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COMPARATIVE PERFORMANCE OF SMART WIRES SMARTVALVE WITH EHV SERIES CAPACITOR: IMPLICATIONS FOR SUB-SYNCHRONOUS RESONANCE (SSR)

Brief Overview of Sub-Synchronous Resonance

Series capacitors have been applied for decades in power systems to increase transfer capability of long transmission lines. The reduction of the series inductive impedance of a transmission line brings benefits for voltage and reactive power control, and increased transient and steady-state stability limits.

As viewed from the terminals of nearby generators, series compensated transmission lines may introduce a *resonance* (a condition where the combination of equivalent inductance and capacitance of the network is either zero or infinite) in the network impedance at frequencies below 60 Hz (sub-synchronous).

The mechanical shaft system of large turbine generators (i.e. steam-powered generating units) is comprised of a couple to several stages of steam injection to turbine planes along a common shaft which is coupled to the electric generator. In steady operation, all turbine shaft sections are rotating at identical speeds, and the deflection (twist) across each interconnecting shaft section remains constant. In steady operation, these masses and springs move together at the same frequency. In terms of dynamics, this rotational arrangement is akin to a linear system of multiple masses interconnected by springs.

If a mechanical or electrical (at the generator terminals) disturbance is applied, the actual speed of each rotating mass will oscillate around the average speed of the entire system. The frequencies at which these oscillations will occur are defined by the *natural frequencies* of the rotating system. It is common for the natural mechanical frequencies of large turbine generator systems to lie between 10 and 50 Hz.

A general concern with series compensation of transmission lines, therefore, is the potential for creating electrical network resonances at points near the natural mechanical frequencies of large turbine generators. The most famous manifestation of sub-synchronous resonance (SSR) was in the early 1970’s at the Mohave generating station in the U.S. southwest. With the network configured such that the generator was connected radially to a 500 kV series compensated transmission line, shaft damage was experienced that required very expensive repairs and idling of the unit for many months. Technical investigations of this event were primarily responsible for the electric power industry’s awareness of SSR and the additional concerns over application of series compensation to transmission lines.

Each application of series compensation to a new or existing transmission line must be carefully evaluated to preclude SSR with existing turbine generators. The necessary technical evaluations are specialized and can be quite complicated, requiring a significant investment of time and resources. All of the possible operating configurations of the transmission network must be considered, and line outages and other contingencies may expose a generator to SSR risk that under normal system conditions would not otherwise be susceptible. Given the extreme consequences (in terms of total cost to repair a damaged generator), a large measure of caution surrounds any prospective series capacitor application. In addition, some form of mitigation, either at susceptible generators or at the series capacitor installation itself, is generally advisable.

Countermeasures for SSR

When SSR involving one or more generators is identified through system screening studies, some form of protection or mitigation is nearly always a requirement. The protection measures are intended to identify a SSR response when it occurs and take action to prevent damage to system equipment, especially generators. Mitigation measures go to the root of the phenomena to preclude undesirable interactions of the generator mechanical system with the electrical network.

A comprehensive discussion of SSR protection and mitigation measures can be found in [1] and [2]. Measures range from sizing of the series capacitors to avoid SSR conditions that would interact with nearby generators, to detection of torsional oscillations in generators followed by unit tripping, to schemes applied to the series capacitors to either bypass or modulate their behavior if subsynchronous currents and voltages are detected. All of the measures increase the complexity of the system, increase the costs, and potentially create system operating restrictions.

Introduction to the Smart Wires SmartValve

The SmartValve, a modular Static Synchronous Series Compensator (SSSC), injects either a leading or lagging voltage via a current transformer to synthesize an inductive or capacitive reactance. The SmartValve thus increases or decreases the transmission line reactance, either pulling more current into the line (capacitive mode) or pushing current away from the line (inductive mode). When the secondary of the transformer is not shorted (i.e. switches S_2 and S_M open, Figure 1), a waveform of desired frequency and magnitude is injected in series into the transmission line. When the secondary is shorted (i.e. switches S_2 and S_M closed), the waveform is isolated and the transmission line appears as its natural reactance plus some small leakage reactance from the SmartValve transformer.

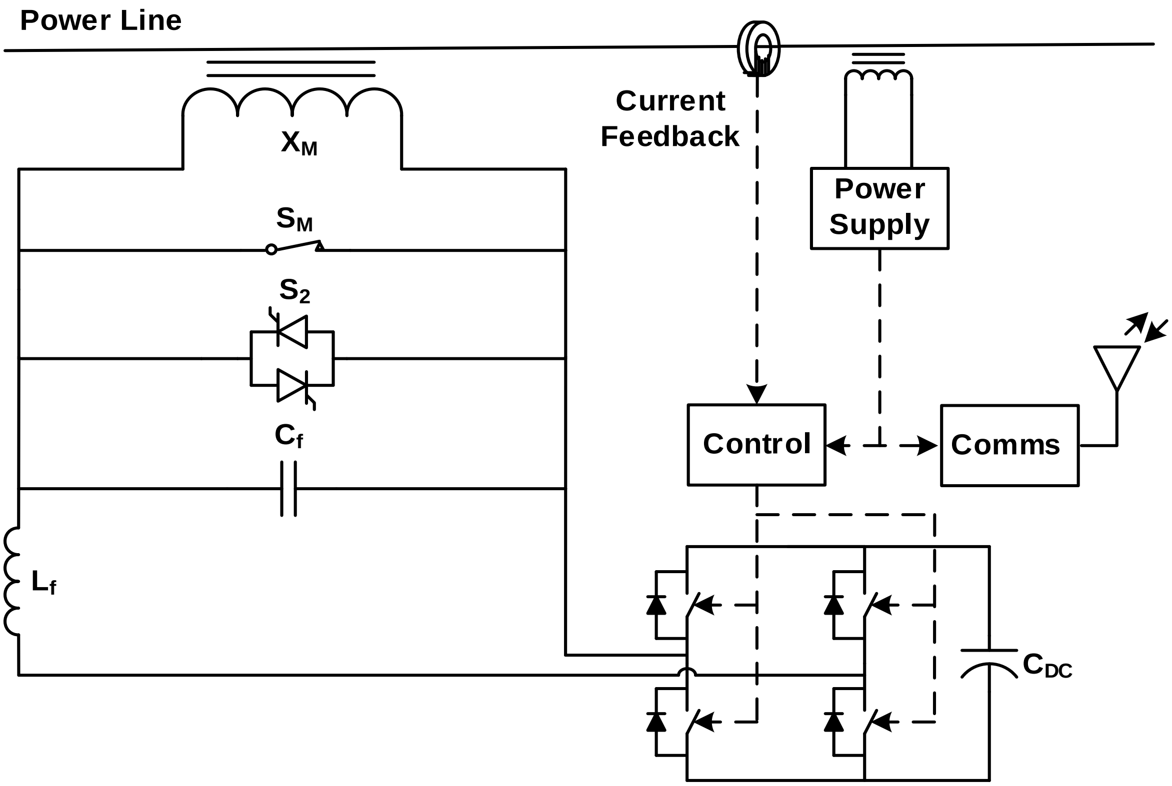

Figure 1: Smart Wires SmartValve concept and schematic

Illustration of SSR with IEEE Second Benchmark Model

The IEEE Second Benchmark Model (SBM) for SSR is used here for illustrating the comparative performance of the SmartValve and a conventional passive series capacitor. A one-line diagram of this model is shown in Figure 2.

The model consists of a single generator (SM1) with step up transformer, two parallel transmission lines, and an infinite bus (SYS1). One of the transmission lines contains a series capacitor sized to compensate for 70% of the series inductive reactance.

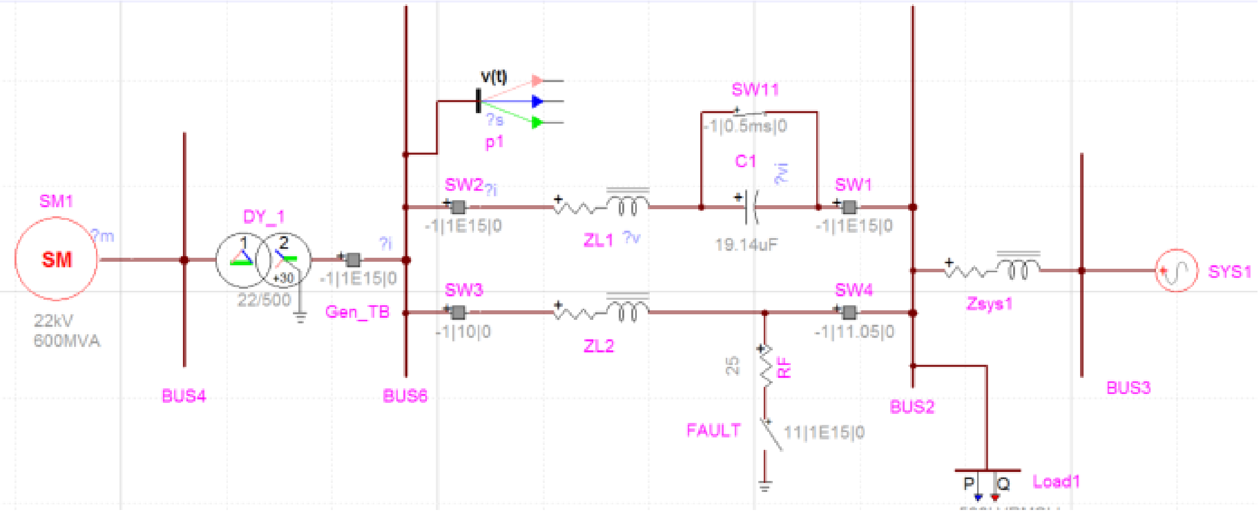

Figure 2: One-line diagram of IEEE SBM for SSR

The generator mechanical system in the SBM is comprised of 4 distinct rotating masses – the HP turbine, LP turbine, synchronous generator, and exciter. The specification of the stiffness of each coupling shaft, as defined in the SBM, results in three natural modes of oscillatory vibration in the generator mechanical system. One of these modes, where the generator rotor and exciter swing against the two turbine sections, has a mechanical natural frequency of 24.65 Hz. The other two oscillatory modes have natural frequencies of 32.39 and 51.10 Hz, and do not come into play in these simulations with the selected level of series compensation.

The series compensation creates a single series resonance point – as viewed from behind the generator armature windings toward the network – at about 35 Hz. As is shown in [1], generator armature currents at the electrical resonance frequency of 35 Hz will induce oscillatory torque in the mechanical system of 25 Hz (i.e. 60 Hz – 35 Hz).

A simulation case using the SBM was run to illustrate the behavior the system when subject to small and large electrical disturbances. The sequence of the simulation is as follows:

- All breakers are closed at t=0
- SM1 is initialized in the steady state solution to produce 400 MW
- At t = 10 s, breaker SW3 is opened, which connects SM1 radially through the series-compensated line ZL1
- At t = 11 s, a fault (through impedance) is applied on the previously opened transmission line, and after 0.05 s (3 cycles) is cleared by opening breaker SW4.

This sequence provides both a small-signal disturbance (opening of the parallel transmission line) and a larger disturbance (initiation of fault and clearing).

Some results from this simulation for the SBM are shown in Figure 3. The initial electrical disturbance created by opening the parallel line results in oscillations in the rotor shaft of SM1 that can be observed between 10.0 and 11.0 s. The slower of these oscillations is the generating unit responding to the change in system impedance (disconnecting the parallel line). The faster oscillations correspond to excitation of the first oscillatory mode of the generator (at 25 Hz).

The 25 Hz oscillations are poorly damped due to the resonance created by the now radially connected series compensated transmission line. The fault at 11.0 s represents a much larger electrical disturbance that leads to negatively damped (i.e. increasing) oscillations of the rotor shaft that in this simulation quickly grow to severe levels. The generator currents after fault clearing are indicative of sub-synchronous torsional interaction (SSTI).

As expected, sizing the series capacitor for 70% compensation of the subject transmission line creates an electrical resonance seen from the generator neutral looking into the power system at 35 Hz, which interacts with the 1st oscillatory mode of the mechanical shaft with a natural frequency of about 25 Hz.

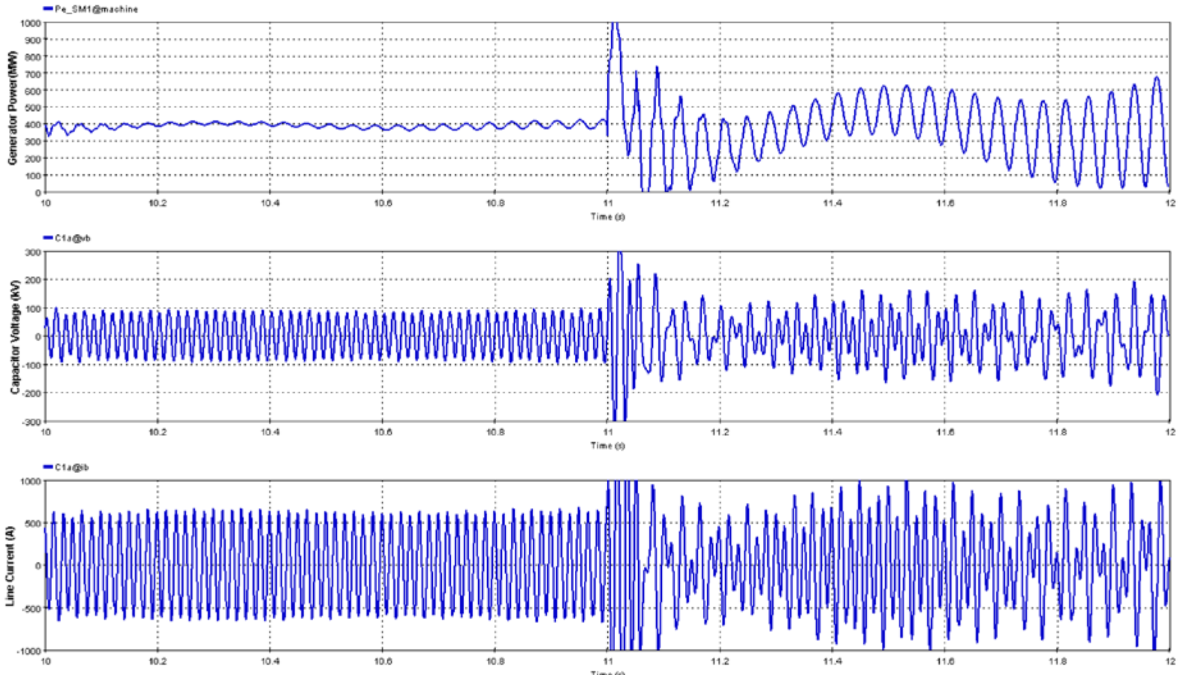

Figure 3: Simulation of IEEE SBM with 70% series compensation of Line 1. Line 2 is opened at t = 10 s, followed by 3 cycle symmetrical fault at t = 11.0 s. Charts show (top): Generator electrical power; (middle): voltage across series capacitor; (bottom): current through series capacitor (line current)

Comparative Performance of Smart Wires SmartValve

The Smart Wires SmartValve can mimic the behavior of series capacitors by injecting a series voltage into the transmission line which lags the line current by 90 degrees. To assess how the Smart Wires SmartValve behaves relative to conventional series capacitors in terms of SSR potential, the SBM was modified as shown in Figure 4. Here the three-phase series capacitor is replaced by a series of SmartValve devices in each phase. Because the SmartValve is a modular product, it was necessary to create a single per phase equivalent of the number of devices it would take to provide the same level of compensation as the series capacitor in the base case.

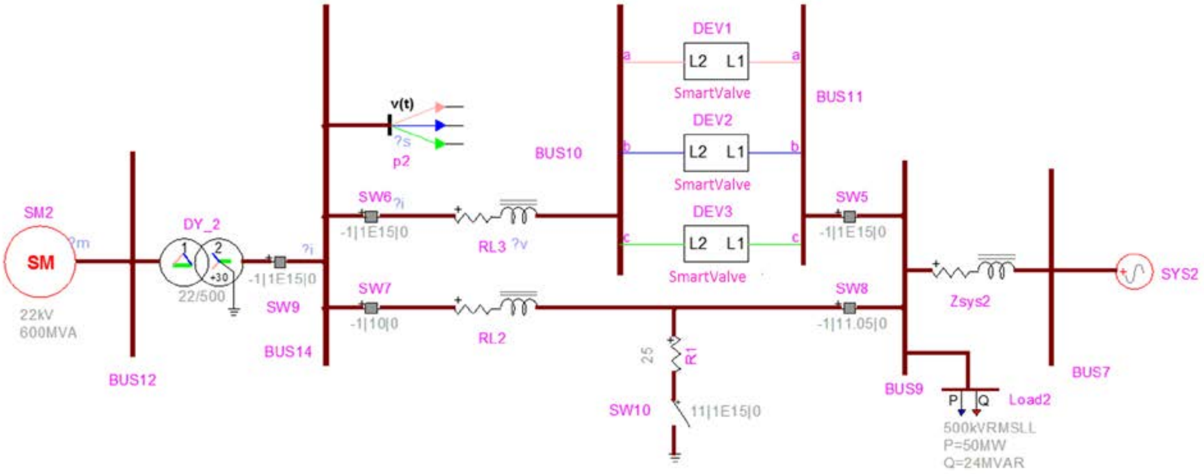

Figure 4: Modified IEEE SBM; series capacitor is replaced by Smart Wires SmartValve devices

Simulation results from applying the same sequence of operations as described above are illustrated in Figure 5. It is clear from the results that the SmartValve devices do not induce interactions with the generator shaft system. A closer view of the period following clearing of the fault (Figure 6) provides further support. With the series capacitor, the onset of growing sub-synchronous oscillations, as evidenced by the series capacitor voltage and line current, is apparent immediately. With the SmartValve devices, there is no evidence of the interaction between the generator torsional modes and the electric network. It is also apparent that, following fault clearing, there is no evidence of SSTI which is so clearly observed in the case with passive series capacitors.

In Figure 7, the voltages “injected” by the series capacitor (passively) and the SmartValve devices are compared, along with the resulting line currents. The graphs are centered on the time at which the parallel transmission line is opened. Prior to opening, the quantities are nearly identical. After opening, however, it is seen that the series capacitor voltage (and current) increase somewhat. The line currents also increase with the SmartValve devices in service, reflecting the transfer of power that was flowing through the parallel transmission line to the line with series compensation. The total series voltage injected by the SmartValve devices, however, remains at the commanded value.

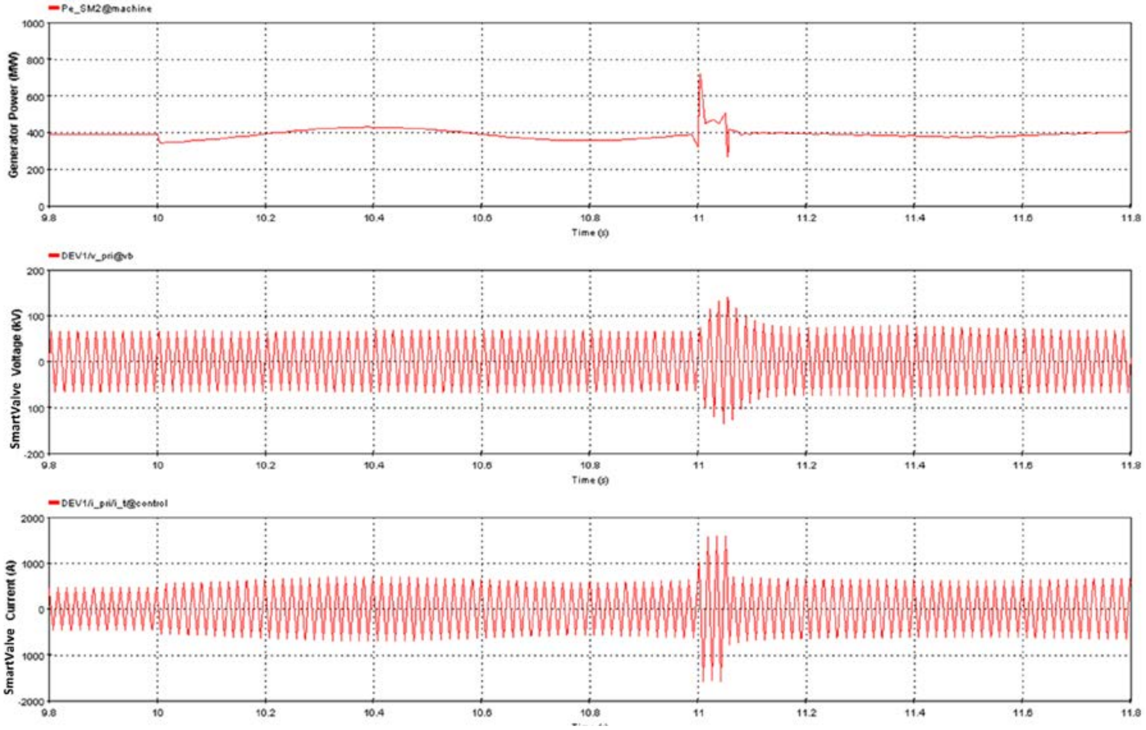

Figure 5: Simulation similar to that shown in Figure 3, with SmartValve devices substituted for the series capacitor on Transmission Line 1. Charts show (top): Generator electrical power; (middle): total voltage inserted by the SmartValve devices; (bottom): Line current

A further note should be made with respect to Figure 5. At the detection of the fault condition, the SmartValve will either automatically go into bypass mode or stay in injection mode. The response will be based on a pre-programmed setting. If the fault current is high enough (e.g. 3 kA for a device with a continuous rating of 1 kA) it automatically go into bypass mode. If it goes into bypass mode, it will not contribute to any "active injected" voltage. It will resume injection mode once the fault current below a pre-programmed threshold value (e.g. 2 kA RMS for 5 cycles for a device with a continuous rating of 1 kA).

In these simulations, the short-circuit contribution from the generator does not exceed the likely limit for the SmartValve, so no bypass operation was initiated.

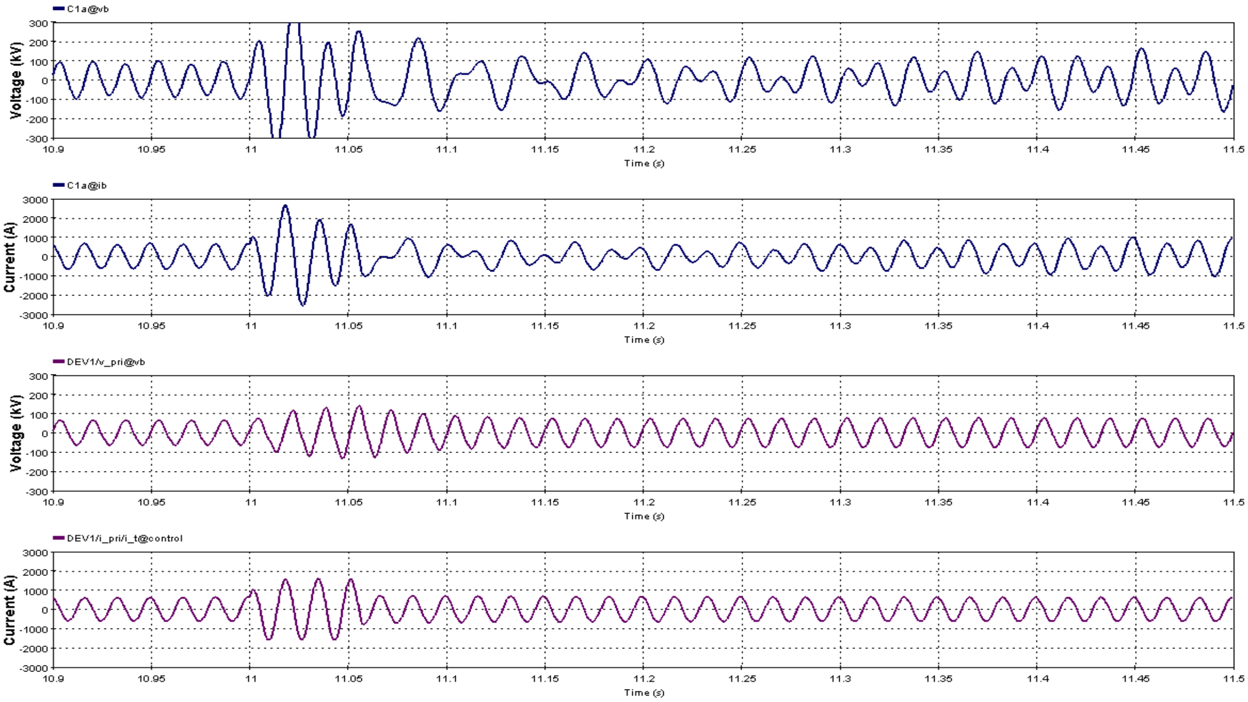

Figure 6: View of system behavior just prior to fault and after fault clearing. Top: Voltage across series capacitor: Top middle: Line current with series capacitor; Bottom middle: total voltage injected by the SmartValve devices; Bottom: Line current with SmartValve devices replacing series capacitor.

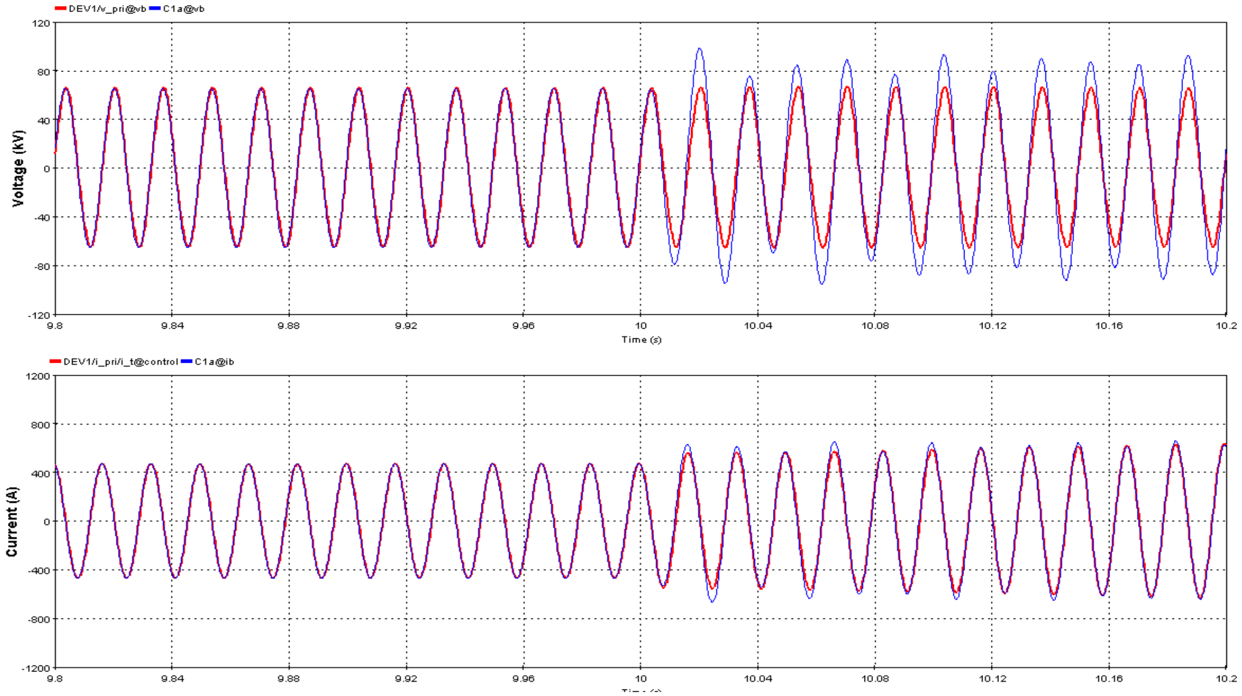

Figure 7: Close-up comparison of series capacitor and SmartValve quantities around time at which generator is configured radially with compensated transmission line. Top: SmartValve injected voltage (red) and voltage across series capacitor (blue); Bottom: Line current with SmartValve (red) and with series capacitor (blue).

Discussion

The Smart Wires SmartValve is an active device that injects a specified 60 Hz series voltage into a transmission line that either leads or lags the 60 Hz line current by 90 degrees. When the injected voltage lags the line current, the SmartValve acts identically to series capacitors that are applied to increase utilization of transmission lines.

A series capacitor is a linear, passive element, meaning that a proportional relationship exists between the voltage across and the current through the element at all frequencies. It is this attribute of series capacitors that is responsible for formation of subsynchronous electrical resonances that may interaction with turbine generator shaft oscillatory modes.

The Smart Wires SmartValve is an active device. The injected voltage is the result of control decisions. Assuming that the phase locked loop in the controller is robust, the SmartValve will inject voltage at rated line frequency only; at all other frequencies, the injected voltage will be zero, making the SmartValve appear electrically as a shorted element (save for the coupling transformer leakage impedance), therefore injecting no capacitance at those frequencies.

Simulations in this paper show that when the parallel line in the SBM is opened, voltage across capacitor increases with increasing line current; voltage injected by the SmartValve remains at commanded level (it is possible that the voltage injected by the SmartValve could be adjusted by an outer control loop that would preserve proportionality, in which case the behavior at 60 Hz would be identical to a passive series capacitor).

Conclusion

The IEEE Second Benchmark Model for Subsynchronous Resonance has been used in industry over the years as a test bench for comparison of methods for computer analysis and simulations, and for the evaluation of prospective measures for mitigating subsynchronous resonance.

Simulations using the IEEE SBM show that active voltage injection from the Smart Wires SmartValve provides reactive compensation at line frequency like conventional series capacitors, but its actions do not extend to other frequencies.

The voltage injected by the Smart Wires SmartValve at frequencies other than the fundamental is zero. It therefore does not behave like a series capacitor except at fundamental frequency, and does not create network conditions that could lead to SSR.

Because the Smart Wires SmartValve is a modular device with high-bandwidth control relative to 60 Hz, the potential exists for the device to be applied in combination with series capacitors to inject voltage at detected subsynchronous frequencies to damp SSR. This will be explored in a follow-on investigation.

References

[1] L. L. Grigsby, "Power System Stability and Control" 3rd Edition, CRC Press, April 2012

[2] EPRI TR-106463: Assessment of FACTS Requirements on the PSE&G System, March 1996