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NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

A Technical Reference Paper Fault-Induced Delayed Voltage Recovery

Version 1.2

Prepared by:

NERC

Transmission Issues Subcommittee
and
System Protection and Control Subcommittee

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116-390 Village Blvd., Princeton, NJ 08540
609.452.8060 | 609.452.9550 fax
www.nerc.com

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- *Version 1.1 was approved March 18, 2009, incorporating the FIDVR definition.*
- *Version 1.2 was approved June 10, 2009 to include Protection System concerns.*

1. Executive Summary

A Delayed Voltage Recovery event, or more popularly today, a Fault Induced Delayed Voltage Recovery (FIDVR), is the phenomenon whereby system voltage remains at significantly reduced levels for several seconds after a transmission, subtransmission, or distribution fault has been cleared. Significant load loss due to motor protective device action can result, as can significant loss of generation, with a potential secondary effect of high system voltage due to load loss. A severe event can result in fast voltage collapse.

"FIDVR events can–and have–occurred following faults cleared in as few as three cycles! The number and impact of FIDVR events can be decreased, but their elimination in the near term is unlikely."

Therefore the Transmission Issues Subcommittee (TIS) provides the following definition:

Fault-Induced Delayed Voltage Recovery — a voltage condition initiated by a fault and characterized by:

- Stalling of induction motors
- Initial voltage recovery after the clearing of a fault to less than 90 percent of pre-contingency voltage
- Slow voltage recovery of more than two seconds to expected post-contingency steady-state voltage levels

Although this phenomenon can occur on any voltage level, it becomes concerning when such events adversely impact the voltage recovery of the Bulk Electric System (BES). Further, if the BES voltage does not recover to 90 percent of the pre-contingency system voltage in a few seconds, the FIDVR can initiate further tripping of load and generation. Longer periods of depressed voltage below such levels can cause damage to customer and electric system equipment.

Therefore, the TIS also provides the following additional definition for NERC:

BES Fault-Induced Delayed Voltage Recovery Event (BESFIDVRE) — Any fault-induced event on any voltage class which results in FIDVR on the BES.

FIDVR is caused by highly concentrated induction motor loads with constant torque which stall in response to low voltages associated with system faults. This results in an excessive draw of reactive power from the grid. FIDVR events become increasingly probable with the increased penetration of low-inertia air conditioner loads that lack compressor undervoltage protection.

FIDVR events can, and have, occurred following faults cleared in as few as three cycles! Both the frequency and impact of FIDVR events can be decreased, but the elimination of FIDVR events in the near term is unlikely.

Planning studies have not been able to replicate FIDVR events very accurately due to an inaccurate modeling of loads. Uncorrected, this modeling deficiency has a two-fold detrimental effect. First, it can result in studies that do not adequately identify potential FIDVR events. Second, it can give false confidence in mitigation plans designed to prevent FIDVR events.

Fortunately, several groups of experts are actively developing better dynamic load models for aggregate induction motor load, utilizing results of extensive single-phase air conditioning performance tests, and detailing analyses of actual FIDVR events. This expertise has developed, by necessity, in response to dramatic, local FIDVR events. However, venues such as the Department of Energy's "Workshop on Residential AC Stalling," April 2008, are providing opportunities for the broader planning world to better understand FIDVR—including its causes, mitigation measures, and the urgency of developing and utilizing better dynamic load models to identify local potential for FIDVR.

The NERC Planning Committee (PC) can make an important and timely contribution to this education process. Six recurring items that can help educate utility planners and, in turn, help mitigate the risk to the BES:

- The FIDVR phenomenon must be more universally broadcast and understood throughout the electric utility planning community.
- Dynamic load models adequate for FIDVR studies should be developed, communicated, and appropriately customized for local use by grid planners.
- Post Event Analysis has been vital in finding model deficiencies and implementing corresponding improvements and should be promoted.
- Understanding and proper planning of power system protection and control action is important in preventing FIDVR events, which are often initiated by single-phase-to-ground faults that progress to multi-phase-to-ground faults because of protection inadequacy or failure.
- The degree of urgency that should be assigned to FIDVR studies is directly related to the degree of air conditioning load penetration. Guidelines or standards should not be issued

to require the same level of effort from Alaskan planners as from those in California, Texas, Arizona, or Florida

- Unit level protection should be standardized for residential air conditioners to remove them from service for undervoltage conditions and lower FIDVR risk.

2. Introduction

A Delayed Voltage Recovery (DVR) event, or more popularly today, a Fault Induced Delayed Voltage Recovery (FIDVR), is the phenomenon whereby system voltage remains at significantly reduced levels for several seconds after a transmission, subtransmission, or distribution fault has been cleared (See Figure 1 for a typical FIDVR). Significant load loss due to motor protective device action can result, as can significant loss of generation, with a secondary effect of unacceptably high, potentially damaging system voltage sometimes following the load loss. A severe event can result in fast voltage collapse.

"FIDVR events can–and have–occurred following faults cleared in as few as three cycles! The number and impact of FIDVR events can be decreased, but their elimination in the near term is unlikely."

FIDVR is caused by highly concentrated constant torque induction motor loads which stall in response to low voltages resulting from system faults. The stalled motors draw excessive reactive power from the grid and require five – six times their typical steady-state running current in this locked-rotor condition. Across many motors, this state can cause the system voltage to be significantly depressed for several seconds after the fault is cleared and this can lead to cascading system failure. An inability to adequately model dynamic loads has contributed to grid vulnerability due to FIDVR.

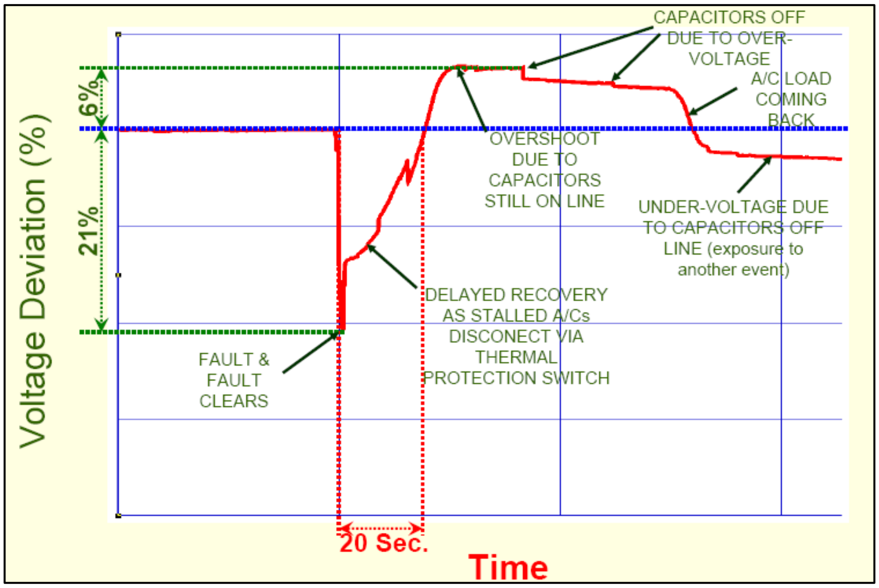

Figure 1: Typical FIDVR Following a 230-kV Transmission Fault in Southern California

The need for improved modeling of induction motor load with constant torque was noted in the mid-1970s, documented in Electric Power Research Institute (EPRI) Project RP849-7, and several technical papers since that time. Anecdotal evidence suggests that modeling improvement initiatives occurred in the early-1970s as a result of the emergence of Power Quality as an end user concern, but these initiatives addressed the broader need to model a range of non-linear loads that were beginning to proliferate on the electric power system.

Anecdotal evidence suggests that the FIDVR phenomenon occurred several times in the mid-1970s without an understanding that inductive motor load, particularly high concentrations of single phase air conditioning (A/C) load, was the cause. However, this changed with an event in the Tennessee Valley Authority (TVA) service area on August 22, 1987, which Gary C. Bullock later published as “Cascading Voltage Collapse in West Tennessee.” The event was precipitated when a 115-kV switch owned by Memphis Light, Gas, and Water Division arced and flashed phase-to-phase while an operator attempted to isolate a damaged airblast circuit breaker. Because the faulted bus lacked a bus differential protection scheme, the fault continued for more than a second and was eventually cleared by backup relays at remote locations. Motor loads in Memphis and the surrounding TVA area began to stall and draw large amounts of reactive power even after the fault was cleared. A depressed voltage condition developed on both the 161 and 500-kV systems in southwestern Tennessee and continued for 10 – 15 seconds. Reverse zone 3 line relays began to trip resulting in a cascade. Memphis lost 700 MW of load during the disturbance. A good portion of this was lost as thermal and overload protection on individual pump and A/C loads tripped. TVA lost an additional 565 MW of load after 13 and 161-kV substations were de-energized due to protective action in response to low and unbalanced voltages in the area. Incidentally, the concentration of A/C load is not surprising since this event developed on a Saturday (*a blistering Saturday)* which set a rare, though short-lived, annual, seasonal system peak!

Post event analysis internally documented observations of the event, performed a simulation, established mitigation measures, and published documentation for the industry. The published paper noted several themes that would recur in post event analysis of later FIDVR events.

- This event could not be duplicated using fault/load flow studies with conventional load models.
- Transient studies using lumped induction motor models as a portion of the load worked better but fell short of duplicating observed system voltage response.
- No real guidelines had been established to determine the nature of area summer transmission loads for large scale voltage perturbations.
- Without an accurate study model, validation of mitigation efforts depended heavily on subjective reasoning.

A series of comparable events followed across the continent with each evoking similar post event response, each confirming the findings from the prior events, and each advancing a more detailed understanding of the common root phenomenon. These events still continue despite the fact that pockets of FIDVR awareness and expertise have developed.

John W. Shaffer of Florida Power and Light Company (FPL) is one of the recognized, pioneering FIDVR experts. He detailed an August 18, 1988 event in his “Air Conditioner Response to Transmission Faults,” published in 1997. A bolted three-phase fault at the Flagami 230-kV switchyard initiated the event. Although the fault was cleared in 3.5 cycles, approximately 825 MW of load was disconnected in the Miami area, almost all due to customer equipment protection. Area voltage was depressed for ten seconds after fault isolation. Simulation using high side load representation and a static model could not replicate the event. However, Mr. Shaffer was able to model the event by including motor and distribution models. The Introduction to his paper noted that “In the last ten years there have been at least eight events in which normally cleared multi-phase fault events in Southeast Florida have caused a significant drop in customer load (200 – 825 MW).”

Robert J. Yinger reported at the Department of Energy's "Workshop on Residential AC Stalling," that Southern California Edison's (SCE) first FIDVR event was observed in 1988. At least 53 subsequent events have occurred. He and SCE have been active in publishing FIDVR information as well as supporting research on and suggesting solutions for the phenomenon. Bradley R. Williams, Wayne R. Schmus, and Douglas C. Dawson wrote a paper, "Transmission Voltage Recovery Delayed by Stalled Air-Conditioner Compressors," published in *IEEE Transactions on Power Systems* in August, 1992. The paper indicated that multiple FIDVR events occurred in SCE's desert regions during the peak air-conditioning period, including a major incident in June, 1990, which affected a 1000 square mile area of Riverside County. The paper also points to FIDVR incidents in the Sacramento area. Further, it attempted to model residential air-conditioners in power system studies.

In recent years, the field implementation of measurement units with higher sampling rates such as Phasor Measurement Units (PMUs) has indicated that FIDVR events are more prevalent that previously thought. These devices record typically 30 samples per second versus a typical SCADA system, which scans every two – four (2-4) seconds and saves into a database one sample every one – five (1-5) minutes. The higher sampling rate has been key to improved FIDVR identification and post event analysis.

Despite the generally isolated nature of FIDVR expertise, notable groups such as Western Electricity Coordinating Council (WECC) have established key research/data initiatives to facilitate the development and promotion of detailed as well as aggregate inductive motor models for use in grid planning studies. WECC partners with air conditioning vendors as well as member utilities in this effort. NERC and TVA in their joint Stability Workshop conducted in May, 2007, in Chattanooga and DOE in its Workshop on Residential AC Stalling, conducted April, 2008, in Dallas, successfully identified individual engineers with FIDVR expertise, provided them a venue to educate the industry, and provided networking opportunities as well for attendees. Still, conditions appear to be trending unfavorably toward an increasing number of FIDVR events unless an even stronger, better coordinated industry response successfully intervenes.

Significantly, utility knowledge regarding FIDVR seems proportional to the geographical/educational proximity to an actual event; and yet, the industry entities and individuals most knowledgeable of, and with the healthiest technical respect for, FIDVR do not share a common definition or criteria for exactly what constitutes a FIDVR event. This has been reasonable since these definitions evolved within the contexts of specific areas being studied for

FIDVR and their future vulnerabilities. A standard definition should be developed for general industry use.

The NERC PC supported by the TIS is well positioned to join and multiply the effectiveness of existing efforts to universally communicate information on FIDVR and to promote appropriate industry standards for its study and mitigation.

In 1990, "Voltage Instabilities Subsequent to Short-circuit Recoveries," was submitted by M. Z. El-Sader, a faculty member of the Electrical Engineering Department of Assiut University, Assuit, Egypt. Clearly FIDVR was a concern beyond North America — reaching across the globe to areas of high induction motor load penetration.

On July 30, 1999, the Southern Balancing Authority experienced its first FIDVR event. A coupling capacitor voltage transformer (CCVT) exploded in the Union City 230-kV Substation (Metro Atlanta). Debris was blown into the bus work which initiated an event that included three separate faults and two breaker failure operations. As a result, delayed voltage recovery of up to 15 seconds was observed over a large portion of North Georgia. 1,900 MW of load and seven small generating units were tripped. Though well beyond events typically studied as even multi-contingency, low probability NERC Category D[1] events, this event showed that the local transmission system had evolved to a state where FIDVR events are possible. Since the 1999 Union City event, planning and operating studies have resulted in a capital project plan and operational strategies which have been implemented since 2004. No significant FIDVR events have occurred in this area since the 1999 event.

3. FIDVR Root Cause

FIDVR is caused by highly concentrated induction motor loads with constant torque which are not adequately modeled in planning studies. These motors can stall in response to low voltages associated with system faults and draw excessive reactive power from the grid. They require typically five–six (5-6) times their steady-state current in this locked-rotor condition with the result that system voltage can be significantly depressed for seconds after the fault is cleared leading to cascade. Eventually, the stalled motors will trip by thermal protection with an inverse time-overcurrent characteristic. This can take from 3 to 20 seconds.

[1] http://www.nerc.com/files/TPL-004-0.pdf

There are many types of loads connected to the grid, including motors, lighting, and electronics. Induction motor penetration is one of the more critical parameters that determine a transmission system's susceptibility to FIDVR events. Small, single-phase induction motors found in A/C equipment have low inertia and can stall within cycles as a result of fault voltages. Larger induction motors are also prone to stalling, though they should be slightly slower to stall and should do so at lower system voltage due to their larger inertia. Stalled induction motors present a high reactive loading to the transmission system further aggravating the initial fault voltage depression. As a result, additional induction motors can slow down and stall and create a voltage cascade.

FIDVR events are usually preceded by large, local loads with a high percentage of motor loads at the time of a fault. When system voltages depress usually for a second or longer, but under some conditions for as little as three cycles, induction motors begin to slow and their reactive power requirement increases. As the reactive power consumption increases, system voltage cannot recover and in some cases depresses even further. If voltages stay depressed long enough, generators trip or over-excitation limiters make them reduce reactive power output, and the system collapses.

FIDVR is worst when there is a concentration of "stall-prone" motors in a region. Not all motors are prone or vulnerable to stalling. For example, large industrial motors often have contactors that will drop the motor out during voltage dips, therefore limiting the negative impact of these motors. Large HVAC units may also have motor protection that will trip the unit offline before stalling occurs. Smaller HVAC units, however, may not have protection that will trip the unit off before stalling occurs. The mechanical torque of the compressor for these units tends to remain relatively constant for the first few seconds which makes the motors more prone to stalling.

Susceptibility to FIDVR is also very sensitive to location. A fault at a higher voltage level can depress the voltage over a wider area. Therefore, the potential for voltage to be reduced by a fault over a wide area, coupled with a large concentration of motor load in that area are important factors that indicate the likelihood of a FIDVR occurring.

This was the case in Arizona Public Service's (APS) July 28, 2003, Hassayampa event, reported by Dr. Baj Agrawal at DOE's recent "Workshop on Residential AC Stalling." A three phase fault on the 500-kV bus was cleared in only three cycles. Yet, FIDVR occurred in the Phoenix area resulting in 440 MW load loss and 2600 MW generation loss with 90,000 customers affected. APS has since added significant dynamic support in the heart of Phoenix by installing combustion turbine generation as one facet of their mitigation plan. It should be noted that the generation loss in this event was traced to a protective relaying issue independent of FIDVR that has been corrected.

The secondary system overvoltage condition that can occur as a FIDVR event unfolds must also be noted. As John Shaffer determined, most of the load lost in the Flagami event in 1988 was due to action of customer equipment protection. Under certain circumstances, with enough load loss, this could result in system overvoltage. This was the case in the July 25, 1995, Arizona Public Service's "Pinnacle Peak Capacitor Fault Delayed Fault Clearing Slow Voltage Recovery Incident 1," reported by Dr. Bajarang (Baj) Agrawal at the recent DOE, Workshop on Residential AC Stalling. Delayed clearing for this single-line to ground capacitor fault occurred at 16 cycles due to current transformer saturation. While there were sustained low voltages after fault clearing, enough load was lost that 10 percent overshoot in voltage recovery eventually occurred.

Of course, if significant load is lost, it is probable that area generation might be lost, also. This could moderate any movement toward overvoltage. This generation loss can be observed in many FIDVR events, Hassayampa and Union City — to name just two.

Finally, it must be recognized that protection and control system deficiencies and (mis)operations often play a significant role in FIDVR events. For example, in the 1987 TVA event which resulted in the first documentation of the phenomenon, the faulted bus lacked bus differential protection. A FIDVR occurred in the same area on July 15, 2007, when a distribution gap type lightning arrestor initially failed to ground, but developed into a three-phase to ground fault. High-side overcurrent relaying applied as a differential protection scheme eventually interrupted the fault as designed. However, the time delay on the relay was set too long, and 800 – 900 MW of load were lost in this event. Had the available fault current not increased since the application of the setting, with the result that clearing was accomplished more quickly than originally designed, the system impact would have been even more severe.

These are just two examples — Protection and controls impacts on FIDVR events abound. Guidance is needed on how to adequately include protection and controls actions and potential misoperations in FIDVR studies.

4. Study Methodology

Traditionally, "dynamic" simulations have been used to assess local system proximity to transient and oscillatory stability limits under various conditions. Voltage dependent static models have worked well for this because, while these instabilities typically result from voltage deviations that can be severe in magnitude, the deviations are usually short-lived versus those associated with FIDVR events.

However, analysis of FIDVR exposure requires truly dynamic simulations utilizing dynamic models with aggregate loads appropriately representing induction motor load penetration, including single-phase A/C load penetration, as well as approximating control action designed to de-energize loads for thermal overloads, under-voltage conditions, or both. The load model should contain other aggregate load components, such as voltage dependent load. However, the assumed induction motor load penetration is the most critical component of the load model.

Appropriate dynamic load models for FIDVR study have not historically been available for several reasons, but primarily because of inability to determine percent induction motor load for area buses, and because of limited understanding of A/C load dynamic characteristics. Methodologies for increasingly accurate aggregation of motor loads have been successively proposed since the 1970's, and foundational understanding of the importance of A/C dynamic characteristics was attained in the 1990's, but only recently has WECC research produced the detailed understanding of A/C dynamic characteristics necessary to support a composite load model with a suitably accurate, aggregate A/C load component. Member utilities such as SCE, Bonneville Power Administration (BPA), and Pacific Gas & Electric (PG&E) partnered in this WECC research and testing effort, as did A/C vendors such as Emerson Climate Technologies and Trane Residential Systems. BPA, APS, SCE, and the California Energy Commission funded much of the effort, which has been led by Dr. Dmitry Kosterev, Chair of WECC's Modeling and Validation Work Group and BPA employee. The result is a composite dynamic load model for use with General Electric's PSLF software that meets the requirements above for FIDVR study. This model simulates stall behavior and thermal overload tripping and is currently under test by WECC's MVWG team. The intent is to follow this development with a similar model for use with Power Technologies, Incorporated's (PTI) PSS/E software.

Of course, the use of this model requires the aforementioned determination of induction motor load penetration, particularly A/C load. It is notable that SCE has determined that its A/C load penetration is 25 percent of coastal load and up to 60 percent of inland load on peak. Obviously, some western utilities are positioning to adequately model and study FIDVR.

The same is true in the east. Southern Company (SOCO) is one leader in the Eastern Interconnection in going beyond modeling and studying FIDVR to also educate others in the industry to the phenomenon and the requirements for its study and mitigation.

SOCO has widely published the lessons learned from its Union City event in 1999. Robert Jones and Lee Taylor are leading in development of a user-defined load model for PTI's PSS/E software that also meets the requirements above for FIDVR study. Also, SOCO has installed load monitors at substations located in regions determined to be more prone to FIDVR events. Recorded dynamic behavior of the loads during fault events is expected to result in insight that can be utilized to refine load models used in dynamic simulations.

EPRI also has projects which span the continent aimed at synthesizing better load and generation models, including but not confined to dynamic modeling. One current project involves validation of models using system fault events.

Unfortunately, many North American electric utilities have neither the model nor the knowledge of the necessary percent induction motor load at the buses to adequately study and plan for FIDVR. Just determining the motor load as percent of total load can be challenging.

Some have attempted to determine the motor load as percent of total load through analysis of actual fault response data relative to modeled performance. But, there are relationships between parameters that can be difficult to overcome. For example, recorded data may be available for a particular stall event on the system. When attempting to replicate the stall event, a stall condition may be simulated when the percentage of motor load is increased from 40 percent to 50 percent. But a similar stalling effect may be simulated by keeping the motor percentage at 40 percent and increasing the distribution impedance by a few percent. The interaction of these two parameters is such that it is difficult to accurately determine either quantity in the model utilizing parameter estimation methods. Instead of curve fitting, the true dynamic model must be determined.

Also, it must be noted that given the development of the dynamic models mentioned earlier, approximating the control action designed to de-energize loads for thermal overload or under-voltage conditions is still very difficult. Replicating FIDVR events that have already occurred is also usually difficult for this reason. The A/C loads stall or trip at relatively high voltage compared to the contactor drop-out of the larger, three-phase motors. It may be that prediction, or even replication of future events, will require the aid of a state estimator. A state estimator could be used to monitor the amount of load that is lost at each bus during the event.

Accurate exciter and power system stabilizer models are also important, and these are often not readily available. However, approximation of these values usually introduces less inaccuracy into the study than the load model parameters already noted.

The urgency of developing the dynamic FIDVR model, or of adopting a standard model and customizing it for local use, depends on local climate and resulting A/C penetration, and other details specific to an area or company.

4.1 Example FIDVR Study Methodology

It might be helpful to detail a method to determine the stability limit in a region (amount of load that can be served depending on available generation).

Peak load levels will normally be worse for this type of stability event; therefore, peak cases should be used. However, sensitivity studies can be performed to investigate alternate generation dispatches when a critical generator may support the voltage in a local region; therefore, an outage of that generator may create a vulnerability to FIDVR.

A FIDVR screening methodology may be used to identify locations for contingency studies. Steady state methods can be used to preliminarily identify large load pockets with relatively weak transmission support, or dynamic studies may be performed with typical values (estimated percent motor load, estimated distribution impedance, breaker clearing times, etc) to achieve the same purpose. In either case, the resulting list of potential FIDVR locations and the scenarios that challenge voltage stability should then be analyzed with dynamic simulations of three-phase normally cleared faults. If unacceptable voltage recovery is determined, mitigation must be considered, such as using an operating guide to dispatch additional generation in the area to attain faster voltage recovery, especially for the near-term. Faults with delayed clearing should also be investigated, weighing risks and consequences. If FIDVR vulnerability is discovered, then several load levels would need to be studied to identify generation or other options that may mitigate the problem at each load level. It may also be wise to perform additional studies with changes in load level and percentage of stall-prone motors to measure sensitivity of the results to load composition. If sufficient generation is not available within the operating horizon, other options may have to be considered including reducing load.

5. System Protection Considerations

This report section was prepared by the NERC System Protection and Control Subcommittee (SPCS, formerly the System Protection and Control Task Force) to address the susceptibility of Protection Systems and their components to the FIDVR phenomenon.

5.1 Transmission Phase Relays

Proposed Standard PRC-023 – Transmission Relay Loadability, is the NERC standard specifying criteria for relay loadability of phase responsive transmission system relays. This standard was created after the August 14th, 2003 Blackout to assure that Transmission System relays would not "limit transmission system loadability, …" and potentially contribute to future Blackouts or disturbances. In order to assure that relays did not "limit transmission system loadability" a number of acceptable methods to calculate relay loadability are presented in the standard. These methods are to be applied to Phase Distance relays, phase overcurrent relays, and Switch onto Fault relays on the Transmission System as defined in the standard. It is noteworthy that the reduced voltages and high power factors that accompany a FIDVR event are similar to severely stressed transmission conditions. Therefore, the efforts to address Transmission Relay Loadability following the severely stressed transmission conditions observed during the 2003 Blackout have significantly decreased the likelihood of Transmission Relay operations during a FIDVR event.

Below is an analysis of how the various phase relays that are applied to the transmission system are affected by the conditions present during a FIDVR event.

5.1.1 Phase Distance Relays without Load Encroachment (w/o LE)

Phase distance relays (w/o LE) are applied widely throughout the transmission system and have been the most susceptible type of relays to tripping during highly stressed system conditions. These conditions are often accompanied by reduced voltage and lower power factors. Loadability of the most common phase distance relays (w/o LE) (mho characteristics) used in North America decreases proportional to the voltage applied to the relay and also decreases with a reduction in power factor. The most common PRC-023 method used to calculate relay loadability is to assume a 0.85 per unit voltage and a 30 degree load angle at the relay and apply a margin. PRC-023 requirements R1.1 and R1.2 describe the margin above thermal loadability that is required as follows:

R1.1 Set transmission line relays so they do not operate at or below 150 percent of the highest seasonal Facility Rating of a circuit, for the available defined loading duration nearest four hours (expressed in amperes).

$$I_{4HR\,Relay} = \frac{\left(0.85 \times V_{L-L}\right)}{\left(1.50 \times 3^{0.5} \times Z_{Relay30}\right)}$$

$$\text{Where } Z_{Relay30} = Z_{MTA} \times Cos\left(MTA - 30\right)$$

To meet R1.1, $I_{4HR\ Relay}$ is compared to $I_{4HR\ Thermal}$

R1.2 Set transmission line relays so they do not operate at or below 115 percent of the highest seasonal Facility Rating of a circuit (expressed in amperes).

$$I_{15\min Relay} = \frac{\left(0.85 \times V_{L-L}\right)}{\left(1.15 \times 3^{0.5} \times Z_{Relay30}\right)}$$

$$\text{Where } Z_{Relay30} = Z_{MTA} \times Cos\left(MTA - 30\right)$$

To meet R1.2, $I_{15min\ Relay}$ is compared to $I_{15min\ Thermal}$

If a line is lightly loaded prior to the FIDVR event, then the chance of a relay trip during a FIDVR is less than a line that is heavily loaded prior to the FIDVR event.

If a FIDVR event is so severe that it causes voltage at the relay to be less than 0.85 per unit or causes a load angle at the relay to be greater than 30 degrees, then the Relay Loadability Rating will be decreased beyond what is calculated.

The Tables below illustrates the reduction in relay loadability for voltage levels below 0.85 per unit voltage and angles greater than 30 degrees. *The tables below assume that the relay loadability was calculated to meet R1.1 and R1.2 exactly and the protective relay is set for a line with a 75 degree impedance angle.*

Table 1 — Phase Distance Relay Loadability for Varying Voltage

Per Unit Voltage	Power Factor Angle	$I_{4HR\ Relay}$ per PRC-023 R1.1	$I_{15MIN\ Relay}$ per PRC-023 R1.2
0.85	30	1.50 x $I_{4HR\ Thermal}$	1.15 x $I_{15MIN\ Thermal}$
0.8	30	1.41 x $I_{4HR\ Thermal}$	1.08 x $I_{15MIN\ Thermal}$
0.75	30	1.32 x $I_{4HR\ Thermal}$	1.01 x $I_{15MIN\ Thermal}$
0.7	30	1.24 x $I_{4HR\ Thermal}$	0.95 x $I_{15MIN\ Thermal}$
0.65	30	1.15 x $I_{4HR\ Thermal}$	0.88 x $I_{15MIN\ Thermal}$
0.6	30	1.06 x $I_{4HR\ Thermal}$	0.81 x $I_{15MIN\ Thermal}$

Table 2 — Phase Distance Relay Loadability for Varying Power Factor Angle			
Per Unit Voltage	Power Factor Angle	$I_{4HR\ Relay}$ per PRC-023 R1.1	$I_{15MIN\ Relay}$ per PRC-023 R1.2
0.85	30	1.50 x $I_{4HR\ Thermal}$	1.15 x $I_{15MIN\ Thermal}$
0.85	35	1.38 x $I_{4HR\ Thermal}$	1.06 x $I_{15MIN\ Thermal}$
0.85	40	1.29 x $I_{4HR\ Thermal}$	0.99 x $I_{15MIN\ Thermal}$
0.85	45	1.22 x $I_{4HR\ Thermal}$	0.94 x $I_{15MIN\ Thermal}$
0.85	50	1.17 x $I_{4HR\ Thermal}$	0.90 x $I_{15MIN\ Thermal}$
0.85	55	1.13 x $I_{4HR\ Thermal}$	0.87 x $I_{15MIN\ Thermal}$

Phase Distance Relays (w/o LE) are affected by reduced voltage or high power factor angle that can occur during a FIDVR event. Phase Distance Relays (w/o LE) with loadability close to PRC-023 minimum allowable limits applied to line terminals subject to high loads (>100 percent line loading) and severely depressed voltages during a FIDVR event should be included in FIDVR event studies.

5.1.2 Phase Distance Relays with Load Encroachment (w/LE)

Phase distance relays with load encroachment are used to increase the loadability of relays and meet loadability criteria per PRC-023. The paper issued by the System Protection and Control Task Force (SPCTF) titled "Increase Line Loadability by Enabling Load Encroachment" (dated June, 7, 2006) lists six methods to increase line loadability. The affects of a FIDVR event on the loadability of these relays follow:

1. "Increase the angle of maximum torque (reach)": This method to increase relay loadability rotates the relays circular impedance characteristic towards a 90 degree angle at maximum relay reach. Therefore, the reach at a load angle of 30 degrees is decreased and the loadability is increased. Since the relay characteristic is unchanged versus a relay without LE, the decrease in loadability due to reduced voltage or increased angle is similar to relays without LE.

2. "Change the impedance relay characteristic from a circle to a lens": Decreased voltage affects loadability of lens relays to the same extent as relays that are circles, however the decrease in loadability due to changes in load angles is less. The thinness of the lens characteristic determines the degree to which load angles are affected. Because of the shape of the lens characteristic,

relays using the lens characteristic are less likely to trip during a FIDVR event.

3. "Add blinders to the characteristic to limit reach along the real axis": A blinder cuts off a portion or slice of the mho circle along a line parallel to the mho circles maximum torque angle (line angle). Blinders are generally applied and set to cut out a big enough slice of the mho circle to inhibit a stable system swing from causing a relay trip. The loadability of the blinder characteristic decreases proportional to the voltage applied to the relay and also decreases with a reduction in power factor. Because the blinder is applied along the maximum torque or line angle, relays using blinders are less likely to trip during a FIDVR event.
4. "For remote zone 3 protection, use an impedance relay offset into the 1st quadrant": An impedance relay offset into the 1st quadrant of an R-X diagram is purely designed for a remote backup function. Depending on the degree of offset, this characteristic may not pick up at all for line loads with power factor angles of 30 degrees. Therefore, the relay loadability is now limited by the shorter zone 2 protection. Since the zone 2 relay characteristic is unchanged versus a relay without LE, the decrease in loadability due to reduced voltage or increased angle is similar to relays without LE, however it is calculated based on a shorter reaching protection zone (zone 2). This type of characteristic is not widely applied in North America.
5. "For a Quadrilateral characteristic, reset the relay": Loadability of a Quadrilateral characteristic is proportional to the resistive setting of the particular relay. Reducing the resistive reach of the relay can increase loadability. The loadability of the Quadrilateral characteristic decreases proportional to the voltage applied to the relay and also decreases with a reduction in power factor. This type of characteristic is not widely applied in North America. Because the resistive reach of the Quadrilateral characteristic is applied along the maximum torque or line angle, relays using Quadrilateral characteristics are less likely to trip during a FIDVR event.
6. "Enable the load encroachment function of the relay": This method to increase relay loadability experiences a decrease in loadability due to reduced voltage and changes in angle similar to relays without LE. However, if the load angle increases beyond the threshold angle (typically 30 – 45 degrees), a step change increase in the relay reach occurs that results in a commensurate step

change in the decrease in loadability. Because of this fact, this solution may increase the likelihood of a relay trip during a FIDVR event that is accompanied by an angle beyond the relays' threshold angle.

Phase Distance Relays (w/LE) can be affected by reduced voltage or high power factor angle that can occur during a FIDVR event but sometimes to a lesser extent than Phase Distance Relays (w/o LE). Phase Distance Relays (w/LE) with loadability close to PRC-023 minimum allowable limits applied to line terminals subject to high loads (>100 percent line loading) and severely depressed voltages during a FIDVR event should be included in FIDVR event studies.

5.1.3 Phase Overcurrent Relays

Phase overcurrent relays are not widely applied to the transmission system. Phase overcurrent relays do not respond to voltage or power factor angle, therefore they do not respond to the reduced voltage or higher power factor angles associated with FIDVR events. If they are applied, these relays respond directly to load current and must be set to meet PRC-023 requirements (see R1.1 and R1.2 above). Any increase in load current beyond their minimum setting could cause operation. Typically, these relays have a time characteristic curve that will take many seconds or minutes to trip at levels slightly above minimum pickup.

It is not likely that these relays will trip during a FIDVR event. Therefore, these relays do not need to be included in FIDVR event studies.

5.1.4 Switch Onto Fault (SOTF) Relays

SOTF schemes are protection functions intended to trip a transmission line breaker when closed on to a faulted line. These relays are essentially a subset of phase overcurrent relays. The phase overcurrent element portion of the SOTF scheme is supervised to limit SOTF operation time to a short period after the breaker is closed. Since the phase overcurrent element is supervised, the phase overcurrent element portion of the SOTF scheme may be set very sensitively. A number of methods used to supervise the phase overcurrent elements used for SOTF are discussed in the NERC SPCTF technical paper titled "*SOTF Schemes in the Context of Line Relay Loadability*". Of these methods, all must meet PRC-023 loadability requirements except for those set with voltage supervision < 85 percent (it is recommended in the SOTF whitepaper that relays with voltage supervision set < 85 percent and >70 percent also meet the PRC-023 requirements).

Given the logic used and the loadability requirements imposed on SOTF schemes, it is unlikely that these types of schemes would trip during an FIDVR event. Therefore these relays do not need to be included in FIDVR event studies.

5.2 Transmission Ground Relays

Relays used to detect ground faults are less susceptible to tripping during high loading conditions than phase relays. Therefore, these types of relays were not addressed in the PRC-023 standard.

Since the conditions produced during a FIDVR event are similar to severe loading conditions, these types of relays are unlikely to respond to FIDVR issues. Therefore, these relays do not need to be included in FIDVR event studies.

5.3 Voltage Relays

5.3.1 Under Voltage Load Shedding (UVLS) Schemes

Section 6.1.5 of this report discusses the possible use of UVLS schemes to “manage FIDVR risk and limit the size of any potential disturbance.” However, even if that strategy is not employed as a solution to FIDVR susceptibility, portions of existing UVLS schemes may operate during FIDVR events. Therefore, UVLS schemes should be included in FIDVR event studies to see how they will operate during a FIDVR event on the system.

5.3.2 Voltage Relays for Generator Auxiliary Power Busses

Voltages relays are applied to protect motors and other generating plant equipment from extended low voltage conditions that could cause stalling or damage to plant equipment.

- Voltage relays connected to generator auxiliary busses fed from operating generators are not likely to be effected by FIDVR events due to generator action to maintain constant voltage. However, generators with older, slower-acting rotating excitation systems can result in slower response to the voltage dip extending several seconds, making generator bus-connected auxiliary systems on those units more susceptible to tripping. The risk is reduced for newer, fast-acting static excitation systems.

Therefore, voltage relays connected to generator auxiliary bus-fed from operating generators need be included in FIDVR event studies, as well as the type of excitation system and maximum excitation limiter settings (if any) on the generator.

- Voltage relays connected to generator auxiliary busses fed from the system may be impacted by FIDVR events since the local generator will have less affect on supporting the voltage to these busses. Other auxiliary equipment and controls may be adversely impacted by the FIDVR event, possibly causing loss of the generating unit and exacerbating the FIDVR event. The potential for a false trip will depend upon the relative size of the generators in relation to the system strength and the ability of the generators to maintain system voltage.

  Therefore, voltage relays connected to generator auxiliary busses fed from the system should be considered in FIDVR event studies, as well as the type of excitation system and maximum excitation limiter settings (if any) on the generator.

5.4 Generator Relays

Generator relays are less likely to be affected by FIDVR events due to generator action attempting to maintain constant voltage. However, generator relays used for transmission system phase fault backup can, and have, operated for prolonged depressed system voltage. These include voltage-restrained overcurrent, voltage-controlled overcurrent, and distance relays. The risk is reduced for newer fast-acting static excitation systems which attempt to maintain constant terminal voltage, but older slower-acting rotating excitation systems can result in a machine attempting to generate full reactive power for several seconds, making the phase fault backup relaying susceptible to trip (depending on relay settings).

For this reason, when performing FIDVR event studies, the type of excitation system and maximum excitation limiter settings (if any) should be included, as well as the settings for phase fault backup relaying, to determine if generators in the study area of concern might trip.

5.5 Frequency Relays

5.5.1 Underfrequency Load Shedding (UFLS) Schemes

FIDVR events are typically not accompanied by a change in frequency. However, some underfrequency relays are supervised by voltage elements. If the voltage drops below the set point of the voltage element, the underfrequency relay is inhibited from operation. This is a method that provides security against false underfrequency relay tripping during certain fault events. Therefore, if a FIDVR event is accompanied by a significant loss of generation and accompanied by a frequency drop below the UFLS scheme set point, some UFLS relays may not operate.

If it is known that a FIDVR event under study will be accompanied by a reduction in frequency, the response of the voltage elements of underfrequency relays should be included in studies. Otherwise, UFLS relays do not need to be included in FIDVR studies.

5.6 Distribution Relays

Stalling of air conditioning loads during a FIDVR event is accompanied by high currents. Distribution circuits are typically protected by phase and ground (or residual) overcurrent relaying. High currents on the distribution system during FIDVR events have been observed to cause tripping of both phase and ground overcurrent relays. This may or may not help to minimize the impact of the FIDVR event.

Including Distribution relays in FIDVR studies should be considered based on the local companies' experiences with distribution relay operations during FIDVR events.

5.7 Protection System Conclusions

The impact of a FIDVR event on the protection system varies depending upon the type of the relays and where they are applied. Some general observations follow:

- Phase distance relays are not likely to misoperate unless the line loading following the fault exceeds 100 percent of the rating.
- Relays with trip ratings beyond the minimum requirements to meet PRC-023 R1.1 or R1.2 are not likely to misoperate during a FIDVR event. For instance, short lines may have very high relay trip ratings and are highly unlikely to trip during a FIDVR event.

- Voltage relays applied in the distribution system are expected to operate for FIDVR events as per their design as a safety net.
- SOTF relays are not impacted by a FIDVR event.
- Voltage relays on the auxiliary load connected to the generator terminal are unlikely to be impacted due to generator action of maintaining constant terminal voltage.
- Voltage relays on generator auxiliary load busses fed from system busses may be impacted adversely if the generators in the vicinity are not able to support the transmission system voltage.
- Underfrequency relays are not likely to be impacted by a FIDVR event
- Distribution system relays may be impacted by a FIDVR event but their impact on the transmission system may not be significant.

6. Solutions

If an election were held among the Transmission Planner community, the winning FIDVR solution would no doubt be the installation of equipment control devices to remove A/C and other induction motor loads from the grid prior to stalling for undervoltage conditions. This must be a component of the long range solution. This equipment protection could be a first step toward application of additional reactive sources such as SVCs to specifically protect against distribution system voltage variations. However, A/C standards necessary to achieve this will not be enacted overnight and retrofit of existing A/C units would likely be even more difficult to accomplish. It could also be argued that system exposure to FIDVR may be a symptom of a larger issue — inadequate dynamic reactive support. Consequently, use of grid solutions will be necessary at least until the threat level of A/C loads can be reduced. These grid solutions cannot ensure prevention of FIDVR events but may contain the events by limiting both their area of influence and their consequences.

6.1 Grid Level Solutions

Grid Level solutions include:

6.1.1 Quicker Clearing of Faults

Fault duration and location are critical factors that drive FIDVR risk. So, strategies to reduce expected fault duration at critical locations can be part of a cost effective plan to manage FIDVR exposures. This could include the reduction of breaker failure operation times, installation of relays selected primarily for their operating speed for faults determined to be critical, application of pilot or transfer trip relaying schemes, use of faster breakers, or replacement of gang operated breakers with independent pole operated breakers.

However, this is not a solution for those events in which 3-cycle clearing resulted in FIDVR.

6.1.2 Addition of Reactive Sources or Relocation of Reactive Sources Relative to Critical Loads

Following the Hassayampa event, APS added significant new combustion turbine generation in the heart of Phoenix to provide voltage support. The ten year plan developed for metropolitan Atlanta following the Union City event includes installation of a 260 MVAR Static Var Compensator (SVC) as well as relocation of key generating units to lower system voltage level interconnections.

Similarly, Center Point Energy is in process of installing two 140 MVAR SVCs in the Houston metropolitan area to mitigate FIDVR events and Georgia Transmission Company (GTC) has installed a 260 MVAR unit planned by SOCO in the Atlanta metropolitan area.

The use of SVCs, StatComs, or even fast switched capacitors for additional dynamic support can be appropriate. However, because of their ability to contribute above their steady state MVAR capability during transient fault events, generators are superior dynamic MVAR sources. Also, SVCs and StatComs must be applied with particular attention to station service configuration and low voltage ride-through capability (see Appendix A). This attention has been given to the installations noted above.

New generation or transmission can reduce FIDVR vulnerability. However, in some cases, new transmission can also allow a fault to reduce voltages over a wider area during the fault, so each situation needs to be carefully analyzed.

The effectiveness of dynamic support is very dependent on its location. Dynamic simulation studies should be conducted to determine sites where dynamic support will provide optimal FIDVR mitigation. This information can be used to install transmission based dynamic Mvars, or for targeting regions for potential new generation.

6.1.3 Limiting Impacted Load

Strategies to limit the amount of load subjected to low voltage should be considered for the most critical FIDVR fault locations. This could be accomplished through sectionalizing a tightly coupled transmission system. The impact on other limits, such as thermal and voltage levels, would also have to be considered in the analysis.

6.1.4 Special Protection Schemes

Special Protection Schemes (SPS) may be used as a safety net to confine the area impacted by FIDVR. If a voltage collapse develops in a load center because of a multi-contingency event, an SPS can contain the disturbance from spreading to larger grid — voltage collapse in Cleveland should not turn lights off in New York. However, use of an SPS for FIDVR mitigation would not comply with TPL-001-1 as now drafted because the SPS action would initiate Non-Consequential Load Loss. **So, while this action would be taken to benefit system reliability, it would constitute non-compliance.**

In fact, the proposed requirements for Non-Consequential Load Loss will almost certainly be an issue for FIDVR regardless of whether an SPS is employed. For example, PGE experienced a sustained three-phase fault on the Newark — Ravenswood 230-kV line on July 12, 2008. The fault cleared within five cycles, but the 500-kV voltage near the fault experienced a decrease of more than 100-kV, and 350 – 440 MW of Non-Consequential Load Loss resulted. This loss was attributed to stalled motor loads.

6.1.5 Under-Voltage Load Shedding (UVLS)

An undervoltage load shedding scheme (UVLS) can be an effective component in a strategy to manage FIDVR risk and limit the size of any potential disturbance. This should be viewed as a safety net. UVLS is generally viewed as ineffective in preventing fast voltage collapse, quite effective in preventing slow voltage collapse. Since changing system conditions may transform a fast-collapse scenario into a slow-collapse scenario, the UVLS option may still be considered when addressing identified fast-collapse vulnerability. In order to be effective, UVLS schemes need to trip load as soon as possible while ensuring security with backup relaying schemes.

6.1.6 Promoting Energy Saving Devices to Reduce Demand

Promotion of the benefits of energy saving devices versus their costs can lower the total amount of load being served, perhaps reducing the likelihood of a FIDVR. However, this could also increase the A/C percent of total load with the opposite effect.

6.2 Unit Level Solutions

As mentioned earlier, promotion of grid-friendly A/C units with undervoltage protection could greatly reduce the likelihood of FIDVR over the long term.

Long term, unit level solutions have two categories:

1. Relays that disconnect A/C compressor motors when they stall – This method requires reliable detection of the stall condition to prevent customer inconvenience.
2. Devices that allow A/C compressor motors to ride through transmission faults – This method would require design changes for compressor motors or addition of power electronic interfaces.

6.3 Southern Company Solutions

The response of the Southern Balancing Authority following the Union City event illustrates how solutions can be combined in formulating a complete mitigation plan. This mitigation plan included:

- Operational FIDVR risk reduction until 2008, avoiding unfavorable generation patterns
- Installation of a 260 MVAR SVC
- Relocation of key generating units from higher to lower voltage interconnections—effectively moving dynamic sources closer to loads

- Conversion of a 500-kV transmission line to 230-kV operation—with the increased line impedance reducing the amount of load subjected to low voltage for FIDVR resulting from faults at critical locations
- Planned new generation in North Georgia
- A three pronged strategy planned to mitigate multiple contingency events which included faster breaker failure clearing at key stations, breaker replacements, and a UVLS scheme.

7. Recommendations

The Transmission Issues Subcommittee recommends that the Planning Committee:

1. Endorse this white paper for use in further educating the industry to the FIDVR phenomenon.
2. Support the WECC dynamic load model developed for PSLF and the SOCO dynamic load model developed for PSS/E by encouraging its general use with local customization for FIDVR studies unless an adequate dynamic load model is already in use.
3. Promote Event Analysis of all FIDVR events to ensure further data acquisition, understanding, and modeling expertise.
4. Tasks the TIS and SPCS jointly with developing a guideline for adequately addressing protection and control considerations in performance of FIDVR studies.
5. Champion a local climate and load density-driven level of effort in FIDVR activities.
6. Support the standardization of unit level solutions for FIDVR by A/C manufacturers.

Appendix A – StatCom Typical Station Service

Figure A-1 shows the typical station service used to supply power to a StatCom.

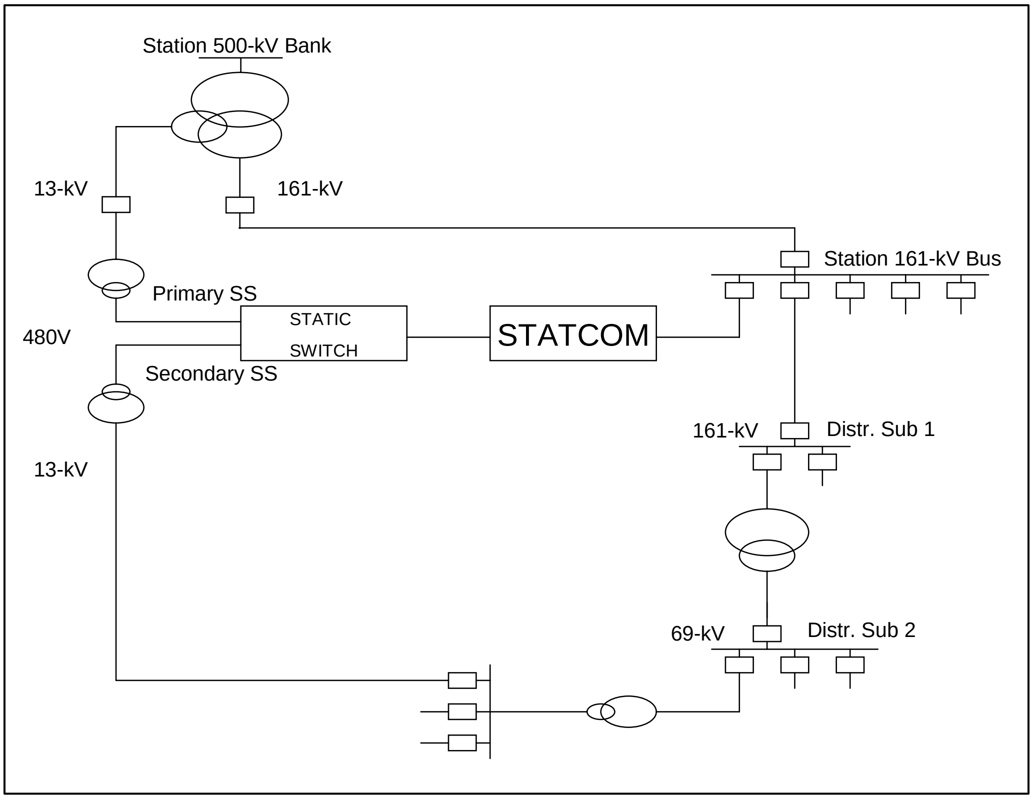

Figure A-1 — StatCom Typical Station Service

The following are typical station service deficiencies:

- Secondary station service source is a subset of primary station service source
- Both are affected by any loss of the 500-kV transformer bank – the very event which threatens a voltage collapse in the area
- Planner/Designer communications did not include the fact that a voltage collapse is the only reason a StatCom was being applied rather than cap banks.

Appendix B – Transmission Issues Subcommittee

David Till
Chairman
Manager, Transmission Planning
Tennessee Valley Authority

Eric M. Mortenson
Vice-Chairman
Senior Engineer
Exelon Energy Delivery

Kenneth A. Donohoo
Past-Chairman
Director System Planning
Oncor Electric Delivery

Wesley Woitt
RE – ERCOT
Supervising Engineer
CenterPoint Energy

Hector Sanchez
RE – FRCC
Supervisor, Bulk Transmission
Florida Power & Light Co.

Dale Burmester
RE – MRO
Manager, Access/Transmission Planning
American Transmission Company, LLC

Dana Walters
RE – NPCC
Manager, Transmission Planning
National Grid USA

Mark Byrd
RE – SERC
Manager - Transmission Planning
Progress Energy Carolinas

Jay Caspary
RE – SPP
Director, Engineering
Southwest Power Pool

Branden Sudduth
RE – WECC
Associate Staff Engineer
Western Electricity Coordinating Council

W. Perry Stowe
Investor-Owned Utility
Director, Transmission Planning Department
Southern Company Transmission Company

Scott M. Helyer
Independent Power Producer
Vice President, Transmission
Tenaska, Inc.

John M. Simonelli
ISO/RTO
Director – Operations Support Services
ISO New England, Inc.

Jeffrey R. Webb
ISO/RTO
Director of Planning
Midwest ISO, Inc.

Israel Melendez
Power Marketer
Vice President, Grid Optimization
Constellation Energy Commodities Group

Patricia E. Metro
Cooperative
National Rural Electric Cooperative Association

Hai Quoc Le
RE – NPCC Alternate
Manager, System Planning and Protection
Northeast Power Coordinating Council, Inc.

Steve Corey
ISO/RTO Alternate
Manager, Transmission Planning
New York Independent System Operator

Robert W. Cummings
NERC Staff Coordinator
Director of Event Analysis & Information Exchange
NERC

Eric H. Allen
Correspondent
Senior Engineer of Reliability Performance and Events Analysis
NERC

John L. Seelke, Jr.
Correspondent
Manager of Planning
NERC

James K. Robinson
Correspondent
TADS Manager
NERC

Anthony Alford
Correspondent
Staff Engineer
CenterPoint Energy

I. Paul McCurley
Cooperative Alternate
Manager, Power Supply
National Rural Electric Cooperative Association

Thomas J. Gentile
Correspondent
Senior Director - Transmission Northeast
Quanta Technology

Yury Tsimberg
Correspondent
Director of Asset Management
Kinectrics, Inc.

Baj Agrawal
Correspondent
Principal Engineer
Arizona Public Service Company

Gary T. Brownfield
Correspondent
Supervising Engineer, Transmission Planning
Ameren Services

Thomas W. Green
Correspondent
Principal Transmission Planning Engineer
Xcel Energy, Inc.

Appendix C – System Protection and Control Subcommittee

John L. Ciufo
Chairman
Manager, P&C Strategies and Standards
Hydro One, Inc.

Jonathan Sykes
Vice-Chairman
Senior Principal Engineer, System Protection
Salt River Project

Michael J. McDonald
Investor-Owned Utility
Senior Principal Engineer, System Protection
Ameren Services Company

William J. Miller
Investor-Owned Utility
Consulting Engineer
Exelon Corporation

George Pitts
U.S. Federal
Transmission Planning
Tennessee Valley Authority

Sungsoo Kim
Canada Provincial
Senior Protection Engineer
Ontario Power Generation Inc.

Joe T. Uchiyama
U.S. Federal
Senior Electrical Engineer
U.S. Bureau of Reclamation

Charles W. Rogers
Transmission Dependent Utility
Principal Engineer
Consumers Energy Co.

Joseph M. Burdis
ISO/RTO
Senior Consultant / Engineer, Transmission
and Interconnection Planning
PJM Interconnection, L.L.C.

Jim Ingleson
ISO/RTO
Senior Electric System Planning Engineer
New York Independent System Operator

Bryan J. Gwyn
RE – NPCC
Manager, Protection Standards and Support
National Grid USA

Philip Tatro
RE – NPCC Alternate
Consulting Engineer
National Grid USA

Henry (Hank) Miller
RE – RFC
Principal Electrical Engineer
American Electric Power

Deven Bhan
RE – MRO
Electrical Engineer, System Protection
Western Area Power Administration

John Mulhausen
RE – FRCC
Manager, Design and Standards
Florida Power & Light Co.

Philip B. Winston
RE – SERC
Manager, Protection and Control
Georgia Power Company

Dean Sikes
RE – SPP
Manager - Transmission Protection, Apparatus, & Metering
Cleco Power

Samuel Francis
RE – TRE
Senior Director of Engineering
Oncor Electric Delivery

Baj Agrawal
RE – WECC
Principal Engineer
Arizona Public Service Company

Josh Wooten
U.S. Federal Alternate
System Protection and Analysis
Tennessee Valley Authority

W. O. (Bill) Kennedy
Canada Member-at-Large
Principal
b7kennedy & Associates Inc.

Robert W. Cummings
NERC Staff Coordinator
Director of Event Analysis & Information Exchange
NERC

Tom Wiedman
Subject Matter Expert – NERC Consultant
President
Wiedman Power System Consulting, Ltd.

Jonathan D Gardell
Subject Matter Expert – NERC Consultant
Executive Advisor
Quanta Technology

Eric A Udren
Subject Matter Expert
Executive Advisor
Quanta Technology

Murty Yalla
Subject Matter Expert
President
Beckwith Electric Company Inc.

David Angell
Correspondent
T&D Planning Engineering Leader
Idaho Power Company

Hasnain Ashrafi
Correspondent
Engineer
Sargent & Lundy

Dac-Phuoc Bui
Correspondent
Engineer
Hydro-Quebec TransÉnergie

Jeanne Harshbarger
Correspondent
System Protection Engineer
Puget Sound Energy, Inc.

Fred Ipock
Correspondent
Senior Engineer - Substations & Protection
City Utilities of Springfield, Missouri

Evan T. Sage
Correspondent
Senior Engineer
Potomac Electric Power Company

Joe Spencer
Correspondent
Manager of Planning and Engineering
SERC Reliability Corporation

Bob Stuart
Correspondent
Senior Director - Transmission
BrightSource Energy, Inc.

James D. Roberts
Correspondent
Transmission Planning
Tennessee Valley Authority