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STATCOM Application to Address Grid Stability and Reliability: Part II

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SUMMARY

As a follow-up to “STATCOM Application to Address Grid Stability and Reliability: Part I”, this paper provides analysis for an example system to examine short-term voltage stability and to demonstrate the performance of a STATCOM, SVC, and also a synchronous condenser. The technologies are examined in relation to reliability criteria, short-term voltage stability, and fault-induced delayed voltage recovery (FIDVR). The performance of the STATCOM, SVC, and synchronous condenser are compared amongst the challenges utilities are facing in today's changing generation portfolio and loading environment that are affecting overall grid stability and the device characteristics required to address such challenges. Voltage correction performance, filtering needs, spatial requirements, and adaptability, among other factors, are considered for a STATCOM, SVC, and a synchronous condenser. This paper demonstrates careful attention needs to be given to generation profile and load profile, along with load characteristics. FIDVR has provided a warning that the characteristics of the load can have a significant impact on system stability. It is anticipated that as loading profiles continue to change, attention will need to be paid to represent the characteristics of such load adequately. For the example here, motor stalling can lead to the loss of synchronism of local generation, system separation, and corresponding voltage collapse. Also, the stalling of motors propagated throughout the load pocket of interest.

KEYWORDS

STATCOM, SVC, synchronous condenser, short-term voltage stability, Fault Induced Delayed Voltage Recovery (FIDVR)

I. INTRODUCTION

The follow describes the example system chosen for this analysis:

- Focus is on a load pocket (20,000 MW) connected to a 138 kV system with a strong 345 kV backbone. 40% of the load is served by remote generation that is 200 miles away and not able to provide reactive power support. The remote generation consists of a large nuclear plant, coal plants, gas turbines, and wind generation.
 - Load pocket is expected to continue to have generation retirements because of aging generation plants and clean air legislation. The local generation will be replaced with remote generation, which will further exasperate voltage problems.
 - Load is expected to continue to increase in the load pocket.
- Load is summer peaking. Of the total load pocket, 40% of the load is estimated to be single-phase residential air-conditioner (a/c) motor load.
- Mechanically Switched Capacitors (MSC) provide compensation on the order of magnitude of one-third of the total load in the region (7000 Mvar).
- Under-Voltage Load Shedding (UVLS) and Under-Frequency Load Shedding (UFLS) are to be avoided as means for mitigating short-term voltage stability issues here.

The simulation program chosen for this work is the Power System Simulator for Engineering (PSS/E), Version 32.1.1. Limiting cases are discussed to identify the location, rating, and response characteristics of dynamic reactive power compensation to address short-term voltage stability problems. Time-domain simulations are included here for critical breaker-to-breaker contingencies in the load area, focusing on key 345 kV (Extra High Voltage (EHV) buses) and 138 kV (High Voltage (HV) buses) buses serving the load area.

A complex load model was used to model the load in PSS/E based on conversion of the constant impedance, current, and MVA (ZIP) load to a composite load model to represent motor and lighting load for residential, commercial, and industrial areas. Most importantly large, small, and air-conditioner (a/c) motor load was modeled based on percent estimates for that type of load in the area. 40% of the load was estimated to be single-phase residential air-conditioner (a/c) motor load and its impedance was modified at certain voltage thresholds to represent stalled conditions.

II. BASE ANALYSIS

This paper focuses on a stuck breaker event resulting from a transmission line fault close to a 345kV substation. Normal operation of the protection of the faulted line opens the far end of the line but leaves a single pole of a near-end circuit breaker closed. The operation of primary and backup protection opens three transmission lines and disconnects 1000 MW of local generation. The delay between the partial operation of the primary breakers and the opening of the secondary breakers is a parameter of the study.

The need for reactive power support in the load area is dependent on the character of the load and, accordingly, it is essential that the appropriate model is used to represent it. Figure 1 shows the voltage at a key bus in the load area for Case A (red) where the composite load model is used with 40% of each load represented as single-phase a/c and for Case F (green) where the load is represented as constant-current-real and constant-suseptance-imaginary (constant I/B load model). Stuck breaker (single-phase stuck pole) timing for these traces is 10 cycles (fault cleared 15 cycles relative to fault inception). The voltages in the load area do not recover when the complex load model is used but they recovery quickly when the constant I/B load model is used. This is because of the stalling of motors when the complex load is used; where the constant I/B load model is not able to recognize the stalling of motors.

Figure 1a shows selected generator rotor angles for the two simulations shown in Figure 1. The simulation made with the complex load model produces the red traces; the green traces are from the

simulation with the constant I/B load model. It is clear that a block of generators pulls out of step with the main system in the simulation made with the complex load model but not in the simulation made with the simpler load model.

Figure 2 shows voltages at a key bus in the load area of interest for cases varying the delay in clearing the faulted stuck breaker phase. Figure 2a shows that the amount of motor load that stalls increases as the delay in clearance is increased. Given information on the character of the load in the system and the behavior as shown in Figures 1, 1a and Figures 2, 2a, the study of reactive power support was made with loads represented by the composite load model.

The voltage recovers adequately with a single-phase fault initiating the event and is not a cause for concern here. The voltage depression during the single-phase fault will depend on the ratio of the zero sequence impedance to the positive sequence impedance where the higher the ratio the less the voltage depression. Note regardless of fault type, the voltage recovers adequately without stuck breaker conditions.

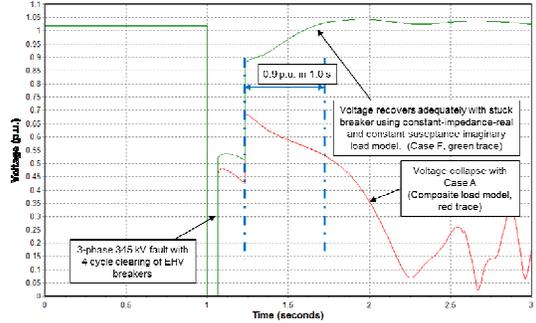


Figure 1. Bus voltage for Case A and Case F.

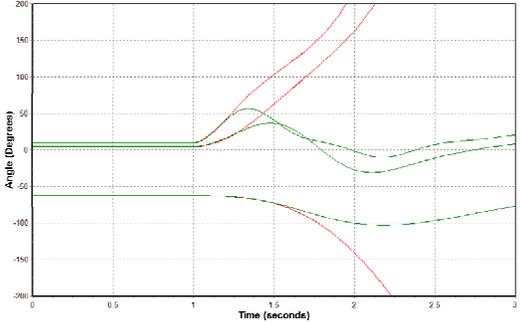


Figure 1a. Selected generator rotor angles for the two simulations shown in Figure 1.

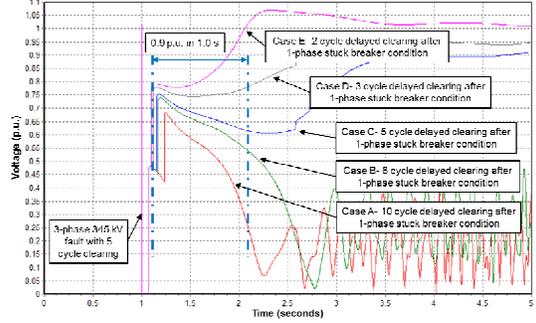


Figure 2. 345 kV bus voltage for delayed clearing cases.

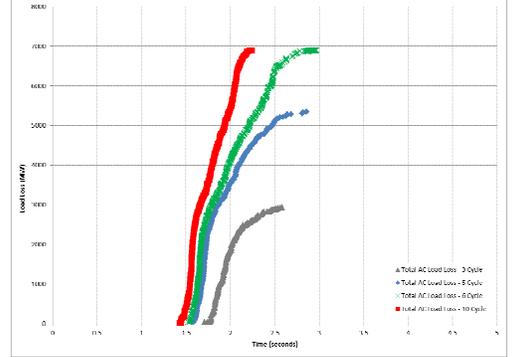


Figure 2a. A/c motor load stalled in load area.

Note the respective magnitudes of three-phase fault current and single-phase fault current will characterize the strength of the system and influence the recovery of the voltage. Large voltage excursions and delayed recovery during weak system conditions will present more onerous requirements for mitigation, influencing controls in terms of allowable gains and response times along with the sizing of discrete capacitive and inductive elements that can be inserted into the system and corresponding filtering requirements.

III. MITIGATION ANALYSIS

The objective of our study was to determine the amount of reactive power support needed in the load area to ensure that voltages will recover after clearance of a stuck breaker event. Figure 3 shows Case A from Figure 1 repeated with (i) SVC, (ii) STATCOM, and (iii) SC to inject reactive power to

support the voltage in the EHV and HV system. To return the voltage to within 0.9 p.u. in 1.0 s as a screening guideline with no motors allowed to stall, the following was determined:

- SVC Device: 2x400 Mvar at 4 locations (total of 3200 Mvar) required
- STATCOM Device: 2 x 300 Mvar at 3 locations with 125% overload for 3s required (total of 1800 Mvar). Without any overload, 4 locations of STATCOM are required with a total of 2400 Mvar injected.
- SC Device: 2x300 Mvar at 3 locations required (total of 1800 Mvar)

Note the locations of the reactive devices are in the 138 kV system within 5 buses relative to the low-side of the faulted 345 kV bus. One additional reactive device is at the faulted 345 kV bus. The exact locations for the compensation considered here in terms of voltage correction are not critical.

For this analysis the SVC was tuned to have nearly the same response time (i.e., 15 ms) as the STATCOM. Thus, the advantage of the STATCOM here is in its ability to inject fully rated current during depressed voltage conditions, where the SVC reactive power is influenced by the square of the voltage. The tuning used for the SVC may or may not be realizable, depending on the equipment design and short-circuit strength conditions of the system.

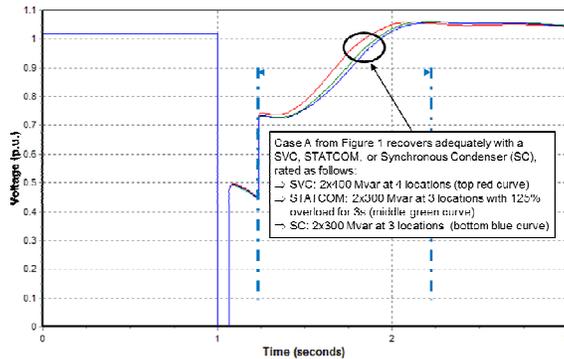


Figure 3. Case A from Figure 1 with (i) SVC, (ii) STATCOM, and (iii) SC added to support the voltage.

Figure 4 shows the reactive power injection for the SVC, STATCOM, and SC by type (total Mvar at one location shown). Note the solutions were applied at a 345 kV bus and up to three other locations at 138 kV. The SC provides 973 Mvar, with $973/600 = 1.62$ of transient response capability governed by the characteristics of a synchronous machine. Note a time-constant for flux to develop in the stator winding of 4.0 seconds ($T'd0$) and a voltage regulator gain of 400 (Ka) was used for the SC, based on the 'GENROU' (round rotor generator) and 'ESAC1A' (brushless excitation system) models, respectively. For the 'seconds' timeframe of interest here, the synchronous condenser will provide reactive power as required by the system and will be limited by the design of the excitation system. The thermal time-constants associated with the machine are on the order of 'minutes'.

Figure 4a shows the reactive power injected for the SC case from Figure 4, comparing a SC with a $T'd0 = 4$ sec to a $T'd0 = 10$ sec. The reactive power does not reach the same peak and is delayed for the $T'd0 = 10$ sec case because flux cannot develop as quickly in the machine. Note the change in time-constant, $T'd0$, of the SC does not affect the initial response of reactive power, which is determined by only the sub-transient reactance of the machine. The 345 kV bus voltage still recovers for this case similar to that shown in Figure 3, however, the slower response allowed for motors to stall throughout the system. Figure 4b shows the 345 kV and 138 kV bus voltages for the STATCOM solution and SC solution with $T'd0 = 4$ sec and $T'd0 = 10$ sec. Note a static excitation system ('ESST4B' model) produces similar results with slightly lower field current and field voltage and a little less reactive power required (less than 20 Mvar per device) than a brushless excitation system.

During the fault the SC provides up to 5x change in current (based on 0.2 p.u. sub-transient reactance) for a change in voltage, which is 0.12 p.u. here (at the location of the synchronous condenser), which estimates the reactive power as $5 \times 0.12 \times 1000 = 600$ Mvar provided during the fault. Following the decay of the immediate response after fault clearing, the response is primarily influenced by the time it takes flux to develop in the machine, under influence of the voltage regulator, shown in Figure 4 by the build-up of the reactive power to its peak. Reactive power will be limited by the excitation system in the timeframe of interest here. The 1.62x rated reactive power supplied is not a cause for concern for the machine in the ‘seconds’ timeframe.

Sudden fault conditions cause a change in the speed and frequency of the machine where a momentary speed difference of 29 RPM and associated frequency change of 0.36 Hz was observed. This provided a momentary power output of 115 MW. While readily observable this has a negligible impact on the system under study. Figure 5 provides a plot of the real power output for each of the SC locations for reference. The blue trace corresponds to a SC located at 345 kV compared to the other two traces that are for SC’s located at 138 kV at different locations relative to the fault. Swinging of turbine generators in the system in response to the fault causes swinging of the phase of the voltages where the SC are connected and this variation of phase causes the SC real power to swing.

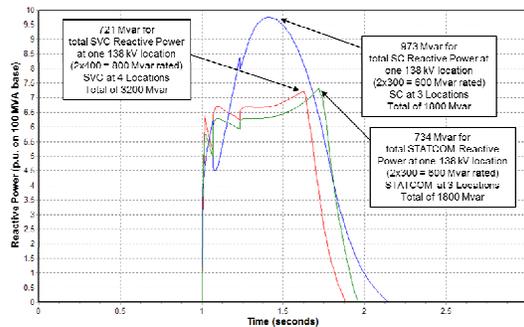


Figure 4. Reactive power injection for mitigation devices described in Figure 4.

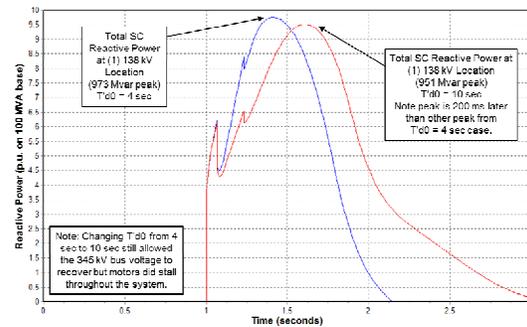


Figure 4a. Comparison of $T'd_0 = 4$ sec to $T'd_0 = 10$ sec for SC case shown in Figure 5.

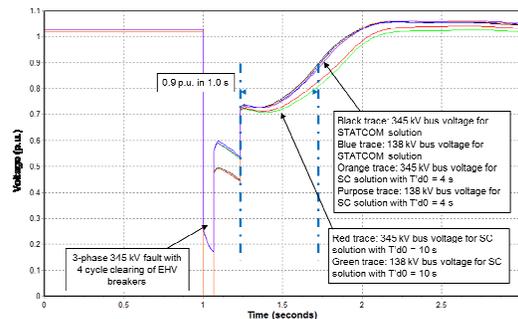


Figure 4b. Bus voltage for comparison of $T'd_0 = 4$ sec to $T'd_0 = 10$ sec cases for SC.

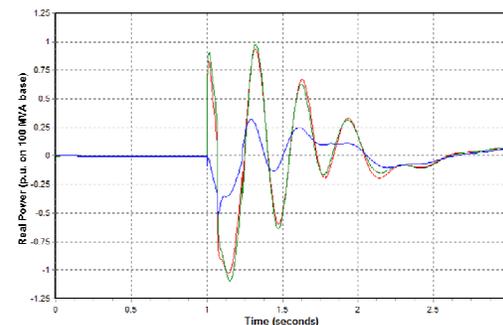


Figure 5. Real power output of the SC at each of the three locations.

The following points are noted:

- The inertia of the synchronous condenser was set to $H = 1.0$ s; however, variations of H between 0.8 s to 1.4 s have a negligible impact on the simulation results. Note fault ride-through capability was not a parameter of study for this application.
- The reactive power supplied during the first 5 cycles of the fault for the SVC, STATCOM, and SC at the compensation locations were similar. Over the next 5 cycles the SVC and STATCOM provided more reactive power than the SC. Then, the response of the SC far exceeded that of the SVC and STATCOM, because of the SC ability to provide a transient response in significant excess of its steady state capability.

- There is a brief period of real power exchange with the system driven by a system induced change in speed of the SC, which has no impact on the findings of the study here.

The focus here was to provide voltage support post-fault to prevent air-conditioner stalling conditions (FIDVR). Note an inductive range on the order of 100 Mvar was identified to control voltages beyond 1.05 p.u., where even more inductive range could be required subject to the voltage suppression required for light-load conditions and operating experience of the utility (not examined here). Such inductive range is inherently supplied by the symmetrical rating of a STATCOM device, but must be specifically accommodated for in an SVC solution by use and rating of a Thyristor Controlled Reactor (TCR). Hybrid designs are realizable, but beyond the scope of this paper.

The amount of reactive power support required relative to variations of planned loading conditions, delayed clearing times, bus configuration, and generating unit outages were examined. Table 1 summarizes the findings for the sensitivities examined.

Table 1
Impacts of Sensitivity Analysis on Solution Options

Ref. No.	Sensitivity Description	Percent Impact on Mvar Required			Total Mvar from Base Case			Total Mvar from Sensitivity Case		
		SVC	STATCOM (with 125% overload)	SC	SVC	STATCOM	SC	SVC	STATCOM (with 125% overload)	SC
1	1-2% increase in MW load	0	0	0	3200 (from 4 locations)	1800 (from 3 locations)	1800 (from 3 locations)	3200 (from 4 locations)	1800 (from 3 locations)	1800 (from 3 locations)
2	Reduce stuck breaker time from 10 to 6 cycles	50% Reduction	39% Reduction	44% Reduction	3200 (from 4 locations)	1800 (from 3 locations)	1800 (from 3 locations)	1600 (from 4 locations)	1100 (from 2 locations)	1000 (from 2 locations)
3	Change to a breaker-and-a-half bus scheme limiting outaged elements	63% Reduction	67% Reduction	75% Reduction	3200 (from 4 locations)	1800 (from 3 locations)	1800 (from 3 locations)	1200 (from 2 locations)	600 (from 1 location)	450 (from 1 location)
4	Outage of 2000 MW nearby generation in 345 kV system	137.5% Increase	133% Increase	156% Increase	3200 (from 4 locations)	1800 (from 3 locations)	1800 (from 3 locations)	4400 (from 4 locations)	2400 (from 3 locations)	2800 (from 3 locations)

IV. CONCLUSIONS

Table 2 summarizes characteristics associated with the solution options examined here. The following observations are provided based on Table 2:

- The STATCOM is an effective solution. Of further consideration for the STATCOM solution is the use of new switching technologies such as the Modular Multilevel Converter (MMC), providing lower losses than conventional designs, and continued advancements in semiconductor technology, requiring less semiconductor devices with increased current and voltage ratings than conventional designs.
- The synchronous condenser provides an alternative solution option with its inherent, initial sub-transient reactive power response to a fault, subsequent ability to provide a transient reactive power response far in excess of its steady state capability, and small footprint. A utilities choice between a STATCOM and a synchronous condenser may come down to appetite and experience for maintaining transmission level interconnected power electronics-based technologies versus rotating machinery.

Table 2 is to be treated as a general guide where prudent studies on the system needs, device ratings, and associated economies must be performed in context of the specific application to determine the preferred, optimum solution option for any given situation. The needs of the system must be carefully considered during the fault and for the post-fault period in terms of voltage support and other system variables that may be of interest.

Figure 6 illustrates the importance of a study to determine the appropriate solution for a given application. For the application here, the STATCOM and synchronous condenser minimum sizes were the same with a much larger SVC needed (approximately twice as much) given its V-I characteristics. Depending on the needs of the system, the type and rating of the optimal solution will vary.

Table 2
Summary of Characteristics Associated with the Solution Options

Ref. No.	Parameter	SVC	STATCOM	Synchronous Condenser (SC) (Brushless Excitation System)
1	Extra Capacitive Transient Response Capability For Application Here (Seconds Timeframe)	None (Passive Capacitive Devices)	125% (Must be Designed Overload)	162% (Based on Machine Characteristics Up to Excitation System Limits)
2	Required Capacitive Mvar Based on Above For Application Here	3200 (4x 2x400)	1800 (3x 2x300) (Most likely in units of 150 Mvar)	1800 (3x 2x300) (Static Excitation System Produces Similar Results Here)
3	Device Voltage/ System Voltage For Application Here	15 kV to 25 kV / (345/138 kV)	15 kV to 25 kV / (345/138 kV)	13.8 kV to 18 kV / (345/138 kV)
4	During Fault Response	Subject to V ² effect (Blocks at ~0.4 p.u.)	Injects Rated Device Current (Blocks at ~0.2 p.u.)	Up to 5x Rated Reactive Current (Sub-transient)
5	Fast Response to Post-Fault Voltage	Yes	Yes	Yes
6	Post Fault Response (Up to 15s)	Subject to V ² effect	Injects Rated Device Current (Up to Designed Overload)	Mvar Capability Determined by Excitation System Limits
7	Controlled Response	40-50 ms (Faster Tuning Possible System/Design Dependent)	15-30 ms (System/Design Dependent)	200-500 ms (Brushless Excitation System)
8	Inertia	None (No Moving Parts)	None (No Moving Parts)	H = 1.0-1.5 (Negligible Impact on Most Transmission Systems) Note higher H values can be achieved by slightly over-sized machine.
9	Real Power	None	None (Unless Energy Storage)	Negligible Impact on Most Systems (External Event Causes Speed Deviation) (Unless Flywheel)
10	Unbalanced Operation and Correction	Yes, On Design Basis (May Need Filter)	Yes, On Design Basis	Limited
11	Harmonic Generation and Correction	Needs Filters (Unless TSC Only) Active Correction Possible	MMC Eliminates Filters (100 Mvar+) Active Correction Possible	Negligible Can Absorb Harmonics
12	Site Adaptability	Limited (Large Passive Elements)	Yes (Modular/Scalable/Upgradable)	No (Rigid Foundation Required)
13	Security/ Environment	Limited (Outdoor Equipment)	Enclosed Building (Except Step-Up XFMR)	Enclosed Building (Except Step-Up XFMR)
14	Operating Losses	Design Dependent (~0.5-1%, Excludes XFMR)	MMC Design (~0.5-1%, Excludes XFMR)	~1.0% (Excludes XFMR)
15	Spatial Requirements	6-12 m ² /Mvar (65-130 ft ² /Mvar)	3-6m ² /Mvar (32-65 ft ² /Mvar)	3-5m ² /Mvar (32-54 ft ² /Mvar)
16	Long-Term Maintenance Items To Consider	Cooling System Spare Parts Software Platform	Cooling System Spare Parts Software Platform	Lubrication and Cooling System (Modern Designs Built for Transmission Oriented Maneuvering)
17	Ability to Operate in Weak System	Automatic Gain Control (AGC) SCR > 2-3 Not Effective in Weak System	Automatic Gain Control (AGC) SCR > 1; Check Harmonic Resonances in Weak System	No Limits to SCR

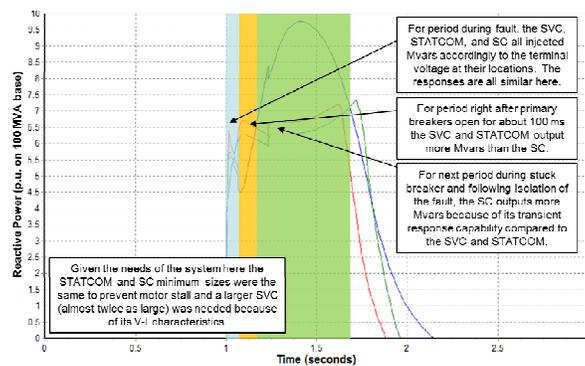


Figure 6. Mvar response of the SVC, STATCOM, and SC for various timeframes.

V. ACKNOWLEDGEMENTS

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