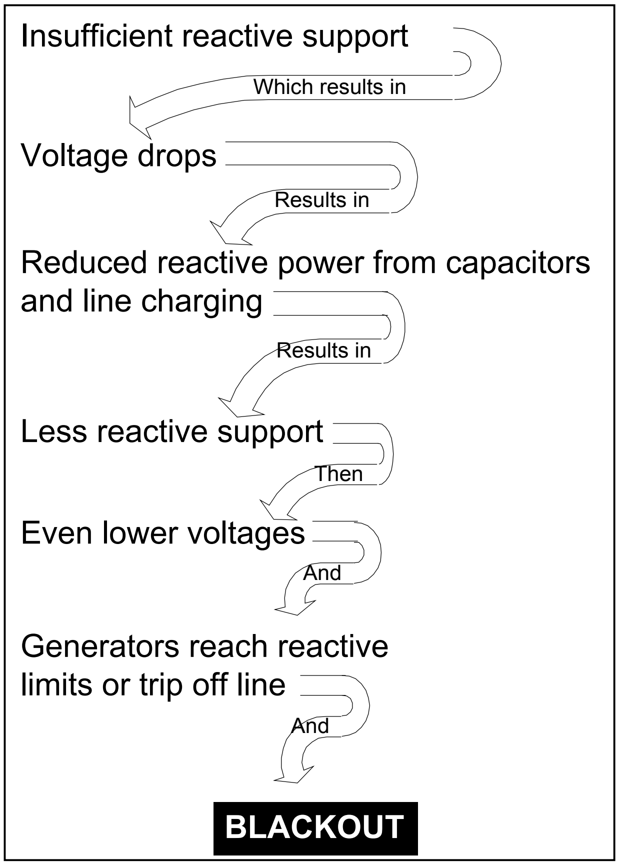
Real Consequences Follow Imaginary Power Deficiencies



(Graphic concept from AEP literature)

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Introduction

Imaginary (or reactive) power has become increasingly important as transmission systems work harder to deliver economic power where it is needed. Application of protection systems to mitigate deficiencies in real power is a mature technology, as underfrequency load shedding has been successfully preventing blackouts for years. Deficiencies in real power cause frequency declines that can normally be detected simultaneously throughout an interconnected system. However, deficiencies in reactive power, that can cause voltage declines are more difficult to mitigate, since voltage depressions may be caused by a variety of local or regional contingencies. After reviewing the phenomena of voltage collapse, and some recent examples, this paper will present some strategies for consideration when applying undervoltage load shedding.

Of course, proper power system planning and operation should ensure there are adequate reserves of reactive power to cater for contingencies, and thereby avoid the severe consequences of voltage collapse. However, system planning and operating procedures are beyond the scope of responsibilities for the average power system protection engineer. Therefore, this paper will not focus on prevention of reactive power deficiencies. Instead, we will address the corrective actions (primarily undervoltage load shedding) required to mitigate voltage collapse and possible system blackout given the inadvertent loss of reactive power to support the system voltage.

Voltage Collapse Phenomena

Reactive Power assists voltage stability.

Previous papers presented to the Western Protective Relaying Conference [1,2] have discussed the voltage collapse phenomena in some detail. The discussion in this paper will therefore be brief, to remind the reader of the process by which voltage instability arises. In particular, we will consider the margin between a given operating point and voltage collapse, or the closeness of the operating point to the edge of a "voltage precipice".

Consider a power system as shown in Figure 1. A generator is supplying real power P through a radial transmission line with a Reactance of X. Line resistance and capacitance are ignored for this example. A source of reactive power to compensate for the reactive power absorbed by the transmission line is shown as a variable capacitance on the right. This capacitance can inject compensating reactive power (Qc) at the load delivery point.

The real power P, delivered to the load is $P=(Vr)^2/R$ where R is the resistance of the load, and Vr is the voltage at the load delivery point.

In the first instance, if Qc is assumed to be zero, as R is decreased from an infinite value (open circuit), the power P delivered will be increased from zero and the voltage Vr will reduce until the point where the magnitude of R matches the magnitude of X (matching impedance). If R is decreased further, the voltage will drop more, and the power delivered will start to decrease. For instance, if the value of X is assumed to be 1.0 pu, and Vs = 1.0 pu, the maximum power that can be delivered will be 0.5 pu, and the voltage at the point of maximum power delivery will be $1/\sqrt{2} = 0.707$ pu.

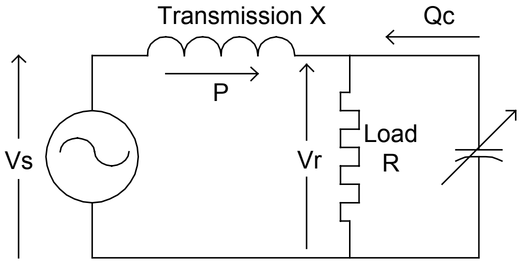


Figure 1 - Radial Power System

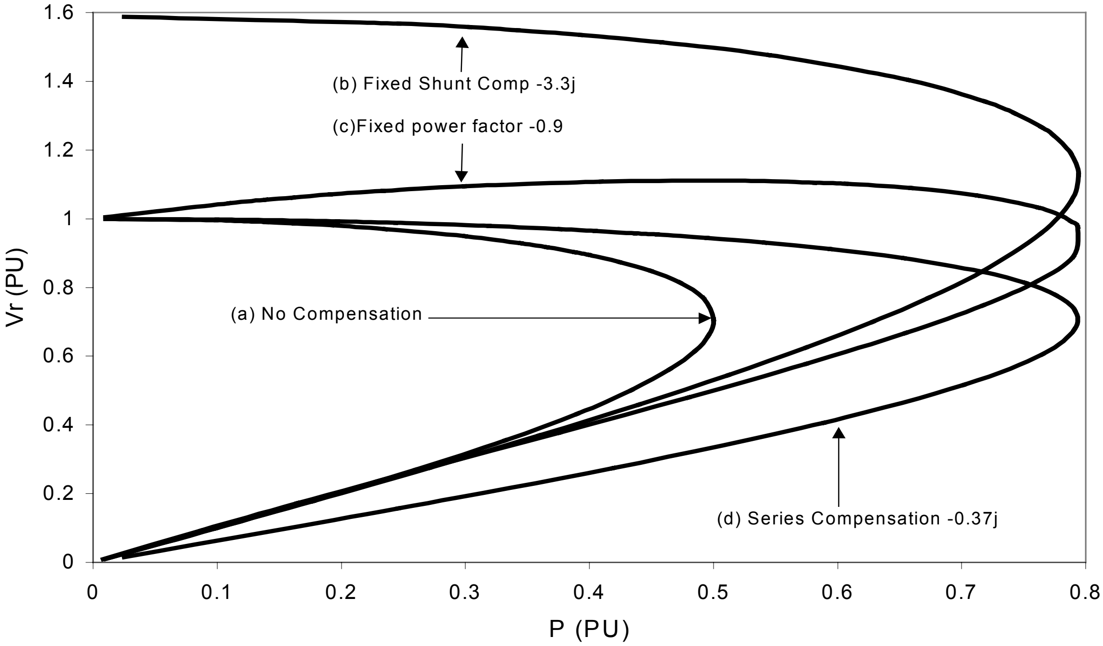


Figure 2 - Power-Voltage (PV) Curves

Curve (a) in Figure 2 shows the relationship of power delivered to Vr, as R is decreased with Qc=0. If the load demands more power than can be delivered by the transmission system, the voltage will simply collapse and the system will be voltage unstable – or possibly black.

Curve (a) is not particularly realistic for practical power systems, since some reactive power will usually be provided at the load delivery point to support the voltage. This reactive power will significantly increase the load transfer capability (hence the phrase “real consequences follow imaginary power deficiencies”). Curves (b), (c) and (d) show how the maximum deliverable power can be boosted to nearly 0.8 per unit by means of additional reactive power supply. Curve (b) shows the effect of a fixed shunt capacitance, of value –3.3j per unit connected at the load supply point. It can be seen that this fixed capacitance would boost the voltage to an unacceptably high level for low load transfer levels. However, for larger loads, it boosts the maximum real power transfer capability to nearly 0.8 per unit.

Curve (c) in Figure 2 shows the effect of a variable source of reactive power that is adjusted to make the total power factor at the load delivery point equal to –0.9 capacitive. This adjustment of the effective load power factor also increases the maximum power that can be delivered to the load.

Curve (d) in Figure 2 shows the effect of strengthening the transmission system by adding a series capacitance to compensate for 37% of the transmission impedance. A similar effect could have been achieved by adding some parallel transmission lines to lower the overall source impedance.

Figure 2 shows that adding sources of shunt reactive power to boost the transmission capability also raises the level of voltage at the “nose” of the PV curve. It is this effect that challenges simple undervoltage load shedding schemes, because the voltage at the point of collapse can be at or above normal voltage levels.

The transmission voltage throughout a power system will normally be controlled within fairly tight limits. Control is achieved by adjustment of reactive power sources and sinks such as shunt capacitors or reactors, or series compensation or reactive power output of generating units or synchronous condensers or static compensators. It is when all sources of reactive power are exhausted, or when a

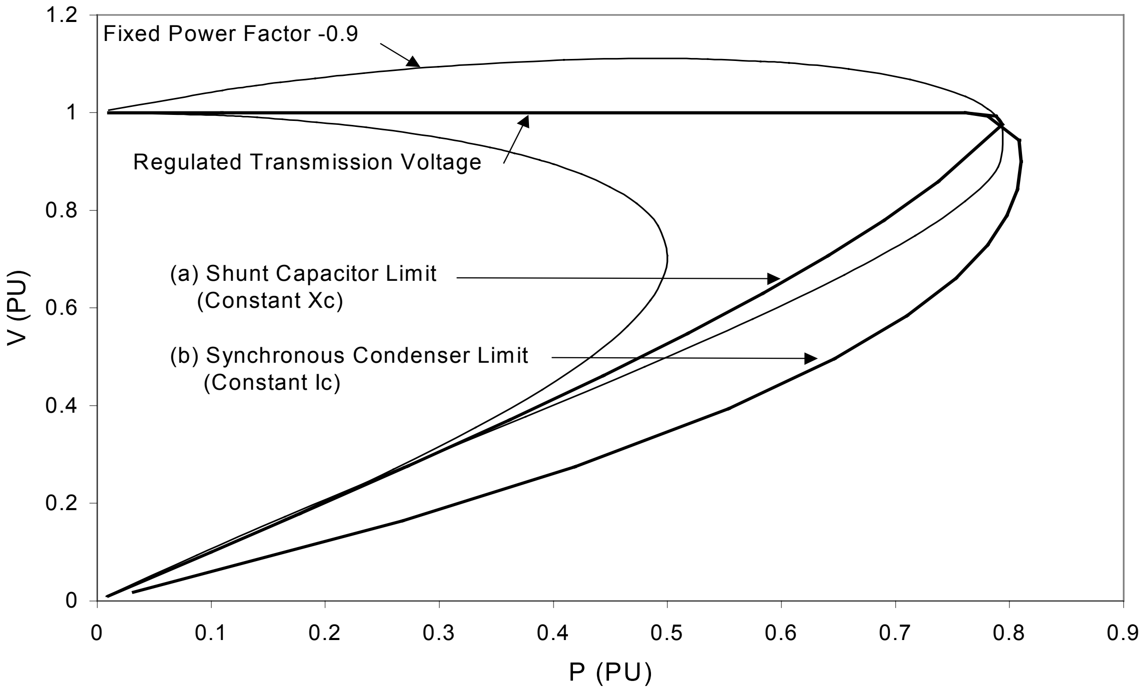


Figure 3 - Limits of Reactive Support

contingency arises, that problems may be realized. If a need for more reactive power than is available arises, there is a danger of voltage collapse. At such times, if the system is heavily compensated with shunt devices, the voltage collapse can be quite precipitous. Figure 3 shows the uncompensated and fixed power factor PV curves from Figure 2, with a normal 1.0 pu operating voltage superimposed. Figure 3 also shows the shape of the power/voltage characteristic when the limit is reached. Characteristic (a) is derived assuming all shunt compensation is provided by shunt capacitors. Since the reactive power output of a shunt capacitor is proportional to the square of the voltage, the power output drops very quickly as the voltage goes down, and the rate of voltage collapse is very fast. Characteristic (b) is derived assuming all shunt compensation is provided by a synchronous condenser that has a fixed reactive current output capability. In that case, the reactive power only drops linearly with the voltage, and the voltage collapse is not as fast as in case (a). In both cases however, it can be seen that a voltage collapse at the limit of reactive support is difficult to predict before the limit is reached. Hence we can envision an analogy to a "voltage precipice". It remains a significant challenge in power system operation to estimate (in real time) how close a given system state is to the edge of the precipice.

Having understood the impact of insufficient reactive power on real power transfer, we can now consider the relationship of reactive power reserve to voltage at different levels of real power transfer. The conventional steady state tool for such consideration is the QV curve as shown in Figure 4. Figure 4 is based on the power system shown in Figure 1. Voltage is considered to be stable when the slope of the QV curve is positive. That is, the voltage rises when more reactive power is injected into the system. Figure 4 shows that at zero real power transfer, the voltage at the receiving terminal is 1.0 per unit if no reactive power is injected. With zero real power transfer we can see that there is reactive power reserve (Qreserve) available. As the real power transmitted rises to the maximum deliverable without compensation (0.5 pu), the reactive power reserve drops to zero. If more power transfer is required (e.g 0.7 pu in Figure 4), reactive power (at least equal to Qmissing) must be injected to maintain system voltage and viability.

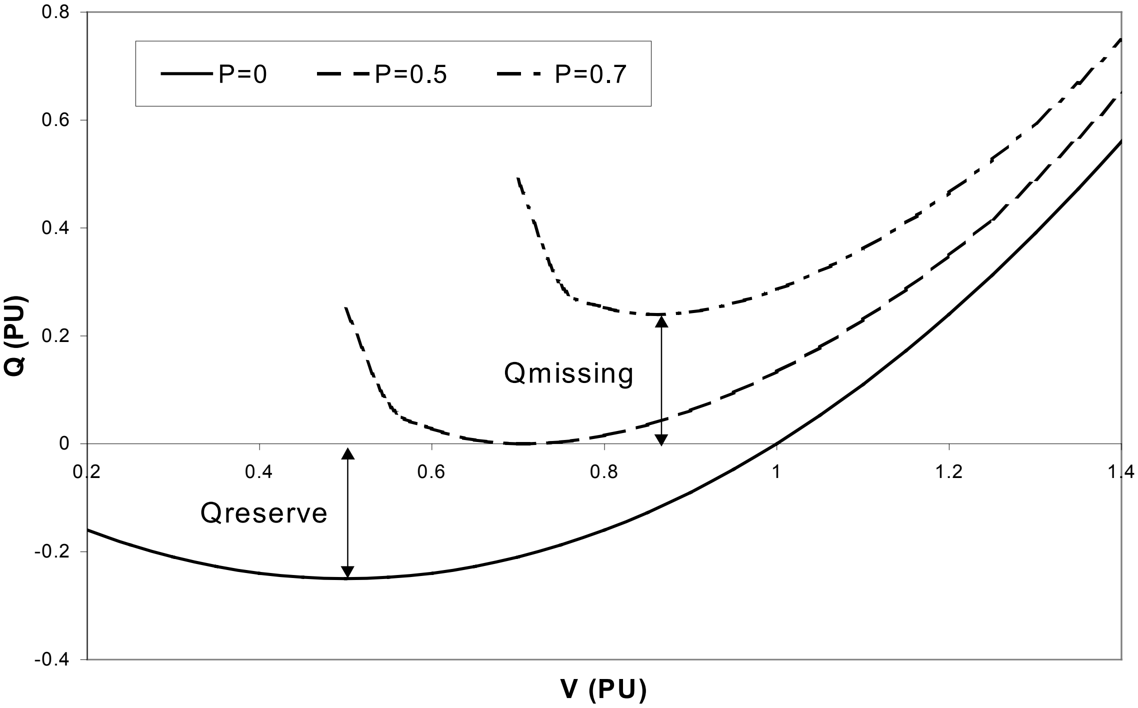


Figure 4 - QV Curves

Analysis of power systems using PV and QV curves is a steady state analysis. Load characteristics, and reactive power source capabilities usually change with time due to a variety of power system control actions. Therefore time dependent simulations (dynamic simulations) are normally used to study power system response to challenging voltage stability situations. The previous discussion is simplified to a steady state basis only to illustrate the importance of reactive power in delivering real power to loads in a transmission system.

Reactive power assists angular stability.

The previous discussion on voltage stability and voltage collapse has considered no rotating equipment requiring synchronism at the receiving terminal. The load has simply been represented as a resistance, and the reactive power support as a capacitance. At the "nose" of the PV curve (a) in Figure 2, when the maximum power is delivered, the angle between Vs and Vr is 45 degrees (and Vr is depressed to a value of 0.707 pu). The angle between the receiving terminal and the sending terminal does not rise to 90 degrees until the load resistance decreases to zero the receiving voltage drops to zero, and the total voltage drop between the sending and receiving terminal is dropped across the transmission inductance (neglecting transmission resistance).

In a power system requiring synchronism between the sending and receiving terminals, the power transmitted depends on the angle between the voltages at each of the terminals. Figure 5 shows the dependency of the power transmitted on the angle when the voltage at the receiving terminal is supported to a value of 1.0 pu.

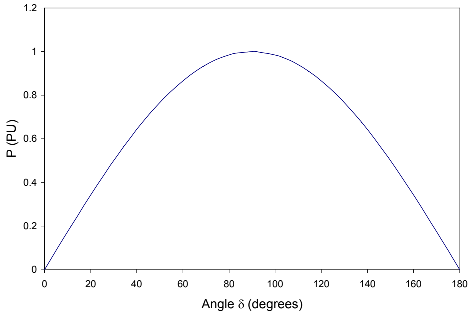


Figure 5 - Power Versus Angle

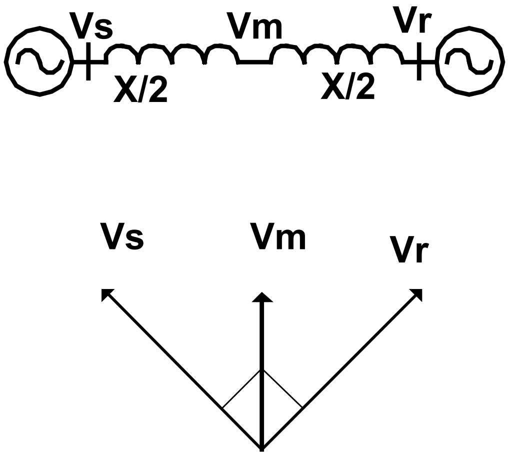


Figure 6 a) – Max. power transfer angles with no mid-point voltage support.

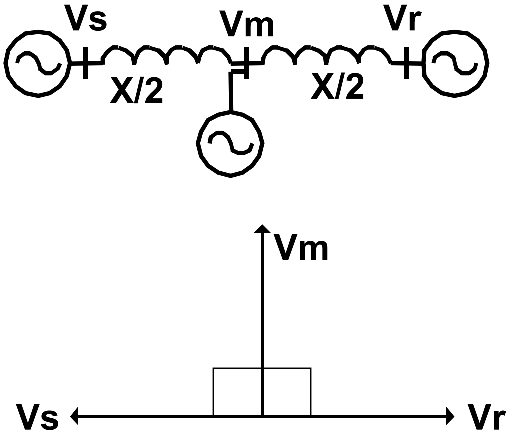


Figure 6 b) – Max. power transfer angles with mid-point voltage support.

Given a system as shown in Figure 6 (a), conventional power system theory indicates that P=Vs*Vr*Sin(δ)/X where δ is the angle between Vs and Vr.

If Vs = Vr = 1.0 pu, then Pmax = 1/X when δ=90 degrees. It should be noted that in this system, the voltage Vm near the middle of the transmission line is approximately 0.707 pu. If a source of reactive power is available at the middle of the line, as shown in Figure 6 b), it can boost the voltage at the mid point to 1.0 pu. When the mid point voltage is boosted, the maximum power that can be delivered between the sending and the mid point bus becomes 2/X simply due to the higher mid point voltage. Thus the injection of reactive power at the mid-point has doubled the amount of power that can be transmitted without losing synchronism. As will be seen in some of the examples following, loss of important reactive power injection at various points in a transmission system can result in loss of synchronism and exacerbate system disturbances.

Some Real Consequences

The following examples of severe impact of insufficient reactive power are not comprehensive but are selected for their general interest, and relevance to North American relay engineers. Many other disturbances have also been exacerbated by lack of reactive power. In fact, by one estimate, “Ninety percent of major system disturbances in recent years include some aspect of voltage collapse.” [3]. The examples will demonstrate the background for some observations regarding design and application of undervoltage load shedding schemes. There will be no attempt in this paper to comment on what could have been done to prevent or mitigate the impact of these disturbances, since they have already been thoroughly investigated and recommendations have already been made.

Quebec, March 13th, 1989.

On March 13th 1989, the province of Quebec in Canada suffered a severe and almost province wide blackout [4]. The disturbance was precipitated by a solar magnetic disturbance in which the earth’s magnetic field experienced large variations. The magnetic field changes caused very low frequency induced currents (Geomagnetic Induced Current or GIC) to circulate through the ground and the transmission network. Since the rate of change of current was very slow (with periods in the region of several minutes, or tens of minutes) the GIC appeared as almost dc to the 60 Hz power system. The low frequency current caused asymmetric excitation of system power transformers, that in turn offset their core flux, and excited much higher than normal harmonics in the transmission system.

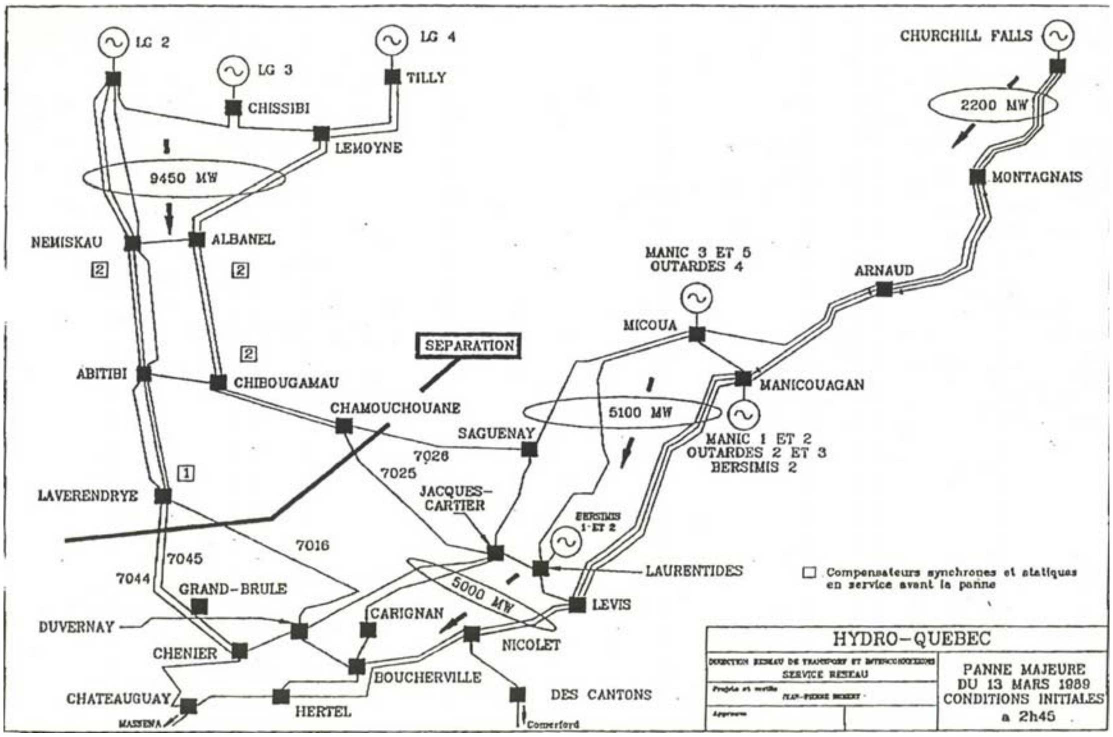


Figure 7 - Diagram of Hydro Quebec system with pre-disturbance power flows on 13th March, 1989 (from Ref. 4).

Several static var compensators (SVCs) that were supporting the 765 kV transmission line voltages absorbed the harmonic currents and were tripped off line by protective relays in rapid succession. The SVCs were located at Laverendrye, Chibougamau, Nemiskau and Albanel substations, as marked with numbers 1 or 2 on Fig. 7. These SVCs were supporting the voltage near the middle of the transmission circuits to allow heavy power transfer of about 9500 MW from La Grande power stations in the North to the load center in the Montreal area in the South.

Immediately after the SVCs tripped off line, the angle between La Grande Substation and Boucherville grew beyond 90 degrees and regions in the North and South lost synchronism with each other.

The out of step conditions between the two regions caused the transmission line protection to operate and separate the systems across the boundary shown in Figure 7.

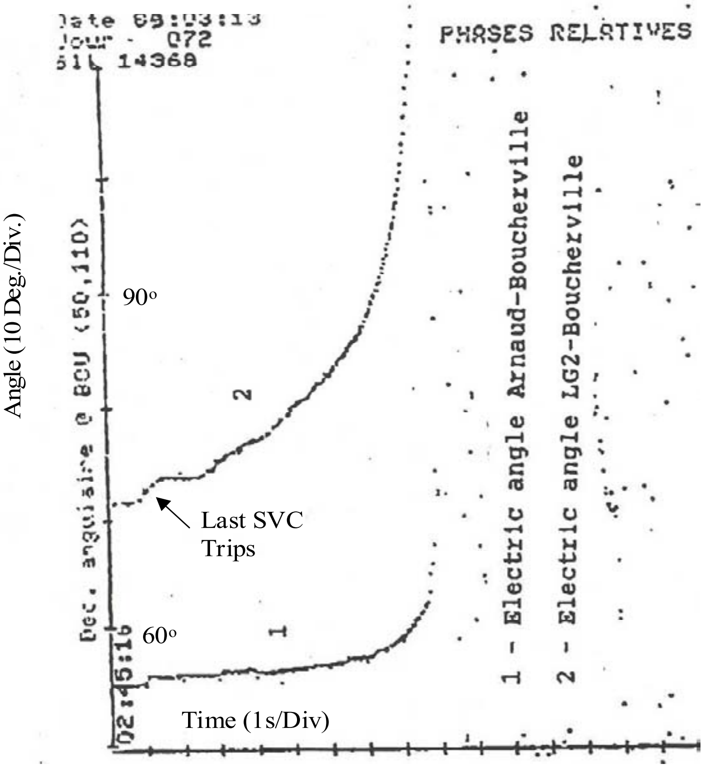


Figure 8 - Angular separation between generation and load areas after loss of reactive power support (from Ref. 4).

Curve 2 on Figure 8 shows the rapid increase of angle between LG2 and Boucherville to greater than 90 degrees, and consequent loss of stability. With sudden loss of 9500 MW of generation supplying a total load of about 19000 MW the system was not viable. The remaining generation in the North East area of the Province also lost synchronism with the load area (see curve 1 on Figure 8), and separated shortly after.

This incident is a good example of the importance of reactive power to boost voltages in the center of a long transmission system and thereby retain synchronism between the generation and load areas. The SVCs at the four intermediate stations can be compared to the reactive power source boosting voltage Vm in Figure 6 (b).

Western United States, 2 July, 1996.

A previous paper [5] has described the large disturbances that occurred in the Western US in 1996. It is interesting to note the impact of insufficient reactive power in those incidents. In the first incident, on 2 July, 1996, the disturbance was triggered by the sudden loss of two major 345 kV lines feeding power into Nevada and associated remedial actions to shed 1000 MW of generation.

After the triggering events, the Western Interconnection survived for about 22 seconds with only a small decline in voltage. However after 22 seconds a critical 230 kV line (AMPS line) tripped, and a few seconds later the generators at McNary generating station in Northern Oregon tripped due to misoperations of the excitation protection systems. Following those incidents, a sudden drop in transmission voltage in Central Oregon and Southern Idaho occurred, resulting in the system breaking into several islands. In all, about 11,800 MW load was lost in a widespread blackout that affected 2 million customers. Figure 9 shows the transmission voltage at a major 500 kV bus in the region. It can be seen that the voltage was maintained at above 525 kV (or about 1.05 pu) until the AMPS line trips, and the voltage collapses.

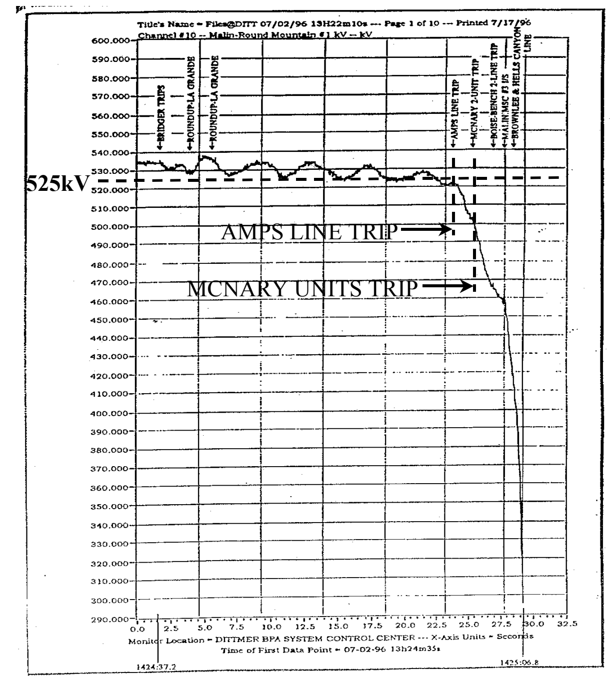


Figure 9 - 500 kV Transmission voltage during 2 July 1996 disturbance.

Figure 9 shows the sudden drop in voltage that can occur when there is a deficiency in reactive support. Compare the rate of drop in voltage of Figure 9 with that shown in Figure 3. Although Figure 3 is a plot of voltage versus power, and Figure 9 is a plot of voltage versus time, the similarities are obvious. In the case of Figure 9, the reactive support suddenly disappeared as the AMPS line and the McNary generators tripped, in a similar fashion to the limit of reactive power being reached in Figure 3. Figure 9 shows the challenges presented to simple undervoltage load shedding schemes. Such schemes need a time delay of some seconds to override local temporary voltage dips. However, as can be seen in Figure 9, simple undervoltage relays cannot sense the system stress until after the last voltage supports have disappeared, and the system is well on the way to blackout.

Western United States, 10 August, 1996.

Reactive power deficiencies also contributed to the second major Western US disturbance in the summer of 1996. In this case, the transmission system became progressively weaker, over a period of several hours. Reactive power sources supporting the voltage became more critical. At 3:47 pm, the generators at McNary generating station tripped in rapid succession for the same reason that they tripped in July. In this case a voltage collapse did not occur, but system oscillations became larger and negatively damped until out of step conditions arose, and unintentional system separations occurred. In this incident, about 28000 MW of load was lost, affecting about 7.5 million customers.

Figure 10 (a) shows the progression of the power oscillations with time. Figure 10 (b) shows on an expanded time scale the tripping of the McNary generators and their relationship to the start of the undamped oscillations.

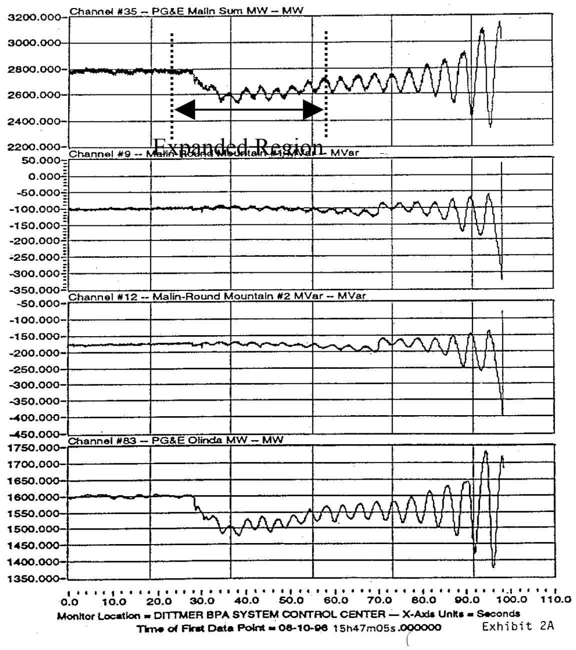


Figure 10 (a) - Undamped Oscillations 10 August, 1996

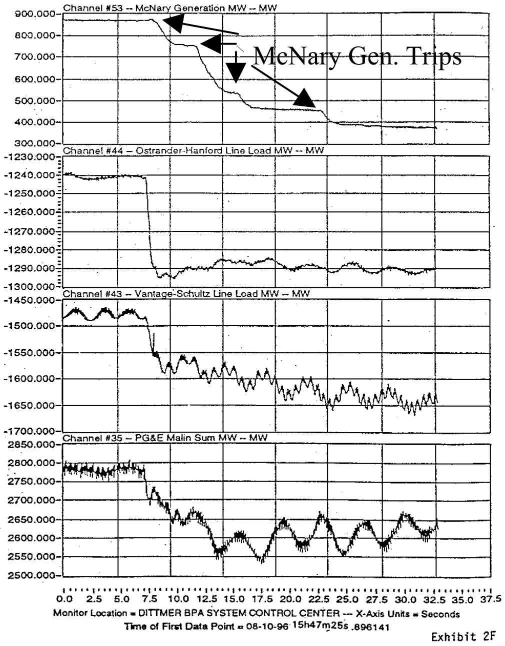


Figure 10 (b) - Time scale Expansion of start of oscillations

This incident is similar in some respects to the 13 August 1989 Hydro Quebec incident in that angular instability followed removal of reactive power sources. However in the case of this 1996 incident real power injection was also removed, and the angular instability was caused by undamped oscillations rather by than excessive power angle across a transmission system. In this case, an increased demand for reactive power from the McNary generators resulted in their being tripped off line. In both cases, the consequences of the lack of reactive power were real and significant.

North East North America, 14 August, 2003.

The Joint US Canada Task Force report (Reference 6) on this blackout notes that the incident was not a typical voltage collapse since voltages were in the normal region during the period leading up to the cascading outage. However, there was certainly a shortage of reactive power during the hours leading up to the incident. The shortage was exacerbated by the loss of the Eastlake 5 generator about 3 ½ hours before the blackout. Figure 11 shows that declining transmission voltage caused a gradual increase in the reactive power demanded from the generator. When the excitation control system sensed excessive reactive power output, the exciter was tripped to manual. When the operator tried to restore automatic control, the excitation system and the generator tripped off line completely.

Loss of generation is a key cause of aggravation of system disturbances. When generators try to make up the shortage of reactive power, some of them may undesirably trip off line if the protection equipment is not properly coordinated with the control equipment. It is that effect that precipitated the catastrophic loss of the McNary generators during the 1996 WECC disturbances. This undesirable sudden loss of reactive capability is what prompted the WECC requirement for verification of the reactive capability and system models of all generators in the Western Interconnection. Figure 11 is a real life example of the cover illustration of this paper where “Application of reactive limiters or tripping of generating plant” are near the bottom of the voltage collapse spiral. The cover illustration was used as a training tool for generator operators to impress upon them the importance of testing generators at the limit of their reactive capability.

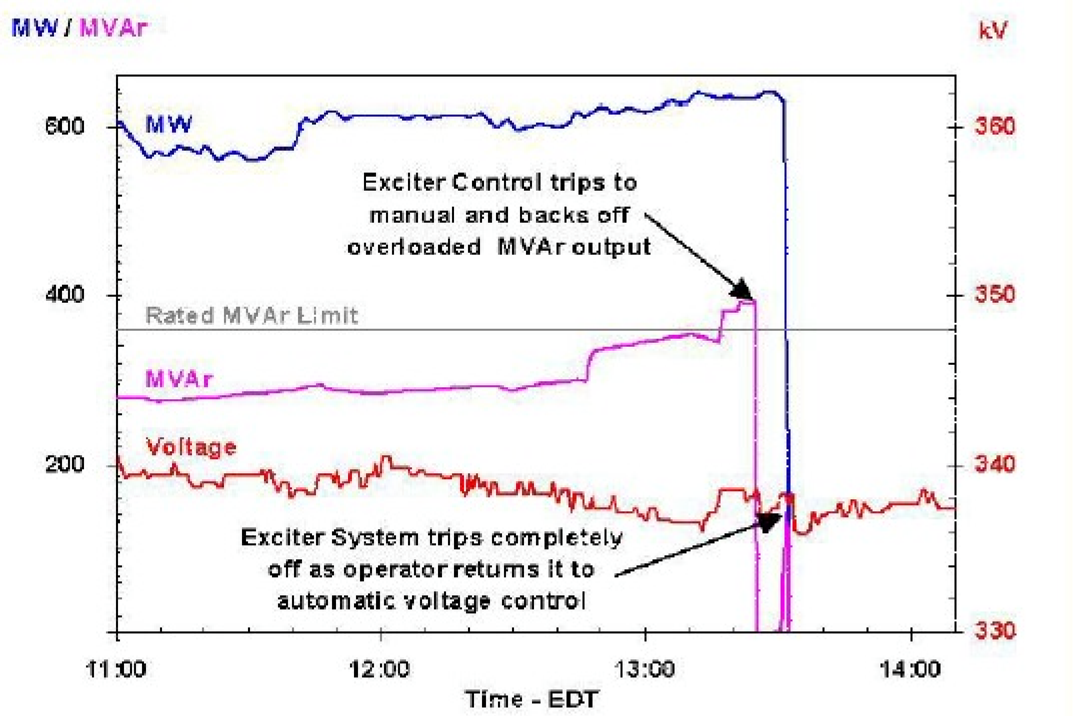


Figure 11 - Reduction of Real and Imaginary power to affected area (Figure from Ref. 6)

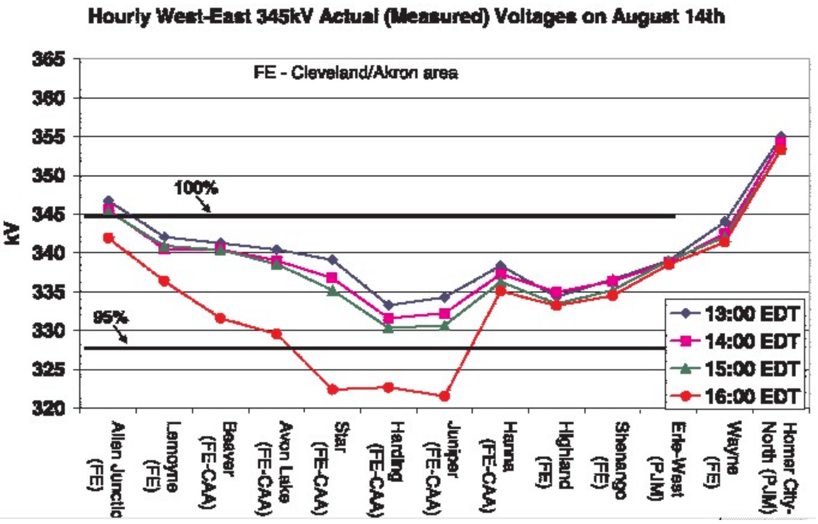


Figure 12 – West to East Voltage Profiles N. Ohio, 14 August 2003

The impact of the loss of Eastlake 5 was not immediate. The power system continued operating satisfactorily after that. It was only the subsequent loss of 345 kV transmission lines feeding the area that eventually caused a cascading disturbance.

Figure 12 (from Reference 6) shows the geographical voltage profile West to East in the Cleveland/Akron area during the four hours leading up to the blackout. The

Harding and Juniper busses are closest to the location of the Eastlake Generating station. It can be seen that although the voltages at Harding and Juniper are among the lowest in the area, they were still above 95% of nominal at 3:00 pm (15:00 EDT).

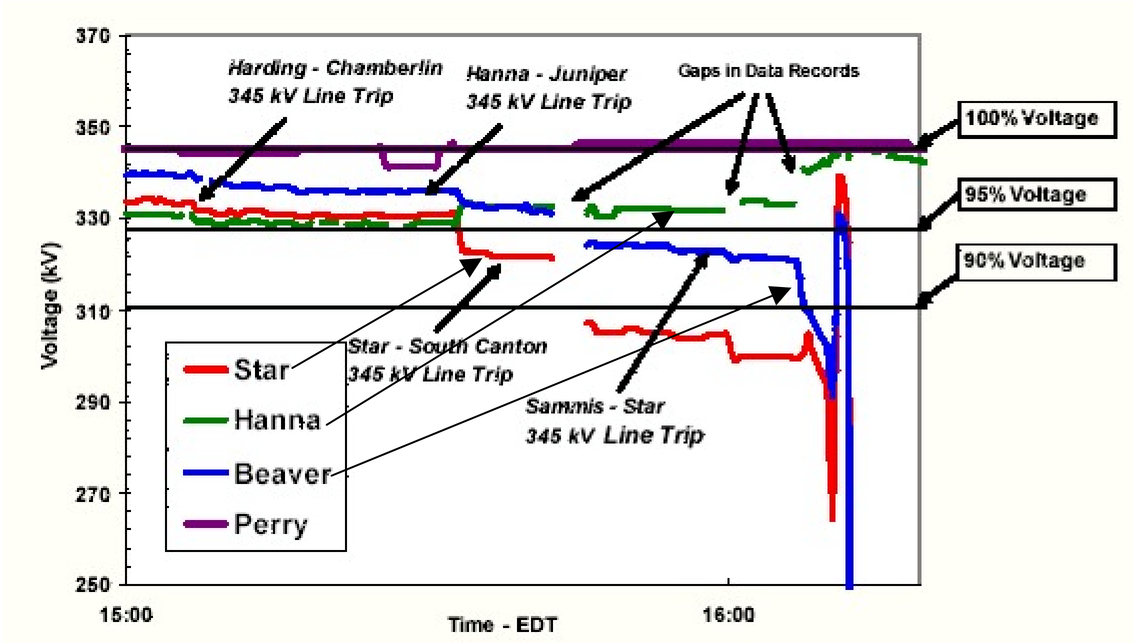


Figure 13 - Voltages in North Ohio in the hour preceding the blackout

When the three 345 kV lines tripped between 3:00 pm and 4:00 pm, the voltages in the Northern Ohio area started collapsing very rapidly. Figure 13 (from Reference 7) shows that after the 3:45 pm. trip of the Star South Canton line, the voltage at Star Substation sagged below 90% of nominal. Although the system had already entered an insecure operating state there was certainly time for load shedding to halt the cascade, though it is probable that simple undervoltage load shedding based solely on magnitude of voltage at a single bus may not have been adequate to diagnose the impending cascade to blackout. A more sophisticated load shedding scheme would likely have been required. The NERC report on the blackout (from Ref. 7) recommends consideration of undervoltage load shedding on more power systems. A later section of this paper presents some thoughts on supplementary measurements to enhance the reliability of undervoltage load shedding schemes.

Sweden, 23rd September, 2003

A major disturbance in Southern Sweden in September 2003 resulted in a slow voltage decay and eventual blackout of a large area including part of Denmark. The initial problem was caused by loss of a major generation source (1175 MW) due to feedwater valve problems, and five minutes later, loss of two 900 MW units and several transmission lines due to a double busbar fault [8]. The near simultaneous loss of nearly 3000 MW of generation resulted in large import of power into a region that had insufficient reactive power to maintain the transmission voltage. The initial drop in voltage resulted in a reduction of load that allowed voltages in the region to be initially maintained (after some fluctuations) in a quasi stable condition. Figure 14 (from Ref. 8) shows the voltage at a location to the North of the most severely affected region. The chart shows at that location, the voltage initially was in the region of approximately 95% of the nominal 400 kV. As can be seen from Figure 14, after some tens of seconds the voltage gradually started to decay. The voltage decay was caused by an increase of load as regulating devices (such as transformer load tap changers) boosted voltages at load delivery points and restored the load that had been lost by the initial transmission voltage decline. Eventually, about 97 seconds after the second loss of generation, the voltage dropped to approximately 83% of nominal, and various distance relays tripped transmission interconnections to the reactive power deficient area. The voltage in the unaffected area rose and the region with the lost generation became an island with severe deficiency of real power. Within a few seconds, the voltage and frequency in the islanded area decayed to a level where generator and other protections operated and completely blacked out the region.

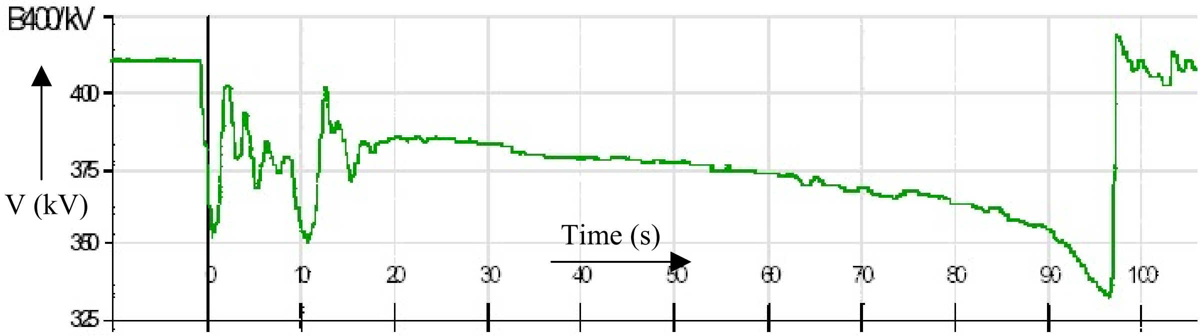


Figure 14 - Voltage Collapse in Sweden on 23 September 2003 (from Ref. 8).

Figure 14 shows that the decay in system transmission voltage was gradual enough to have benefited from the application of an undervoltage load shedding scheme. The voltage magnitude immediately before system separation was significantly depressed, for sufficient time to allow time delayed undervoltage relays to sense the problem. Ironically, an undervoltage load shedding scheme had been previously applied in Southern Sweden (Ref. 9) but had been taken out of service some years before September 2003. It is interesting to note that re-installation of undervoltage load shedding was not one of the recommendations following this incident. It was caused by a triple contingency for which system response is difficult to plan. The recommendations discuss future avoidance of such a rare sequence of events, and improved processes to speed system restoration.

Peru, 14th October, 2001

A case of classic voltage collapse happened in Peru in October 2001, which is used as a final example of real consequences of imaginary power deficiency. In this case, Figure 15 shows a pre-disturbance system configuration where the SINAC area was exporting 78.8 MW to the ElectroAndes area. The ElectroAndes area in turn was exporting 20MW to the Huánuco substation.

The disturbance was triggered by failure of a step down transformer in the ElectroAndes area that suddenly removed the 78.8 MW of pre-disturbance import. At this time, the ElectroAndes area started importing power through line L-120 in contrast to the 20MW that was previously being exported on

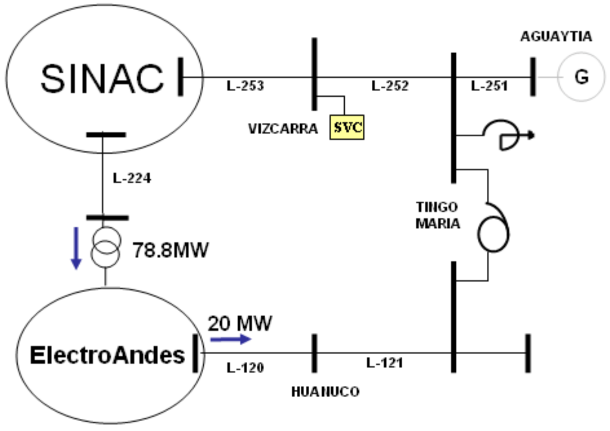


Figure 15 - Pre-disturbance power flows

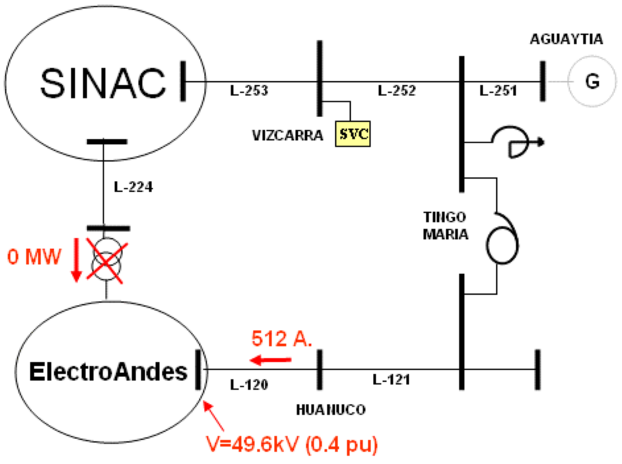
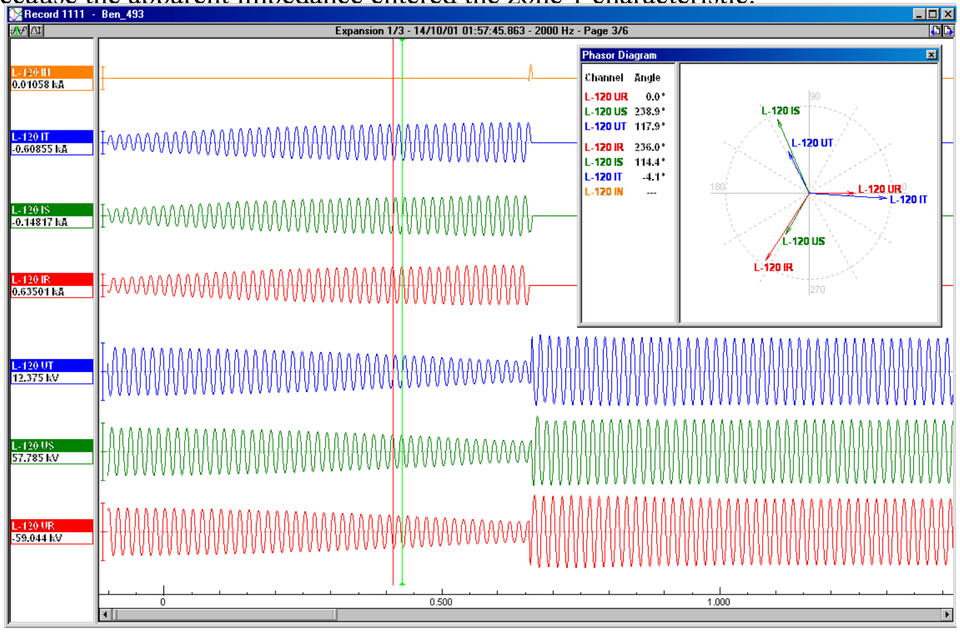


Figure 16 Power Flow Reversal after loss of 80MW

that line (see Figure 16). The response of the loads in the ElectroAndes area provided a unique opportunity to observe a voltage collapse due to insufficient reactive power.

Figure 17 shows the sampled current and voltage record retrieved from the relay that was protecting line L-120 at the ElectroAndes terminal. It can be seen that the current is increasing and the voltage decreasing, until the line terminal trips about 0.65 seconds after the start of the record. The terminal tripped because the apparent impedance entered the zone 1 characteristic.



Channel	Angle
L-120 UR	0.0°
L-120 US	238.9°
L-120 UT	117.9°
L-120 IR	236.0°
L-120 IS	114.4°
L-120 IT	-4.1°
L-120 IN	---

Figure 17 - Current and voltage samples from relay at ElectroAndes terminal of L-120

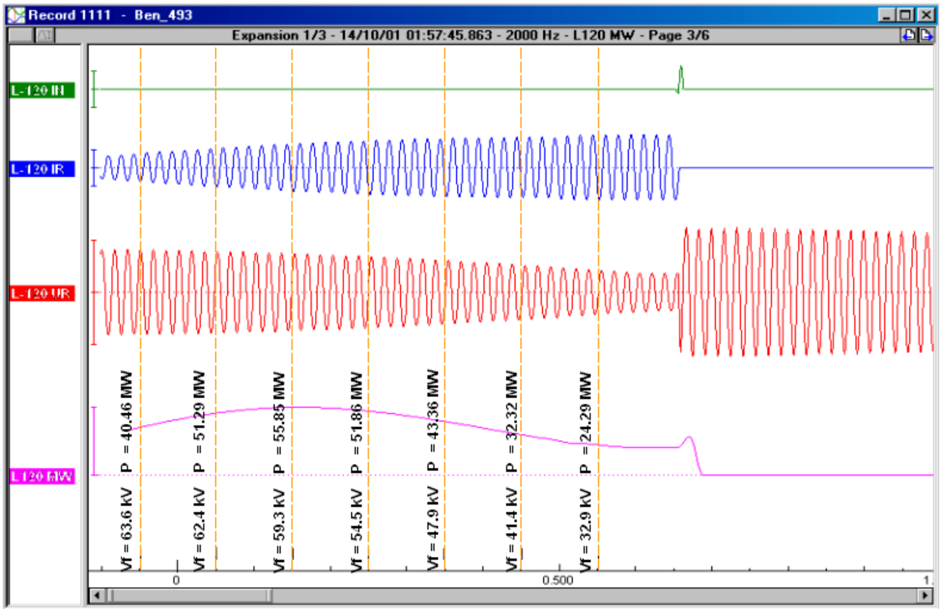


Figure 18 – Phase to Neutral Voltage and Power with respect to time.

When the real power versus time is plotted as shown on Figure 18, it can be seen that the imported power increases until a maximum value of 56 MW is reached, then starts decreasing again. Figure 18 also shows that the phase to neutral voltage at the ElectroAndes terminal is decreasing steadily. 56 MW is the maximum power that can be imported into the ElectroAndes system (through line L-120) given the reactive power available to support the voltage. Since the required pre-disturbance power is 60 MW, stability is not possible. In this case it is uncertain whether the instability is true voltage instability or angular instability due to an inability to support the voltage at the intermediate points in the transmission network (similar to the Hydro Quebec incident on 13th March, 1989). In any case, the plot of power delivered with respect to phase to phase voltage as shown in Figure 19, is interesting in its similarity to a classic PV curve with voltage collapse. The shape of Figure 19 may be due to a combination of voltage independent load, and angular instability, but is a striking example of power voltage relationship

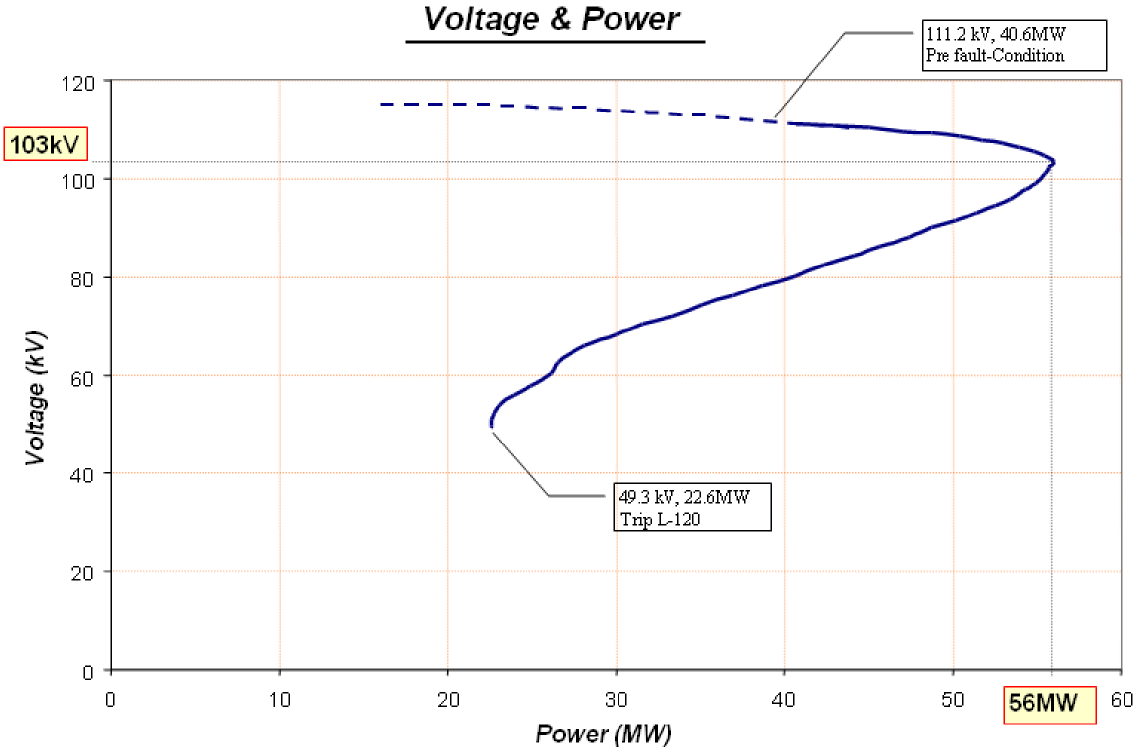


Figure 19 - A Real Life PV Curve

Undervoltage Load Shedding (UVLS)

Although UVLS has been widely applied as a safety net in various parts of North America for many years (see references 10,11, and 12), there is renewed interest in the principle since the 14th August, 2003 US-Canada blackout. However, as can be seen from the previous discussion, voltages can be so near normal operating levels immediately prior to a collapse, and collapse can be so fast in some instances that simple undervoltage and time measurements such as those applied in the Puget Sound area and as described in references 10 and 11 may not always be effective. A task force of the Western Electricity Coordinating Council (WECC) has produced undervoltage load shedding guidelines (reference 13) that notes in part “Although most systems may find UVLS very effective in preventing voltage collapse, it may not benefit all systems. For example, systems with fast voltage decay characteristics (less than a second) may find direct load tripping to be a better alternative. However, systems that may be at a risk of fast voltage decay may be at a risk of slower voltage decay under different conditions."

Unlike frequency that has a constant average value throughout a synchronized system, voltage levels can vary significantly. Underfrequency load shedding works well since system frequency is normally very close to nominal levels and underfrequency load shedding relays can be applied at load delivery points, and set sensitively to provide reliable system protection. However the local voltage at any single bus in a network can be depressed for a variety of reasons (such as faults, load pickup, temporary outages) that cannot be mitigated by load shedding. Not in all cases can simple undervoltage load shedding relays be set to be secure against undesired operation, yet operate quickly enough to avoid voltage collapse. References 10 and 11 describe two cases where the simple undervoltage load shedding principle has been applied and proven to work by experience (10) and/or simulation (11).

Some additional information may be used to enhance the reliability of undervoltage load shedding schemes. Reference 14 and Section 2 of reference 13 both note the possibility of using additional inputs to UVLS to improve the security against false tripping. Reference 12 has provided some examples of where additional information has enhanced undervoltage load shedding schemes.

In Florida, the Fast Acting Load shedding scheme (FALS - Reference 15) uses a matrix of various inputs to determine the probability of imminent voltage collapse. These inputs include status of lines, reactive power output of various generators, voltage levels at a variety of busses, and loading of some lines. In addition, a sensitive underfrequency relay (set at 59.9 Hz) with a one minute memory latch is applied at the load shedding location to provide additional security. The principle is that even if the matrix gives a command to shed load, the local underfrequency relay must have detected a disturbance within the past minute in order to allow the load to be disconnected. It is expected that any disturbance of a magnitude large enough to require load shedding will have caused at least a small frequency excursion system wide.

In Sweden (References 9 and 16) an undervoltage load shedding scheme was applied that also used information from a matrix of events similar to the FALS. BC Hydro (Reference 12) incorporates the reactive power output from some generators or synchronous condensers that respond to depressed voltage in the threatened areas as additional inputs to undervoltage detectors to initiate load shedding.

Reactive Power Reserve Measurement

Reactive power reserve is a good candidate for an additional input into an undervoltage load shedding scheme. If system studies show that a source of reactive power is an important contributor to supporting voltage in a region, then that source being completely inserted or being at or close to rated capacity is a sign of a system under voltage stress. A discussion on how to measure the status of reactive power reserve follows.

a) **<u>All shunt capacitance is switched in.</u>** This could be determined by the status of switches. If all shunt capacitor switches are closed, that could be an indicator that reactive power reserve from a group of capacitors is exhausted. However the converse is not necessarily true. For instance all reactive power reserve could be exhausted even though all switches are not closed. This would be the case if one or more capacitor banks were out of service for maintenance, and not available to be switched into service. It would also be true if a capacitor switch failed to close when ordered to close. In such a case the switch would indicate the capacitor off line, and theoretically available, but practically not. A more positive indicator of exhaustion of shunt capacitor reactive power supply is the automatic controller (if existing) continuing to call for more capacitance to be switched in. For manually switched capacitors, the system operators will be aware of exhaustion of shunt capacitor power.

b) **Static condensers or synchronous condensers at or near their full rating**. These devices have a fixed current rating. If these devices are operating near, or at their current rating, it is an indication they have little or no remaining reserve capacity. A BC Hydro undervoltage load shedding scheme is supervised by a group of synchronous condenser outputs being within 90% of their rated capacity. It should be noted that the maximum output of this group of condensers depends on the number of units on line. Thus the status of the unit is an important input into the logic.

c) **Static Var compensators (SVCs) being at their full output.** These devices at full output are actually shunt capacitors fully inserted. The primary current produced by an SVC is not a good indicator of its approach to maximum capability, because this current depends on the system voltage magnitude. A better indicator of full output or close to full output should be obtained from the SVC control system that controls the thyristor firing angles or switches for the capacitors.

d) **Generators being at their full reactive output.** The rated reactive power output of a generator is very dependent on the real power output and the terminal voltage. Figure 20 shows the real and reactive power capability of a generator.

It can be seen that the maximum reactive power output varies from about 40 Mvar at full load and 1.1 per unit terminal voltage to about 140 Mvar at no load and 0.9 per unit terminal voltage. Therefore simple measurement of reactive power output of a generator will not indicate how close it is to a limit. The capability diagram could be programmed into a "smart" device that measured real and reactive power output and terminal voltage to determine exhaustion of reserve.

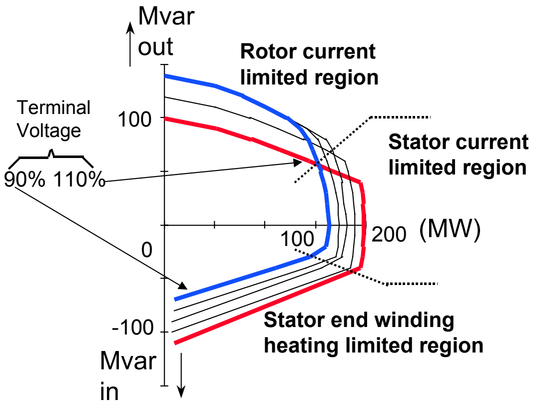


Figure 20 - Generator Capability Diagram

Alternatively, since the rated reactive power output is limited by the field current, the excitation system can be used to give a reliable indication of the approach to reactive power limit. Modern generator excitation systems usually have indicators of the field current being at its maximum limit, and may even have adjustable set points that could be used to indicate closeness to a limit. Entergy has reported use of a maximum excitation limiter as an indicator of the need for undervoltage load shedding (Reference 17). BC Hydro also uses generator field current as an input to an undervoltage load shedding scheme (Reference 12).

System Topology

When very fast load shedding is required to avoid voltage collapse, or angular instability due to low voltages, direct load shedding is an alternative that can be considered to undervoltage load shedding. For instance, Reference 13 points out that the speed of the voltage collapse shown in Figure 9 might be too fast for successful application of undervoltage load shedding, and suggests direct load shedding might be more appropriate.

In the case of direct load shedding, specific contingencies that are known to result in unacceptable system performance may initiate remedial actions such as load shedding. Planning studies and simulations usually identify the contingencies and remedial actions. These contingencies are determined from the status of the line(s) or generator(s) for which remedial actions must be initiated in the event of loss of the equipment. If the status determination and communications equipment are sufficiently secure that the probability of false tripping can be neglected, then direct load shedding can be applied without additional supervision. In some cases it can be desirable to monitor the system response to the contingency as well to improve the security of the scheme against misoperation. Reference 18 describes the studies and considerations behind the design of a special protection system to provide very high security against incorrect operation and undesirable load shedding.

Figure 21 shows the logic of the hybrid direct tripping and undervoltage load shedding system at one of several load shedding stations. This logic is based on the status of two out of four 380 kV transmission lines being out of service together with the 380 kV transmission voltage being low, and local indication of subtransmission voltage having dipped within the previous minute ("local transient undervoltage"). The system uses inputs from two independent special protection systems at remote locations (named SPS A and SPS B). For improved reliability, either SPS plus local transient undervoltage plus 380 kV transmission voltage being low will initiate load shedding. If both SPS indicate the two lines are out of service, and the 380 kV transmission voltage is low, load shedding can be initiated independently of the local transient undervoltage measurement. By application of direct load shedding logic, the undervoltage load shedding scheme is designed to shed the first stage of load within 0.3 seconds of the contingencies arising.

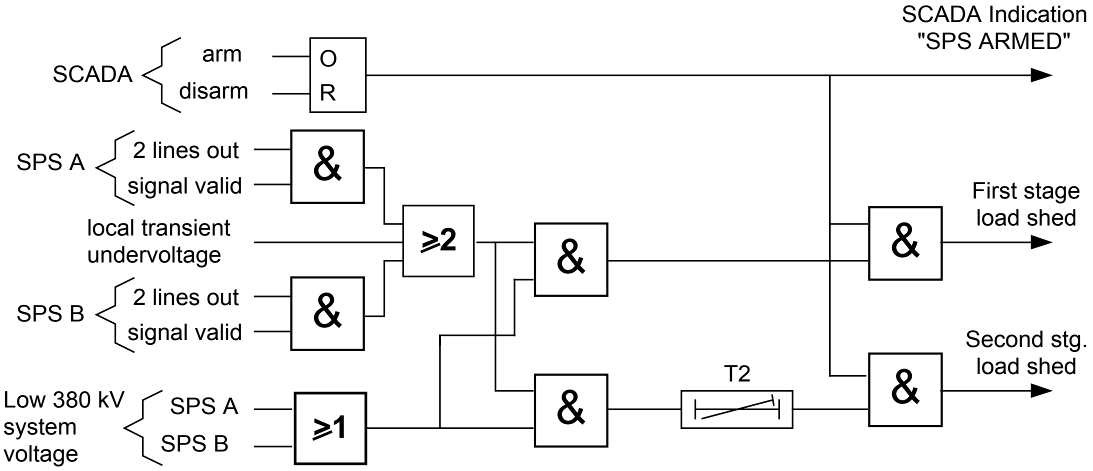


Figure 21 - Hybrid direct and undervoltage load shedding scheme logic

Conclusion

When considering the impact of reactive power support we can understand that insufficient reactive power can lead to angular instability, as well as voltage collapse. The lack of reactive power has been a significant factor in several major power system disturbances. When angular instability is a factor, or the voltage collapse is very fast, the speed of operation of special protection systems (or remedial action schemes) can be a critical factor.

Simple undervoltage load shedding schemes that depend on measurement of a local voltage and trip after a time delay, can be effective and are widely applied. However when the critical voltage is close to normal operating voltage, or if high speed remedial action is required, additional measurements can often be helpful in improving the reliability of undervoltage load shedding. Some caution needs to be used when considering the application of "undervoltage load shedding" since the actual implementation may need to be more sophisticated than simple time delayed undervoltage tripping of local load.

Reactive power reserve is a useful additional measurement in an undervoltage load shedding scheme, although numerous other measurements including system topology may be usefully applied.

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