Understanding and Solving Short-Term Voltage Stability Problems

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***Abstract*—Based on actual incidents, short-term voltage instability is an increasing, but often overlooked, industry concern. A common scenario is a large disturbance such as a multi-phase fault near a load center that decelerate motor loads. Following fault clearing with transmission outages, motors draw very high current while simultaneously attempting to reaccelerate, and may stall if the power system is weak. Massive loss of load and possibly area instability and voltage collapse may follow. We describe actual incidents. Fast-acting generator excitation controls, fast-acting reactive power support devices (SVC, STATCOM, SMES), or fast load shedding can prevent voltage collapse.**

Proper analysis requires dynamic modeling of aggregated motor loads, with equivalents for distribution feeders. Power electronic based voltage support devices must be realistically modeled to determine required size, location, number, and type.

Based on simulations, we conclude that voltage-sourced converter devices (STATCOM, SMES) are attractive countermeasures against load loss and voltage collapse. Factory built distribution–connected distributed devices may be cost-effective compared to larger transmission-connected devices.

***Index Terms*—induction motor, power system, reactive power, SMES, STATCOM, superconductivity, voltage collapse, voltage stability**

I. Terminology

Load factor: Motor active power loading divided by rated apparent power.

SVC: Static Var Compensator.

STATCOM: shunt-connected STATic COMpensator employing voltage-sourced converters.

SMES: Superconducting Magnetic Energy Storage.

D-SMES: Distributed SMES.

Short term voltage stability: Voltage stability maintained in the time frame of a few seconds. The term *transient voltage stability* is also used, but short-term voltage stability is the preferred term of a joint IEEE/CIGRÉ task force on Power System Stability Terms, Definitions and Classifications.

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II. Introduction

MANY short-term (few seconds) voltage incidents with loss of load have occurred in recent years [1–9]. Problems are likely to increase in the future because of:

1. Growing use of low inertia compressor motors for air conditioning, heat pumps, and refrigeration;
2. Growing urban heat islands and possible global warming, causing increased use of air conditioning with higher load factor;
3. Increasing amounts of voltage-insensitive loads with electronic power supplies;
4. More intensive use of transmission;
5. Increasing use of capacitor banks for reactive power compensation.

The problem is associated with motor loads, often shunt capacitor bank compensated, that draw very high current when starting or when slowed because of disturbances. Heavily loaded, constant torque type mechanical loads are the most onerous—these loads (i.e., air conditioner compressor motors) may comprise up to 50% of summer peak load [25]. The potential for voltage stability problems is heightened because both shunt capacitor bank reactive power, and induction motor electrical torque decrease with the *square* of the voltage.

HVDC inverters are also fast-acting unfavorable load [12]. Briefly, conventional HVDC converters have high shunt capacitor bank/filter compensation, and inverter reactive power demand increases with sagging voltage—both effects are destabilizing.

Generators, if nearby, may ensure voltage recovery. The time-overload capability of generator field and armature circuits may be used.

Load characteristics, and the possibility of fast voltage collapse, affect the type of reactive power compensation required. For fast-acting loads, power electronic types of reactive power compensation (SVC, STATCOM) tend to be required rather than the common mechanically switched compensation.

A related longer-term scenario involving motor loads assumes a power system survives the first few seconds following a severe disturbance, with motors re-accelerating to normal speed. The outages, however, may cause field current overload of generators. After tens of seconds of time delay, overexcitation limiters reduce field current to continuous

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capability; alternatively, power plant operator invention or protective tripping may occur. The field current and reactive power reduction can result in cascading field current limiting, armature current overloads, and also in generator and transmission line tripping by backup relays. With onerous loads, and inadequate reactive power compensation or other countermeasures, a fast collapse follows. The July 2, 1996 cascading outage in the western U.S. followed this sequence, with collapse in the southern Idaho load area approximately 20 seconds after the initial disturbance [10,]. During this disturbance temperatures were very high, and much of the load was air conditioning, refrigeration, and agricultural pumping.

Vulnerability to short-term voltage instability exists during summertime operation with high stress. For example, several hours of operation at depressed voltage and small reactive power reserves occurred during heat waves in the Northeastern U.S. on 6 and 19 July 1999 [11]. Disturbances during these periods could have caused a fast voltage collapse over a large, highly populated area, with inadequate time for manual load shedding.

In this paper we review the important and timely topic of short-term voltage stability analysis. We provide simulation examples, with comparison of several types of power electronic based voltage instability countermeasures.

III. Reliability Criteria

Many planning and operating engineers are insufficiently aware of potential short-term voltage instability, or are unsure on how to analyze the phenomena. Reliability criteria often does not address short-term voltage stability. To be consistent with angle stability criteria involving three-phase faults near generators, three-phase faults should also be applied in load areas. Currently, voltage stability analysis is mostly done by power flow program based simulation of a point in time several minutes following a disturbance. Some power companies in summer peaking areas employ undervoltage load shedding with many seconds of time delay inadequate for short-term scenarios. Dynamic simulation tends to be for angle stability, with inadequate load models, and with short circuits applied near generators rather than near loads.

IV. Review of Incidents and Literature

A. Southern California

Southern California Edison Company reported incidents occurring in rapidly growing desert area such as Palm Springs [1]. Residential air conditioners stalled on phases affected by subtransmission and distribution faults. The resulting phase imbalance from motors drawing 4–6 times normal current caused ground relays to operate and trip entire distribution areas. Laboratory tests indicated that residential air conditioners stall for five cycle fault clearing for voltage below 60%. Residential air conditioners trip after 5–10 seconds by thermal relay protection. The time delay depends on the source impedance or voltage stiffness, which affects the current drawn by the stalled motor and the resulting heating.

B. Southern California, Tuesday, August 5, 1997 [2]

Southern California Edison Company was operating at a new summer peak. A small plane contacted shield wires of two 500-kV lines. Subsequently, one of the lines was reclosed into a three-phase fault, with two-cycle fault clearing. The fault caused voltage dips to 0.6 per unit at distribution busses, with stalling of residential air conditioners. Fifty-nine distribution circuits tripped, and approximately 3525 MW of load was lost. Voltages took 20–25 seconds to recover. The fast, low voltage tripping of industrial and commercial load was essential to the recovery. Tripping of distribution circuits by ground overcurrent relays took 2.5–3 seconds, which would be too slow to prevent complete area collapse for a slightly more severe condition such as higher residential air conditioning load (weekend load).

C. Phoenix Area, July 29, 1995 [3]

The event occurred on a Saturday afternoon during very hot weather (44°C, 112°F). Much of the load was residential air conditioning. A 230-kV capacitor bank fault with delayed clearing resulted in loss of five 230-kV lines and two 230/69-kV transformers. About 2100 MW of load was lost. Voltage recovery took up to 20 seconds (Figure 1). Presumably, many residential air conditioners stalled, and then tripped off after some seconds to allow eventual recovery of the remaining power system. Recordings show high reactive power output of area generators during the recovery period. High reactive power output from generators at the nearby Palo Verde nuclear plant was essential for the recovery.

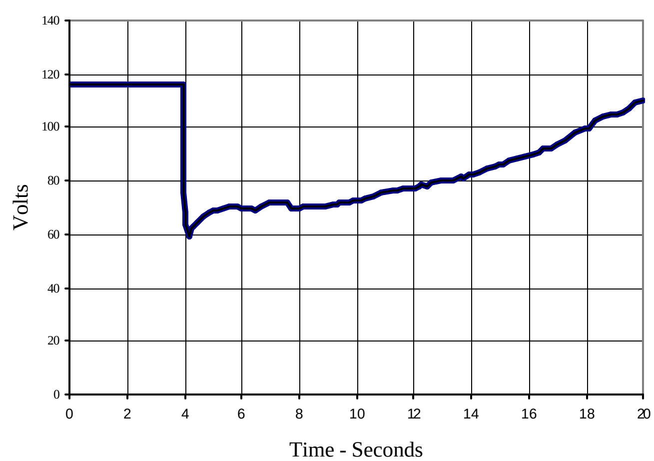

Fig. 1. Residential voltage recovery for Phoenix area incident on July 29, 1995.

D. Miami, Florida [4]

At least eight multi-phase faults have occurred in Southeastern Florida resulting in loss of load. Three-phase faults occurred in the Miami area on August 18, 1988 and May 3, 1994. Similar to the above events, voltage recovery was slow, taking around ten seconds. In order to reasonably match the actual results, a detailed equivalent for distribution feeders was required, together with dynamic modeling of aggregated motor load. Assumptions on low voltage tripping of load were also required.

E. Atlanta Area, July 30, 1999 [5]

Three short circuits and two breaker failures at two adjacent substations occurred. Five generators tripped and 1900 MW of load tripped. Voltage recovery took 15 seconds.

References 6–9 describe similar problems elsewhere. It's likely that many comparable unreported events have occurred.

In all cases, adequate dynamic reactive power support was not available which resulted in a large loss of load. The eventual tripping of stalled air conditioners allowed a very slow voltage recovery.

V. LOAD CHARACTERISTICS AND MODELING

A. Load Components

Favorable loads for voltage stability are static, voltage-sensitive load such as heating and conventional lighting. Following a disturbance, the mechanisms of longer-term voltage instability include load restoration by tap changing transformers and distribution voltage regulators, and current limiting at generators [12,13].

With the increasing use of air conditioning in past decades, even many northern areas of the U.S. are summer peaking (Minneapolis for example). Summertime peak load may also include agricultural pumping and other industrial motor load.

A second trend is electronic loads that have very fast dynamics resulting (if they survive the fault) in a nearly constant power characteristic. The primary examples are loads with electronic power supplies and some types of electronic ballasted lighting. Reference 14 suggests these loads may continue in service at quite low voltages. Manufacturers, trade associations, and end users are trying to reduce unnecessary dropout of loads.

Adjustable speed drives are an exception to the unfavorable characteristics of electronic loads. A drive, with dc capacitor link, provides a buffer between the power system and the unfavorable characteristics of an induction motor (very high current at reduced speed, electrical torque proportional to square of voltage). Laboratory tests of two drives showed insignificant dynamics, and substantial voltage sensitivity of active and reactive input power [14]. Again, the trend of manufacturers and end users is to harden the drives and controls to reduce unnecessary dropout.

B. Basic Induction Motor Characteristics

Figure 2 shows typical torque–speed and current–speed characteristics. The curves could be an aggregated characteristic of many motors. Voltage collapse potential is apparent from this simple sketch.

A short circuit reduces electrical torque by the square of the voltage, decelerating the motors. The slow down or slip increases depends on the mechanical torque characteristic and the motor inertias. The mechanical torque characteristics of air conditioning compressor motors are insensitive to speed changes, and the mechanical starting times (2H) may be as small as 0.5 seconds. The mechanical torque demand of an air conditioners increase with ambient temperature and humidity.

The internal voltage (flux) of motors initially support voltage, reducing the short circuit induced voltage dips and reducing the decelerations. The internal voltages decay rapidly with backfeed into the short circuit.

With fault clearing and a weakened source system, voltages will partially recover. High motor currents will impede voltage recovery on fault clearing. The power factors of the slowed motors are low, with the high reactive currents strongly affecting voltage magnitudes. Fast operating reactive power compensation, however, will aid voltage recovery.

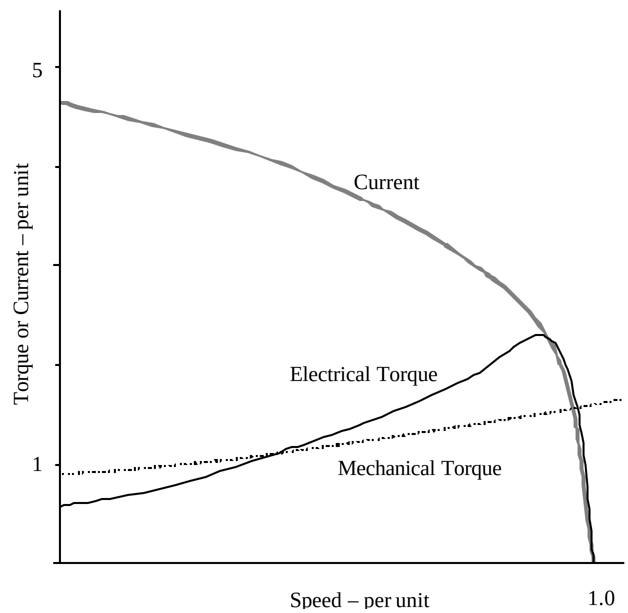

Fig. 2. General torque–speed and current–speed characteristics for air con-ditioner compressor motor. Electrical torque varies with voltage squared. Power factor decreases at low speed. Mechanical torque increases with ambient temperature.

If electrical torques are greater than mechanical torques, motors will reaccelerate to near normal speeds. If not, motors will rundown and stall—drawing high currents at low power factor. Stalling of motors near ends of feeders may cause cascade stalling of other motors. Motor tripping may occur within a few cycles because of motor control or protection response to low voltage, after a few seconds by power system overcurrent relays, or after many seconds by motor thermal protection.

C. Motor Modeling

Dynamic motor modeling is *essential*. The simplest induction motor model is a reactance in series with the rotor resistance divided by slip. Since rotor inertia prevents slip from changing instantaneously, the motor responds initially to short circuits and other switching as an impedance load—which is favorable to voltage stability. The term *impedance jump* is used. Short circuit clearing increases voltage with an upward impedance jump in motor current and power. The slip dynamics are fast and in a fraction of a second the motor attempts to reach a stable equilibrium of electrical and mechanical torques. If voltages do not recover to near normal on short circuit clearing, however, electrical torques to reaccelerate motors are reduced by the square of the voltage.

As discussed above, rotor electromagnetic dynamics are also important. This leads to third or fifth order models [12, 13,15–18]. Fifth order models represent double cage or deep bar effects important for motor starting, and results in better modeling of reduced speed and stall conditions. In some dynamic programs, the fifth order model representing double squirrel cage or deep bar effects is equivalenced to a third order model [17].

With today's computer capability, the simple first order model (slip dynamics only) is not recommended. Modeling of the inertia and electromagnetic dynamics, which are quite fast in small motors or aggregates of small motor, may require smaller time steps or sub-time steps, especially in computer programs using simple explicit numerical integration methods.

The relatively simple induction motor models with inertia and rotor electromagnetic dynamics found in production-grade dynamic programs are generally satisfactory for small speed and voltage changes, but must be used with care for larger speed and voltage changes. More detailed models include saturation of magnetizing reactance and leakage reactance [17,29]. The three-phase motor models of conventional dynamic programs represent the general behavior of single-phase motors for small speed changes [19].

Data sets are available for individual and aggregated motors [12,20,21], or can be developed from available information [26,29].

D. Motor Stalling, Tripping and Restart

Because of mechanical and electrical torque characteristics, and low inertia, residential air conditioner compressor motors on phases affected by short circuits will slow considerably and draw high current. *All* may stall if the network is weak [25].

For single- and two-phase faults, the fault voltage of single-phase loads depends on transformer connections between the fault and the load. For example, for a single-phase fault on the primary side of a delta–wye transformer, the secondary phase to neutral voltages is 58% on two phases and is 100% on the third. Considering the feeder voltage drops associated with high motor currents, compressor motors on two phases will likely stall.

As mentioned above, unless disconnected by power system overcurrent relays, most residential air conditioners trip only by thermal protection many seconds after stalling. Typical air conditioners will automatically restart in about 30 seconds after pressure bleed-off [19].

Commercial and industrial motors generally will trip for severe voltage reduction. Some commercial motors have a protection module that trips at around 70% voltage with about 0.1 second delay [1,4]. This tripping may be very important in avoiding voltage collapse

Industrial and agricultural motors have a wide variety of controls, ranging from electromechanical contactor-type starters to sophisticated digital motor control centers, sometimes with additional power quality devices. Common electromechanical starters are connected to a phase–phase voltage of the incoming line. If the phase–phase voltage is depressed, the contactor relay will de-energize and disconnect the motor. This typically occurs at 40–75% voltage with a few cycles of time delay. Other electromechanical controls aren't sensitive to incoming voltage. Electronic controls, however, typically have higher sensitivity to incoming voltage, and motor disconnection may occur for 80–90% voltage. In summary, some industrial motors and drives will trip for voltage dips below approximately 90%. Some stalled motors may stay connected for some seconds for voltages above 60–70%.

Other loads, such as discharge lighting and loads with electronic power supply, will trip for voltage dips of certain magnitude and duration [14,25,28].

E. Aggregation of Loads and Distribution Equivalents

It's said that voltage stability is *load stability*, and angle stability is *generator stability*. Thus voltage stability analysis requires faults in load areas and more detailed representation of subtransmission, distribution, and loads [12,20,22]. At substations, bulk power delivery transformers should be represented (leakage reactance on the load MVA base typically 10–15%). This reactance is a large fraction of the total reactance between the high voltage bus and the aggregated load. These transformers (e.g. 115-12.5-kV) are typically around 10–40 MVA and specific data is usually available. They are often automatically controlled LTC transformers, which is important for longer-term simulation.

Especially with longer feeders, an equivalent impedance for distribution feeders is desirable. Loads and distribution capacitors can be placed both at the distribution bus and at the end of a feeder equivalent. Distribution capacitors should not be netted with load, but represented separately.

Load equivalents should include one or two dynamically modeled induction motors, discharge lighting, transformer/motor saturation, and static load. Motors may include a large industrial motor equivalent, and a small motor equivalent (e.g., air conditioning). Motor data set sources are suggested above.

Widely used dynamic programs include default load equivalent model to facilitate simulation. The default data can be overridden based on particulars of load composition, season represented, and on-peak versus off-peak conditions. Examples are the GE PSDS composite load model and the PTI PSS/E complex load model (use PTI's CIM5 series of motor models to model the motor portion of the load and the CLOD model to model the other non-motor loads). Auxiliary programs can also facilitate more detailed load models, keeping the power flow base case bus load power at the high voltage bus invariant.

F. Summary of Load Characteristics and Modeling

Although the (aggregated) motor modeling described above is far from perfect, the basic physics are captured. Engineers must interpret results, refine modeling as necessary, and apply appropriate safety margins in planning and operation. The commonly used static models of motors, on the other hand, are totally inadequate and must not be used. Most fundamentally, static models do not represent the high current drawn by induction motors that have slowed during a short circuit, resulting in grossly optimistic results.

Air conditioning load during high ambient temperature is the most onerous. This is because of compressor torque–speed characteristic, low inertia, and high load factor. Slow tripping of stalled residential air conditioners makes short term voltage instability a serious concern. The overloads and voltage depression caused by stalled motors can cause cascading tripping of lines and generators, leading to area collapse within a few seconds.

VI. Voltage Support Devices

Several options are available to prevent short term voltage instability. Network reinforcements include new lines and transformers, and transmission or distribution series compensation. Fast undervoltage load shedding (approximately one second time delay) is an option [23], but many residential air conditioner motors may still stall. Residential air conditioner designs with faster tripping of stalled motors would be valuable, and is a requirement in some countries.

A. Shunt Support Alternatives and Characteristics

Shunt support devices, however, are frequently the first choice. Choices include mechanically switched capacitor and reactor banks, SVCs, and voltage-sourced converter based STATCOMs. Voltage-sourced converter devices can include, in addition to the STATCOM function, energy storage for active power support (e.g., SMES or battery).

Mechanically switched shunt compensation must be switched rapidly and must be properly sized. Capability for rapid on–off switching is significantly limited. Therefore the more costly power electronic based devices are often chosen for short-term voltage stability support.

Combining electronic and mechanical switching with coordinated control, however, is cost-effective. The SVC or STATCOM is a “pilot” to direct mechanical switching of capacitor/reactor banks. Controls commands mechanical switching for high SVC or STATCOM reactive power output. The power electronic device then repositions, and compensates for improperly sized mechanical switching.

High shunt support is needed for only a few seconds while motors draw high current during re-acceleration. Thus, electronic shunt compensation with short-term ratings is attractive.

Power electronic based devices have other advantages such as controlling load rejection overvoltages and improving power (voltage) quality. Voltage is precisely regulated and mechanical tap changing can be greatly reduced [27].

B. SVC versus Voltage-Sourced Converter Devices

Power system SVCs and voltage-sourced converter devices (e.g., STATCOM or SMES) regulate a bus voltage via the reactive current/power output. Over the control range, a droop (slope) characteristic of a few percent is used to avoid excessive control action and to coordinate with other voltage control equipment. A fundamental difference between SVCs and voltage-sourced converter devices is evident when the control limits are reached—which occurs for a few percent drop or rise of system voltage. SVCs at their boost limit become very expensive ac capacitor banks. Voltage-sourced converter devices, however, inherently provides constant current output down to low voltage (Figure 3). At 70% voltage, for example, SVC output is 70% current or 49% reactive power, while STATCOM/SMES output is 100% current or 70% reactive power. This difference can be crucial in supporting re-acceleration of motors following a short circuit [24]. Voltage-sourced converter devices provide superior performance for equal reactive power ratings; alternatively, a smaller STATCOM or SMES will equal the performance of a larger SVC.

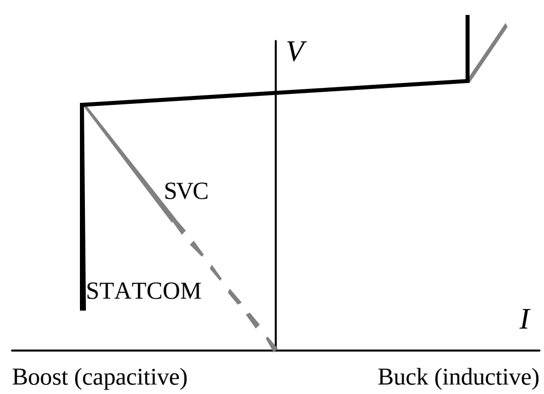

Fig. 3. STATCOM and SVC characteristics.

Voltage-sourced converter devices have other advantages such as smaller size and higher speed. Smaller size facilitates relocation and factory, rather than site, assembly. Higher speed or bandwidth is valuable in power quality applications such as flicker control. Voltage-sourced converter devices have symmetrical boost and buck reactive power ranges, but fixed or switched shunt compensation can bias the output range as desired.

SMES with its energy storage and discharge capability adds additional flexibility for stability and power quality support.

C. Transmission Level versus Distributed Voltage Support

Conventional shunt capacitor banks are most commonly at distribution level. Power company SVCs or STATCOMs most commonly regulate transmission voltage (a coupling transformer connects the medium voltage power electronic components to the transmission level).

Larger, transmission level devices achieve economies of scale and provide support for several nearby substations. On the other hand, HV or EHV coupling transformers, even with short term ratings, are a significant cost, and significant on-site construction is required. Reactive power must be transmitted through the coupling transformer, through transmission lines, and then through bulk power delivery transformers and feeders to the load areas requiring high current during motor reacceleration.

An alternative is several small factory built devices connected at distribution level and distributed at major bulk power delivery substations [28,31,32]. Smaller size allows more options in the design, and reduces problems such as connection of thyristors or power transistors in series.

We next compare performance, including benefits of energy storage.

VII. CASE STUDY

A. System Description

Our case study looks at a fast voltage collapse/short-term voltage instability/slow voltage recovery problem that a transmission network could experience for the loss of one of its two 345-kV transmission sources. Figure 4 shows the one-line diagram of the transmission network.

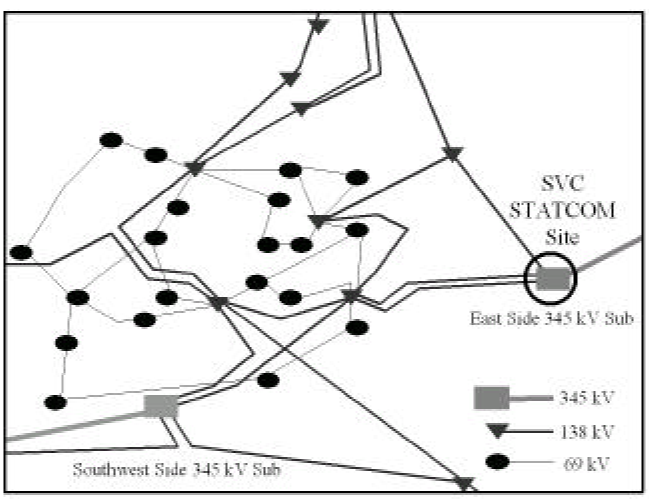

Fig. 4. Transmission network.

We first improved the load's power factor. Transmission capacitor banks were added so that the outage of either 345-kV source caused no steady-state low voltage problems.

The load for the area of concern has a summer peak of approximately 1500 MW. The loads are broken down into the five following load types.

Load Type	Percentage
Small Motors	45%
Large Motors	15%
Discharge Lighting	20%
Constant Power	5%
Remaining	15%

The small and large motors are modeled using PTI's CIM5 model and the other loads are modeled using PTI's CLOD model. The remaining load type is a mix of constant current and constant impedance for the real part and constant impedance for the reactive part.

The loadflow base case included all of the area's 138/12-kV and 69/12-kV distribution transformers and included an additional 3% impedance to model the 12-kV distribution feeders.

Figure 5 shows the fast voltage collapse/slow voltage recovery problem for the faulting and loss of the east side 345-kV source.

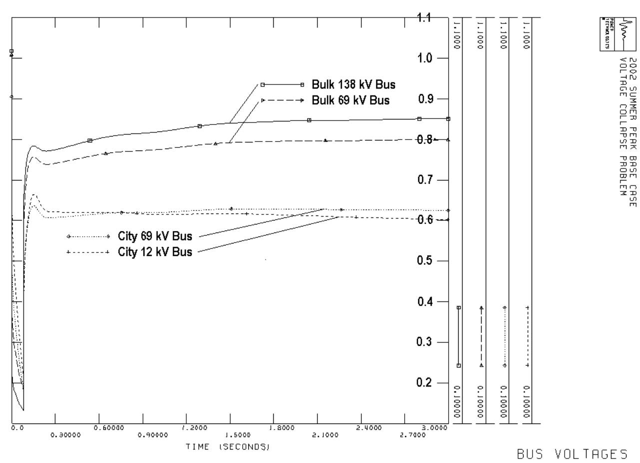

Fig. 5. Voltage problem.

B. Large SVC

Figure 4 shows the east side location of a 300 MVAr SVC installation. Figure 6 shows results for the fault and loss of the east side 345-kV source. The SVC was very effective in improving the 138-kV voltage recoveries, but only marginally effective in improving the 69-kV and 12-kV load voltages. We tried larger SVCs with similar results.

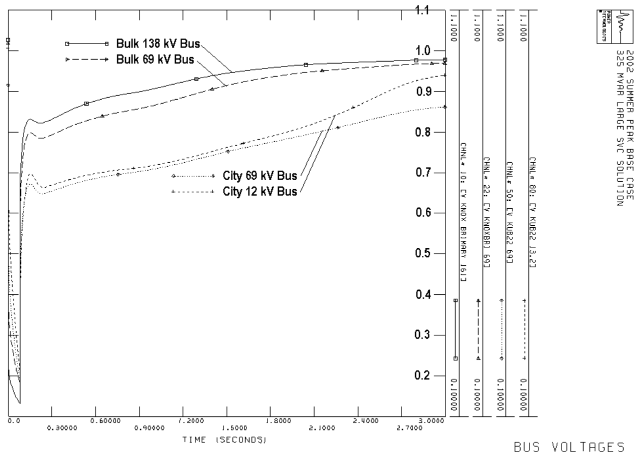

Fig. 6. 300 MVAr SVC solution.

C. Large STATCOM

Figure 4 shows the east side location of a 300 MVAr STATCOM installation. Figure 7 shows results for the fault and loss of the east side 345-kV source. Similar to the SVC results, the STATCOM improved the 138-kV voltage recoveries, but was only marginally effective in improving the 69-kV and 12-kV load voltages.

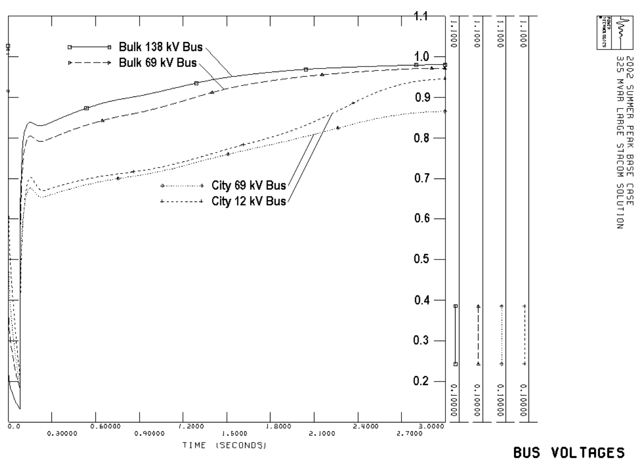

Fig. 7. 300 MVAr STATCOM solution.

D. Distributed D-SMES [30,31]

Figure 8 shows two different D-SMES solutions. The triangle solution has ten D-SMESs located at four substations. Three D-SMESs are at the two locations fed from the east side substation, and two D-SMESs are at the two locations fed from the southwest side substation.

The oval solution has eight D-SMES. One D-SMES is at each of the eight substations.

Each D-SMES is 8 MVA, has 2.3 times overload capability for one second, and an 8 MVAr D-SMES controlled capacitor bank.

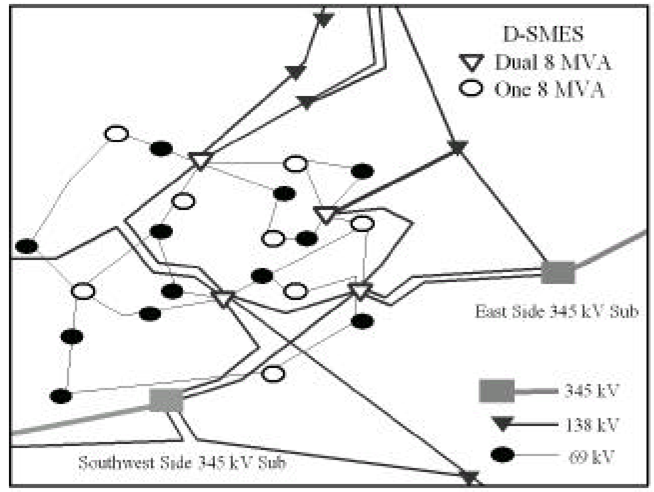

Fig. 8. Two different D-SMES solutions. The triangle solution has ten D-SMESs located at four substations. The oval solution has one D-SMES at each of the eight substations.

Figure 9 shows results for the fault and loss of the east side 345-kV source. The ten D-SMES grouped at the four different locations were more effective in improving the 138-kV voltage recoveries, and significantly more effective in improving the 69-kV and 12-kV load voltages.

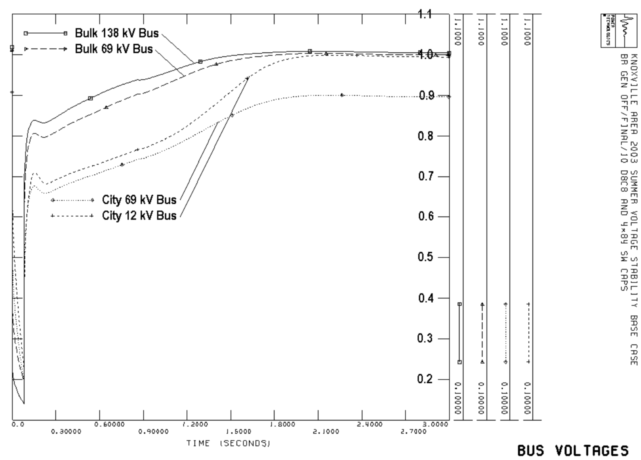

Fig. 9. 10 D-SMES grouped solution (triangles on Figure 8.)

Figure 10 shows results for eight D-SMES at separate substations. Even with two less units, this fully distributed D-SMES solution has the fastest 138-kV, 69-kV, and 12-kV voltage recoveries.

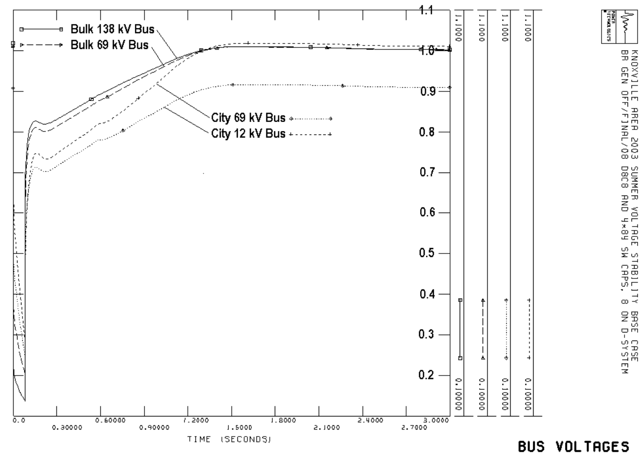

Fig. 10. 8 D-SMES distributed solution (ovals on Figure 8).

E. Discussion of Results

Power electronic devices such as SVCs, STATCOMs, and D-SMES are very useful in preventing fast voltage collapse problems. Since fast voltage collapse occurs at the load when motors begin to stall, the more distributed, closer to the load solution recovers the voltages at all levels of the transmission and distribution system faster.

VIII. CONCLUSIONS

Short-term voltage instability/fast voltage collapse or unacceptability slow voltage recovery is a growing industry problem. We have described the problem and the analysis methods, and have discussed solution methods.

Based on simulations, we conclude that voltage-sourced converter devices (STATCOM and D-SMES) are attractive countermeasures against load loss and voltage collapse. Factory built distribution–connected distributed devices may be cost-effective compared to larger transmission-connected devices.

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