FINGRID

Utilizing Equivalent Short-Circuit Ratio (ESCR) approach for assessing the slow converter driven stability and tuning the voltage controllers

1.2.2023

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Change log

Date	Version	Changes
15.6.2022	1.0	First official release.
1.2.2023	2.0	Introduced a need to verify voltage controller tuning by external voltage change rather than voltage controller reference change. Changed terminology from $\mathrm{ESCR}_{\mathrm{HV}}$ to VCSCR.

1 Introduction

The purpose of this paper is to provide background information and actions concerning slow converter stability issues that might arise in Finnish network. Focus of the paper is in utilizing the equivalent short-circuit ratio for screening of the converter driven stability and determining the voltage control tuning.

Short circuit ratio (SCR) is well known value used to define grid strength. The change from synchronous generation dominated grid to converter dominated grid makes the metric insufficient for screening the slow converter driven instability and determining the voltage controller tuning parameters. The investigation of stability issues in converter dominated grid requires highly detailed wide-area simulation models. The paper presents an equivalent short-circuit ratio (ESCR) based method, originally introduced in the Cigre Brochure [1].

Chapter 2 presents a background for the paper including motivation and theory on the converter driven stability. Chapter 3 presents the ESCR approach by going through the definition and calculation method for SCR and ESCR. The chapter also discusses the stability studies in case a low ESCR value is detected as well as the automatic voltage regulator tuning by using Voltage Controller Short-Circuit Ratio (VCSCR) based method (earlier referred as $\mathrm{ESCR}_{\mathrm{HV}}$).

2 Background

2.1 Change to converted dominated grid

The large-scale integration of renewable production has brought up new stability aspects and study needs compared to traditional synchronous generator dominated power system. Many of these new aspects are becoming more and more relevant when the share of converter connected generation is increasing due to connection of renewables and decommissioning of synchronous generators.

Traditionally the electricity has been produced with hydro and turbo generators. In these synchronous generators, turbine is rotating the rotor in synchronous with grid frequency. The synchronous generators are inherently resisting frequency and voltage changes occurring in the network. Renewable energy sources, such as wind and solar power plants, are typically connected to grid via a converter. The converter connected generation do not have such inherent behavior like synchronous generators to resist frequency and voltage changes or inject fault current. The converter system measures the electric quantities, such as voltage magnitude and angle, and responses to changes in the system as programmed. To date, grid following converters (GFL) are the most widely used technology for integrating converter connected generation into power grid which mainly rely on Phase-Locked Loop (PLL) to get synchronized with the grid [2]. Already now Fingrid requires several grid supporting abilities such as voltage control as primary control mode and fault current injection from the converters. These abilities do not however match the inherent capabilities of synchronous generators.

The existing grid following technology for converter connected generation still requires synchronous generators in the system. The converters are measuring the voltage phase angle by PLL and inject current in the measured phase. The converters are prone to instability if the share of converters is high compared to the synchronous generators in the area. This instability is driven by the slow converter control loops, such as PLL or voltage controller, and it is referred as a slow converter driven stability [3].

There exists as well a fast converter driven stability class that is driven by fast control loops of power electronic-based systems, such as IBRs, HVDC, and FACTS [3]. The converters might as well interact with network or other converter(s) in subsynchronous frequencies. This phenomena is referred to as a resonance stability [3]. Fast converter driven stability and resonance stability phenomena are not discussed in this paper.

2.2 Converter driven stability

This chapter presents slow dynamic converter driven stability issues in low- and high-level controls of a converter. Grid forming converter (GFM) solutions are not discussed in this paper.

2.2.1 Low-level control instability

Converter connected generation are different to traditional electricity generators as they are synchronized with the electricity network via power electronics converters.

Phase-locked loop (PLL) plays a critical role in this synchronization between the inverter and the grid. Its main function is to measure the voltages at the point of common coupling (PCC) and automatically perform the required frequency and angle estimation depending on the converter control technology. To maintain stable operation of the converter, the PLL tracks voltage phase angle to inject the required current at the PCC.

The ability of PLL to track the voltage phase angle in the case of network faults can be extremely challenging in weak networks [3]. If the voltage phase angle estimated by the PLL is inaccurate during a fault, the current will not be injected correctly and will further impact the voltage waveform at the PCC. This could lead to unstable power system oscillation and eventually tripping of the wind farm.

2.2.2 High-level control instability

Fingrid requires converter connected generation with nominal power of 10MW or more to operate in constant voltage droop control. Also step response time from 0 to 90% of the final value is required to be fast, from 0.2 to 1.0 seconds. The overshoot must not exceed 15% of the final value. [4] [5]

Fast voltage control benefits the voltage stability of the network. Fingrid's network includes long 400kV lines which consume high amount of reactive power during high transmission situations. To keep the voltage of the network at an acceptable level during N-0 and N-1 situations the voltage support from power plants is needed. By including the fast voltage control, it is ensured that the voltage control will react to first voltage swing in case of voltage dip to support the system stability.

Dominating inter-area oscillation mode frequency in the Nordic grid varies between 0.3-0.5Hz. Voltage control step response below 1.0 second mitigates the risk of converter connected generation amplifying the oscillations. In some areas of Fingrid's network the local oscillation modes can limit the transmission capacity. Typically, in these areas the oscillation frequency is higher and the phase shift between the measured voltage and converter connected generation reactive power is so that oscillation is amplified. In these areas converter connected generation shall be equipped with Power Oscillation Damping (POD) to cancel out the weakened damping.

For converter connected generation, the primary method for adjusting voltage is to adjust the reference point (or point of common coupling, PCC) voltage of the power generating facility (hereafter 'power plant') typically located at the bus on the high voltage side of the plant main transformer(s). Typical reference value for the voltage control setpoint is 118 kV in Fingrid's 110 kV main grid and recommended slope is 4%. The voltage control principles are explained in more detail in the grid code [4]. Example of voltage control principle in converter connected power plant is presented in Figure 1.

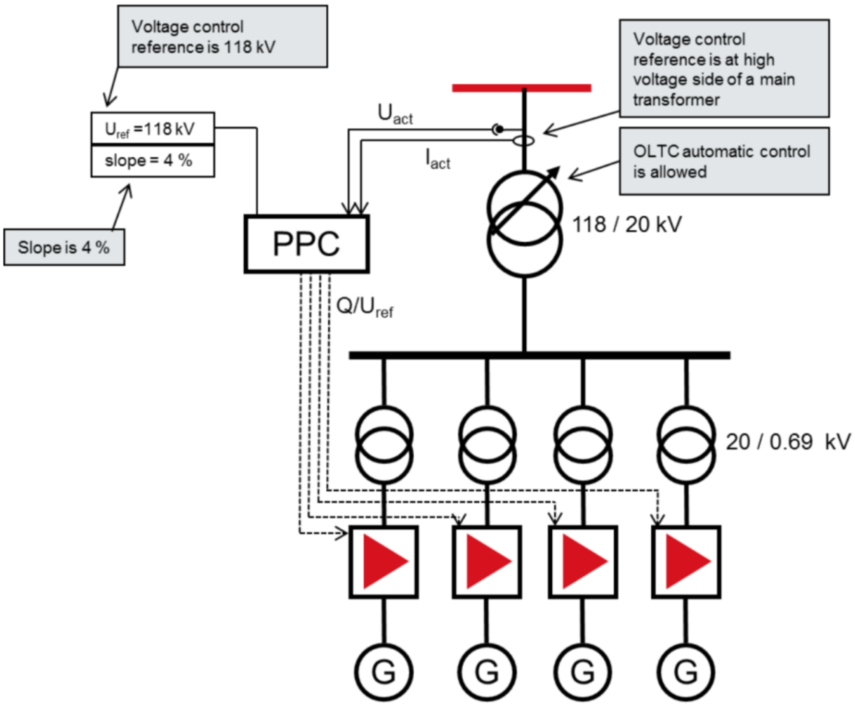

FIGURE 1. VOLTAGE CONTROL PRINCIPLE OF CONVERTER CONNECTED POWER PLANT [4]

The voltage controller tuning is conventionally done in a single machine infinite bus (SMIB) model, where background impedance is set to match the fault level of the point of connection delivered by Fingrid or measured during commissioning. Plant level voltage controller typically consist of PI controller. The control structure varies between different manufacturers. The PI controller proportional and integral gains, along with other parameters, are selected to fulfil the grid code requirements [4] for having a rise time of 0.2–1.0 s with than 15 % overshoot.

The voltage controller tuning is greatly affected by the background network of the connection point i.e. grid strength. Fairly accurate assumptions of the correct gain values can be given based on the short-circuit ratio (SCR) value and X/R ratio. Example of integral gain which gives specific rise time is presented in Figure 2. In this example proportional gain is integral gain divided by 50. The values were derived in SMIB model with background network X/R = 5.67 and generator P = 200MW. Dynamic models used were WECC-models REGCA1, REECA1 and REPCA1.

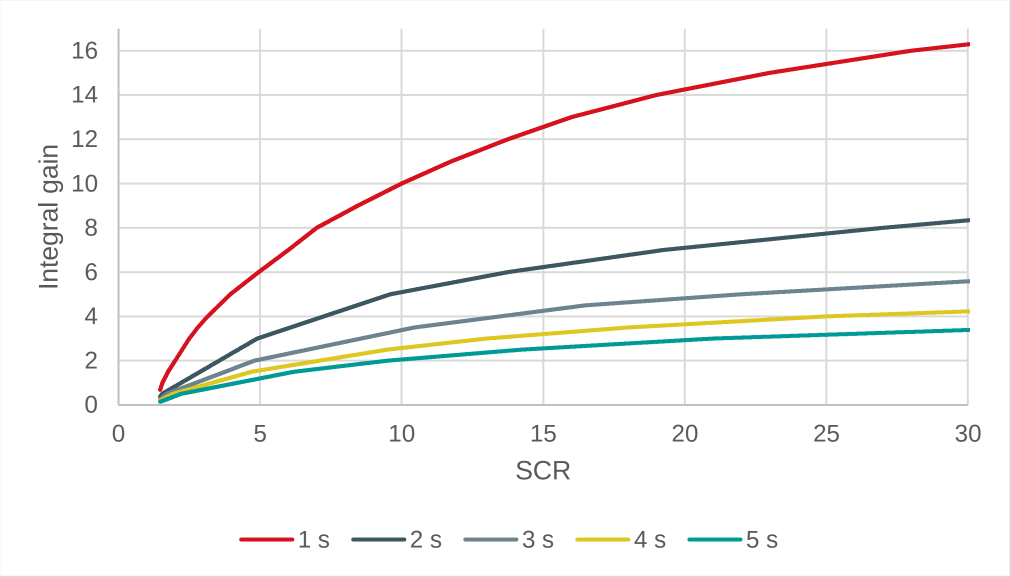

FIGURE 2. INTEGRAL GAIN IN REPCA1 MODEL TO GET SPECIFIC RISE TIME AS FUNCTION OF SCR

Based on the experiences, the SCR gives a good initial tuning parameter values in synchronous generator dominated areas in the grid. However, when voltage controller tuning is done in SMIB model, multiple stability issues can arise in real operation. Main reasons for incorrect or unstable operation are:

1. Incorrect background impedance value in SMIB or only high short-circuit level case is studied

In real life operation network short-circuit level can vary depending on the network conditions. The voltage control performance must always be simulated in high short-circuit level operation and exceptional low short-circuit level operation. The voltage control rise time and overshoot should be inside specifications in all possible network conditions.

2. Multiple parallel converters connected power plants in the same area

The SMIB model ignores all parallel power plants and devices that also adjust the grid voltage in same area. The amount of converter connected power plants that control the main grid directly has been low before, so this assumption used to be valid. Now the number of converters is rising rapidly, and the growth is focused in specific areas. These power plants can get the voltage reference even from the same bus or from vicinity of a bus regulated by another power plant. The droop makes sure that after settling period the voltage control responsibility is shared and well managed with parallel plants. Still, if multiple plants are connected to the same area, they share the same background network, and this affects the response during the rise and settling time. From the Figure 3 we see how parallel wind power plants affect the response of the studied wind power plant to a voltage change. Now with the lower combined SCR, the PI controller gains should be lower to achieve stable response to a voltage change. If parallel plants are not considered, the response to voltage change will be too fast or even unstable. Example of parallel converter connected power plants affecting the step response presented in Figure 3 is done with project specific custom models in real life network model. This change in behavior is not limited to only some of the turbine manufacturers.

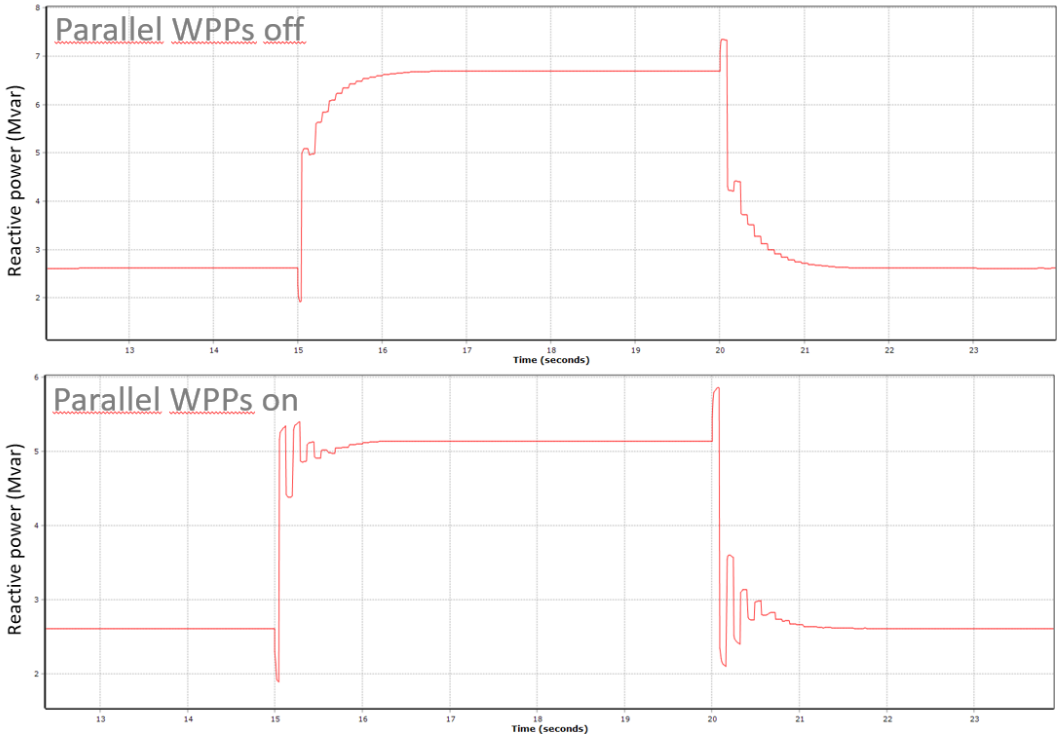

FIGURE 3. EFFECT OF PARALLEL WPPS TO STEP RESPONSE TO VOLTAGE CHANGE

3. Misinterpretation of the grid code tests

The voltage controller step response tests during commissioning have been traditionally done by changing the voltage setpoint of the power plant’s (park) controller. This approach gives good results for synchronous generation dominated network. However, if there are multiple parallel plants adjusting the voltage in the same area there is a high risk of misinterpretation of network conditions. When making the voltage setpoint change in one power plant other parallel plants will oppose the change. This will not give the same response as when the voltage change comes from the main grid and all units adjust to the same direction. What parallel plants opposing the setpoint change will cause:

a) The final voltage value is not what expected for specific reactive power infeed = misinterpretation of the grid strength, network seems much stronger

b) The rise time is slower than it would be for a voltage change from background network = possible unstable operation is not visible during commissioning

The effect can be clearly seen in simulations as presented in Figure 4. In this simulation identical power plants are connected to same high voltage bus. The normal operation is that the voltage change comes from the network side that switching a shunt reactor at PCC presents.

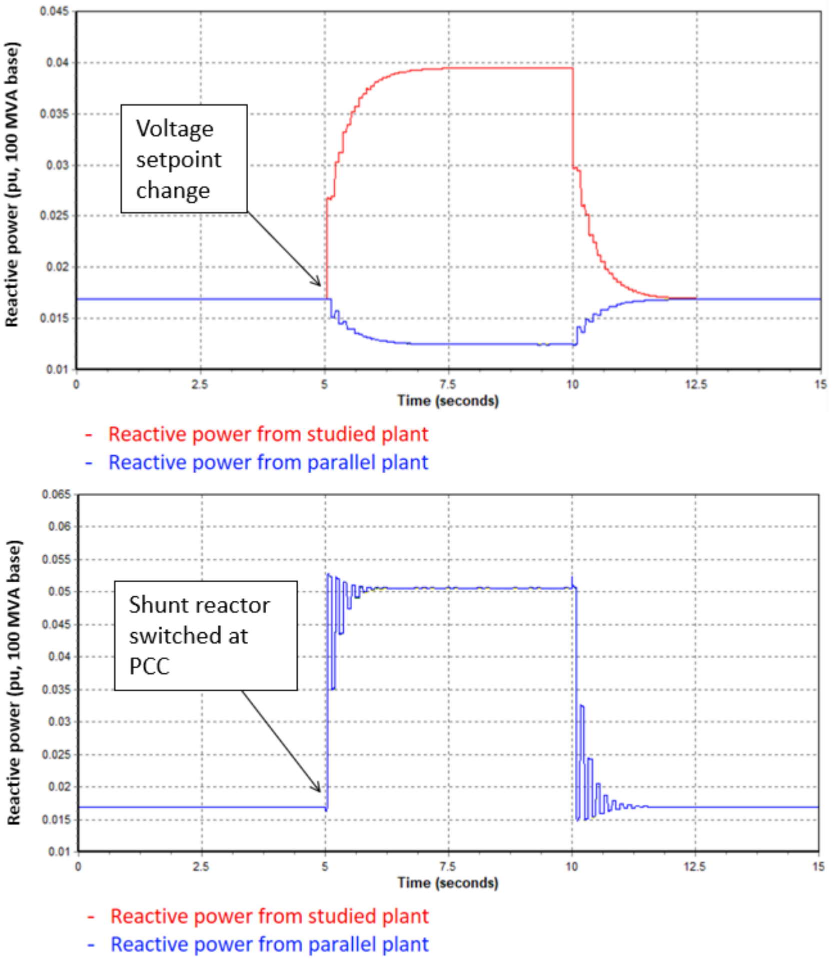

FIGURE 4. REACTIVE POWER FROM STUDIED PLANT AND IDENTICAL PARALLEL PLANT. STEP WITH SETPOINT CHANGE (ABOVE) AND SHUNT AT PCC (BELOW). IN BELOW FIGURE THE SIGNALS ARE OVERLAPPING.

Based on the results, there is a need to complement the commissioning strategy to include step response test with voltage change coming from background network. The voltage step can be done with compensation devices or on load tap changers of the main grid. The model validation in SMIB against the commissioning measurements can be impossible because parallel plants are not modelled in SMIB. Making the background network of SMIB stronger to achieve similar step response as seen in voltage setpoint change during commissioning does not present real life operation.

There should be no tuning of the power plant done based on the results obtained by the step response by doing voltage setpoint change.

4. Tuning the voltage controller of the PPC by voltage reference change

The voltage controller tuning has been traditionally verified by changing the voltage setpoint (Vref) of the PPC. In real life, fast changes in voltage controller setting value does not typically occur. The actual purpose of the voltage controlling device is to respond to voltage changes caused by actions in the external grid.

The simulations have shown that some turbine types and power park controllers tend to have a significantly faster rising times to external voltage change than to Vref changes. The Figure 5 shows an example where the voltage controller of the PPC has been tuned to have around 0.9s rise time in with Vref (red curve). When an external change to voltage reference is made by switching a shunt reactor in the PCC, the rise time decreases to around 0.4 s with over 20 % overshoot. This example shows the need to utilize external voltage changes rather than Vref change when the voltage controller tuning is verified.

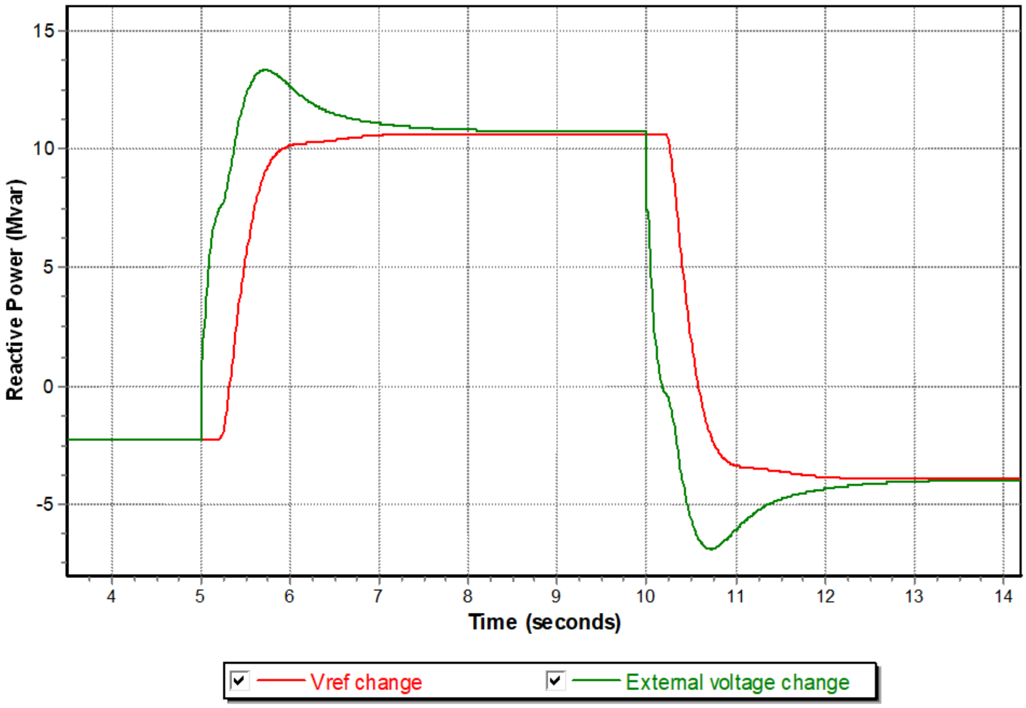

FIGURE 5 COMPARISON OF STEP RESPONSE TEST BY DOING A VOLTAGE STEP CHANGE (RED CURVE) AND BY ADDING A SHUNT REACTOR TO PCC (GREEN CURVE).

3 ESCR approach

3.1 Definition and use of SCR

Short-circuit ratio (SCR) is widely used in the industry for assessment of the strength of the connection point for converter connected systems. SCR is commonly used as a screening method to assess the need for more detailed stability studies. SCR is as well widely used to tune the controls such as voltage controller of converter connected systems. SCR can be calculated by using the following formula

$$SCR = \frac{S_{net}}{P_{con}}$$

where the S_{net} is network’s fault level created by synchronous generators and P_{con} is the nominal active power of the converter connected system. SCR can be seen as an indication of the system’s ability to respond changes caused by current injection. System having high SCR can be called as a strong system that is not highly affected by changes created by the converter connected system. Accordingly, a system with low SCR, called as a weak system, is greatly affected by current fed by converter connected system. System with low SCR is more vulnerable to issues such as control system instabilities or control interactions.

SCR can be seen as suitable tool for the defined purposes for areas with high penetration of synchronous generators. For example, in systems having even up to tens of converter connected devices, such as wind power plants, the SCR does not work as a suitable metric.

3.2 Calculation of ESCR and VCSCR

Cigre Brochure B4.62 [1] introduced several different metrics that are considering the parallel converter connected devices: Composed Short-Circuit Ratio (CSCR), Equivalent Short-Circuit Ratio (ESCR) and Weighted Short-Circuit Ratio (WSCR). In a meshed system, such as Finnish 400kV, 220kV and 110kV network, the ESCR was considered more optimal metric than WSCR or CSCR.

In ESCR calculation, all the converter connected devices in the system are considered in the calculation. The device’s active power is weighted based on their electric closeness to the studied wind power plant. The formula for ESCR calculations is following:

$$ESCR_i = \frac{S}{P_i + \sum(WPIF_{ji} * P_j)} = \frac{S}{P_i + \sum(\frac{\Delta V_j}{\Delta V_i} * P_j)}$$

where P_i is the maximum active power of studied converter connected unit, P_j is the maximum active power of other converter connected unit, S is the network short-circuit contribution to the connection point of the studied converter connected unit and $WPIF_{ij}$ is meaning wind power interaction factor between converters j and i. The wind power interaction factor is representing the electric closeness of the studied converters. The $WPIF_{ji}$ can be calculated with power flow simulations by creating a voltage step in the studied converter bus i. The calculation can be done by dividing the voltage change in the other converter bus j (ΔV_j). with voltage change in the studied converter bus i (ΔV_i).

Fingrid has developed a python program that calculates the ESCR values for all of the converters modelled in the network. The script calculates two different ESCR values: $ESCR_{MV}$ and VCSCR (previously called as $ESCR_{HV}$). In $ESCR_{MV}$, the value is calculated by doing the voltage step for converter medium voltage bus and in *VCSCR* to the regulated high voltage bus. The calculation of *VCSCR* uses WPIF-filtering to achieve optimal controller tuning as it was found out in the studies that the electrically distant power plants with lower WPIFs have even less impact on the voltage control response than what the WPIF indicates. In the filtering process the WPIF values are calculated with an exponent to have exponential filtering of the value. Current approach is to apply exponent of 3.5. Fingrid is using the $ESCR_{MV}$ values to screen the need for more detailed stability assessment. The *VCSCR* value is for finding initial tuning parameters for the voltage controller.

In Figure 6 is presented a simple example for calculating the SCR_{HV}, SCR_{MV}, *VCSCR* and $ESCR_{MV}$ values for a system with two 100 MW wind power plants and background network strength of 700 MVA. In the example the SCR_{HV} can be calculated by dividing the grid strength (700 MVA) with wind power active power (100 MW). In this example the short-circuit-power visible in medium voltage level is slightly lower (500 MVA) than the short-circuit-power in HV level due to the impedance of HV-MV transformer.

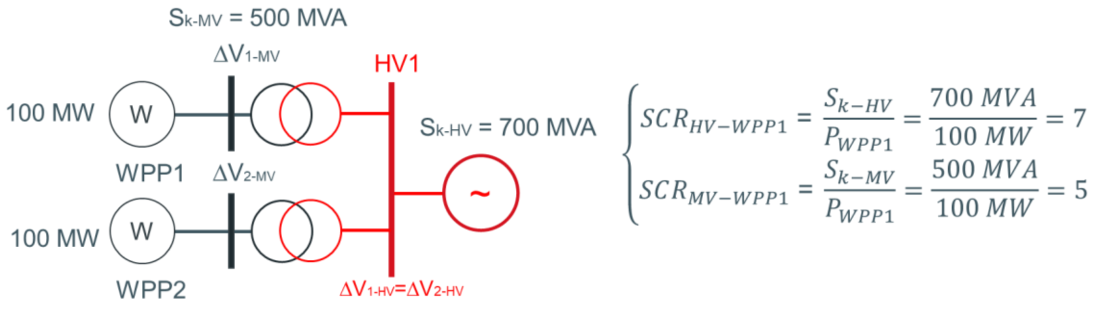

FIGURE 6 EXAMPLE FOR SCR AND ESCR CALCULATION FOR SIMPLE SYSTEM INCLUDING TWO WIND POWER PLANTS

The calculated SCR_{HV} values are not considering parallel wind farm WPP2 which might lead to too fast tuning of the voltage controller that might lead to high overshoot or unstable behavior. The $WPIF_{HV}$ can be calculated for the WPP1 by doing a voltage change $\Delta V_{1\text{-HV}}$ to WPP1 HV bus and looking the voltage change $\Delta V_{2\text{-HV}}$ at WPP2 HV bus. In this example, both wind power plants have the same HV bus they are controlling which leads to wind power interaction factor of $1^{3.5} = 1$. In the connection process, the delivered VCSCR value would be used for voltage controller tuning.

$$VCSCR_{WPP1} = \frac{S_{k-HV}}{P_{WPP1} + \left(\frac{\Delta V_{2-HV}}{\Delta V_{1-HV}}\right)^{3.5} * P_{WPP2}} = \frac{700\,MVA}{100\,MW + 100\,MW} = 3.5$$

The calculated SCR_{MV} values are not considering parallel wind farm WPP2 which might be optimistic metric to use to screen needs for more detailed EMT studies. The needed $WPIF_{12\text{-}\mathrm{MV}}$ can be calculated for the WPP1 by doing a voltage change $\Delta V_{1\text{-}\mathrm{MV}}$ to WPP1 MV bus and looking the voltage change $\Delta V_{2\text{-}\mathrm{MV}}$ at WPP2 MV bus. The WPIF leads to value 0…1 depending on the electrical distance between the wind power plant MV-busses. In this example, the voltage change on medium voltage bus 1 was 1.0 kV that caused a voltage change of 0.6kV for medium voltage bus 2. Thus, $WPIF_{21}$ can be calculated to have a value of 0.6 and $\mathrm{ESCR}_{\mathrm{MV\text{-}WPP1}}$ to have a value of 3.125. In the connection process, the delivered $\mathrm{ESCR}_{\mathrm{MV}}$ value would be used for assessing the need for detailed EMT based studies.

$$ESCR_{MV-WPP1} = \frac{S_{k-MV}}{P_{WPP1} + \frac{\Delta V_{2-MV}}{\Delta V_{1-MV}} * P_{WPP2}} = \frac{500\,MVA}{100\,MW + 0.6 * 100\,MW} = 3.125$$

3.3 Stability studies in case of low medium voltage ESCR

The $ESCR_{\mathrm{MV}}$ value is used for screening of low-level controller stability. It describes how large the number of grid-following converters are sharing the same short-circuit power in one area. Low $ESCR_{\mathrm{MV}}$ value is representing that it is more likely that there will be risk for low-level controller unstable operation. The low-level controls operate in microsecond timescale and therefore cannot be simulated in RMS transient stability software. To simulate low-level controller stability, EMT type software must be used with vendor specific power plant models.

From the EMT simulations it has been seen that SCR and $ESCR_{\mathrm{MV}}$ do not correspond each other directly. It has been seen that power plants are typically more stable in lower $\mathrm{ESCR}_{\mathrm{MV}}$ values in large scale EMT-model than similar SCR in SMIB-model. The real-life operation depends on the network topology, power flow situation, local load and initial short-circuit level. The large scale EMT-model is not available for project developer due to model confidentiality and compatibility issues.

Correct measures to verify stable operation in specific $ESCR_{\mathrm{MV}}$ shall be discussed together with Fingrid (TSO), owner of the connecting grid (such as DSO) and plant supplier. Based on the CIGRE report the $\mathrm{SCR}_{\mathrm{MV}}$ values below 2 have a higher probability of low-level controller instability [1]. For screening purpose, the same threshold can be used for $ESCR_{\mathrm{MV}}$ value. Stable operation can be verified with studies including EMT-type simulations.

In case of unstable operation caused by low-level controllers is observed in simulations or real-life operation, active power output must be lowered to stabilize the power output. Other possible solutions are re-tuning the inner controls for weak grid operation, implementing grid-forming functionalities, installing synchronous condenser or changing the network condition by topology change.

3.4 Automatic voltage regulator tuning with high voltage VCSCR

The optimal way of tuning the voltage controller of the power plant would be to include all detailed power plants models to large network model. This way the plant interactions would be correctly captured. This is usually not possible due to model confidentiality and compatibility issues. Also, the power plant models might not be available for power plants coming in the area in near future.

The filtered *VCSCR* value can be utilized to consider the parallel converter connected power plants in voltage controller tuning. For voltage controller tuning the background network impedance Z_{SMIB} is changed corresponding to the VCSCR value:

$$Z_{\mathrm{SMIB}} = \frac{U_{PCC}^2}{P_{\mathrm{n}} \cdot VCSCR}.$$

The X/R ratio is kept same as it is in normal short-circuit level. Example of the SMIB topology is presented in Figure 7.

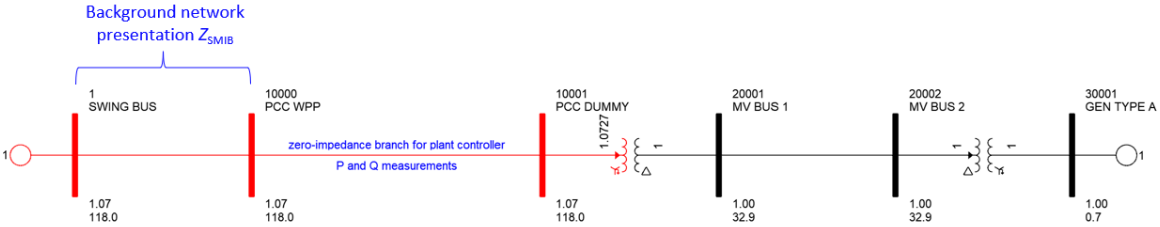

FIGURE 7 EXAMPLE OF SMIB TOPOLOGY

The VCSCR tuning gives good estimation of what voltage controller parameters should be, however the method does not always guarantee optimal results. Depending on the topology of the real-life network, if it is radial or meshed, the approach can give too slow, or too fast step response. According to studies including real network topology and multiple wind power plants with project specific custom-models, the VCSCR tuning effectively reduces overshoot and instability of voltage control. In all cases the VCSCR tuning prolongs the rise time compared to common tuning method with SCR.

Low VCSCR values can initiate a need to tune existing converter connected power plants that might face unstable operation without action. If unstable voltage controller operation is observed the following actions must be done until stable operation is achieved:

1. Change operation mode to Q-control and use setpoint 0 Mvar
2. Lower active power output

If previously presented actions do not stop the unstable operation, the power plant must be disconnected from the network. It should be noted that active or reactive power oscillation amplitude may be rather low. Unstable voltage controller operation might not be seen in measurement data with low sampling rate.

It should be noted that SMIB model with VCSCR defined background network should be only used for voltage controller tuning as it does not present any real-life network solution.

Tuning of the power plant voltage controllers considering VCSCR is discussed more detailed in [6].

4 References

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