Benefit of Static Compensator (STATCOM) plus Superconducting Magnetic Energy Storage (SMES) in the Transmission Network

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Superconducting Magnetic Energy Storage (SEMES)
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Static Synchronous Compensator (STATCOM)
Electrical Power Research Institute (EPRI)
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American Electric Power (AEP)
Unified Power Flow Controller (UPFC)
Static Condenser (STATCON)
New York Power Authority (NYPA)
Convertible Static Compensator (CSC)
Static Synchronous Series Compensator (SSSC)
Interline Power Flow Controller (IPFC)

ABSTRACT

Utilities are beginning to install Flexible AC Transmission Systems (FACTS) devices in their transmission networks. One particular feature of FACTS devices provided by Siemens is that the electronic poles of the inverter share a common DC bus. This allows multiple FACTS devices to be coupled through their respective DC busses. In addition, it is feasible to operate in conjunction with other types of devices such as SMES systems.

The technical advantages of a combination STATCOM plus SMES system in the transmission network are illustrated. It is shown that the combined system provides enough degrees of freedom to regulate the bus voltage and provide power oscillation damping (POD).

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INTRODUCTION

In recent years a new class of high power electronic compensators that use Gate Turn-Off (GTO) thyristors have been developed and installed in the USA. These compensators generate a synchronous sinusoidal voltage waveform that is interfaced to the transmission network via transformers. The devices can be connected in shunt at a bus for voltage regulation or they can be connected in series with a transmission line to regulate power flow. Much of this development work has been supported by Electric Power Research Institute (EPRI) FACTS program.

The first such installation was a ±100 MVAR Static Condenser (STATCON, now renamed as STATCOM) at the TVA Sullivan substation commissioned in 1995 [1]. Leading or lagging reactive current is drawn from the AC system to regulate the bus voltage.

This was followed by the American Electric Power (AEP) Unified Power Flow Controller (UPFC) project at the Inez Kentucky station which has two ±160 MVA inverters. During Phase I of the project the first inverter was connected in shunt [2]. In Phase II the second inverter was installed in series with the Big Sandy to Inez transmission line to allow the installation to operate as a UPFC [3].

The New York Power Authority (NYPA) is installing two +/-100 MVA inverters, a Convertible Static Compensator (CSC), that can be operated in STATCOM, UPFC, Static Synchronous Series Compensator (SSSC) and Interline Power Flow Controller (IPFC) modes [4]. Phase I of the project is almost complete; at time of writing both inverters had been commissioned as STATCOM. Phase II, scheduled for completion in 2002, will install two series transformers and allow UPFC, SSSC, and IPFC modes to be commissioned.

A feature of most utility FACTS devices already built (or in the pipeline) is that the inverter electronic poles share a common DC bus. One advantage of a common DC bus is that it allows multiple FACTS devices to be coupled to create systems with increased functionality and modes of control. In such systems, the inverters can exchange real power across through their respective DC busses [2,3].

Other types of device may be interfaced at the terminals of the DC bus. For example, it is feasible to connect an energy storage device such as a SMES [5,6]. The storage device cannot be connected directly because the STATCOM maintains a somewhat constant DC bus voltage, rather it is interfaced through a DC chopper circuit which can vary the magnitude and polarity of voltage applied to the coil. The addition of energy storage allows the combined system to exchange both reactive and active power with the AC network (i.e. 4-quadrant operation) giving control advantages.

This paper shows how a SMES system can be connected to the AC system via the DC bus of a STATCOM. The capability of the STATCOM is enhanced because it can negotiate both active and reactive power with the network. It is shown how the combination of STATCOM and SMES allows bus voltage regulation and power oscillation damping to be achieved simultaneously.

STUDY SYSTEM

AC Network

The study system is shown in Figure 1. There is a 700 MVA generator at Bus A connected through transmission lines to an infinite bus, Bus C. The STATCOM is connected at Bus B. The initial conditions are 310 MW in the transmission line and Bus B regulated to 1.0pu by the STATCOM rated at ±160 MVAR. When there is a disturbance, there is a lightly damped low frequency oscillation (0.5 Hz) between the generator and the infinite source. More data details are given in the Appendix.

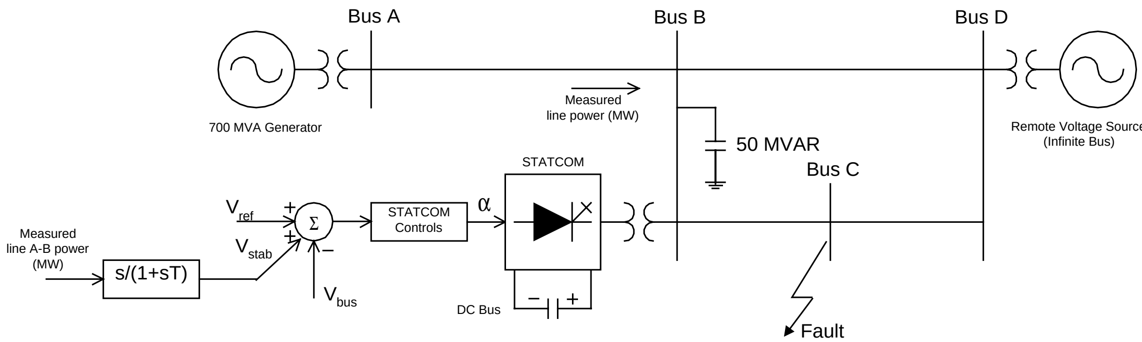

Figure 1:.STATCOM + POD Circuit Arrangement

The generator rotor swing oscillation is stimulated by applying a solid 3 phase short circuit (10 cycle duration) at the mid point of the auxiliary transmission line (Bus C). The fault is cleared by removing the auxiliary line from service (no reclosing).

STATCOM System

The STATCOM is an electronically generated three-phase voltage source that is connected to the AC system via a shunt transformer as shown in Figure 1. When operating as a pure STATCOM (without losses or SMES attached) the generated voltage is exactly in phase with the AC system voltage. If the generated voltage is greater that the terminal voltage then the device will supply VARs (i.e. is capacitive) to the system. If the internal voltage is less than the terminal voltage, the device will absorb VARS (i.e. is inductive) from the system. The control system of the STATCOM is extremely fast and therefore can rapidly change the magnitude (and phase) of the electronically generated voltage.

The magnitude of AC voltage generated by the STATCOM is directly proportional to the DC bus voltage. Therefore, the generated voltage, which controls the STATCOM VARS, is controlled by changing the DC bus voltage. Changes in DC bus voltage are accomplished by supply or absorbing real power to or from the DC bus to charge or discharge the DC capacitor. This is accomplished by advancing or retarding the generated voltage angle with respect to the AC terminal voltage.

In practice, the STATCOM has a small amount of losses (e.g. resistance in windings, switching losses etc.) and to compensate for these the electronically generated AC voltage angle is slightly in retard of the AC system terminal voltage angle. The difference in angle (α) between system voltage and generated voltage allows real power to flow and hence compensate for the losses in the STATCOM circuit.

When the DC chopper is employed to transfer energy to/from the SMES coil then the DC bus voltage will be charged or discharged. This change will be sensed by the STATCOM controller which will automatically adjust its control angle (α) to keep the DC voltage at the required level. In doing so it will naturally adjust to compensate for the energy request of the SMES system. The STATCOM control automatically adjusts for the power demand of the SMES and transfers the required energy to/from the AC network.

SMES System

The SMES system is comprised of three major elements: the SMES coil, DC chopper circuit, and the SMES control system. Connection to the STATCOM is shown in Figure 2 (switch A closed).

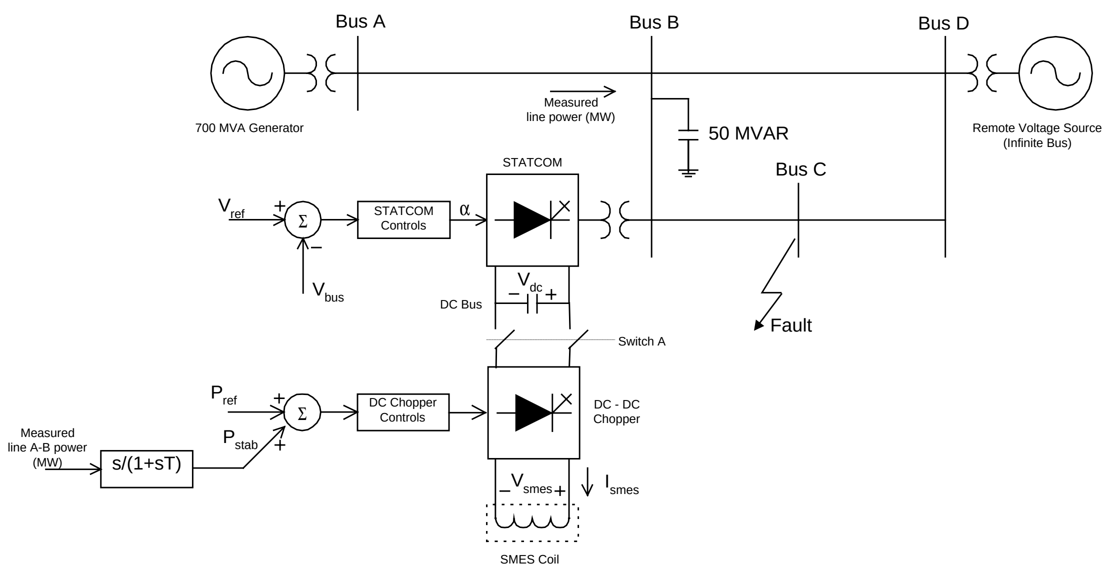

Figure 2. STATCOM + SMES with POD Circuit Arrangement

The SMES coil in these tests is rated at 4 kA with a 100 MJ capacity. The current in the coil is unidirectional and is maintained by the SMES controller between 3kA and 4kA. Prior to the disturbance, a value of 3.5 kA is flowing in the coil.

The DC-DC chopper is modeled with algebraic equations. Based on the requested power transfer and measured current in the coil then the desired SMES voltage is calculated. From the desired SMES voltage and the STATCOM DC voltage a value of chopper duty cycle can then be computed.

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RESULTS

The simulations are performed with PSCAD-EMTDC [7].

STATCOM Only

The system is as given in Figure 1 and there is no stabilizing signal (i.e. Vstab=0) feeding into the voltage control loop.

The BLACK curves in Figures 3 to 6 show the system response.

Figure 3 shows the under damped power oscillation in the A-B line. Figure 4 shows how the bus voltage is well regulated to the set point. Figure 5 shows the quadrature current output (i.e. MVAR) of the STATCOM.

In the post contingency period the bus voltage is well regulated however the system oscillation mode is underdamped.

STATCOM with POD

The system diagram is given in Figure 1 and the stabilizing signal that adds into the voltage control loop is defined by the relationship in Equation 1, where Pmeas is the measured real power flowing in the transmission line between busses A and B, 's' represents the derivative function. The signal is limited between ±0.05 pu.

$$Vstab = \frac{3.75e-4}{1+0.2s}.s.Pmeas$$

Equation 1.

The BLUE traces on Figures 3 through 6 show the system response.

From Figure 3 it is seen that the power oscillation is much better damped than the STATCOM only case although the bus voltage is now modulated, Figure 4. The stabilizing signal is shown in Figure 7.

STATCOM Plus SMES with POD

The system diagram is given in Figure 2. The stabilizing signal is defined in Equation 2 and is limited between ±20 MW. The gain has been selected to achieve the same damping as for the STATCOM+POD case.

$$Pstab = \frac{0.3}{1+0.2s}.s.Pmeas$$

Equation 2.

The RED traces on Figures 3 to 6 show the system response.

Figures 3 and 4 respectively show that the power oscillation is well damped and the bus voltage is well regulated. In Figure 6 the phase component of STATCOM current is non-zero and this corresponds to real power transfer to and from the SMES system. Figure 8 shows the stabilizer signal, the level of power (20 MW) required to damp the oscillation is quite small relative to the rating of the STATCOM.

The SMES voltage and current waveforms are shown in Figure 9. The SMES current remains fairly constant around 3.5 kA however the modulated power is achieved by changing the SMES voltage.

The STATCOM+SMES with POD combination can be effective at damping low frequency oscillations at the same time providing voltage regulation.

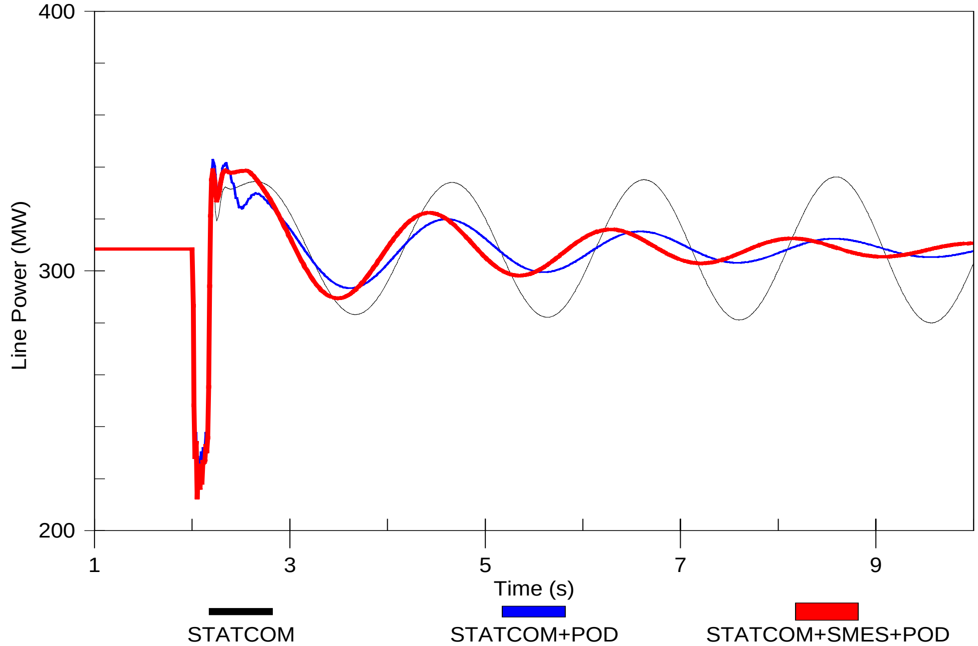

Figure 3. Line Power Oscillation

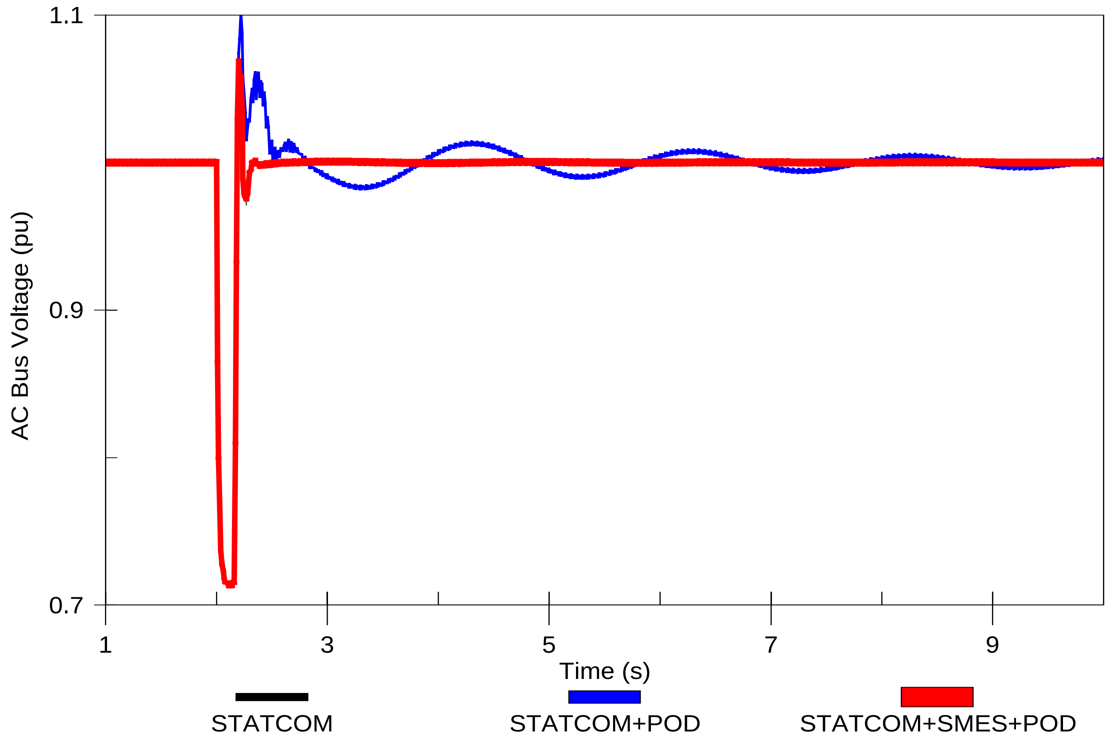

Figure 4. AC Bus Voltage

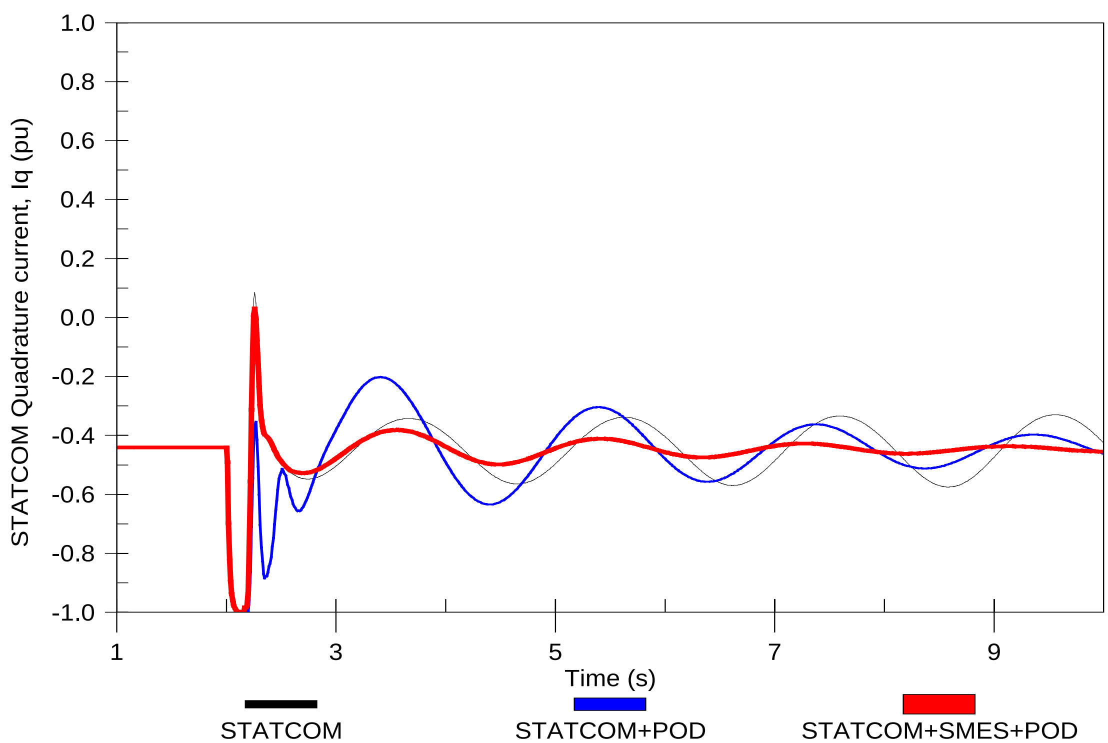

Figure 5. STATCOM Quadrature Current Output

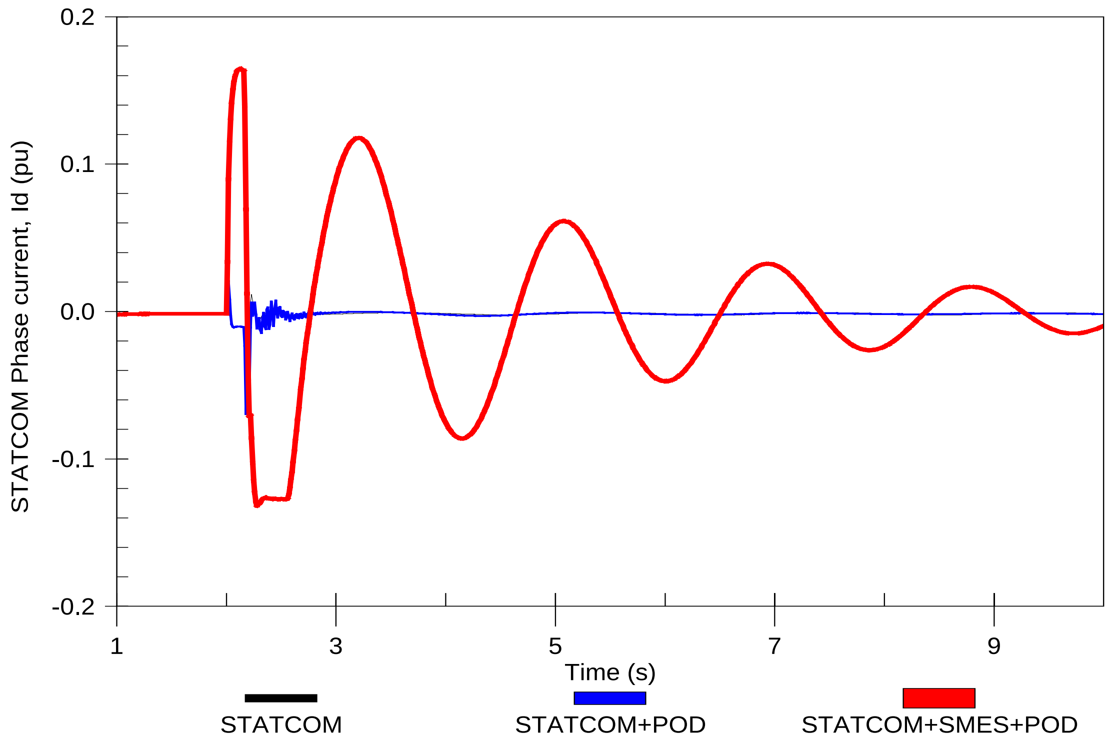

Figure 6. STATCOM Phase Current Output

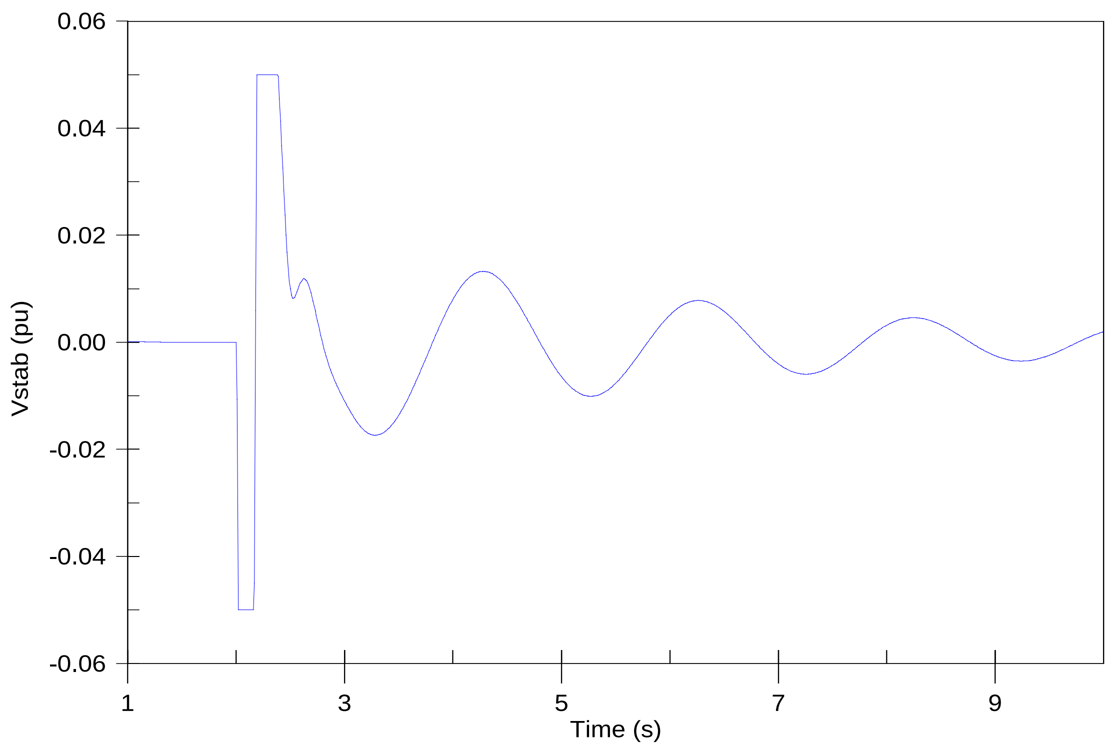

Figure 7. Stabilizer Signal for Voltage Control Loop of STATCOM

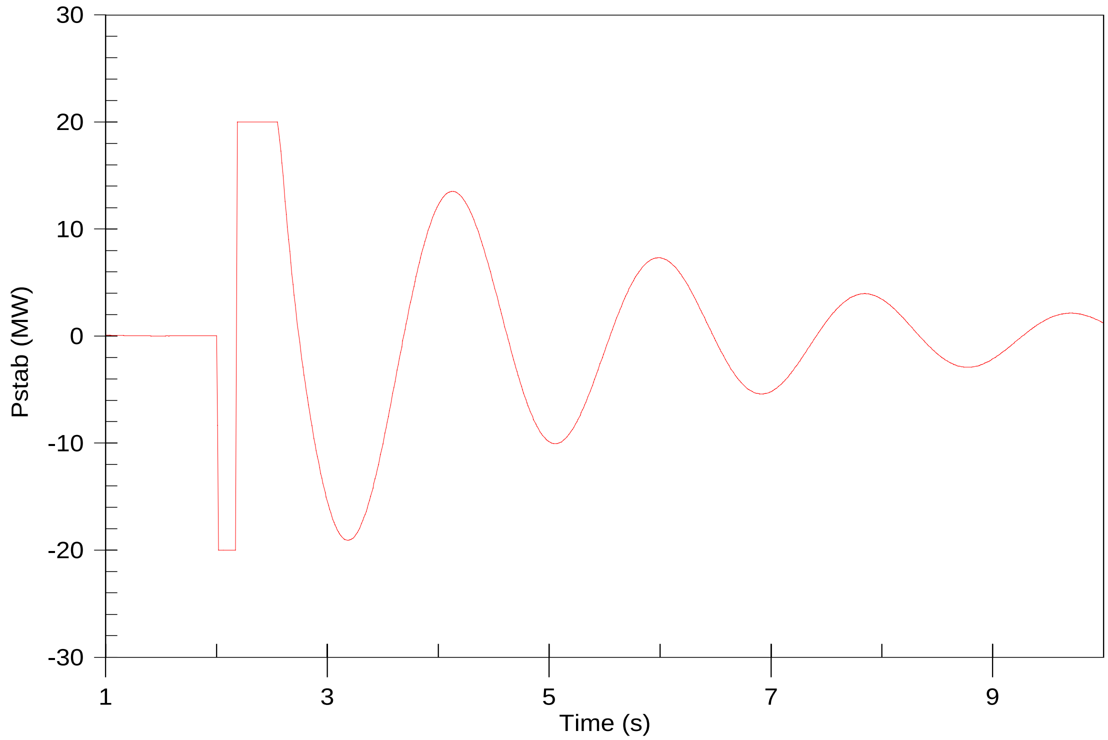

Figure 8. Stabilizer Signal for Power Reference of SMES Controller

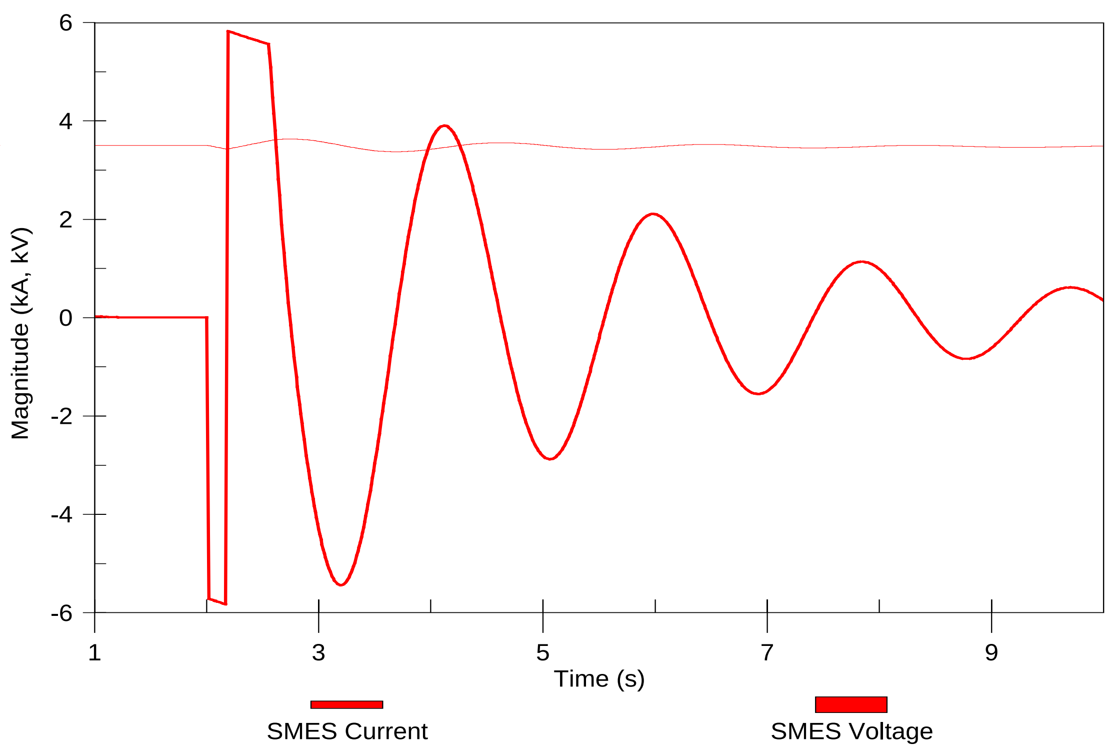

Figure 9. SMES Coil Waveforms

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CONCLUSIONS

A benefit of adding a SMES system to the DC bus of a STATCOM has been considered.

The power oscillation damping performance of a STATCOM has been compared with a STATCOM+SMES combination. An active line power signal conditioned to provide an auxiliary control signal to the voltage reference (in the case of STATCOM) or SMES power reference (in the case of STATCOM + SMES combination) was compared. The ability of both schemes to damp machine rotor swing oscillations at 0.5 Hz has been demonstrated.

The results illustrate that a STATCOM alone (i.e. no POD) will regulate voltage in the post contingency period but will not naturally add much damping to power oscillations. The STATCOM with POD signal applied to its voltage reference may damp swing oscillations following a disturbance however this is achieved at the expense of voltage regulation. The combination of STATCOM plus SMES with POD modulating the SMES output will allow the system to both regulate voltage and provide oscillation damping.

The amount of real SMES power required to damp system oscillations is quite small (20 MW) relative to the STATCOM rating (160 MVAR). The controls of the STATCOM were not specially modified to accommodate the operation of the SMES coil.

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APPENDIX: SYSTEM DATA

- Base Frequency = 60 Hz
- Bus A Generator: Rating =700 MVA, H=8.9sec, Xd'=0.3 pu
- SMES: maximum current 4kA, 100 MJ energy capacity
- STATCOM rating: ±160 MVA, transformer leakage 15%
- Line A to B: X= 22 Ohms
- Line B to D: X = 14 Ohms
- Line B to C & C to D: X = 22 Ohms
- All lines have X/R=20.

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