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STATCOM Application to Address Grid Stability and Reliability: Part I

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SUMMARY

This paper reviews the application of STATCOM technology for reliability criteria, voltage stability, and fault-induced delayed voltage recovery (FIDVR). It further discusses a multitude of challenges utilities are facing in today's changing generation portfolio environment that are affecting overall grid stability, the device characteristics required to address these challenges, and the comparative performance of Flexible AC Transmission System (FACTS) technologies, in particular the STATCOM compared to an SVC, for such applications. Advantages of a STATCOM over an SVC in terms of voltage correction performance, filtering needs, spatial requirements, and adaptability are reviewed. In response to transient stability issues during stressed system conditions in a harsh environment, a STATCOM has the potential to be the preferred evaluated technical and economic solution.

KEYWORDS

STATCOM, SVC, FACTS transient stability, voltage stability, reliability criteria, stability criteria, Fault Induced Delayed Voltage Recovery (FIDVR), motor loads

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I. INTRODUCTION

This paper first describes reliability criteria published by the North American Electric Reliability Council (NERC), where the latest versions are discussed in this paper at the time of writing. The interest of this paper is on Category C and D violations, which involves the loss of multiple transmission elements in response to single-line-to-ground and three-phase faults for normal and backup fault clearing conditions, with the desire to avoid the loss of load and cascading outages. Key to such conditions is the Fault-Induced Delayed Voltage Recovery (FIDVR), where attention to detail is required on the amount of various types of load represented at each location of a system, particularly for small induction type motors for air conditioners. Blackout events have been attributed to voltage stability conditions related to such load. This paper further discusses additional utility challenges, desired solution characteristics based on reliability criteria, and FIDVR, leading to a comparison of advanced solution options of a STATCOM to an SVC, where the STATCOM has the potential to be the preferred evaluated technical and economic solution.

II. RELIABILITY CRITERIA

NERC has a family of Transmission Planning (TPL) Standards for system reliability, designated TPL-001-0.1 through TPL-004-2a, with the most current versions listed below from [1]:

- TPL-001-0.1 and TPL-001-3: System Performance Under Normal (No Contingency) Conditions (Category A)
- TPL-001-2 and TPL-001-4: Transmission System Planning Performance Requirements
- TPL-002-0b and TPL-002-2b: System Performance Following Loss of a Single Bulk Electric System (BES) Element (Category B)
- TPL-003-0a, TPL-003-0b, TPL-003-2a, and TPL-003-2b: System Performance Following Loss of Two or More BES Elements (Category C)
- TPL-004-0, TPL-004-0a, TPL-004-2, and TPL-004-2a: System Performance Following Extreme Events Resulting in the Loss of Two or More BES Elements (Category D)

TPL-001 through TPL-004 (and their revisions) are critical because they address the category of outage, from no contingencies to extreme events resulting in two or more (multiple) elements removed or cascading out of service, the initiating event(s) and contingency element(s), and system limits in terms of system stability with a range for thermal and voltage limits, allowable loss of demand or curtailed firm transfers, and allowable cascading outage conditions. The initiating event and contingency elements range from all facilities in service to disturbances such as three-phase faults with delayed clearing, and a host of other conditions covered in TPL-003 and TPL-004. Normal clearing and delayed clearing are defined as below in the TPL Standards:

> *"Normal clearing is when the protection system operates as designed and the Fault is cleared in the time normally expected with proper functioning of the installed protection systems. Delayed clearing of a Fault is due to failure of any protection system component such as a relay, circuit breaker, or current transformer, and not because of an intentional design delay."*

TPL-001-2 and TPL-001-4 address transmission system planning performance requirements with the purpose stated as follows in the TPL standards:

> *"Establish transmission system planning performance requirements within the planning horizon to develop a Bulk Electric System (BES) that will operate reliably over a broad spectrum of system conditions and following a wide range of probable contingencies."*

TPL-001-2 and TPL-001-4 contain a table defining a category from P0 (no contingency) to P7 (multiple contingency, common structure) with the initial condition, event, fault type, BES level (EHV or HV), interruption of firm transmission service allowed (yes or no), and non-consequential load loss allowed (yes or no), which are all important to consider for system planning. Further detail on TPL-001-2 and TPL-001-4 are beyond the scope of this paper.

An important distinction to consider in voltage stability analysis and consideration of solutions is meeting reliability criteria in satisfying the NERC TPL standards, and additionally the desire to avoid the loss of load and cascading outages for a defined set of conditions. The planning year of interest, season, import/export conditions, interplay of power and voltage conditions between different voltage levels, generator dispatch, load characteristics, project staging, planned system augmentations, fault clearing philosophy and timing, breaker configurations, special protection schemes, and load shedding schemes, along with existing shunt/series compensation and equipment ratings all come into play. The representation of motor load is particularly important along with its response to FIDVR. Operational concerns and relieving congestion outside of what is required to satisfy the NERC TPL standards are also important, but not focused on in this paper.

III. FAULT INDUCED DELAYED RECOVERY VOLTAGE

FIDVR events are driven by the stalling of induction motors causing a significant reactive power draw on the electrical grid, which can lead to significant load loss and fast voltage collapse. FIDVR is summarized in [2] as follows:

> *"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"*

The root cause of FIDVR is further described in [2] as:

> *"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.*

In response to the need for appropriate motor representation, models have been developed for both PSLF and PSS\E, with the need to define the penetration level by area of the different load types including the FIDVR-type load. Refer to [2] for further information. Examples are included of events in [2] where dynamic compensation such as SVC was applied to guard against FIDVR, along with a list of other potential solution options, summarized below for reference:

- Installation of equipment control devices to remove A/C and other induction motor loads from the grid prior to stalling for undervoltage conditions as a long term option, and utilize grid solutions to address inadequate dynamic reactive power support, such as:
- Quicker clearing of faults
- Addition of reactive sources or relocation of reactive sources relative to critical loads
- Limiting impacted load
- Special Protection Schemes (SPS)
- Under-Voltage Load Shedding (UVLS)

- Promote energy saving devices to reduce demand

A FIDVR strategy employed by the Southern Balancing Authority was summarized in [2] as follows:

- Operational FIDVR risk reduction until 2008, avoiding unfavorable generator 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.

Figure 1 shows a plot of the WECC voltage performance parameters [3]. The applicability of WECC criteria, which is based on rotor angle stability requirements, needs to be considered when applying the criteria to a voltage stability analysis, which may be strongly influenced by the load and its recovery characteristics, including the FIDVR phenomenon described previously. The use of rotor angle stability requirements for voltage stability purposes may lead to over-conservative or under-conservative designs for specific applications.

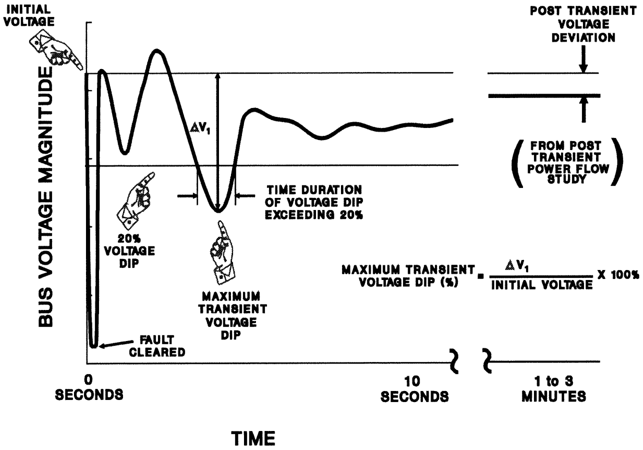

Figure 1. Voltage performance parameters for WECC Criteria
(Taken from "WECC Reliability Criteria" document dated April 2003) [3].

To guard against FIDVR, it has been observed that utilities have been using criteria of requiring the voltage to return to 0.80 p.u. or 0.90 p.u. one to two seconds after the fault is cleared, with the intent to avoid conditions where induction motors may stall.

IV. ADDITIONAL UTILITY GRID CHALLENGES

Utilities are facing additional grid challenges amongst the NERC TPL standards and the desire to avoid load interruption and cascading outages while dealing with FIDVR. The following summarizes these issues:

1. NERC Category C and D contingencies covering single-line-to-ground (SLG) faults and three-phase faults, respectively, for normal and delayed clearing conditions. For a Category C contingency, the system must remain stable, within voltage and thermal ranges, have controlled /planned loss of demand, and no cascading outages. Note bus configuration and relaying times can have a significant impact on the findings for such cases.

2. System must recover voltage to within a range of 0.80 p.u. to 0.90 p.u. in a couple seconds to avoid FIDVR in many instances.
3. Local generation sources are being decommissioned near load centers because of pollution legislation and environmental restrictions on existing generation near the load. Loss of local generation sources causes weak short-circuit conditions, i.e., low short-circuit duty and high short-circuit impedance near load, and exasperates voltage stability problems in terms of voltage regulation, speed of recovery required, amount of dynamic reactive compensation, and need to limit voltage overshoot, along with increased harmonic and filtering requirements.
4. New generation resources to replace local capacity losses are more often remotely located, including renewable resources, which can be 100-300 miles or more away from the load, further decoupling the generation supply from the load. Use of remote generation causes system operations to be more constrained local to the load, creating the need for improved overall system control. Note reactive power does not travel over long distances, and thus near-load Var deficiency is an increasing concern.
5. In a deregulated environment, utilities have less control of generator location and dispatch conditions than historically, which are now economically driven with quickly changing generating patterns. Traditional system solutions of generation re-dispatch are not viable (especially in cases dealing with highly intermittent replacement sources) or are increasingly constrained in many cases to solve system stability, reliability, and congestion problems.
6. Load areas are approaching saturation in local voltage support through load tap changing (LTC) transformers and Mechanically Switched Capacitors (MSC). Power-Voltage (P-V) analysis and resulting curves can demonstrate the saturation of such devices and need for reactive power reserves and quick control. Lack of traditional system and equipment solutions drives the need for other solutions such as advanced power electronic solutions.
7. Right-of-way constraints prohibit or significantly delay the build-out of new transmission and can impact the location and spatial constraints for dynamic reactive power solutions.
8. Load growth and its sensitivity to disruptions, power quality, and voltage quality demands high quality, reliable service, which may require advanced solutions to be more strategically located and sized.
9. Public and political pressures to utilize green and environmentally sound advanced solutions, which may also require advanced solutions to be more strategically located and sized.

Given the number, diversity, and complexity of the challenges, the problem definition and required solution is multi-dimensional and will most likely require compromise in terms of the system reinforcement(s), staging, and economics. Likely, there is no ‘one size fits all’ solution. However, it may be desirable to plan solution options such that they cover a wide range of operating conditions and will be able to be utilized for future system conditions. Given the challenges previously described, the following lists desired solution characteristics:

a. Need to provide voltage regulation and fast-acting voltage support to prevent NERC criteria violations, transient instability, and cascading outages. Must respond in ‘cycles’ timeframe to recover voltage in response to FIDVR. Needed for items 1-6 and 8.
b. Need to provide reactive power compensation during weak system conditions, significantly depressed voltages, and address the potential for overshoot. Furthermore, because of generation characteristics, black start capability is most likely desirable. Needed for items 1-6 and 8.
c. Need to consider harmonics and filtering. Minimal device-driven harmonics generated with reduced filtering needs and tolerant to existing harmonics anticipated to be desired. The avoidance or reduction of filtering may also avoid detuning and other considerations that may be of concern over the life of the installation. Needed for items 3-5 and 8.
d. Need to address reduced spatial requirements most likely important. The solution will most likely need to be able to fit at or near the load area. Needed for items 7-9.
e. Need to provide for increased utilization of existing equipment, control thereof, reduced congestion, and consider future system constraints with ability to adapt to them, considering maintainability and the overall economic feasibility. Needed for items 3-7 and 9.

Table 1 summarizes the grid challenges and anticipated desired solution characteristics. Desired solution characteristics are listed at the top of Table 1 and the challenges are listed along the left-hand side of Table 1, each referencing the bulleted text describing the solution and challenge, respectively. An ‘x’ in the table indicates the solution characteristic is primarily needed to address that particular grid challenge.

Table 1
Grid Challenges and Desired Solution Characteristics

Challenge || Primary Solution Characteristic->	Voltage Regulation and Fast-Acting Capable (a)	Act in Weak, Low Voltage, & Overshoot Environment + Black Start (b)	Have Reduced Harmonics & Filtering Requirements (c)	Reduced Spatial Requirements (d)	Increase Utilization of Existing Equipment & Adaptability (e)
NERC Criteria / Avoid Load Loss (1)	x	x			
FIDVR Response (2)	x	x			
Reduced Local Generation (3)	x	x	x		x
Increased Remote Generation (4)	x	x	x		x
Generator Dispatach Constrained (5)	x	x	x		x
Saturated LTC and MSC (6)	x	x			x
Right-of-Way Constraints (7)				x	x
Load Growth and Sensitivity (8)	x	x	x	x	
Public and Political Pressure (9)				x	x

Traditional (conventional) solutions such as series reactors, series capacitors, mechanically switched capacitors, and mechanically switched reactors will not address challenges (1) through (9), though they may be economical. Conventional solutions cannot provide the dynamic response required to address transient stability problems such as FIDVR. Advanced overhead line or underground HVDC solutions may also not be desirable because of the economics involved and other factors in some cases [4, 5]. Constraints for infrastructure expansion and the use of generation have already been addressed as part of the grid challenges in Table 1.

Two alternatives remain as advanced solution options, the Static Var Compensator (SVC) and the Static Synchronous Compensator (STATCOM). The next section provides background on the STATCOM solution and comparison to the SVC. Note the Thyristor Controlled Series Capacitor (TCSC) and Unified Power Flow Controller (UPFC) are solution options where dynamic power flow and voltage control are desired.

V. THE STATCOM SOLUTION

STATCOM technology has been around for decades and had widespread use for the correction of arc furnace and flicker compensation [6, 7]. Benefits of a STATCOM solution over convention solutions such as a synchronous condenser and a thyristor-based solution, i.e., the SVC, have been covered in [8]. Mitsubishi Electric Corporation installed the world’s first Distribution-STATCOM (D-STATCOM) in 1979 for Kansai Electric Power Company, Japan, for voltage flicker suppression, reactive power compensation, and grid stabilization based on Gate Turn Off thyristor (GTO) technology (33 kV +/- 20 Mvar) [9].

For transmission applications, Mitsubishi Electric Corporation also provided the world’s first commercial STATCOM installation for Kansai Electric Power Company, Japan, utilizing a large capacity GTO to increase the steady-state stability limit and control power oscillations at the Inuyama Substation (154 kV +/- 80 Mvar) [10, 11]. Consequently, Mitsubishi Electric Corporation has also installed the world’s largest STATCOM for Chubu Electric Power Company, Japan, at the Toshin substation to increase stability and over-voltage suppression utilizing Gate Commutated Turn Off thyristor (GCT) technology (275 kV +/- 450 Mvar) [12, 13].

A key advantage of STATCOM over SVC is that it utilizes self-commutated semiconductor switching devices in the core converter design topology and operation, such as the gate turn-off thyristor (GTO) and the gate-commutated thyristor (GCT), and also the more recently applied insulated gate bipolar transistor (IGBT) and the injection enhanced insulated gate bipolar transistor (IEGT). These devices employ advanced switching techniques and configurations, such as a 3-level 3-pulse (180 Hz) pulse-width modulated (PWM) schemes, to produce a 60 Hz waveform for the DC sourced input. For comparison, the SVC utilizes conventional thyristor technology with no turn off capability, thus the devices are line-commutated and depend on the system to turn off. These more traditional thyristor elements are in the form of the electrically triggered thyristor (ETT) and the more recently established light triggered thyristor (LTT).

The advanced semiconductor devices allow the STATCOM to use energy from the power system to charge and discharge a DC capacitor through a coupling transformer and a set of converters consisting of the semiconductor devices. The STATCOM can supply leading, lagging, or no reactive power depending on the voltage and its phase angle compared to that of the power system. The following advantages are realized by the STATCOM, relative to an SVC:

- Elimination of Thyristor Controlled Reactor (TCR) and Thyristor Switched Capacitor (TSC) and associated filtering. Little to no filtering is required for STATCOM subject to design and system conditions.
- Reduction of installation space on the order of 30% to 50%.
- Significant increase in performance at low voltages where SVC reactive power injection decreases relative to the square of voltage (V^2) while STATCOM reactive power injection decreases relative to voltage (V).
- STATCOM can be convertible to a future back-to-back arrangement and is black start capable.

For reference, Figure 2 shows the basic configuration for an SVC and Figure 3 shows the V-I characteristics for an SVC. Figure 4 shows the basic configuration for a STATCOM and Figure 5 shows the V-I characteristics for a STATCOM.

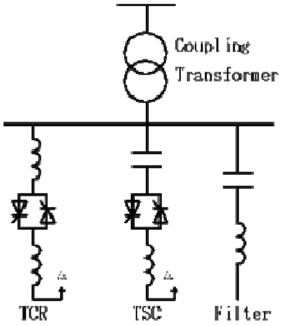

Figure 2. Basic configuration of an SVC.

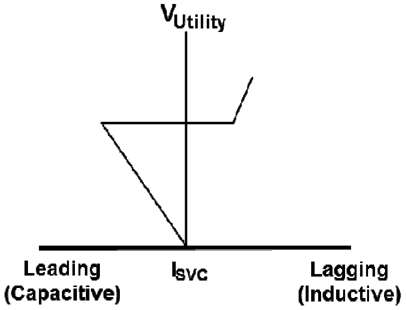

Figure 3. V-I characteristics of an SVC.

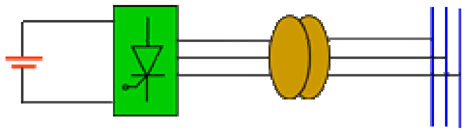

Figure 4. Basic configuration of a STATCOM.

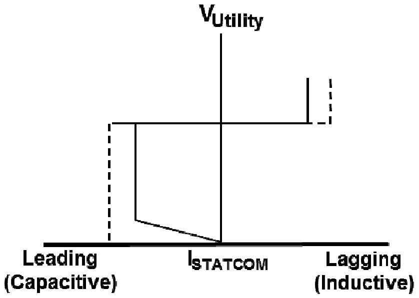

Figure 5. V-I characteristics of a STATCOM.

Table 2 summarizes the advantages of a STATCOM compared to an SVC relative to Table 1. An ‘x’ denotes that the device is capable to address the characteristic to a degree, where an ‘xx’ denotes that the device has significantly superior design features/advantages to address the characteristic.

Table 2
Advantages of STATCOM to SVC Based on Table 1

	SVC	STATCOM
Voltage Regulation and Fast-Acting Capable (a)	x	xx
Act in Weak, Low Voltage, & Overshoot Environment + Black Start (b)	x	xx
Have Reduced Harmonics & Filtering Requirements (c)		xx
Reduced Spatial Requirements (d)		xx
Increase Utilization of Existing Equipment and Adaptability (e)	x	xx

Another advantage STATCOM merits over SVC is its response characteristic to dynamic conditions is proportional to voltage, as opposed to that of SVC which is proportional to the square of the voltage – this provides an overall superior response capability for the reactive compensation performance of the STATCOM. Table 3 demonstrates this significant key feature of the STATCOM technology and solution over that of the SVC. Table 3 lists the system voltage in p.u., which may be representative of the voltage upon recovery of the system after a fault or disturbance, the reactive power (Q) supplied by an SVC driven by the square of the voltage (V^2), the reactive power supplied by a STATCOM driven by the voltage (V), and the ratio of the STATCOM Q to the SVC Q, which quantifies the advantage of the STATCOM to the SVC as a multiple of increased Q supplied by the STATCOM relative to the SVC.

From Table 3, it is observed that over a system voltage range of 0.40-0.95 p.u., such as that during recovery from a disturbance, the increase in the reactive power supplied by the STATCOM compared to an SVC is 1.59x on average and in the low range of 0.40-0.65, which may be representative of voltages during a FIDVR event, the advantage is nearly 2.0x on average, and up to 2.5x.

Given the advantages of STATCOM shown in Tables 2 and 3, it is anticipated that the STATCOM will provide an economical solution to grid stability and reliability. For instance if twice the SVC solution is required to address performance and utility criteria compared to STATCOM, in consideration along with the other benefits described in Tables 1 and 2, the STATCOM could be the overall superior evaluated economic solution. Further, a superior advantage of the STATCOM over the SVC for specification purposes is that it has an inherent symmetrical operating range, where it can provide as much inductive reactive power as capacitive reactive power, which makes it operationally advantageous for voltage regulation and the control of overvoltages during light load conditions.

Table 3
Benefit of STATCOM Compared to SVC Considering Voltage Performance

System Voltage P.U.	SVC P.U. Q	STATCOM P.U. Q	STATCOM Benefit (Multiple of Increased Q Relative to SVC)
0.40	0.160	0.40	2.50
0.45	0.203	0.45	2.22
0.50	0.250	0.50	2.00
0.55	0.303	0.55	1.82
0.60	0.360	0.60	1.67
0.65	0.423	0.65	1.54
0.70	0.490	0.70	1.43
0.75	0.563	0.75	1.33
0.80	0.640	0.80	1.25
0.85	0.723	0.85	1.18
0.90	0.810	0.90	1.11
0.95	0.903	0.95	1.05
		Average (0.40-0.95):	1.59
		Average (0.40-0.65):	1.96

VI. CONCLUSIONS

This paper discussed desired solution characteristics based on reliability criteria, FIDVR, and additional utility challenges, leading to the comparison of advanced FACTS solution options of a STATCOM over an SVC, where the STATCOM has potential to be a preferred technical and economic solution.

Part 2 will provide a simulation example, results, and comparison of STATCOM to SVC to further illustrate the key issues described in this paper.

VII. RELEVANT TERMS AND DEFINITIONS

The following is a list of terms and definitions that are either directly relevant to this paper or are important for the reader to consider when reviewing the information provided:

Voltage dip. A temporary reduction of the voltage at a point in the electrical system below a threshold. If during a voltage dip the voltage falls below an interruption threshold, the event is sometimes considered to be both a dip and an interruption [14].

Voltage sag. An rms variation with a magnitude between 10% and 90% of nominal and a short duration between 0.5 cycles and one minute [15].

Power system stability. Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [16].

Rotor angle stability. Rotor angle stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. It depends on the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system. Instability that may result occurs in the form of increasing angular swings of some generators leading to their loss of synchronism with other generators [16].

Voltage stability. Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. Instability that may result occurs in the form of a progressive fall or rise of voltages of some buses. A possible outcome of voltage instability is a loss of load in an area, or tripping of transmission lines and other elements by their protective systems leading to cascading outages. Loss of synchronism of some generators may result from these outages or from operation under field current limit [16, 17].

Short-term voltage stability. Short-term voltage stability involves dynamics of fast acting load components such as induction motors, electronically controlled loads and HVDC converters. The study period of interest is in the order of several seconds, and analysis requires solutions of appropriate system differential equations; that is similar to analysis of rotor angle stability. Dynamic modeling of loads is often essential. In contrast to angle stability, short-circuits near loads are important. The term *transient voltage stability* is deprecated [16, 18].

VIII. ACKNOWLEDGEMENTS

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