynchronous Oscillations**

I. INTRODUCTION

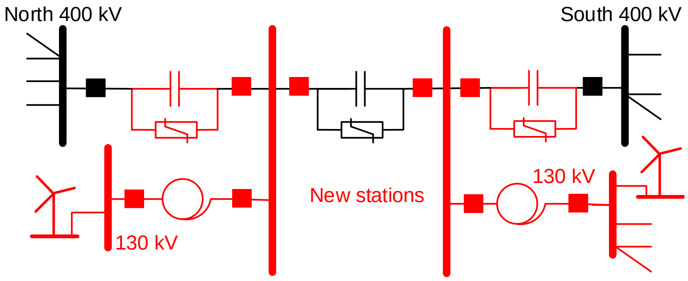
SERIES-CAPACITORS have had a prominent position in enhancing the transmission capacity and stability in Sweden, as it has created a radial increase for long-distance transmission in a very economical manner. In January 1950, the first series capacitor, operating at 220 kV, was taken into operation at the station Alfta [1]. In 1954, the first 400 kV series capacitor was commissioned due to the success of the Alfta project [2]. As a result of series compensation, limitations due to transient stability and transmission capacity were no longer considered a problem. Furthermore, by compensating the parallel transmission lines from north to south, so that they all had the same resistance-to-reactance ratio, series capacitors also served to enhance load distribution between the parallel circuits. Thus, the series capacitor became, for several reasons, an essential component of the Swedish transmission system [3]. However, there is an increased demand to handle the expected load increase and to connect wind power plants (WPP) at the series-compensated network sections. Moreover, several series-capacitor installations are reaching the end of their life cycle, necessitating refurbishment or renewal. Typical WPP installations are shown in Fig. 1, where the new portions of the power system are indicated in red. Several transmission lines typically interconnect stations in the north and south; hence, the new middle stations alter the typical



(a) A typical WPP project when the series-capacitor is located between the station in the north and the new middle station.



(b) A typical project where the series-compensated network section includes two series-capacitor installations and one WPP.



(c) A typical project where the series-compensated network section includes three series-capacitor installations and two WPPs.

Fig. 1. The above figures illustrate typical series-compensated network sections that are considered in Sweden. The new portions of the power system are indicated in red. The black dashed lines represent a preexisting station.

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characteristics of the series-compensated network sections. Furthermore, the new middle stations are sometimes connected with two compensated transmission lines, as illustrated in Fig. 1c. When one or more compensated lines link to a station without any uncompensated lines, the topology becomes complex concerning subsynchronous phenomena and resonances. Furthermore, the black dashed lines represent a preexisting station connecting the distribution network. However, the station represented by the blacked dashed lines does not exist on all network sections; this varies depending on the referred network section.

Modifying the series-compensated network sections requires several studies to ensure safe operation [4]–[8]. Therefore, the Swedish transmission system operator (TSO), Svenska kraftnät, conducts several planning studies using electromagnetic transient (EMT) tools in addition to studies conducted using conventional steady-state and phasor-based transient tools. The steady-state power flow and voltage profile studies usually decide the overall design, such as the series capacitor location, rating, and the number of installations required between north and south. Typically, these studies determine which of the topologies shown in Fig. 1 is selected. Furthermore, EMT tools are used to study phenomena such as switching overvoltage (SOV), transient recovery voltage (TRV), and temporary overvoltage (TOV), such as ferroresonance. Moreover, EMT and frequency domain tools are used to investigate subsynchronous oscillations (SSO) involving the WPPs and series-compensated lines.

There is a shortage of comprehensive summaries concerning how transmission system operators plan series-compensated network sections containing wind power plants. Moreover, an evaluation of the system design concurrently with design considerations for series-capacitor specifications is rare. Therefore, this work outlines the system planning studies involving series-compensated network sections in Sweden and discusses mitigation strategies for each phenomenon under investigation.

The remainder of this work is structured as follows. The initial planning studies that determine the overall design parameters are briefly covered in Section II, whereas the studies using EMT and frequency domain tools are thoroughly covered in Section III. Moreover, other phenomena such as power quality and geomagnetically induced currents (GIC) are discussed in Section IV. Subsequently, Section V discusses how the study results are incorporated into the series capacitor design specification to achieve the best possible system solution.

II. THE INITIAL PLANNING OF SERIES-COMPENSATION

The initial planning aims to specify the design parameters for a new series capacitor. The design parameters that must be considered in the initial planning studies are

1. rated series capacitor current, I_N
2. overload current
3. maximum swing current
4. capacitive reactance per phase, X_C
5. peak voltage magnitude of the metal-oxide varistor (MOV) protective level, U_{pr}
6. the series capacitor location
7. the number of series capacitor installations that are required between the north and south

A. *Power-flow and Phasor-based Transient Studies*

The series capacitor's rated current and overload current (parameters 1 and 2) are established using the power-flow study tool PSS/E. Furthermore, the maximum swing current (parameter 3) is typically examined using phasor-based transient simulations in PSS/E. The swing current is generated by the electromechanical oscillations of synchronous machines, which generally range between 0.5 Hz and 2 Hz. The capacitive reactance per phase (parameter 4) is determined by power flow and voltage stability studies, as well as the operational experience of the power-flow distribution between lines. Moreover, when determining the MOV protective level (parameter 5), the voltages associated with non-fault currents flowing through the series capacitor, such as the overload current and swing current, must be considered [9], [10].

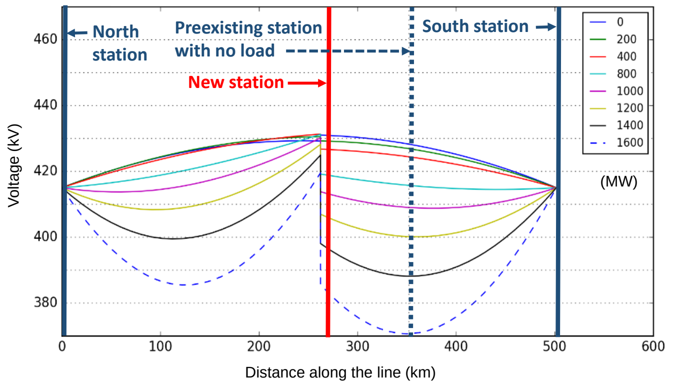
B. *Voltage profile*

Series compensation is an efficient method to control the voltage profile of long transmission lines [4]. The voltage profile of the series-compensated network section is crucial in determining the positions and number of series capacitor installations between north and south. Therefore, the design parameters 6-7 are determined during the steady-state voltage profile studies. An example of a voltage profile study is shown in Fig. 2, which illustrates a comparison between the topology shown in Fig. 1a and in Fig. 1b. Maximum and minimum voltages from the study is an essential component to determine how the project's topology is planned. Fig. 2 illustrates that, depending on the power flow, the voltage in the preexisting station could become excessively low if only one series-capacitor installation exists. The voltage profiles also depend on the WPP's operating state and the load in the preexisting station.

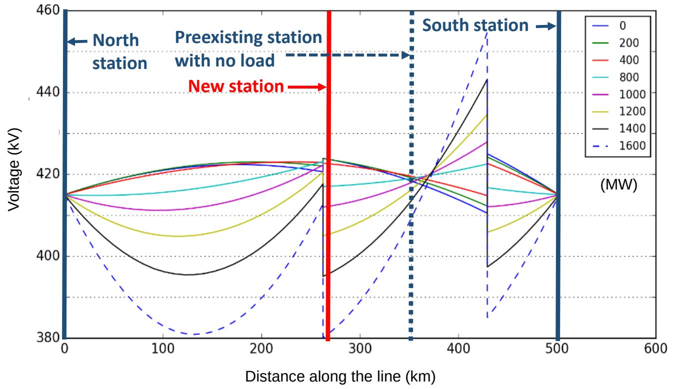
C. *Voltage- and Current Reversals*

The Swedish protection philosophy for series-compensated lines is described in [11]. Series-compensated lines are usually protected by distance- and differential protection. The series-compensation significantly affects the apparent impedances measured by the distance protections. Furthermore, the phasor currents and voltages occupy different positions in the complex plane compared to uncompensated systems. The term current inversion indicates a change of current direction, i.e., if the source-to-fault impedance becomes capacitive. Moreover, if the source-to-fault impedance remains inductive while the relay-to-fault impedance is capacitive, a voltage inversion occurs.

During the series-capacitor planning stage, protection studies are undertaken using the steady-state short-circuit calculation tool PSS/E. In the short-circuit program, the MOV protected capacitor is modeled by the Goldsworthy impedance as $Z_c = R_c(I) - jX_c(I)$, [12]. As the fault current I increases, the Goldsworthy impedance shifts from



(a) The north station in Fig. 1a is located at 0 km. Furthermore, the series capacitor is situated at around 260 km, directly followed by the new station. The dashed line represents the preexisting station at about 350 km, followed by the south station at about 500 km.



(b) The north station in Fig. 1b is located at 0 km. Furthermore, the first series capacitor is situated at around 260 km, directly followed by the new station. The dashed line represents the preexisting station at about 350 km. Moreover, the second capacitor is situated between the preexisting and south stations.

Fig. 2. The figure compares the voltage profiles of the topology shown in Fig. 1a with the topology shown in Fig. 1b, respectively. The north-to-south power transfer dependence is illustrated in both figures.

solely capacitive to capacitive-resistive. Consider the system Thévenin reactance X_{th} and the line up to the fault reactance X_l (without capacitor). If the fault current is not sufficiently high, it may happen that the source-to-fault impedance becomes capacitive and $X_{th} + X_l - X_c(I) < 0$. At the relay point, both voltage inversion and current inversion cause the current to lead the voltage. This may cause protection equipment to incorrectly identify the direction of a fault. An approach to detect voltage inversion is for the protection to remember and use the voltage polarity prior to the fault. Current inversion is more difficult to detect and cannot be handled in the same manner; therefore, current inversions are studied when planning the series-compensated network sections. The MOV protective level (parameter 5) is one parameter that may be adjusted to mitigate current inversion.

D. *Composite Short-Circuit Ratio*

The power system short-circuit strength (or weakness) is a relative concept considering both the system characteristics at a specific connection point and the size of the WPP to be installed [13]. The short circuit ratio (SCR) is a regularly employed metric for quantifying the relative impedance of a power system as perceived from a connecting point. The SCR is defined as the ratio between short circuit apparent power, from a three-phase to ground fault at a given location in the power system, to the rating of the WPP connected. Furthermore, the composite short-circuit ratio (CSCR) is calculated as:

$$CSCR = \frac{CSC}{P_{WF}}, \tag{1}$$

where P_{WF} is the sum of all wind power plants' nominal power ratings. The composite short-circuit apparent power CSC is evaluated by creating a common medium voltage bus and tying all WPPs of interest together at that common bus. When planning the series-compensated lines with WPPs in Sweden, special consideration is given to the CSCR. In the case of series capacitor bypass, the CSCR may become excessively low. Other, more rigorous methods, such as the equivalent short-circuit ratio (ESCR), have been shown to be difficult in terms of establishing what limits to consider or what actions that should be taken when employed as an area-wide screening tool (see [13] for the ESCR definition). Therefore, the CSCR is used to evaluate if further EMT studies and vendor discussions are required. The possibility of handling low CSCR depends on many factors, such as manufacturer type, control implementation, and parametrization. Therefore, ongoing discussions with turbine manufacturers on reasonable levels are recommended. However, guidelines exist in [13], where an SCR $<$ 3 is considered very weak.

III. ELECTROMAGNETIC TRANSIENT STUDIES

The EMT studies are conducted using PSCAD/EMTDC, with detailed models of components such as lines (modeled using frequency-dependent models), series capacitors, arresters, and transformers. The model is terminated through Thévenin equivalents at the boundary nodes. Manufacturer models are used to represent the wind farm under study.

A. *Switching Overvoltages*

High-speed auto-reclosing is used for Swedish 400 kV lines to increase reliability. In the case of a single-line-to-ground fault, which accounts for more than 80% of the faults on Swedish 400 kV lines [14], the healthy phases will have trapped charges that could lead to increased SOVs after reclosing. The magnitude of the trapped charge is depending upon several factors, including any residual charge in the series capacitors (if they are not bypassed). EMT simulations are carried out under different power-flow conditions and fault locations to evaluate the risk of flashover due to SOVs. Without line-end arresters, the SOV is usually lowest at the line's switched end and highest at the open end. However, line-end arresters significantly mitigate the open-end voltage. This effect is evaluated for each simulation by recording the maximum voltage in any of the three phases (case-peak) at the line ends and at five to ten equidistant points along the line. The SOV study employs the probabilistic method by taking the instant the breakers reclose following the 0.7 s dead time as a random variable. From the statistical distribution of

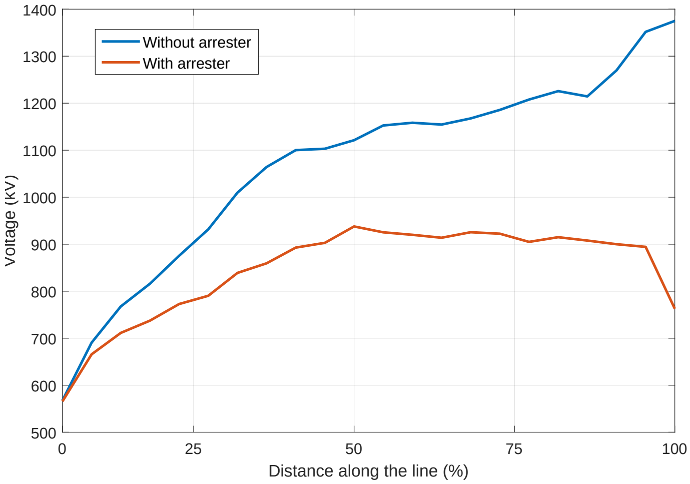


Fig. 3. SOVs are calculated as a function of the line's length by using the 2% maximum value at equidistant points along the line, with and without arresters, respectively.

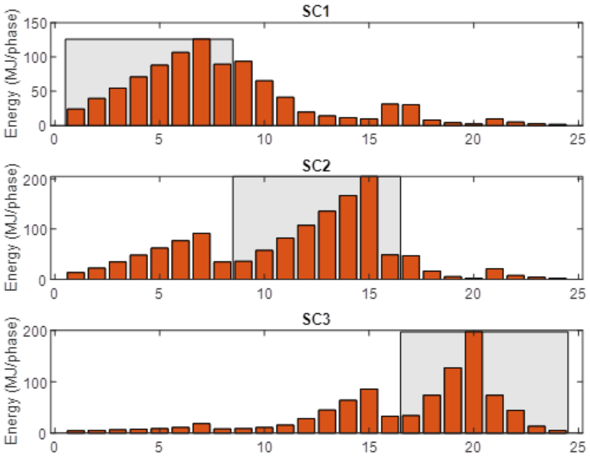


Fig. 4. Example of screening for MOV energy.

SOVs obtained by 200 reclosures, the 2% overvoltage level is retrieved as defined in [15]. The overvoltage profile is determined as shown in Fig. 3 by using the 2% maximum value at equidistant points along the line, with and without arresters, respectively. Furthermore, the risk of surpassing the line's insulation withstand capability under predetermined wind conditions is evaluated based on the 2% SOV profile provided in Fig. 3. Risk levels above 10% are deemed unacceptable. However, according to [16], the line's insulation shall withstand the representative slow-front overvoltage of 950 kV, which is also considered a reasonable target for achieving a flashover risk below 10%.

B. Zone and Duty Cycle

The MOV must be designed for the greatest amount of energy it will be exposed to during faults. The faults are stated in a fault duty cycle, which specifies the types of faults, the duration of the fault, and the pause time between subsequent faults. A distinction is made between internal faults, during which the series capacitor may be bypassed, and external faults, during which the series capacitor shall not be bypassed.

Using Fig. 1c as an example, the following are considered internal faults:

- a fault located on any of the three 400 kV line segment between stations north and south (see Fig. 1c)
- a busbar fault on any of the two stations between stations north and south
- a fault on any line between busbar and transformer/reactor

External faults are all faults located outside the transmission circuit between stations north and south, i.e., on parallel circuits or elsewhere in the transmission system, including stations north and south.

The risk of busbar faults or line faults with subsequent circuit breaker failure (e.g., on the short lines from the busbar to the transformers in the new stations) is small compared to the risk of faults on any 400 kV line segment between north and south or other lines connected to stations north or south. Therefore, the internal zone includes these faults. In addition, the consequence of faults on any 400 kV line segments between north and south is a loss of the total transmission capacity between stations north and south. The result of bypassing one or more series capacitors on the circuit during this scenario is minor.

Screening studies are carried out to determine the energy requirements of the MOV for different fault types and locations within the internal and external zone, respectively. The actual project vendor will undertake the detailed MOV dimensioning later during the project. Fig. 4 shows an example of an energy calculation for the network section corresponding to Fig. 1c, where SC1, SC2, and SC3 correspond to the three series capacitors. The bars represent MOV energy for three-phase faults and different fault locations along the line. The grey-shaded area corresponds to faults within the line segment for the respective series capacitor.

C. Transient Recovery Voltage

Series capacitors significantly impact the TRV [5], [6], [17]. Therefore, preliminary TRV studies are conducted during the system planning stage. The TRV is defined as the voltage across the circuit breaker contacts following the breaker opening, i.e.,

$$u_{trv} = u_s - u_l, \qquad (2)$$

where u_s and u_l represent the source- and line sides' phase-to-ground voltages, respectively.

The circuit breakers are tested according to the IEC standard [17], where the TRV peak values and rate of rise of recovery voltages (RRRV) are specified according to several test duties. The breaker capability is specified as an envelope associated with the rated short-circuit breaking current of the circuit breaker. In series-compensated systems, the TRV peak value is the most profound concern, whereas the RRRV is typically not a problem. The TRV behavior is different depending on the power system topology. Studies involving a single series-compensated line usually demonstrate that the line side preponderant contributes to the high TRV peak values. In

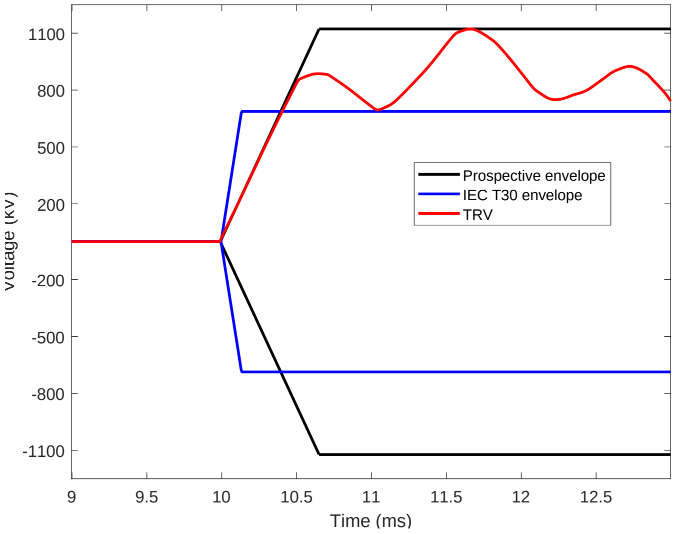


Fig. 5. The worst possible prospective TRV of a project planned as shown in Fig. 1c.

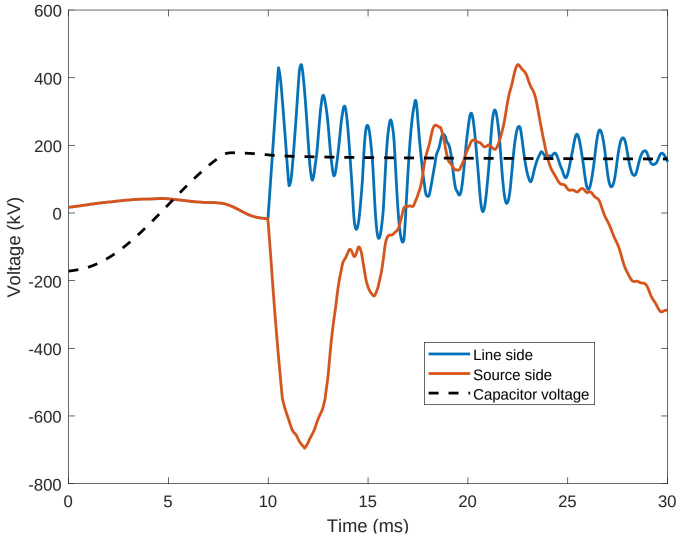


Fig. 6. Voltages at the source- and line-side of the circuit breaker contacts.

contrast, both the source- and line sides contribute if adjacent series capacitors exist on both sides of the breakers.

Next, consider the project envisioned as shown in Fig. 1c, comprising three series capacitor installations and two WPP stations. The short-circuit currents encountered by the breakers at the series-compensated lines were in short-circuit calculations less than 30% of the breakers' rated current; this test is referred to as T30 in [17]. For test duty T30 and 420 kV rated voltage, the breakers tested TRV peak value capability is 687 kV. Without line-end arresters, preliminary simulations in the project planning yield maximum peak values of approximately 1400 kV. Furthermore, line-end arresters reduced these peak values to approximately 1100 kV and maximum RRRV to about 1.7 kV/μs. The simulation of the worst possible prospective TRV is shown in Fig. 5. Furthermore, Fig. 6 shows how the phase-to-ground voltages on each side of the circuit breaker contribute to the high TRV peak value illustrated in Fig. 5. The black dashed line in Fig. 6 represents the capacitor voltage, which is limited by the MOV protection level. After a fault has been cleared, the capacitor remains charged at the MOV protection level, contributing to the line-side of the TRV peak value. However, for the project shown in Fig. 1c, arresters on the source side are equally important to mitigate the middle breakers' TRV peak values. The fault location and instant of fault inception were varied to find the worst case. However, only three-phase-to-ground faults were considered. Ungrounded faults can yield higher peak values than grounded faults, but they are deemed too uncommon to be considered. Manufacturers are consulted to ensure the circuit breakers can withstand the TRV peak values.

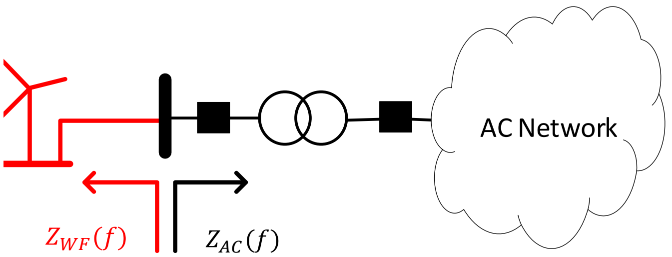


Fig. 7. Illustration of how the AC network impedance is separated from the wind power plant's impedance characteristics.

D. Temporary Overvoltages

Long lines may induce TOVs because of the Ferranti effect. However, TOVs mainly manifest as ferroresonance when series-compensated lines are involved. Ferroresonance severely impacts power quality and can also cause potential damage to electrical equipment when excessive voltages and currents are induced. A ferroresonance case study involving a series-compensated line was conducted in [7]. The case study illustrates how TOVs may occur in series-compensated systems. Moreover, the operational scenarios outlined in [8] provide prerequisites for TOVs manifesting as ferroresonance in the Swedish series-compensated system. Typically, for series-capacitor installations, as shown in Fig. 1a, the ferroresonance risk is more predictable due to the uncompensated line connection. Thus, ferroresonant behavior is improbable if the uncompensated line remains connected. However, it is more difficult to anticipate the risk of ferroresonance for projects planned according to, e.g., as shown in Fig. 1c. Two series-compensated lines will connect a no-load transformer if the WPP disconnects. In this instance, the general prerequisites for sustained ferroresonance are met [8].

E. Subsynchronous Oscillations

Numerical screening methods together with time domain simulations are efficient methods to investigate the complex nonlinear problem of SSO and to also develop countermeasures. The numerical screening utilizes a linearized power system representation; therefore, the solutions are only valid for small signal analyses. However, according to the

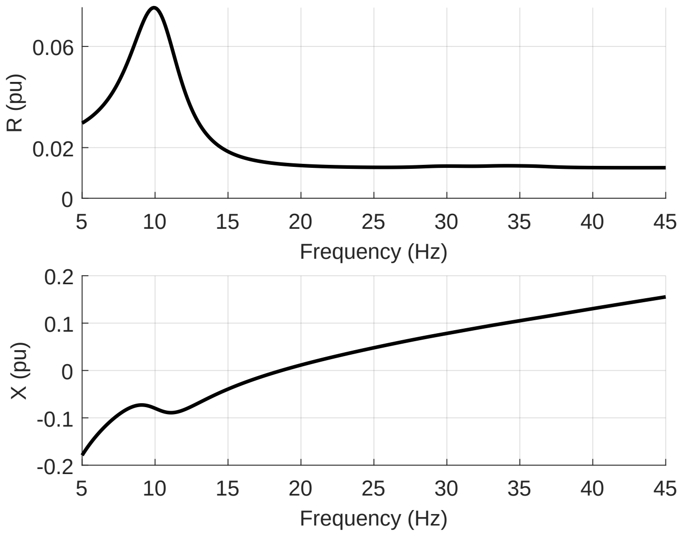


Fig. 8. AC network impedance for the project envisioned in Fig. 1c. The impedance is calculated from the 130 kV side of the transformer that links the WPP that is closest to the north station.

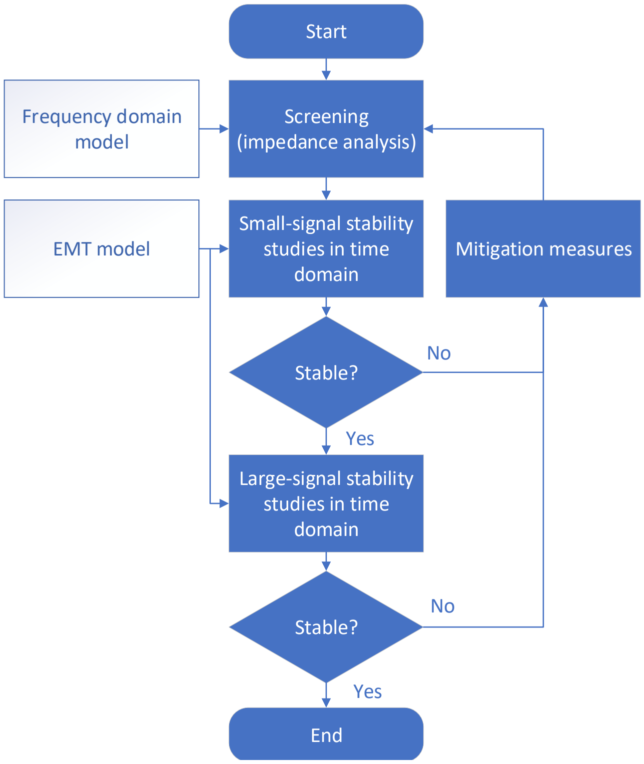


Fig. 9. Flowchart outlining the study's procedure.

literature [18], [19], the linearized solutions can use linear control theory to provide criteria for scenarios necessary to study in time-domain simulations. Consequently, the analyzed cases in time domain simulation are chosen because they fall below the margins appended to an impedance-based stability criterion [19].

In a typical project, the SSO risk evaluation examines WPP interconnections for the induction generator effect (IGE) and subsynchronous control interactions (SSCI). Using frequency domain tools, positive sequence impedance scans are undertaken early in a project to identify the most crucial operational conditions. As illustrated in Fig. 7, the AC network impedance Z_{AC} and WPP impedance characteristics Z_{WF} are separated in the studies. In the project's early stage, only the AC network impedance is known and can be used. For the project envisioned in Fig. 1c, the AC network impedance Z_{AC} is shown in Fig. 8 during a specific operational condition. Series resonances occur when the circuit reactance X fulfills the following conditions:

$$X(f_0) = 0 \quad \text{and} \quad \frac{\mathrm{d}\left(X(f)\right)}{\mathrm{d}f}\bigg|_{f=f_0} > 0, \tag{3}$$

where f_0 is the cross-over frequency. For the impedance Z_{AC} shown in Fig. 8, the cross-over frequency is calculated to $f_0 = 18.7$ Hz. The two factors used to evaluate the risk for SSO are: (i) how high the cross-over frequency is and (ii) how low the electrical damping is at the cross-over frequency. The complex circuit behaves as a series RLC circuit around a particular series resonance frequency; therefore, the effective inductance L is derived from an equivalent series RLC circuit by considering a point f slightly away from the point f_0 as:

$$L = \frac{fX(f)}{2\pi(f^2 - f_0^2)}. \tag{4}$$

Consequently, the network damping factor is calculated as

$$\zeta = \frac{R}{4\pi L f_0}, \tag{5}$$

where R is the circuit's resistance at the cross-over frequency f_0. For Z_{AC} shown in Fig. 8, the damping is calculated to $\zeta = 8\%$ at $f_0 = 18.7$ Hz, which is considered low.

In Sweden, discussions have begun to inform wind turbine manufacturers and park developers of the studies' conclusions and the concern for future SSO phenomena. The conversations provide park developers and vendors with information about upcoming requirements for collecting EMT vendor-specific models and the associated impedance characteristics (i.e., Z_{WF} shown in Fig. 7). In the later phase of the project, after the EMT model and impedance characteristics of the WPP have been gathered, the combined impedance of the AC network and WPP is utilized again using (3) and (5) to identify operational scenarios with increased risk of SSO. Finally, EMT simulations are conducted for selected scenarios based on screening investigations, as well as for disturbances that may involve nonlinear behavior or WPP disconnection problems (e.g., that may result in ferroresonance). Fig. 9 illustrates a flowchart of the study's methodology, containing a description of the mitigating measures' iteration. The preferred mitigation measure is to discuss re-tuning the WPP control system with park developers and vendors. Other mitigation strategies are sometimes acceptable, such as WPP disconnections caused by contingencies and protections that trigger when subsynchronous currents are detected. Furthermore, studies including transformer saturation have to confirm that potential ferroresonant waveforms are damped out by the WPP, but also investigate how phenomena may interact with one another.

The rapid increase of power electronic devices in the Swedish system has generated an increasing need to minimize the risk of control interactions between devices. However, system studies rapidly become too complicated and computationally intense when many devices are involved. Consequently, only the WPPs within a series compensated network section is usually evaluated in EMT studies, e.g., the two WPP connections for the project analyzed in Fig. 1c.

IV. OTHER PHENOMENA CONSIDERATIONS

A. Power Quality

To mitigate unbalance, overhead lines in the Swedish transmission system are transposed. If a new station is built along an existing line, the transposition scheme is updated to avoid excessive unbalance in the new station.

When the bypass switch of the series-capacitor is closed, the resulting circuit consisting of the capacitor in parallel with the current limiting reactor will have a resonance frequency of 600 Hz to 900 Hz. In case of a significant harmonic current in the line, this could lead to a high circulating harmonic current, which could overheat the reactor. Therefore, power quality meters continuously monitor harmonic currents on series-compensated lines.

B. Geomagnetically Induced Currents

Power systems with long transmission lines from north to south, specifically in the high latitude region of the northern hemisphere, are prone to GIC during geomagnetic disturbances. A series-compensated line introduces a high-impedance path to GIC. In Sweden, all network sections between the north and south are built using series-compensation. Hence, the GIC becomes blocked in the 400 kV network between the north and south. However, caution is needed when modifying the series compensated network sections and the distribution network; a high-impedance block may also re-distribute GIC in the network and increase GIC in other system circuits. Therefore, measurements implemented to monitor GIC have been the first step when modifying the series-compensated network sections.

C. Corona Discharge and Risk of Lightning Faults

Depending on the power flow, operating voltages exceeding those that are typical of uncompensated lines may occur on series-compensated lines. The voltage profile study illustrated in Fig. 2b shows that the voltage might become high close to the series capacitor installation. Increased operating voltages impact the risk of flashover due to lightning strikes. Moreover, there is an increase in corona discharges, leading to increased audible noise levels and higher corona losses. Consequently, the corona losses, lightning fault rate, and audible noise levels have been calculated for each line.

V. FINAL DESIGN CONSIDERATIONS AND DISCUSSION

Initial planning studies discussed in Section II establish the conditions for further detailed studies; however, the detailed studies discussed in Section III and Section IV may reveal the necessity for design modifications. Consequently, some concluding design considerations follow in this section.

A. Line-End Arresters

Studies conclude that line-end arresters will significantly mitigate both SOV and TRV. Line-end arresters will therefore be installed on the Swedish series-compensated lines. SOVs and TRVs are mitigated further with a lower arrester voltage rating. However, with a lower arrester voltage rating, there is an increased risk of TOVs exceeding the arrester's capabilities. Therefore, the rated voltage of $U_R = 390$ kV was considered the best option.

B. Series Capacitor Bypass

Before the line circuit breaker opens, it is possible to rapidly bypass the series capacitor by using spark gaps or other fast bypass techniques, thereby significantly mitigating the TRV. However, the fast bypass techniques typically introduce a vendor-dependent solution, prohibiting easy refurbishment from different vendors. Furthermore, spark gaps are also less robust compared to gapless solutions. Therefore, Svenska kraftnät endeavors to utilize gapless solutions. Instead, dialogues are undertaken with manufacturers to ensure that the circuit breakers can withstand the TRV experienced with line-end arresters in the simulations.

C. MOV Protection Level Revised

The MOV's purpose is to limit transient overvoltages across the capacitor by conducting excess transmission line current that would otherwise result in excessive capacitor voltage. The protective level is often expressed with the relationship to the rated segment voltage (or current) as:

$$U_{pr} = kI_N X_C \sqrt{2}, \tag{6}$$

where k is the per unit magnitude of the protective level. The selection of k must take into account the voltages associated with non-fault currents flowing through the series capacitor, such as the overload current and swing current. However, current reversal studies and TRV studies impose upper limits on k. Studies discussed in this work has concluded to specify $k = 2.0$ pu. Typical protective levels range between 2.0 pu and 2.5 pu.

D. Remedial Action Schemes and Subsynchronous Oscillation Protection

Undesirable phenomena are more predictable for projects planned as shown in Fig. 1a. Thus, the uncompensated line helps to maintain the middle station busbar voltages within specified limits and increases stability while it remains connected. However, for projects planned according to Fig. 1b or Fig. 1c, the risks of unwanted interactions or electromagnetic resonances are more challenging to handle. Consequently, mitigation measures include WPP disconnections (triggered by contingencies) and subsynchronous current protections that bypass the series capacitor. The power flow in the Swedish transmission system is usually from north to south (see Fig. 1), and the WPP shall contribute with power in the same direction. However, if the line between any new station and the south station trips, the direction of power flow shifts, and other line segments may become overloaded. Consequently, remedial action schemes that disconnect or dispatch down WPPs under particular high-load operational scenarios are required. However, these schemes need coordination with other schemes concerning SSO and electromagnetic resonances, such as ferroresonance.

VI. CONCLUSIONS

There is a shortage of comprehensive summaries concerning how transmission system operators plan series-compensated network sections containing wind power plants. Therefore, this work provided in-depth summaries of essential studies conducted at Svenska kraftnät using frequency domain- and EMT tools. Furthermore, based on the study findings, this work evaluated design considerations for series-capacitor specifications to achieve the best possible system solution. Design considerations regarding current inversion, TRV, and SOV, included reducing the MOV protection level and installing line-end arresters. Moreover, this work discussed mitigation measures for SSO and TOV based on frequency domain analysis and EMT simulations. Mitigation measures included WPP disconnections (triggered by contingencies) and subsynchronous current protections that bypass the series capacitor. However, discussions with park developers and vendors about re-tuning the WPP control system are considered the most successful and cost-efficient mitigation measure for SSO.

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