Evaluating Advanced VAR Compensators for Improving Power System Voltage Stability

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Abstract--an evaluation of advanced VAR compensators for improving power system voltage stability is presented. The evaluation includes a comparison of the dynamic performance of three categories of advanced VAR compensators through dynamic simulation in a simple utility system, as well as design, application, operation, and other considerations. The three categories of devices discussed include power-electronically-switched capacitors, inverter-based systems without energy storage, and inverter-based systems with energy storage. Conclusions on relative advantages and disadvantages of the three categories of devices are presented.

***Index Terms*--inverters, load modeling, power electronics, power system voltage stability, shunt capacitors, static VAR compensators, synchronous condenser.**

I. NOMENCLATURE

AVC: Adaptive VAR Compensator.
D-SMES: Distributed Superconducting Magnetic Energy Storage.
DSTATCOM: Distribution Static Compensator.
D-VAR: Dynamic VAR Compensator.
Voltage Stability: The ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition.
SVC: Static VAR Compensator.

II. INTRODUCTION

THE potential effects of voltage instability resulting from the slow recovery of the power system voltages following a major disturbance, such as a transmission line fault, are well documented in the literature [1-3]. Transmission utilities have traditionally addressed voltage stability concerns by installing large SVCs or synchronous condensers to provide the necessary dynamic reactive power support to the system following a major disturbance.

The emergence of new advanced VAR compensators utilizing power electronics with binary switched capacitors and inverter-based systems with or without energy storage provide utility transmission planning engineers with alternative solutions to the voltage stability problem. Superconducting magnetic energy storage systems (D-SMES) utilizing magnetic energy storage in the form of a superconducting coil and inverter technology have lead the way in utility applications of these new advanced VAR compensators [4]. Other commercially-available advanced VAR compensators are now increasingly being applied on utility systems for voltage stability support as well as for voltage regulation purposes. Also, these devices are used to improve the fault ride-through capability of wind turbines in wind farm applications.

An evaluation of commercially-available advanced VAR compensators for improving power system voltage stability is presented to highlight the differences in design and performance of these devices. For the purposes of evaluation, commercially-available advanced compensators are grouped into three categories, namely:

- Power-electronically-switched capacitors.
- Inverter-based systems without energy storage.
- Inverter-based systems with energy storage.

The evaluation includes a discussion of the design and basic concept of operation, performance of the compensator through dynamic simulation in a simple utility system, application, operation, and other considerations.

III. EVALUATION OF ADVANCED VAR COMPENSATORS

A. Compensator Design and Concept of Operation

1) Power-electronically-switched capacitors

Compensators utilizing power-electronically-switched capacitors (e.g., AVC) typically consist of three or more stages of low-voltage capacitors. Capacitor stages are typically sized in binary increments, i.e., if the size of the first stage of capacitors is *Q* kvar per phase, the size of the second and third stages would be *2Q* and *4Q*, respectively. Reactors are typically used in series with each stage of capacitors for detuning to eliminate harmonic resonance and large inrush currents. Capacitors are charged to peak system voltage and switched through thyristors at peak voltage to eliminate any switching transients.

The AVC can respond to voltage fluctuations in one cycle, or as fast as ½ cycle in specially-designed units. Single units with capacity of up to 24 Mvar at 690 V or 120 Mvar at 15 kV can be applied for dynamic voltage support. A step-up

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transformer would typically be used to step the output voltage up to distribution or transmission voltage level.

Since the AVC uses binary-switched capacitors, the reactive power output occurs in discrete steps. In a three-stage unit the total output can be varied over 7 discrete steps, and in 15 steps in a four-stage unit. Since shunt-connected capacitors are utilized to provide reactive power output, the reactive power output is proportional to the square of the bus voltage.

2) *Inverter-based systems without energy storage*

These compensators (e.g., D-VAR and DSTATCOM) utilize shunt-connected voltage-source inverters to control the reactive power flow. Reactive power flow is controlled by adjusting the magnitude of the voltage output from the inverter relative to the bus voltage. Units typically have output filters and a step-up transformer to connect to the distribution bus. Typical D-VAR units are rated 480 V and consists of multiple 250 kVA inverter modules arranged for an output of up to ±8 Mvar continuous. Units have a one-second overload capability ranging from 2.3 to 3 times the continuous rating. After one second the output ramps down to its continuous rating in another second.

The reactive power output of an inverter-based compensator is proportional to the bus voltage.

3) *Inverter-based systems with energy storage*

The D-SMES is currently the only commercially-available inverter-based system that has been applied with energy storage for voltage stability applications. The system is similar to the D-VAR, with an additional superconducting magnetic energy storage module with peak output power capability of 3 MW and an average output power capability of 2.5 MW over the first 0.5 seconds of discharge [4].

The reactive power output of this compensator is also proportional to the bus voltage.

B. Compensator Performance Evaluation

1) *Simulation model of power system*

To evaluate the relative performance of the three categories of advanced VAR compensators for voltage stability support, a 138-kV utility system with three relatively weak ties was selected. See Figure 1. The three-phase short-circuit MVA at the three ties were:

- Bus #41: 670 MVA.
- Bus #3: 335 MVA.
- Bus #42: 1340 MVA.

Shaw Power Technologies Inc.'s PSS/E load flow and dynamic simulation software was used to perform the dynamic simulations.

The dynamic response of the power system following a major disturbance (i.e., short-term, large-disturbance voltage stability) is largely determined by the characteristics of the system loads and the strength of the power system. Analysis involving system dynamic response to identify potential short-term voltage instability is critically dependent on the modeling of the system loads. Load modeling guidelines for power flow and dynamic simulations are presented in [5]. Guidelines include recommendations on the modeling of discharge lighting, dynamic induction motor models, dynamic synchronous machine models, transformer saturation, load shedding, dynamic constant energy load models, load changes due to tap changer operation, etc. The effects of certain types of air-conditioner motor loads, which may stall at voltage levels below 60% of nominal lasting for 5 cycles or longer is particularly important in considering the behavior of motor loads [1].

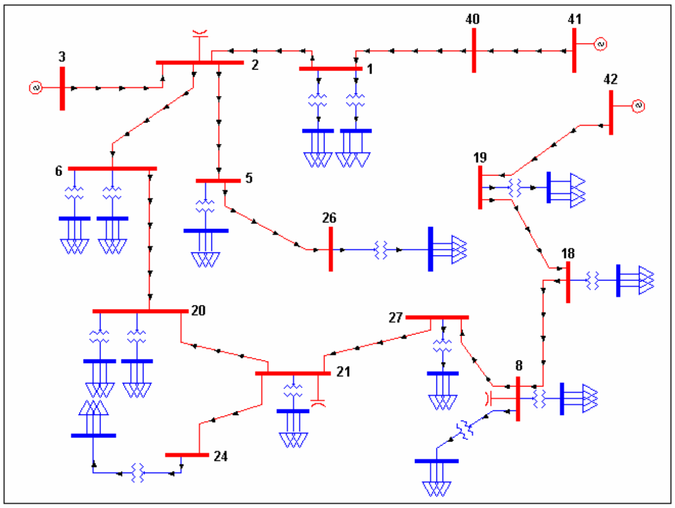

Fig. 1. Simplified one-line diagram of 138-kV utility system used in the dynamic simulations to evaluate performance of advanced VAR compensators.

When using PSS/E for voltage stability simulation utility system loads are typically split according to the percentage of large induction motors, small induction motors, discharge lighting, transformer saturation, constant power loads (other than motor loads), and remaining loads. The remaining loads are assumed to have a real power variation based on voltage raised to a specified power (K_p), and a reactive power variation based on the square of the voltage. For the system shown in Figure 1 the following load distribution was assumed for loads at each load bus:

- Small motor load: 45%.
- Large motor load: 15%.
- Discharge lighting: 20%.
- Constant power: 5%.
- Other loads: 15% (with K_p equal to 1.55).

2) *Simulation models of advanced VAR compensators*

PSS/E simulation models of the AVC, D-VAR, and D-SMES were used to represent the dynamic performance of the three categories of advanced VAR compensators. A base rating of ±8 Mvar continuous and one-second overload capability of 18 Mvar were selected for the D-VAR and connected through a step-up transformer at bus #21. This rating was determined to ensure that the voltage recovers to 80% of nominal in 20 cycles (333 milliseconds) or less at all transmission buses in the system as dictated by the

NERC/WECC reliability criteria for a category B disturbance [6]. Although these criteria do not specifically address short-term, large-disturbance voltage stability performance requirements, it was used in this paper as a measure of the rate of voltage recovery for comparing the relative performance of the advanced var compensators. All parameters used for the D-VAR model were identical to those described in [4], but without the superconducting magnetic energy storage module. The parameters of the D-SMES were identical to that of the D-VAR, except for the addition of the 3 MW peak output power capability of the superconducting magnetic energy storage module. An AVC with continuous output rating of 18 Mvar, which is based on matching the one-second overload capability of the D-VAR, was used and connected through a step-up transformer to bus #21.

3) Simulation results

The "worst case" dynamic response of the utility system shown in Figure 1 occurs when the tie to bus #42 is lost due to a transmission line fault occurring on the line between buses #19 and #42 and the subsequent opening of the line circuit breakers to clear the fault. The fault clearing time was assumed to be 5 cycles. Simulation of the "worst case" fault and line tripping included a case without any advanced VAR compensator and cases with each of the three categories of compensators connected via step-up transformers to bus #21.

Dynamic response voltage profiles at three 138-kV buses closest to the tie lost after the fault is cleared (i.e., buses #8, #18, and #19) were recorded for each of the four simulation cases, as well as the instantaneous reactive power output (and real power output in the case of the D-SMES) for the three advanced var compensators. The time it takes for the voltage to recover to 80% of nominal after fault clearing, as well as the voltage level 10 seconds after the fault was cleared were determined from the dynamic voltage profiles for each 138-kV bus in the system. The bus voltage levels 10 seconds after the major disturbance give an indication of the overall effect of the advanced var compensators on the steady-state post-disturbance bus voltage profiles prior to the operation of any transformer tap changers.

Figure 2 shows the dynamic voltage profiles at the three buses closest to the tie lost after the fault is cleared and without advanced var compensators applied in the system. The time to recover to 80% of nominal voltage after fault clearance ranges from 578 to 647 milliseconds (i.e., approximately 35 to 39 cycles) at the three buses. This is well beyond the NERC/WECC planning criterion of 20 cycles. Furthermore, the voltage level of approximately 82% of nominal 10 seconds after the fault is cleared is well below 90% of nominal at all three buses.

Figures 3(a) and 3(b) show the dynamic voltage profiles and reactive power output of a ±8 Mvar D-VAR. The advantage of the one-second 18 Mvar overload capability of the D-VAR is clearly shown in the initial voltage profiles. However, the bus voltage levels are reduced as the reactive power output ramps down to the continuous output rating as reflected in Figure 3(b).

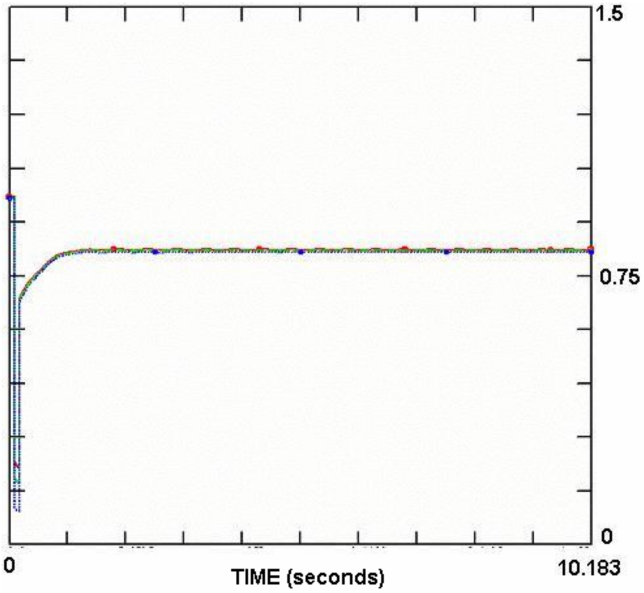

Fig. 2. Profiles of dynamic voltage response at buses #8, #18, and #19 without any advanced VAR compensator. Voltage level 10 seconds after the fault is cleared is about 0.82 per unit (82%) of nominal at all three buses.

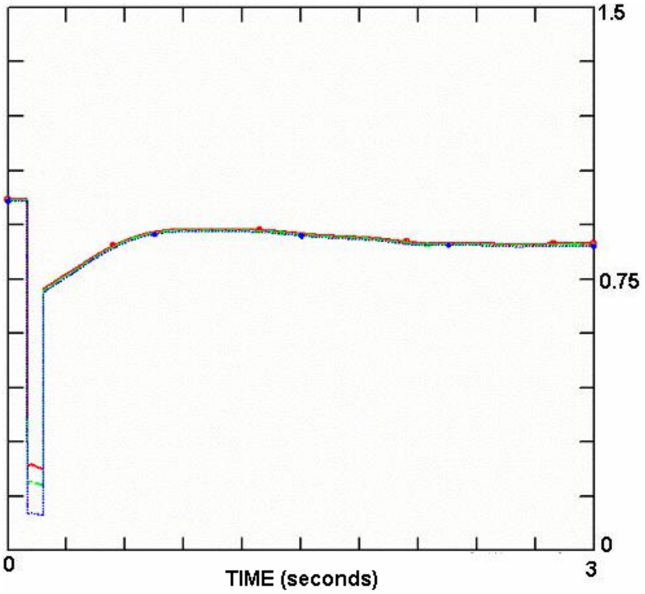

Fig. 3(a). Profiles of dynamic voltage response at buses #8, #18, and #19 with a ±8 Mvar D-VAR connected via a step-up transformer to bus #21. Voltage level 10 seconds after the fault is cleared ranges from 0.84 to 0.85 per unit (84 to 85%) of nominal at the three buses.

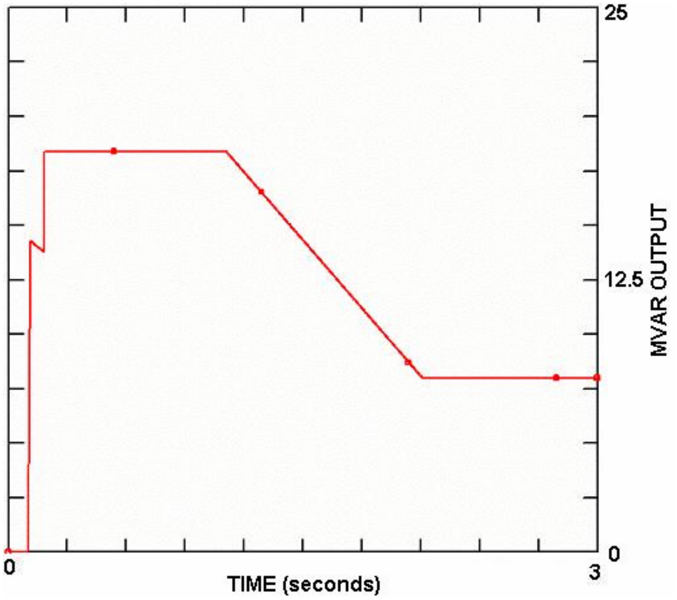

Fig. 3(b). Reactive power output of a ±8 Mvar D-VAR connected via a step-up transformer to bus #21. Peak reactive power output is slightly more than 18 Mvar.

Figures 4(a) and 4(b) show the dynamic voltage profiles and reactive power output of a ±8 Mvar, 3 MW peak output power D-SMES connected via a step-up transformer to bus #21. As with the D-VAR, the advantage of the one-second 18 Mvar overload capability of the D-SMES is clearly shown in the initial voltage profiles. However, the bus voltage levels are reduced as the reactive power output ramps down to the continuous output rating as reflected in Figure 4(b). Also, the real power output capability of the D-SMES has very little effect on the voltage profiles when compared to that of the D-VAR.

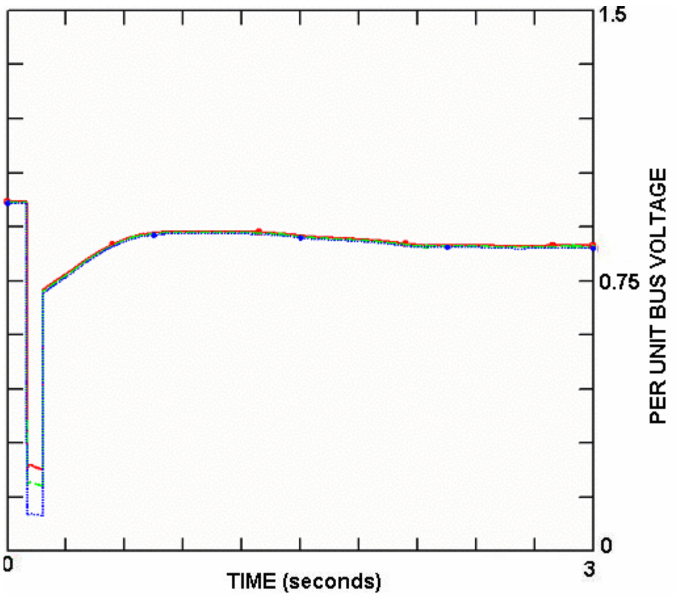

Fig. 4(a). Profiles of dynamic voltage response at buses #8, #18, and #19 with a ±8 Mvar, 3 MW peak output power D-SMES connected via a step-up transformer to bus #21. Voltage level 10 seconds after the fault is cleared ranges from 0.84 to 0.85 per unit (84 to 85%) of nominal at the three buses.

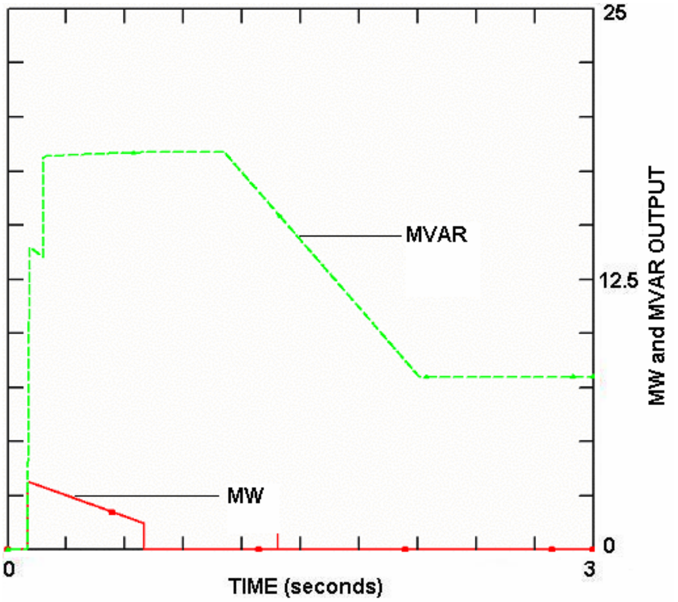

Fig. 4(b). Real and reactive power output of a ±8 Mvar, 3 MW peak output power D-SMES connected via a step-up transformer to bus #21. Peak real power output is 3 MW and peak reactive power output is slightly more than 18 Mvar.

Figures 5(a) and 5(b) show the dynamic voltage profiles and reactive power output of an 18 Mvar AVC connected via a step-up transformer to bus #21. The initial voltage profiles closely match those attained with the D-VAR and D-SMES. The ultimate voltage levels are higher than those attained with the D-VAR and D-SMES (approximately 89% of nominal) due to the higher continuous reactive power output capability of the AVC. The initial voltage recovery is slightly slower compared to that attained through the D-VAR and D-SMES.

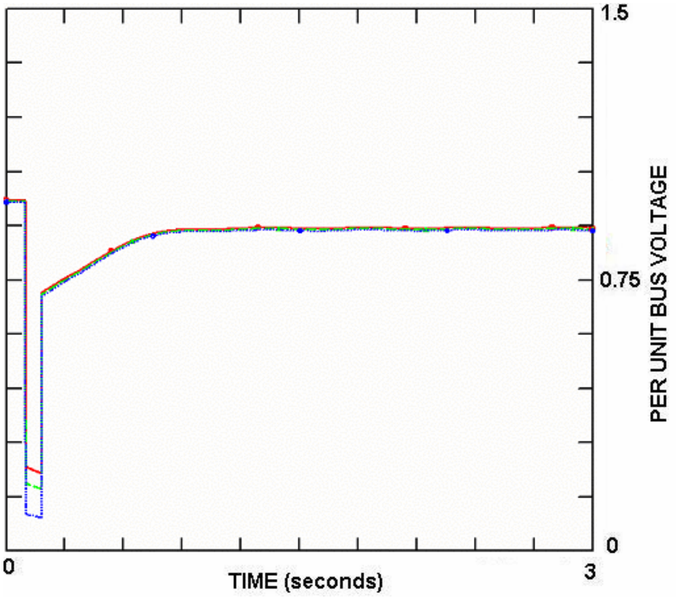

Fig. 5(a). Profiles of dynamic voltage response at buses #8, #18, and #19 with an 18 Mvar AVC connected via a step-up transformer to bus #21. Voltage level 10 seconds after the fault is cleared is about 0.89 per unit (89%) of nominal at all three buses.

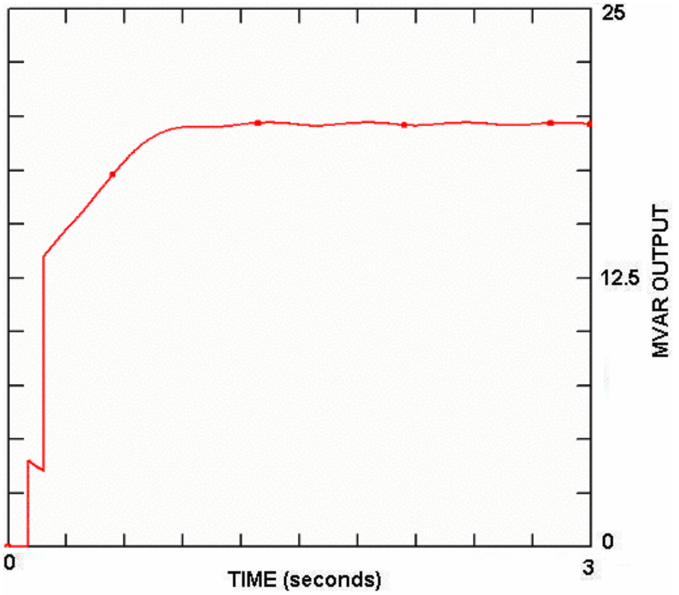

Fig. 5(b). Reactive power output of an 18 Mvar AVC connected via a step-up transformer to bus #21. Peak reactive power output is about 19.5 Mvar.

Table I summarizes the initial voltage recovery times and ultimate voltage levels at all the 138-kV buses in the system.

TABLE I
SUMMARY OF VOLTAGE RECOVERY TIMES AND VOLTAGE LEVELS 10 SECONDS AFTER THE FAULT IS CLEARED

Bus #	Time for voltage to recover to 80% of nominal (milliseconds)				Per unit voltage 10 seconds after fault is cleared			
	No comp.	D-VAR	D-SMES	AVC	No comp.	D-VAR	D-SMES	AVC
1	0.3	0.3	0.3	0.3	0.86	0.87	0.87	0.89
2	96	0.5	0.3	16	0.85	0.86	0.86	0.88
3	48	0.3	0.3	0.3	0.85	0.86	0.86	0.88
5	118	14	0.5	32	0.85	0.86	0.86	0.88
6	233	65	47	90	0.84	0.86	0.86	0.88
26	122	17	0.5	36	0.85	0.86	0.86	0.88
20	**407**	133	112	169	0.84	0.86	0.86	0.89
21	**407**	120	101	156	0.84	0.87	0.87	0.91
24	**409**	121	103	158	0.84	0.87	0.87	0.91
27	**486**	172	151	211	0.83	0.86	0.86	0.90
8	**578**	219	194	259	0.82	0.85	0.85	0.89
18	**610**	231	206	272	0.82	0.85	0.85	0.89
19	**647**	243	217	284	0.82	0.84	0.84	0.89
40	0.3	0.3	0.3	0.3	0.87	0.88	0.88	0.90
41	0.3	0.3	0.3	0.3	0.88	0.89	0.89	0.90

The results summarized in Table I give a clear indication of the relative performance of the compensators considered:

- The initial times of voltage recovery to 80% of nominal voltage are least with the D-SMES due to its one-second overload reactive power output capability and its 0.5-second 3 MW peak/2.5 MW average real power output capability. However, the slightly-improved voltage recovery times compared to that of the D-VAR come with an additional cost for the energy-storage module, which may not be economically justifiable.
- The initial voltage recovery times of the D-VAR and D-SMES are less than that of the AVC. Considering that the overload reactive power output *capability* of the D-VAR and D-SMES units is the same as the continuous rating of the AVC within the first second of voltage recovery, the faster response is due to the fact that the *actual* reactive power output of the inverter-based systems is proportional to the voltage, while that of the power-electronically-switched capacitor system is proportional to the square of the voltage. Since the bus voltages are initially depressed due to the fault, the inverter-based systems have a higher initial reactive power output. Compare Figures 3(b), 4(b), and 5(b).
- The voltage levels attained 10 seconds after the fault is cleared is higher with the AVC than with the D-VAR and D-SMES. This is due to the fact that the actual reactive power output of the power-electronically-switched capacitor system is substantially higher than that of the inverter-based systems after the initial voltage recovery period. After the initial voltage recovery, the overload capability of the inverter-based systems is no longer available. Compare Figures 3(b), 4(b), and 5(b).
- All three advanced VAR compensators are effective at enabling voltage recovery to 80% of nominal voltage in less than 20 cycles (333 milliseconds) after the fault is cleared.

C. Application and Other Considerations

Due to practical limitations on the step-up transformer turns ratio, the connection of *low-voltage* advanced VAR compensators to transmission voltage levels is usually accomplished via two step-up transformers. In most cases the low-voltage advanced VAR compensator connects through its own step-up transformer to a distribution substation medium-voltage bus. Thus, reactive and real power injection for dynamic stability support is actually done at distribution-voltage level. This situation does not apply to medium-voltage compensators utilizing power-electronically-switched capacitors. These compensators can connect to the transmission voltage bus via its own step-up transformer, or otherwise directly to the distribution substation medium-voltage bus.

Shunt capacitor banks, applied at transmission voltage levels, can be used in conjunction with and controlled by advanced VAR compensators to improve system voltage recovery. This offers a means for more economically providing the total reactive power support required after a major disturbance on the system. In a compensation system consisting of advanced VAR compensators and switched shunt capacitors, the advanced VAR compensators are utilized to rapidly raise the system bus voltages after the fault is cleared and then energizing the shunt capacitor banks soon afterwards at a voltage level that results in a substantially higher reactive power output from the shunt capacitors.

Advanced VAR compensators can be distributed throughout the system to improve voltage stability for different contingency conditions, or for a single "worst case" contingency condition in a larger system.

Since the advanced VAR compensators usually controls the voltage level of the bus to which it is connected, these compensators can be used to provide dynamic reactive power compensation for normal fluctuations due to load changes and changes in system configuration. Compensators can also use shunt-connected reactors to extend the range of inductive dynamic VAR compensation for voltage regulation applications.

Advanced compensators utilizing *low-voltage* inverters or power-electronically switched capacitors are limited in reactive power output capability. Due to the high currents and number of inverter modules involved, *continuous* reactive power ratings of 10 Mvar for inverter-based systems and 24 Mvar for power-electronically-switched capacitor systems represent economical upper limits in the design. Medium-voltage inverter-based systems with ratings up to 36 Mvar at 4 kV are also commercially available. Medium-voltage advanced VAR compensators utilizing power-electronically-switched capacitors rated up to 120 Mvar at 15 kV are also commercially available.

The cost of low-voltage inverter-based systems without energy storage is about the same as that of power-electronically-switched capacitor systems with continuous reactive power output ratings equal to that of the overload capability of the inverter-based systems. Due to the cost of the energy-storage module, the cost of inverter-based systems with energy storage is considerably higher than that of the other two categories of systems discussed.

IV. CONCLUSIONS

Advanced VAR compensators utilizing power-electronically-switched capacitors or inverter-based systems with or without energy storage can be used effectively to improve power system voltage stability. The performance evaluation presented indicates that inverter-based systems provide the most effective *initial* reactive power support to allow more rapid initial voltage recovery in the time frame less than one second after a fault is cleared. Inverter-based systems with energy storage provide slightly-improved performance over that of inverter-based systems without energy storage during the initial voltage recovery period due to their brief real power output capability. However, the slightly-improved voltage recovery times obtained in the sample utility system used in this paper come with an additional cost for the energy-storage module, which may not be economically justified. Compensators with power-electronically-switched capacitors provide more effective reactive power support for voltage recovery in the time frame beyond one second after the fault is cleared due to the higher continuous reactive power capability compared to inverter-based systems with the same overload capability.

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VI. BIOGRAPHIES

Ernst H. Camm received his BSc (Eng) degree in Electrical and Electronic Engineering from the University of Cape Town, South Africa in 1984 and his MSEE degree from the Ohio State University in 1992. From 1984 to 1990, he held various positions in Plant and Project Engineering. He is currently a Senior Engineer in the Engineering Services Department of the Power Systems Services Division at S&C Electric Company.

Ernst has been actively involved in system analysis associated with dynamic stability, capacitor-switching transients, and power quality at S&C for 11 years. He has presented several industry seminars on custom power devices for power quality improvement and on devices for mitigating capacitor-switching transients. He has authored and co-authored several IEEE papers and magazine articles on these subjects. He is an active member of the IEEE's Modeling and Analysis of System Transients Working Group and the Shunt Capacitor Application Guide Working Group.

Ernst is currently actively involved in system analysis associated with the application of advanced VAR compensators for improving dynamic stability and for wind farm applications.

Thompson Adu (S’87–M’96–SM’00) received the B.Sc. degree (honors) in Electrical Engineering from the University of Science and Technology, Kumasi, Ghana, in 1982, and the M.Sc. and Ph.D. degrees from the University of Saskatchewan, Saskatoon, SK, Canada, in 1989 and 1993, respectively. He is currently employed by S&C Electric Company in the Power Systems Services Division after working for Volta River Authority, Saskatchewan Power Corporation and Mehta Tech, Inc.

For 15 years Thompson has been actively involved in power system analysis, planning and protection. He has performed planning studies pertaining to new generation additions and interconnections to the power grid and network adequacy studies including capacity, transfer capability, power quality and stability studies. Thompson has presented several industry seminars on power system analysis. He was technical course instructor on detection of abnormalities in the electric power systems using digital algorithms, a course which has been offered at several electric utilities (both locally and internationally). He has authored and co-authored several IEEE papers and magazine articles on these subjects.

Thompson is presently actively involved in system analysis related to voltage instability arising from power system abnormalities and the use of FACTS devices to mitigate this problem. He is also actively involved in wind power generation and interconnection studies, including the use of advanced VAR compensators to improve the low-voltage ride through capabilities of wind turbines.