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Methods for Risk Assessment of SSCI Stability Issues Between Renewable Generation and Series Compensated Transmission Systems

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SUMMARY

Application of series capacitors in high-voltage transmission lines can lead to subsynchronous control interactions (SSCI) between the series capacitors and renewable energy sources such as wind or solar generation. SSCI can lead to dynamically-unstable power systems, high-magnitude voltage and current oscillations, and damage to power equipment in the generation, transmission, and distribution systems before the instability is detected and the source of the instability is isolated. This paper describes, at a high level, some basic methods of assessing the risks of SSCI and an evaluation of various SSCI mitigation strategies.

KEYWORDS

Subsynchronous interaction (SSI), SSI mitigation, renewable generation, series capacitors, series compensated transmission lines, frequency scan, bypass filter, remedial action schemes (RAS), subsynchronous current detection, topological bypass, thyristor controlled series capacitors (TCSC)

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Introduction

Recent expansions in both renewable energy and transmission capacity have increasingly placed the transmission of power generated by wind and solar technology through series compensated transmission lines. The application of series capacitors on HV transmission lines can lead to subsynchronous control actions (SSCI) between the series capacitors and the electrical and control systems of renewable generation.

SSCI, whether it is as straightforward as the induction generator effect (IGE) in simple induction machines (for example, Type 1 and Type 2 wind turbine generators, or thermal solar generation), or it is a more-complex interaction of a generator's voltage and current controllers (Type 3 and Type 4 wind turbine generators, or full DC-AC conversion in solar generation or even back-to-back DC installations), can lead to dynamically-unstable power systems. [4]

A SSCI instability can lead to high-magnitude voltage and current oscillations and damage to power equipment in the generation, transmission, and distribution systems before the instability is detected and the source of the instability is isolated. A specific example of this type of event is described by D. Kidd and P. Hassink in [1].

This paper describes, at a high level, some basic methods of assessing the risks of SSCI in series compensated systems with renewable generation, and also compares various SSCI mitigation strategies available in the industry.

Reactance Frequency Scans

Scans of positive sequence impedance (R + jX) as a function of frequency are described in detail for both the system side (disconnect the generator in focus and scan "outward" into the transmission system) as well as the generator side (disconnect the system from the generator in focus and scan "inward" into the generator). [2] [3] Summing the two scans together (because the two elements are connected in series) produces a set of curves that are useful in identifying SSCI risks. Figures 1, 2, and 3 below demonstrate a hypothetical set of scans (note that the turbine-side scan is not an actual result of a scan of any specific generator):

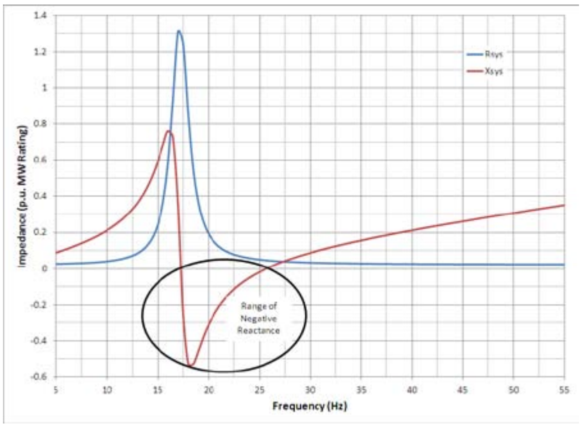


Figure 1
System-Side Scan

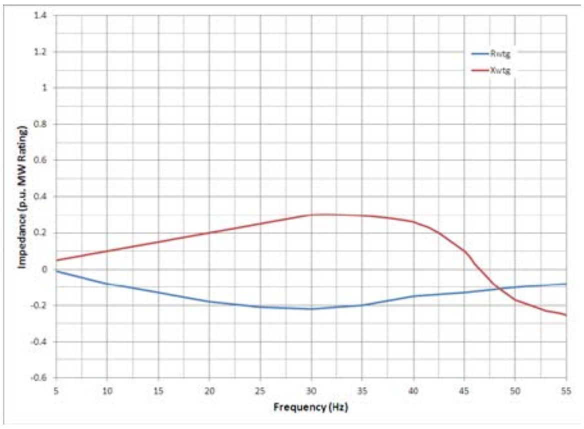


Figure 2
Turbine-Side Scan

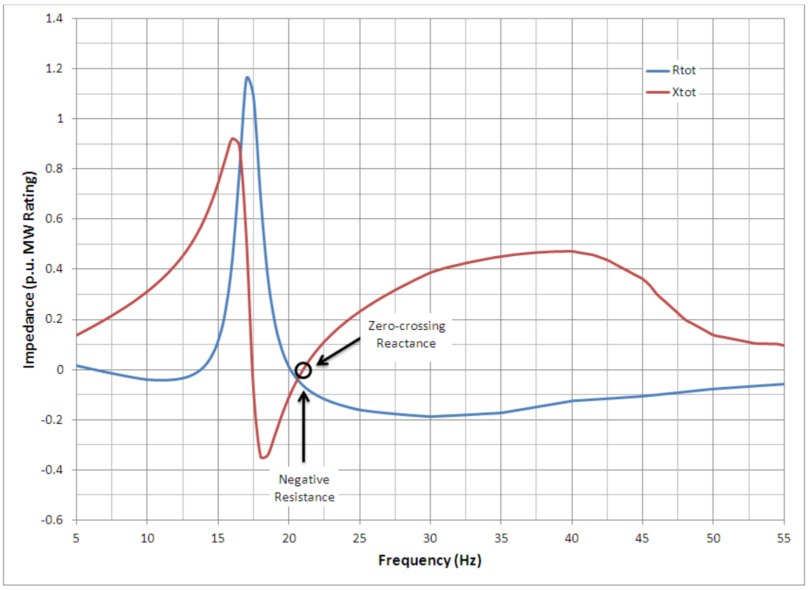


Figure 3
Turbine + System Scan

Figure 1 shows a system side scan of a series compensated system with a fairly severe outage placing the generation in a near-radial condition with series compensated transmission lines. The area of the reactance curve circled (from about 17-26Hz) is where the reactance is less than zero (i.e. net capacitive).

Figure 3 shows, in the ideal screening case, an unstable resonant condition at about 21Hz. The resonant condition is where the reactance crosses zero (with a positive slope – the negatively-sloped zero crossings are generally associated with a band-block resonance with a high resistance instead of a band-pass resonance, which is what we are looking for). The resonance is unstable because the effective resistance at that same frequency is negative.

Generator-side scans are often problematic for one or more of the following reasons: (1) the actual generator manufacturer/designer has not yet been selected and this screening is taking place before that decision is made, (2) not all generator manufacturers have developed accurate time-domain models that are adequate to evaluate the effective complex impedance versus frequency relationship, (3) renewable generation developers often have an arms-length relationship with their equipment suppliers, (4) large renewable generation stations (e.g. wind farms) may use equipment from multiple vendors that have significantly different characteristics, and (5) those manufacturers who have a solid understanding of this phenomena and have adequately modelled their equipment and controls in the time-domain guard those models as proprietary and a third party performing analysis often must work with “black box” models that are cumbersome and of limited utility.

Because of the challenges associated with turbine-side scans, a fast and effective screening technique is to use system-side reactance scans, with the generation in-focus disconnected, looking out into the system. Other generation in the area can be modelled simply, as a series RL in front of a voltage source (e.g. Ra + jX”d for a synchronous machine), connected to the system through and appropriate series RL representing the transformers and lines connecting the generator to the transmission system. For other renewable generation this can be done as well, and the impedance values used can be estimated by typical values found for other kinds of generation, with an appropriate magnitude relative to their MW rating. It is not as important to hit these values 100% accurately, because as a first-pass scan the results will be indicative and not authoritative.

The use of linear positive sequence elements in the system reduction allows the frequency scan to be completed quickly for a large number of outage conditions. Plotting reactance versus frequency curves facilitates a quick and intuitive review which leads to the identification of a few “red flag” cases that, like in Figure 1, show a frequency range of interest that has the potential to cause a resonance.

A note on units for reactance: the rated maximum MW output of the generator, or of the entire installation (e.g. the entire wind farm), as an impedance base is a useful tool because it can be quickly adapted to outages within the installation. The short-circuit ratio (SCR), or the ratio of the 60Hz short-circuit MVA divided by the rated MW output of a generator or of the whole installation, is simply the inverse of the reactance if it is expressed in per-unit of the MW base (as contrasted with using the per-unit of the MVA base). For example, a system-side reactance of +j0.40 p.u. at 60Hz is the same thing as a SCR of 2.5. The SCR is a measure of how strong the system is, how "hard" the generation must "push" (through a power angle) to transmit power into the system.

An outage at the wind farm that takes out, for example, half of the wind turbines, will cut the MW rating in half and double the Z_{BASE} used for per-unit calculations. It will also double the SCR since the remainder of the system is mostly unchanged.

On Figure 1 the maximum frequency where there is negative reactance is about 26Hz. This is at a zero-crossing point with a positive slope, which means it is a band-pass resonant frequency for the system-side circuit. Consider a simple radial circuit from a wind turbine generator to the grid that goes through a series compensated transmission line:

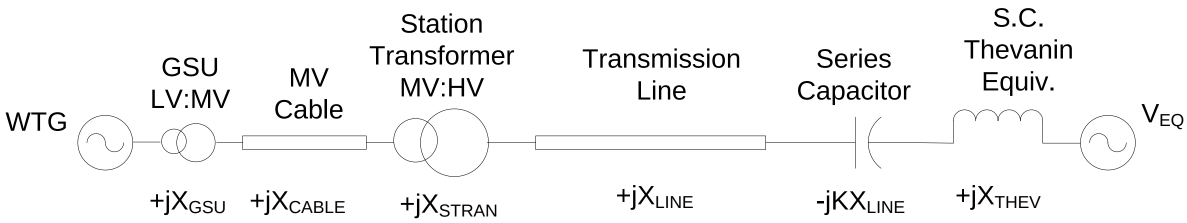


Figure 4
Simplified Radial Circuit

In Figure 4 above, the SCR and the resonant frequency of the system-side scan can both be calculated as follows :

$$SCR = \frac{1}{X_{GSU} + X_{CABLE} + X_{STRAN} + (1-K)X_{LINE} + X_{THEV}} \tag{1}$$

$$f_{RES} = f_0 \sqrt{\frac{KX_{LINE}}{X_{GSU} + X_{CABLE} + X_{STRAN} + X_{LINE} + X_{THEV}}} \tag{2}$$

Where K is the value of line compensation (as a fraction of total line reactance) and f_0 is the system power frequency.

For a wind farm at full power rating with all WTG's online, typical values of reactance are (in p.u. of the MW rating) about 4% to 6% for the GSU, about 2% to 4% for the MV cable, and about 8% to 12% for the station transformer. Large wind farms often have a short sub-transmission lines (e.g. 138kV) connecting the station transformers to the another substation with another transformation to the transmission voltage (e.g. 345kV) with another 10% to 20% reactance. This provides for a total reactance between about 15% and 40% for the connection between the WTG (which can be treated as a lumped-equivalent for the purposes of a system-side scan) and the sending side of the HV transmission line.

From Equation (2) it can be seen that resonant frequency is maximized for a given value of K in the case of a very large wind farm (lower Z_{BASE} for a higher MW rating), a very tight connection with only two transformations (15% reactance), a very long transmission line, and a very strong short circuit Thevanin equivalent representing the grid. In this situation, *SCR* varies roughly with the inverse of the length of the transmission line.

Table 1 below shows the results of calculations using Equations (1) and (2) for a variety of different radially-connected systems:

Table 1
SCR and f_{RES} Calculations for Several Example Radial Systems

$X_{GSU\text{->}STRAN}$	X_{THEV}	X_{LINE}	*K*	*SCR*	f_{RES}
15%	3%	10%	10%	3.70	11.3 Hz
15%	3%	10%	30%	4.00	19.6 Hz
15%	3%	10%	50%	4.35	25.4 Hz
15%	3%	10%	70%	4.76	30.0 Hz
15%	3%	25%	10%	2.47	14.5 Hz
15%	3%	25%	30%	2.81	25.1 Hz
15%	3%	25%	50%	3.28	32.3 Hz
15%	3%	25%	70%	3.92	38.3 Hz
15%	3%	50%	10%	1.59	16.3 Hz
15%	3%	50%	30%	1.89	28.2 Hz
15%	3%	50%	50%	2.33	36.4 Hz
15%	3%	50%	70%	3.03	43.0 Hz

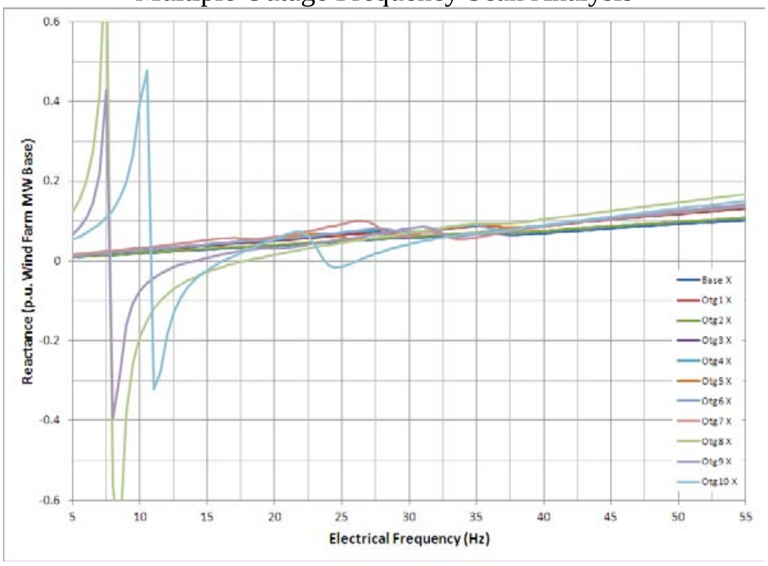
The importance of the relationship between *SCR*, *K*, and f_{RES} is that, through an analysis of system-side frequency scans, you can quickly find the maximum subsysnchronous frequency of interest and largely ignore frequencies above this value. In cases where the outages do not place the wind farm completely radial to the series capacitors and there is no zero crossing reactance in the screening, the analysis above can be used to calculate a maximum frequency of interest.

By the simplifying reduction of the system to a configuration of linear positive sequence impedance values, many different outages can be quickly screened using time-domain current injection or voltage disturbance tools combined with FFT's of voltage and current [2], or by simply inverting the complex impedance matrix after scaling all of the system reactance's proportional (for inductive elements) or inversely proportional (for capacitive elements) to the testing frequency. The latter technique is orders of magnitude faster than the former in terms of processing time.

Outages can be systematically selected to produce an exhaustive search for outages that create a band of negative reactance in the subsynchronous frequency range, or they can be strategically selected based on what outages place the flow of power more and more radial to the series capacitors in the transmission system.

After screening system-side reactance versus frequency for a large number of probable (and some improbable) outage cases, all reactance scans can be plotted on the same graph for a quick first-pass review of the results. Figure 5 below shows an example of such an analysis:

Figure 5
Multiple Outage Frequency Scan Analysis



From this analysis, several options may be available for follow-up. Among those options are:

1. None of the outages, or at least none of the outages with a reasonable likelihood of occurring, produce a range of frequencies with a negative reactance. In such a case, it may be (depending on the generation technology selected) that the wind turbine (or other device with potential for SSCI) has a net positive effective reactance over the frequency range of interest, and thus there is no potential for resonance and low risk for SSCI.
2. Only a few outages with negative reactance are identified, and they are severe and unlikely, however they need to be addressed. Rerunning those outages again with the series capacitor bypassed may suggest a remedial action scheme (RAS) where the series capacitor bank is automatically bypassed under certain system conditions. More on this in the next section.
3. Modest or even likely (e.g. N-1, like described in [1]) outages create a range of frequencies with significant negative reactance. These cases should be studied further, preferably with an accurate time-domain model of the wind turbine technology, to see if there is indeed a problem.
4. There is negative reactance in part of the subsynchronous frequency range in the base (N-0) condition, suggesting a potential SSCI problem that may not be easily solvable. These cases, again, should be studied in more detail with an accurate time domain model of the wind turbine technology.

Note that, in addition to the reactance scans identifying frequency ranges with negative reactance, they can also be used to evaluate issues associated with low SCR. In general, the more-severe the outage, the lower the SCR. The worst-case SCR can be visually seen as the highest reactance at a frequency near 60Hz. For example, in Figure 5, of the 10 outages the highest reactance was about 0.17 p.u. at 55Hz, so the lowest SCR among those cases was about 60Hz/(55Hz*0.17p.u.) = 6.4, which is a relatively strong system compared to the MW rating of the bank. Some renewable energy technologies may have difficulty transmitting rated power as SCR gets too low. This analysis allows a quick assessment of conditions that may lead to problems associated with low-SCR.

Mitigation Strategies

An assortment of strategies to mitigate unstable SSCI conditions is available for consideration. They vary widely in terms of both complexity and expense. Several of them are described and compared below.

Remedial Action Schemes (RAS)

The best and easiest way to mitigate an unstable SSCI condition is to simply interrupt the interaction. This can be done by either tripping the generation offline, or by bypassing the series capacitor bank, before the instability causes elevated subsynchronous voltages and currents to damage power system equipment. Because of the economics involved, it is generally better to bypass the series capacitor bank before you trip the generation, however this may not always be the case.

Note that bypassing series capacitors will usually effectively mitigate an unstable SSCI condition, however the action will also lower the SCR as well. This may or may not lead to other problems related to low SCR. Also, many RAS schemes require a reliable and timely communication path between the series capacitor bank and the relay making the bypass decision. This is generally not an issue for new series capacitor banks, but may be an issue for existing banks, especially if they are at a midline position.

RAS – Topological Bypass

A "topological bypass" scheme can be automated, where the positions of a list of line and/or transformer circuit breakers (i.e. the system topology) are evaluated, and certain combinations produce a bypass and lockout request for a given series capacitor bank, and other combinations produce an insertion request (or perhaps an insertion permissive, so the operator can manually insert the bank) for the same bank. Such logic is generally simple to come up with and to execute, and it is generally fast enough to remove the series capacitor bank from the resonant circuit before an instability can grow to damaging levels.

Often the outages identified by the screening technique described in the previous section as having potential for risk of unstable SSCI can be quickly and easily mitigated using the topological bypass technique, even before the renewable generation technology is selected. In many cases, outages that place a wind farm in a radial or near-radial condition to the series capacitor bank also places the system in a condition where very little power is flowing through those series compensated lines, largely negating the need for series capacitors.

RAS – Power Flow Based Bypass

A general rule could be followed of "only insert the series capacitor when it is needed, and leave it bypassed otherwise," and this could lead to an avoidance of many SSCI issues. A technique used effectively to mitigate torsional instabilities in thermal generation (because thermal generation is less-susceptible to SSR at higher power levels) is to measure both magnitude and direction of power flow through the transmission line that has the series capacitor bank in it, and bypass the bank if power flow falls below a certain value and/or reverses in direction. At a higher power flow (with a dead band in between the two thresholds to avoid repetitive bypass and insertion) the bank is automatically reinserted.

Because severe outages that put a wind farm radial or near-radial to the series capacitors might, at the same time, reduce power flow or even reverse the direction of power flow, such a scheme might be possible to set thresholds on magnitude and/or direction of real power flow for the purposes of automatic bypass and reinsertion that will effectively mitigate the problem.

One benefit to this technique is that the power-flow measurement can be done near the series capacitor bank (line-to-ground voltage measurements may need to be added at site) if there is an issue transmitting this information through a communications path to the site. This kind of technique could be used at a midline location, for example, if reliable and timely communications from a remote location are impractical and/or a greater degree of series bank autonomy is desired.

RAS – Segmentation Schemes

Series capacitor banks can be broken up into multiple switchable segments. Sometimes they are made multi-segment due to equipment limitations, especially for large banks (e.g. voltage limitations of the bypass switch). They can also be segmented to allow for some flexibility in RAS bypass schemes. For example, a bank that is split in a 1/3, 2/3 fashion will have 4 compensation levels: 0%, 33%, 67%, and 100% (expressed as a fraction of maximum compensation, not as a fraction of line reactance).

Segmentation allows for flexibility in RAS bypass schemes. For example, the screening method described in the previous section may show a slight negative reactance in a given frequency range for a given outage condition with all of the compensation in, and then with 1/3 of the compensation bypassed the frequency shifts downward and the reactance "dip" no longer crosses zero. This may be useful in cases where the SSCI instability needs to be avoided, but the SCR drops too low if all of the compensation is bypassed.

RAS – Detection of Subsynchronous Currents

When a SSCI instability is going to cause equipment damage, a large magnitude of subsynchronous current conducts through the series capacitor bank which is causing (half) the problem. Unlike torsional instabilities where SSR currents may be very low magnitude and remain low in magnitude while still damaging the torsional system, SSCI instabilities generally result in high-magnitude, unmistakeable, and relatively-easy to detect subsynchronous currents.

A relay can be programmed to monitor the level of subsynchronous current through the series capacitor bank over a range of frequencies (this range can be left as wide open as practical, or narrowed to the frequency ranges of interest as identified by the studies, depending on tradeoffs between accuracy, timeliness of detection, and range of frequency detection), and alarm and bypass thresholds with delays appropriate to the SSCI risk can be selected. A similar scheme may be used to trip the wind farm offline based on local measurements of subsynchronous voltage and currents. [1]

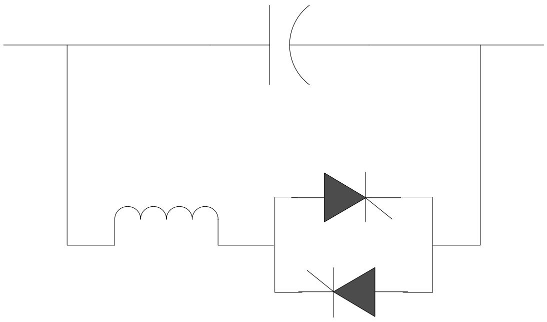
While the currents are generally easy to detect, some instabilities are so severe that this technique may not be fast enough to bypass the bank (or trip the wind farm) before damage occurs. The relative severity of the instability may be accessible via system + generation frequency scans by looking at the magnitude of the negative resistance and the slope (Ohms per rad/s) of the reactance curve at the zero-crossing reactance frequency to derive the effective inductance and to calculate a time constant (2L/R). While indicative, such a method to estimate the severity of the instability is only accurate for simple induction machines or synchronous machines in an induction generator effect (IGE) instability.

To assess the severity of the instability accurately requires an accurate time domain model and/or specific equipment testing to recreate/simulate the specific instability identified.

Thyristor Controlled Series Capacitors (TCSC)

Figure 6 below shows a TCSC:

Figure 6
TCSC



TCSC technology has been traditionally applied in long-distance AC transmission connections where its power oscillation damping (POD) functionality was required. Depending on the valve firing algorithms used, however, it has also been demonstrated as effective at mitigating torsional destabilization (also known as subsynchronous resonance, or SSR) caused by the use of series capacitors. [5] Some valve firing algorithms, however, do not mitigate SSR.

The vernier action of the thyristor valve firing can make the series impedance of the TCSC much more resistive and much less negatively reactive (or even positively reactive in some cases) over the frequency ranges of interest, which can effectively mitigate SSCI resonance. Again, however, this is firing control algorithm-dependent. Some algorithms work very well, while others can actually make the problem worse.

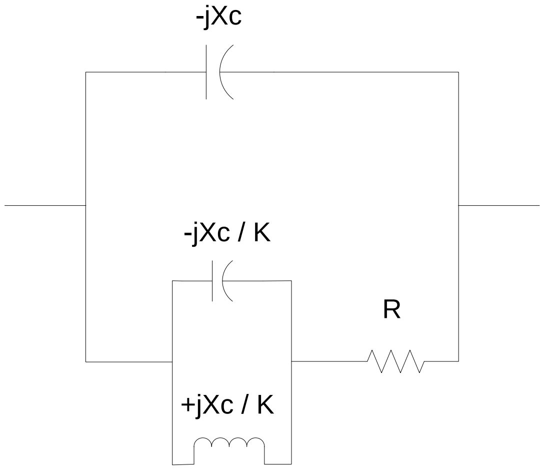
Evaluating the efficacy of SSCI or SSR mitigation of a TCSC poses the same sorts of problems discussed in the previous section regarding turbine-side impedance scanning. It requires an accurate time-domain model that contains the control algorithms that will be used in the application, the performance is heavily dependent on these proprietary and guarded algorithms, and at the end of the day you must trust the model developed by the TCSC manufacturer (or their analysis if they don't give you a "black box" model for use in your own analysis).

TCSC is generally very expensive and complex compared to the RAS schemes described previously. Water cooling at high voltages is generally required for valves in continuous vernier operation. While there are a few operating TCSC's in the world, SSCI has never been the primary purpose of application. While SSR mitigation has been demonstrated in the field [5], SSCI has not yet been demonstrated other than in simulation.

Passive Damping Filters

Figure 7 below shows a passive damping filter placed in parallel with a series capacitor bank:

Figure 7
Passively Damped Series Capacitor



Where K is the level of recirculating current in the parallel LC tank circuit, the idea of this circuit is to increase the level of effective series resistance for a broad band of subsynchronous frequencies and also to lower the magnitude of the negative reactance of the bank for frequencies below a frequency value that goes up and down with the value of K. The parallel LC tank circuit is tuned to power frequency to block/minimize steady-state Watts losses through the filter resistor.

SSCI from Type 3 and Type 4 wind generation is generally well-mitigated with a small recirculation value and thus a small passive filter circuit. This solution is easily analysed without special time-domain modelling or "black box" models containing proprietary algorithms. It can even be accurately modelled using the positive sequence reactance frequency scan technique described in the previous section.

This solution is more complex and more expensive than the RAS schemes described above, and generally less-complex and less expensive than a TCSC. The filter requires no water cooling. The filter can be added in parallel with the fixed series capacitor bank later and even controlled by a separate and relatively autonomous control system as it does not increase any steady-state or transient duties on the existing series capacitor bank equipment. In fact, the resistor will help to increase damping of the bypass device, which will reduce duties on the bypass circuit by dissipating most of the stored $0.5CV^2$ energy in the resistor rather than in other components.

One major drawback of the passively damped series capacitor is that it has not yet been applied on an actual series capacitor bank. The principles of passive damping circuits and LC tank circuits, however, have been applied many times in harmonic filter banks and a few times in SSR blocking filters placed between the neutral bushing and ground of GSU transformers to block specific SSR currents.

Mitigation at the Generator Level – Control Algorithms

The manufacturers of renewable energy and their associated voltage and current controllers represent a wide range of awareness, familiarity, and expertise with respect to SSCI phenomena. A few manufacturers of wind turbines, for example, are able to "tune" their controls to provide, for example, more positive reactance at subsynchronous frequencies and less effective negative resistance, or even positive effective damping resistance, through the subsynchronous frequency range, which makes their equipment less-susceptible (or even immune) to SSCI instabilities.

For Type 3 wind turbines, as an example, mitigation at the wind turbine control level may be available depending on the vendor selected. [4] This particular technique, however, is often impractical because the person who is performing the analysis and identifies the potential risk often has no say in which wind turbine vendor gets selected.

Conclusions

A method, positive sequence system-side reactance frequency scan, to quickly screen for SSCI stability risks is described, with suggestions on how to approach a follow-up analysis based on the results. While more-rigorous approaches are generally preferred, often the time domain analysis of the renewable generation technology is impractical or even impossible because the specific manufacturer of that equipment may not even be known at the time of the study.

Several SSCI mitigation methods are shown and compared. They range from relatively simple and inexpensive RAS schemes to more-complex and expensive passive damping and TCSC equipment. In the vast majority of cases, SSCI can be addressed using simple analysis to rule out the likelihood of interaction or with RAS bypass schemes described in this paper. It is for this reason that more complex and more expensive solutions such as TCSC and passive damping filters are almost never chosen, though some utilities can hedge their bets by leaving space in the yard for the addition of a filter or a conversion to a TCSC and "hooks" on the bank to more-easily adapt the bank in the future, should either the system change or new analysis comes to light highlighting a significant SSCI risk.

BIBLIOGRAPHY

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[1] D. Kidd, P. Hassink "Transmission Operator Perspective of Sub-Synchronous Interaction" (TD2012-000514, 2012 IEEE PES Transmission & Distribution Conference & Exposition, Integrating Wind Power into Series-Comensated Transmission Systems: System Studies)

[2] M. Sahni, D Muthumuni, A. Gole, A. Kulkarni "Advanced Screening Techniques for Sub-Synchrnous Interaction in Wind Farms" (TD2012-000609, 2012 IEEE PES Transmission & Distribution Conference & Exposition, Integrating Wind Power into Series-Comensated Transmission Systems: System Studies)

[3] G. Irwin, A. Isaacs, D. Woodford "Simulation Requirements for Analysis and Mitigation of SSCI Phenomena in Wind Farms" (TD2012-000600, 2012 IEEE PES Transmission & Distribution Conference & Exposition, Integrating Wind Power into Series-Comensated Transmission Systems: System Studies)

[4] E. Larsen "Wind Generators and Series-Compensated AC Transmission Lines" (TD2012-000371, 2012 IEEE PES Transmission & Distribution Conference & Exposition, Integrating Wind Power into Series-Comensated Transmission Systems: Modeling and Controls)

[5] J. Hauer, W. Mittlestadt, R. Piwko, B. Damsky, J. Eden "Modulation and SSR Tests Performed on the BPA 500 kV Thyristor Controlled Series Capacitor Unit at Slatt Substation" (95SM532-2PWRS, IEEE/PES Summer Meeting, July 23-27, 1995)