VOLTAGE SUPPORT IN HEAVILY LOADED EHV SYSTEMS

Harrison K. Clark, Senior Engineer

This is the second in a series of articles on voltage collapse, stability, and related voltage control aspects of the transmission planning task. John Undrill’s article on voltage collapse in the October, 1983 Newsletter was the first in the series, and described the phenomena of voltage collapse in its simplest form; a load area served by a long, heavily loaded transmission line. It was clear from that article that the amount and type of voltage control equipment in a “receiving” system can be critical to reliable system operation. This article will explore the reactive power injection requirements of long, heavily loaded transmission networks, and relate those requirements to the characteristics of common reactive power sources. This subject has become increasingly important as utilities operate transmission systems closer to their limits and as the number of reactive support options increases.

The reactive power injection requirements to serve a constant power load at a given voltage over a given distance (A of Figure 1) are essentially the same as for transmission of the same constant power from a remote generator over the same distance (B of Figure 1). The generator would typically provide the reactive requirements of its associated transmission line, but consider the generator to be at unity power factor, and the required reactive power to be supplied by another source denoted by Q. If the load is removed from the left system, and the generator is removed from the right system, and the two are joined, the result is a long, heavily loaded line with midpoint reactive injection requirements twice those of either the load or generator case (Figure 2). This total injection will be labeled Q1.

![Figure 1](image1)

![Figure 2](image2)

It is useful to explore the characteristics of the transmission system in terms of the demands it places on the equipment selected to provide Q1. This discussion will deal primarily with steady state characteristics. The dynamic or transient requirements will be addressed in a later article. Since switched shunt capacitors and SVS’s are the logical sources of Q1, attention will be focused on their performance.

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First, consider a shunt capacitor bank for the reactive power injection, Q. A 437 MVAR bank will allow a transfer of 1.4 times SIL (1245 MW) with the midpoint bus voltage at unity (point 2 on Figure 3). If the power transfer is increased, the midpoint bus voltage will fall. From the family of curves in Figure 3, it can be seen that operation beyond 1290 MW is not possible since there is no intersection between the QI vs voltage curve and the Q characteristic of the capacitor bank (point 3 on Figure 3). At 1290 MW, there is a 90 degree angle between system 1 and system 2, and transfer is at the steady state stability limit. This is demonstrated on the familiar power-angle curve in Figure 4. Note also that the midpoint bus voltage falls to 90% due to this 45 MW increase in transfer (Figure 5).

It is interesting to note the shape of the voltage versus power transfer curve and the point at which instability occurs, and compare it with the uncompensated system (i.e., with QI at zero). The uncompensated 1.0 SIL loaded system reaches 90% voltage upon a 19.6% transfer increase, and can stand additional transfer before reaching instability, while the compensated system is at the edge of instability upon only a 3.6% transfer increase. The system compensated with fixed capacitors clearly operates much closer to its steady state stability limit than the base system.

Next consider the impact of an infinitely large capacitor bank switched in small increments by thyristors so that smooth voltage control is provided. Its droop would be negligible, giving the characteristic of a vertical line at 1.0 p.u. voltage in Figure 3. With midpoint bus voltage held at unity, the angle across each of the lines can approach 90 degrees before instability occurs, and the total angle between system 1 and system 2 can approach 180 degrees. The resulting power angle characteristic is also shown in Figure 4.

If the SVS is of limited size, it will regulate voltage up to its full capacitive output, then behave as a fixed shunt capacitor bank for higher line loadings. This might be acceptable for a modest sized SVS, such as one rated at 437 MVAR. It would hold voltage between points 1 and 2 (Figure 3), and allow voltage to drop between points 2 and 3. Beyond point 3, instability would occur.

It is theoretically possible to operate this example system up to 1422 MW with QI supplied by a capacitor bank or an SVS on its upper limit (point 4 in Figure 3). At 1422 MW this system is operating at 90°. Operation beyond 90° or 1422 MW is possible, but only with an SVS sized to remain in its continuously regulating range.

Consider, as an example, an SVS capable of 1402 MVAR at full output. It will operate satisfactorily at 1600 MW transfer (point 5 of Figure 3). However, if transfer exceeds 1700 MW, there is no longer an intersection between the SVS characteristic and the QI vs voltage curve (point 6) and the system will be unstable. This point corresponds to the sharp peak on the power-angle curve (Figure 4) where the transition from variable admittance voltage control to fixed capacitor bank occurs. The operating characteristic of such a system is also demonstrated in Figure 5.

The line lengths and shunt capacitive compensation levels considered in this article are rather extreme, but do demonstrate the nature of the voltage support approach to increased transfer levels. In any system where shunt compensation approaches about half of normal line charging, symptoms of these characteristics may be found. Under normal operating conditions, these symptoms may be masked by the complexities of the system and voltage control from system generators (especially those near the system midpoint). However, they may become all too obvious when an emergency condition stresses such a system somewhat beyond expected and typical overloads.

Though shunt capacitors and SVS's are effective at increasing transfer capability, their performance characteristics must be understood and carefully considered by planners and operators. The heavier the use of switched shunt capacitors, the closer the system will be to its steady state stability limit. If an SVS is to be used to allow transfers near the 90 degree point, the possibility of instability when conditions push the SVS to its limit must be recognized.

In future newsletters the performance characteristics of shunt compensation as they affect transient stability will be discussed. Performance characteristics of series compensation, including a comparison with shunt compensation, will also be covered.
**PREDICTING THE RISK OF VOLTAGE COLLAPSE**

N. Dag Reppen, Senior Engineer

Baldwin P. Lam, Analytical Engineer

Load-flow based transmission system reliability programs allow one to quantify the risk of system problems such as circuit overloads and unacceptable high and low voltages. Risk may be expressed as the probability or the frequency and duration of each event class. The same technique, modified to include a non-divergent load flow, now makes it possible to determine the risk of voltage collapse as well.

Efficient reliability programs are designed to look out and evaluate contingencies that the system may not be able to handle. If the purpose of the analysis is to compute the frequency of low voltage problems, a substantial number of the cases tested may not solve with conventional load flow techniques, simply because there is no solution. One or more areas of the system may have suffered a var deficiency that may lead to voltage collapse. In these cases the conventional Newton Raphson or decoupled load flow will "blow up", leaving no trace as to which portion of the system suffered the calamity.

This problem was addressed in a recent EPRI project[1] resulting in the development of a nondivergent load flow process for the decoupled load flow. Further development and testing of this algorithm at PTI has confirmed the method's suitability for reliability assessment. The method makes it possible to detect system situations that may lead to voltage collapse and to determine the location and the geographical extent of the var deficiency. A similar algorithm has since been developed for the Newton Raphson load flow solution with equally good results.

To understand the principle of the method, consider that a load flow program consists of repetitive solutions of a set of network equations. A set of bus voltages that corresponds to specified load and generation powers is sought. For each pass through these equations a correction (dV) to each bus voltage is computed and new bus voltages (Vnew) are obtained by adding the correction to the previously computed bus voltages (Void). The following equation describes this voltage update.

\[ V_{\text{new}} = V_{\text{old}} + \mu \cdot dV \]

Note that a factor \( \mu \) is applied as a multiplier to the voltage correction. This value is set to 1.0 at the beginning of the load flow solution and will remain at this value as long as the power mismatches (the differences between the specified powers and those computed from the updated bus voltages) decrease from one iteration to the next. If, on the contrary, the power mismatches show an increasing tendency, then the nondivergent load flow algorithm will cause \( \mu \) to decrease. If \( \mu \) has to be decreased towards 0 in order to avoid divergence, then no improvement is possible over the old bus voltages. A no-solution case has been detected and a full load flow output can be obtained of this nonsolvable case. If the cause of the no-solution is an actual var deficiency in a particular area, then the solution will show power mismatches in this area along with depressed voltage levels. Moving away from the area suffering the var deficiency, the power mismatches will gradually disappear and the bus voltages rise towards normal levels. The remainder of the system not subject to the var deficiency will be solved perfectly.

The technique which we have coined, 'adaptive deceleration' allows the prediction of frequency of voltage collapse within an area. It also produces information that can be used to estimate the geographic extent of the var deficiency.

In some systems voltage collapse has become a limiting condition for determining power transfer limits. Figure 1 shows voltages at two buses A and B as a function of power transfer during a specific contingency. The curves to the left of the vertical line can be obtained by repeat solutions of a conventional load flow program. The curves to the right of this line, however, are in the 'blow up' region of conventional load flow programs but can be determined by the nondivergent load flow algorithm. The solution shows the voltage at bus A dropping while a gradual increase in power mismatches on this bus indicates a var deficiency and a voltage collapse condition. The portion of the system which does not experience var deficiencies will be solved perfectly as indicated by the absence of power mismatches. In the figure a much higher level of transfer is required before bus B is subject to a var deficiency.

![Figure 1](image_url)

The nondivergent load flow has been included in PTI's transmission system reliability program, TPLAN. Special procedures were required to detect voltage collapse situations reliably without interfering with cases solvable by the conventional load flow. Just as a conventional load flow will have trouble with certain cases where a solution does exist, so will the nondivergent load flow occasionally misbehave. However, in tests on a variety of systems ranging from 25 to 1100 buses the small number of cases that still cannot be classified by failure category have generally had little impact on computed reliability indices. This method promises to become an important part of planning and operating studies on systems that may experience var deficiencies.

Reference


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**LOOK FOR PTI AT THE T&D EXPOSITION**

PTI will host an exhibit as part of IEEE's 9th Conference on Overhead and Underground Transmission and Distribution, to be held in the Bartle Exposition Hall, Kansas City, April 29 to May 4, 1984. The booth will be staffed by PTI engineers who will be taking a break from presenting technical papers and attending technical sessions. They will be prepared to discuss our full line of engineering services, software products, and hardware. The booth will display video tape courses on "Electric Power System Operation" and "Distribution System Operation" (PTI Newsletters, January 1982 and January 1984, respectively), and will include a video monitor for demonstration. In addition, PTI will be displaying our Power System Stabilizer (PTI Newsletter, January 1984). Please stop by to say "hello" at Booth 612.
EXPANDED COMPUTER SUPPORT FOR PSS/E

The PSS/E Power System Simulator program is now supported in IBM MVS-XA, Apollo, and Sperry 1100 computers in addition to VAX, Prime, Data General, and IBM VM systems.

IBM installations of PSS/E include support for color graphics on IBM 3279 CRT terminals and IBM 3287 printers. Monochromatic graphics are provided on IBM 3290 CRT terminals and IBM 3800 laser printers. The capacity of PSS/E on IBM VM systems can be up to approximately 7000 buses; IBM MVS installations can accommodate 4000 buses currently and expanded capacity in this environment is planned.

The Apollo version of PSS/E includes all program features at a capacity of 12000 buses. Each Apollo computer is a single-user CPU with the capability of being connected as a "node" in a ring of Apollos. Each Apollo node is a work station with built-in high resolution multipage graphics display.

The Versatec V-80 electrostatic printer-plotter continues to be the preferred hard-copy graphics unit for PSS/E. PSS/E now permits the Versatec to be driven by the KMW VP-31 vector processor, hence relieving the host CPU of the workload of producing rasterized graphic output.

For further information on PSS/E, please contact Tim Laskowski at PTI.

FALL 1984 SHORT COURSE SCHEDULE

All courses scheduled for presentation at PTI offices in Schenectady, N.Y.

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<th>Course Name</th>
<th>Dates</th>
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<tr>
<td>Power Plant Performance</td>
<td>September 10-14, 1984</td>
<td>$900</td>
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<tr>
<td>Power System Dynamics</td>
<td>September 17-21, 1984</td>
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<tr>
<td>Utility Economics &amp; Finance</td>
<td>September 24-28, 1984</td>
<td>$900</td>
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<td>Underground Cable Systems</td>
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<td>Cable &amp; Accessory Failure Analysis</td>
<td>October 10-12, 1984</td>
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<td>Power System Scheduling &amp; Operation</td>
<td>October 15-19, 1984</td>
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<td>Transmission Reliability Assessment</td>
<td>October 23-26, 1984</td>
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<td>Power System Planning Techniques</td>
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<tr>
<td>Power Plant Maintenance Scheduling</td>
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For further information and registration contact:
Margaret R. Stambach
Manager, Educational Programs
Power Technologies, Inc.
1482 Erie Blvd.
Schenectady, N.Y. 12301-1058
Telephone (518) 374-1220