

# Concepts of Undervoltage Load Shedding for Voltage Stability

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**Abstract** - Undervoltage load shedding is an economical solution (or partial solution) to the voltage stability challenges facing electric utilities. Simulations, for an equivalent system and for large scale representation of the Puget Sound (Seattle) area of the Pacific Northwest, lead to several concepts for an undervoltage load shedding program. Application factors such as undervoltage relay settings and time delay are discussed. Pacific Northwest utilities are implementing undervoltage load shedding for the 1991-1992 winter operating period.

**Keywords** - voltage stability, voltage collapse, undervoltage load shedding, load shedding, load modeling, undervoltage relaying.

## Introduction

Voltage instability and/or collapse has many facets and many potential solutions. Appendix B shows a time frame chart [1] of voltage stability dynamic phenomena. Note that once collapse begins — perhaps due to on-load tap changing and current limiting at generators — faster phenomena such as induction motor dynamics will become important.

Pacific Northwest utilities are facing significant voltage stability problems. Interrelated problems exist from Vancouver, Canada to the Puget Sound (Seattle-Tacoma) area to the Portland, Oregon area. Pacific Northwest voltage instability is likeliest during cold or abnormally cold winter weather conditions. Important outages are loss of cross-Cascade Mountain single- or double-circuit 500-kV lines and loss of large thermal plants between Seattle and Portland. The joint probability of cold weather and a critical outage is low, but load growth is high; without system additions, the problems will get worse with time. Although a high proportion of the load is electric heating, there are subareas with concentrations of industrial motor load.

There are many solutions to voltage stability problems, ranging from control changes or additions to main circuit additions to conservation and load curtailment. Some measures will take several years to implement. Regarding

controls, blocking of tap changing may not be particularly effective because thermostats on electric space heating will restore load if distribution voltage is allowed to sag.

Undervoltage load shedding is a partial solution to voltage stability challenges analogous to the use of underfrequency load shedding in other circumstances. Following the 1965 Northeast blackout, application of underfrequency load shedding became accepted utility practice. As power systems have matured, however, voltage problems are often likelier than islanding with a large generation-load imbalance. As with underfrequency load shedding, undervoltage load shedding provides protection for unusual disturbances outside planning and operating criteria. Undervoltage load shedding may also be very desirable because of delay of planned facilities.

Calculations for value-based (probabilistic-based) system design have shown that low cost solutions to voltage problems such as undervoltage load shedding are cost-effective while more expensive options are not.

One argument for undervoltage load shedding is that load will be lost anyway during abnormal voltage — because of contactor dropout, discharge lighting extinction, or electronic power supply shutdown. It is better to have the load shedding under utility control, with known trip settings and time delays.

At least one other utility (Ontario Hydro) is using undervoltage load shedding to help solve a voltage stability problem [2].

Undervoltage load shedding raises many issues (Appendix A). The experience and judgement of power system engineers familiar with protective relaying, system operations, distribution engineering, load characteristics, and bulk system simulation are required for the development of a workable design.

Puget Sound and Portland area utilities are implementing a large-scale undervoltage load shedding program for 1991-1992 winter operation. The utilities prefer decentralized undervoltage load shedding over direct detection of outages and transfer tripping of many feeders. This paper will describe initial studies. Based partly on simulation results, concepts of undervoltage load shedding are developed.

The paper is organized as follows:

Equivalent system simulations,

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Large-scale simulations for the Puget Sound area,  
 Concepts of undervoltage load shedding,  
 Future possibilities for load shedding,  
 Conclusions.

### Equivalent system simulations

Concepts and insights can best be developed using a small model which allows results to be easily tractable. We can then verify concepts via large-scale simulation. Figure 1 shows an equivalent system that we have used for both steady state and dynamic analysis of voltage stability. Steady state analysis includes  $P$ - $V$  and  $V$ - $Q$  curves.

The sending end has two generators transmitting 5000 MW to the receiving area over five 500-kV lines. Gen 1 is large mechanically, representing the inertia and speed control effects of a large interconnected power system. It is, however, relatively small electrically so that its reactive power support is limited — in a large interconnection only relatively close generators can provide reactive support. All generators and their controls are represented in detail.

The receiving area has a generator, an industrial load served directly from the transmission system, a residential load served by a fairly high impedance subtransmission equivalent, and shunt compensation. The load characteristics can be varied to represent different aspects of voltage instability.

**Transient voltage collapse and undervoltage load shedding.** For load areas with voltage stability problems, a first contingency outage may leave the system vulnerable to a *fast* voltage collapse if a second contingency

occurs. The second contingency may be a line or generator outage caused by undesirable operation of protective relaying. Overloads and low voltages from the first contingency usually causes the relaying. Undervoltage load shedding must be fast enough to arrest the rapid voltage decay.

Transient voltage collapse is often associated with concentrations of induction motor loads. We will assume that the industrial load in Figure 1 is 100% motor, and that the residential load is 50% motor and 50% resistive. The overall load is then 75% motor and 25% resistive.

For simulation, several motor data sets from the EPRI LOADSYN computer program [3,4] were used for third order dynamic motor equivalents. We represented undervoltage load shedding on 5% of total load; load was tripped if voltage stayed below 0.9 pu for 1.5 seconds.

Figures 2 and 3 shows results for tripping one 500-kV line (point A), followed by stabilization. At point B, a second line is tripped, causing rapid voltage decay. At point C, 5% of the load is shed 1.5 seconds after voltage decayed below 0.9 per unit. Figure 2 shows voltages at loads and Figure 3 shows speed of the various motors. The gray line on Figure 2 is for the motor loads represented as *static loads* — constant real power and constant impedance reactive power. With dynamic models, motor flux dynamics slow the voltage decay. This clearly shows the importance of dynamic representation of motors.

**Longer-term dynamics.** Figure 4 shows a related simulation — except only one 500-kV line is tripped and a slower time frame is represented. Following the outage,

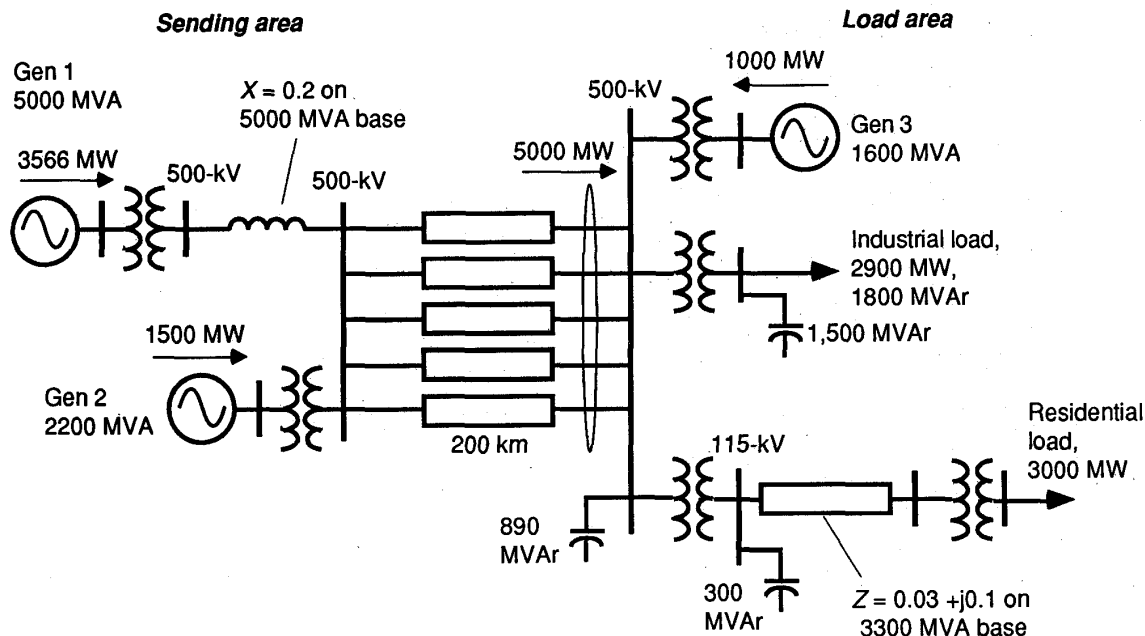


Figure 1. Equivalent system.

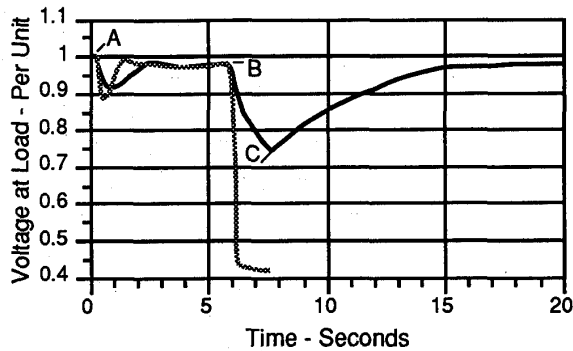


Figure 2. Voltage at loads (the voltage at the two loads are nearly coherent). Point A: trip one 500-kV line; Point B: trip second 500-kV line; Point C: trip 5% of total load by undervoltage load shedding with voltage setpoint of 0.9 pu and 1.5 second time delay. Gray line is for static modeling of induction motors.

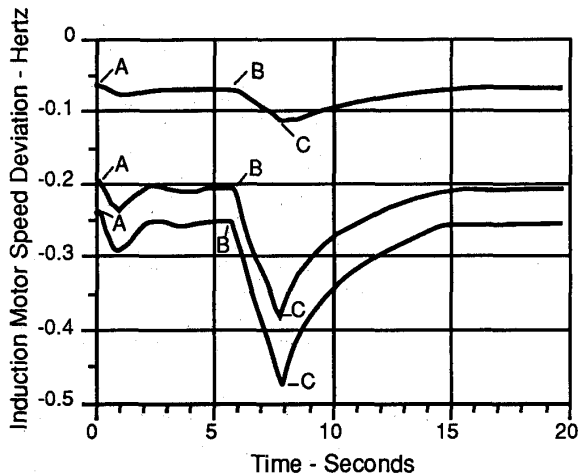


Figure 3. Speed deviation of induction motor equivalents. Top curve is for large industrial motor with low slip. Middle and bottom curves are for residential motor equivalents.

load is added (at the residential bus) to approximate load restoration by tap changing and a morning pickup type of load buildup. Time compression is used, where the next load addition is applied soon after steady-state conditions are reached. The stability program used does not have models for tap changing. We approximated current limiting at generators by setting exciter ceiling values close to continuous field voltage ratings.

The outage and load buildup results in gradual voltage decay to below 0.9 pu. The same 5% undervoltage load shedding happens at Point F after the 1.5 second time delay. Note that the voltages do not fully recover and that more manual or automatic load shedding may be desirable.

Other cases investigated load characteristics that were more voltage sensitive. For example, if the industrial load

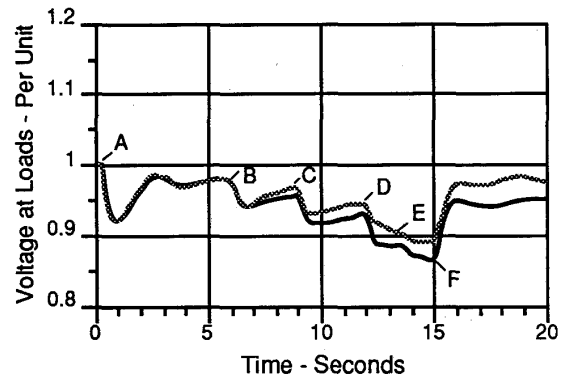


Figure 4. Voltages at loads: gray curve is for industrial load, black curve for residential load. Trip one 500-kV line at Point A. Resistive load added at the residential load bus: 200 MW at Points B, C, and D; 100 MW at Point E. At Point F, trip 5% of total load by undervoltage load shedding with voltage setpoint of 0.9 pu and 1.5 second time delay.

was an aluminum reduction plant, three of the five 500-kV lines could be tripped with stable, but quite low, voltages.

### Large-scale system simulations for the Puget Sound area

We are using large-scale simulation to design an undervoltage load shedding program for the Puget Sound and Portland load areas. The voltage stability problems are primarily for wintertime conditions when the load is quite voltage sensitive. For the voltage stability studies, We are using the EPRI LOADSYN program [3-5] to improve the load modeling. As input to LOADSYN, utilities have made extensive analysis of residential/commercial/industrial load class percentages by bus. Very detailed representation of subtransmission networks have been developed.

For preliminary study, the Puget Sound area was represented with 11,539 MW of load on 165 busses (the full western interconnection was represented — over 2800 busses). We added busses to represent feeder reactance equivalents. Generation in the Puget Sound area was 3227 MW, including 1280 MW at a thermal power station at the extreme southern part of the Puget Sound area.

In the preliminary study, we estimated loads at most busses to be (on average) 58% residential, 27% commercial, and 15% industrial. We used the LOADSYN default data base for western U.S. winter loads with electric heating. The approximate static voltage sensitivity for the real part of the load was  $\Delta P/\Delta V = 1.3$ . For reference, a voltage decay of 10% (on average) reduces load by 1477 MW. About 30% of the load is motor. On busses with loads greater than 50 MW, motor equivalents were represented as dynamic devices — total of fifty-two motors.

To approximate generator field current limiting due to maximum excitation limiters, we again set exciter limits to near rated continuous field voltage. We represented

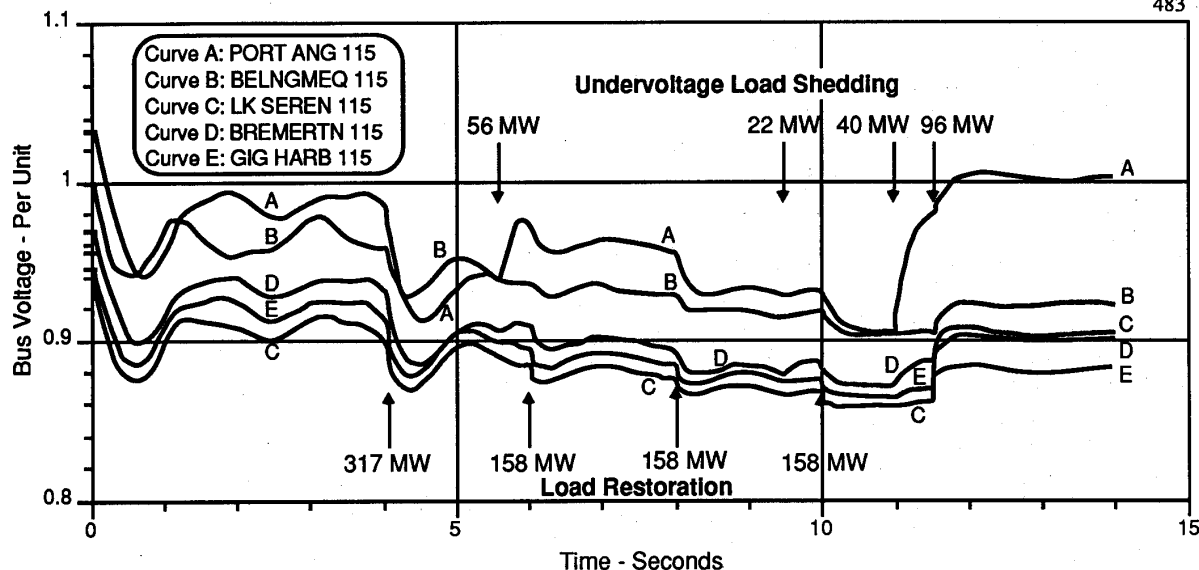


Figure 5. Initial disturbance is outage of the Chief Joseph–Monroe 500-kV line. Load additions and undervoltage load shedding as shown.

undervoltage load shedding on many loads. The trip settings were 8–10% voltage drop for 1.5–3 seconds.

Figure 5 shows results from a transient stability program simulation. The disturbance was outage of the Chief Joseph–Monroe 500-kV transmission line, one of five 500-kV lines transmitting generation from eastern Washington state to the Puget Sound area loads. The condition was extra heavy winter loads with the Chief Joseph–Monroe line loaded to 1559 MW. Following the outage, and after steady-state conditions are reached, additional load was added at forty-seven busses to approximate load restoration by tap changing and thermostats. Time is compressed, with steady state reached between the load additions at two second intervals (artificial damping of electromechanical oscillations was added because of the time compression).

Figure 5 shows voltages at five load busses. Load restoration and undervoltage load shedding are shown on the figure. The 56 MW and the 40 MW load shedding blocks are both near Port Angeles (northern part of the Olympic Peninsula at end of radial transmission). The first block has 1.5 second time delay while the second block has 3 second time delay. Without the staggered time delay, load shedding causes large voltage rises. Note that more automatic or manual load shedding is needed to return voltages to acceptable levels.

Sensitivity cases showed that the proportion of motor load (30%) was low enough that dynamic motor representation was not critical. This implies that power flow simulation (snapshots at different points in time) would be adequate for most of the undervoltage load shedding design work.

Power flow load models should be voltage sensitive and include tap changer equivalents.

### Concepts of undervoltage load shedding

The above, plus Appendix A and unpublished reports, support concepts of undervoltage load shedding for voltage stability.

- Load characteristics are vital in the analysis of voltage stability and undervoltage load shedding. Two extremes can be considered: a high proportion of motor load (summertime with air conditioning load), and a high proportion of resistive load (wintertime with electric space heating).
- For static analysis, constant power loads may be an acceptable approximation when a high percentage of the load is motor. Otherwise, voltage sensitive loads should be modeled.
- In an area or subarea with a high percentage of motor load, part of the undervoltage load shedding should be fast (sensitive setting and time delay of around 1.5 seconds). There is danger of a complete blackout (loss of operating point intersection of system and load characteristics). For simulation, motors should be represented as dynamic devices, including rotor flux dynamics.
- In an area or subarea with a high percentage of voltage sensitive loads (heating and lighting), undervoltage load shedding design is not as critical or sensitive, and stabilization at a low voltage is likely without load shedding—if unexpected relaying does not occur. For simulation, dynamic representation of motors is less

critical, and "snapshot" power flow simulation instead of dynamic simulation may largely suffice. (Stabilization at voltages as low as 0.5 pu occurred for the January 12, 1987 voltage collapse in Western France [6].)

- In an area or subarea with a high percentage of voltage sensitive loads, voltage recovery may "stall" at an unacceptably low voltage following initial load shedding. Undervoltage load shedding with more sensitive setting and longer time delays is needed to return to normal voltage (the alternative is dispatcher-directed load tripping).
- In a subarea with coherent voltage decay, the undervoltage load shedding should be staggered in time to avoid large voltage rises and overshedding.
- The load shedding design should be "robust" in that the performance is not overly sensitive to unavoidable modeling errors — particularly in load modeling. This means that enough load must be covered by undervoltage load shedding. Relay settings must provide proper protection for a wide range of conditions. Undervoltage load shedding might typically be applied to 10–20% of area load.
- Undervoltage relays should only respond to balanced or positive sequence voltage decay. One method is to connect trip contacts from relays in each of the three phases in series. Other methods are positive sequence filtering and blocking by unbalanced voltage detection.
- Pickup settings of undervoltage relays should be 8–15% below lowest normal voltage. A voltage deviation relay is preferred. To cater to a gradual collapse during morning pickup, the washout time should be about 30 minutes.
- The voltage source for undervoltage relays should be the unregulated (generation side) bus. Longer-term dynamics programs require models for undervoltage relays where the voltage source is from a remote bus.
- Undervoltage relays may be applied to trip non-critical loads in order to prevent costly interruption of nearby manufacturing processes.
- Operation of zone 3 or overcurrent relays on overload/low voltage should be monitored during simulations. Time delay of these relays are generally less than 1.5 seconds. Simulations show no such relay operations are threatening for the Puget Sound area.
- In the absence of a mid-term or long-term dynamics program, a conventional transient stability program can approximate longer-term phenomena.

There are other concepts or issues such as relay arming criteria and methods, and load restoration methods that are outside the scope of this paper.

### Future possibilities for load shedding

Voltage stability problems will probably be with us for the foreseeable future. Undervoltage load shedding — while providing low cost protection against voltage collapse — hopefully is not the ultimate answer. There is natural reluctance to expose customers to unnecessary interruptions.

Emerging technologies such as distribution automation/load management provide attractive future possibilities to painlessly shed load during emergencies. The need may be for relief long enough for start-up of combustion-turbine generation.

First, methods must be developed to detect impending voltage collapse. Activation of reactive reserve at generators and static var compensators is a sensitive indicator.

Second, economical and relatively fast communications (seconds instead of minutes) are needed. Unlike transient stability, very high speed communications are not needed for most forms of voltage stability. In the future, fiber optics networks such as ISDN (Integrated Services Digital Network) may be the answer. Some load management systems in service today are, however, suitable. For example, reference 7 describes a combination satellite and land-based radio system that communicates to load-shedding radio switches at residences.

Third, control and actuator equipment is needed at end users. Imagine, for instance, that "smart homes" have computers to receive a cost of power signal. During emergencies, the cost of power can be set high, so that thermostat set points are instantly lowered for electric heating and water heating, and raised for air conditioning. Considerable load relief might be obtained within some seconds. Reference 8 reports a step in this direction.

An alternative is simple local detection of voltage decay at or near the end-user — perhaps built into the customer controller. The difficulty is that the customer voltage is often regulated by tap changers, and the voltage falls only after boost limits are reached.

Other forms of distribution automation may control tap changers, order voltage reductions, and control available shunt compensation [9].

### Conclusions

Undervoltage load shedding may be an idea whose time has come. Concepts for undervoltage load shedding — based on small-scale and large-scale simulation studies — are proposed.

Based on the above concepts, Puget Sound area utilities are evaluating the following undervoltage load shedding program:

- 5% of load shed at voltage 10% below lowest normal voltage with 1.5 second time delay.
- 5% of load shed at voltage 8% below lowest normal voltage with 3 second time delay.
- 5% of load shed at voltage 8% below lowest normal voltage with 6 second time delay.

In many cases, undervoltage load shedding will trip the same loads as the presently installed underfrequency load shedding [10]. In fact, both load shedding relays may be mounted on the same panels and use the same potential and trip circuits. The undervoltage relays, however, must use three-phase potential from an unregulated (high side) bus. There is very low probability of mis-coordination between the two systems.

Undervoltage load shedding is one of the lowest cost solutions to voltage stability problems. Other measures being evaluated (which take longer to implement) include more shunt and series capacitors, static var compensators, and new transmission. The role of undervoltage load shedding may be mainly as protection for disturbances outside deterministic planning criteria.

Utilities will probably face voltage stability problems for the foreseeable future. Because of the possibility of undesirable or unnecessary operation of undervoltage load shedding, better solutions are desirable. Advances in technology in predicting impending voltage collapse, in distribution automation, and in computers and communications may provide future options to *painlessly* shed load.

**Acknowledgements** – BPA engineers Melvin Rodrigues and Gordon Comegys developed the power flow and stability data sets. Diana Woods ran the simulation cases. Engineers from Puget Sound Power & Light, Snohomish County PUD, Seattle City Light, Tacoma City Light, and BPA provided guidance and many contributions.

## References

1. E. S. Cate, et al., "Time Frame Notion and Time Response of the Models in Transient, Mid-Term and Long-Term Stability Programs," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-103, No. 1, January 1984.
2. M. B. Awad, S. Mantenuto, and V. F. Carvalho, "Containment of a Voltage Instability Problem in Eastern Ontario," Proceedings of the Transmission and Stations Planning and Operations Subsections, Canadian Electrical Association, 1986.
3. General Electric Company, *Load Modeling for Power Flow and Transient Stability Computer Studies*, EPRI Final Report EL-5003, January 1987.

4. F. Nozari, M. D. Kankam, and W. W. Price, "Aggregation of Induction Motors for Transient Stability Load Modeling," *IEEE Transactions on Power Systems*, Vol. 2, No. 4, pp. 1096-1103, November 1987.
5. W. W. Price, et al., "Load Modeling for Power Flow and Transient Stability Computer Studies," *IEEE Transactions on Power Systems*, Vol. 3, No. 1, pp. 180-187, February 1988.
6. Y. Harmand, et al., "Analysis of a Voltage Collapse Incident and Proposal for a Time-Based Hierarchical Containment Scheme," *Cigré* 38/39-02, 1990.
7. H. E. Caldwell, Jr., "Load Management Reaches for the Stars," *Transmission and Distribution*, pp. 58-62, February 1991.
8. M. G. Adamiak, D. C. Roberts, and S. D. Ketz, "A Microprocessor-Based System for the Implementation of Variable Spot Pricing of Electricity," *IEEE Computer Applications in Power*, pp. 43-48, October 1990.
9. C. Crider and M. Hauser, "Real-Time T&D Applications at Virginia Power," *IEEE Computer Applications in Power*, pp. 25-19, July 1990.
10. C. W. Taylor, F. R. Nassief, and R. L. Cresap, "Northwest Power Pool transient stability and load shedding controls for generation-load imbalances," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-100, pp. 3486-3495, July 1981.

## Appendix A

### Some Issues of Undervoltage Load Shedding

1. What are the consequences of operating below normal voltages for tens of seconds or minutes? Some factors are overheating or damage of motors, uncontrolled drop-out of loads (motors and loads with regulated power supplies), problems with motor starting (particularly for compressor loads), and poor performance of other sensitive loads. Low voltage, particularly if unbalanced because of single-phase motor stalling, could eventually cause transmission or power plant relay operation.
2. How much of the undervoltage load shedding should be fast (say with 1.5 second delay)? This depends on the amount and the characteristics of motor load in a subarea. Fast arresting of voltage decay may prevent interruption of critical manufacturing processes. The 1.5 second delay is based on typical induction motor flux decay transients.
3. What percent of the total load should have undervoltage load shedding? For highly voltage sensitive loads, this depends on issue number 1 and on the desirability of automating dispatcher-directed load tripping.
4. What is the highest practical time-undervoltage relay setting? At a particular relay location, there is a lowest normal voltage, perhaps 0.95 per unit of rated voltage. Assuming a voltage relay with 1% accuracy, is a relay

setting 5% below lowest normal voltage, with seconds of time delay, practical? Should undervoltage relaying be applied at stiffer or weaker load busses?

5. How advantageous are voltage deviation relays, and what washout times are needed? This depends on the voltage regulation at the relay measuring point. If, for example, the voltage is normally about one per unit, we may wish a 0.9 per unit relay setting — provided the voltage does not sag to say, 0.93 per unit, during very heavy load pre-outage conditions — in which case we would prefer a voltage deviation relay with a -0.1 per unit setting.

6. Are inverse time delay relays advantageous?

7. For fast voltage collapse, are  $\Delta V$ ,  $dV/dt$  phase-plane relays advantageous?

8. What special monitoring facilities should be provided?

9. How should load restoration be accomplished? Should some load be restored automatically, and, if so, what time/voltage criteria should be used? What are cold-load pick-up problems?

**Carson W. Taylor** joined the Bonneville Power Administration in 1969 after earning degrees from the University of Wisconsin and Rensselaer Polytechnic Institute. As a Principal Engineer at BPA, his work includes power system control and protection, system dynamic performance, ac/dc interaction, and power system planning.

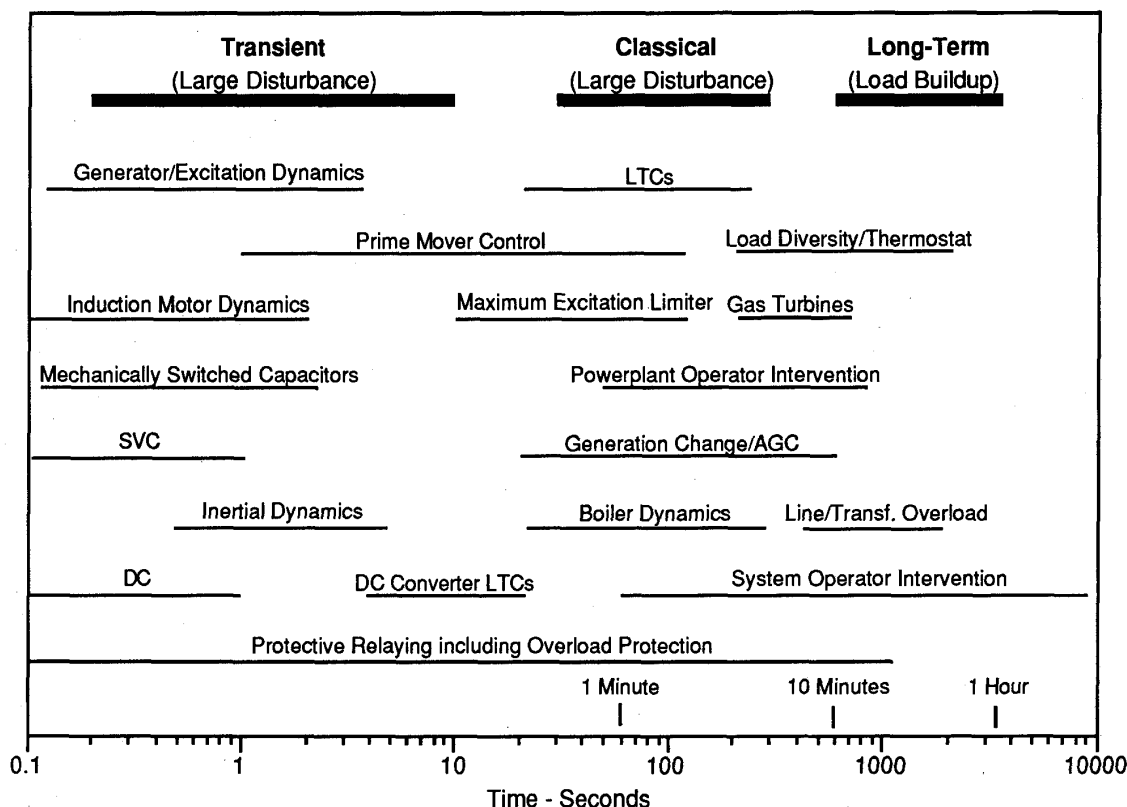


Mr. Taylor is an IEEE Fellow. He chairs the IEEE Working Group on Special Stability Controls and is active in other work of the System Dynamic Performance Subcommittee. He is convenor of the Cigré Task Force on Modelling of Voltage Collapse Including Dynamic Phenomena. Mr. Taylor has written many IEEE and CIGRE papers.

Besides his BPA activities, Mr. Taylor has taught power system engineering as an adjunct professor and at seminars. In 1986, he established *Carson Taylor Seminars*, a company specializing in electric power system education.

#### Appendix B

#### Time Frames for Voltage Stability Phenomena



Note:

Once instability begins, faster phenomena becomes important.

## Discussion

**C. F. Henville**, (BC Hydro, Vancouver, BC, Canada): Undervoltage load shedding will challenge protection engineers to find secure and dependable schemes in a fairly new concept. It is clear they will have to work closely with system planners particularly in finding reliable settings (which requires a good knowledge of "normal minimum voltage"). The IEEE Power System Relay Committee has started a new working group to document various approaches and concerns related to the concept.

Here are some additional concerns to those mentioned in the paper.

- a) Even the most sophisticated voltage relays have some hysteresis, usually at least one or two percent. This is often intentional, to prevent chattering near the operating point. The hysteresis will exacerbate the problems with having relaying operating points as close to normal operating levels as appears to be necessary to achieve the intended results. Maybe special zero hysteresis relays will have to be developed.
- b) An important principle of protection engineering is that loss of a power supply or sensing signal should not cause undesirable tripping. Undervoltage load shedding will violate this principle unless special precautions are taken. Possible precautions include
  - i) use of at least two different relays connected to different vts, with their outputs in series.
  - ii) use of a window for voltage level so that very low voltages (such as loss of signal) do not cause load shedding.
 Use of three phase to phase connected relays in series, and blocking by unbalanced voltage detection will assist security when the vt secondaries are protected by fuses (such that a secondary short circuit on one phase will still leave two phases energized). However, when vt secondaries are protected by miniature circuit breakers, all three secondary voltages are lost for a short circuit on any one phase. Positive sequence filtering is not particularly useful in assisting security when settings of about 0.9 pu are being considered, because positive sequence voltages are depressed significantly during unbalanced faults, or if a single vt secondary fuse is blown.
- c) Special relays such as dv/dt or inverse time undervoltage can be developed, but system planners should define the required characteristics as soon as possible to allow development time.

Manuscript received February 19, 1991.

**WILLIAM A. MITTELSTADT**, Bonneville Power Administration, Portland, Oregon: The author provides an excellent summary of the issues and concepts involved in the application of undervoltage load shedding. A few questions come to mind regarding this subject.

Could the author please provide more details and an update on the implementation plans for use of undervoltage load shedding in the Puget Sound area? Have simulation studies been done with the load shedding program mentioned in the conclusions of the paper?

It is recognized that other approaches are being considered as a long term solution. Has an estimate been made of how much additional time this may gain before additional transmission or other solutions would be needed?

The idea of automatically tripping some load such as water heaters by communication is very interesting. Do any utilities that you are aware of use this form of control? What operating time would be expected? Typically transmission planning criteria indicate that no firm load should be lost for outage of a specified number of lines under peak load conditions. Would this be an acceptable way of shedding load without violation of the criteria?

The idea of lowering set points on thermostats based on an adjustable cost of power signal is interesting. Some means may be necessary for the customer to report back the settings so that the effective load shedding could be estimated. Typically, how long

would a system be in an emergency state when such a measure would need to be in effect?

Thank you again for the interesting paper? We look forward to hearing more in the future on this effort.

**Carson W. Taylor**, Bonneville Power Administration, Portland, Oregon: As requested by Mr. Mittelstadt, I will provide an update on the undervoltage load shedding program being implemented in the Puget Sound area. The time delays have been changed so that the program is as follows:

- 5% of area load shed at voltage 10% below lowest normal voltage, 3.5 second time delay.
- 5% of area load shed at voltage 8% below lowest normal voltage, 5 second time delay.
- 5% of area load shed at voltage 8% below lowest normal voltage, 8 second time delay.

Shorter time delays, as described in the paper, will be used in subareas if simulations can demonstrate the need for faster load shedding.

The "lowest normal voltage" is the voltage measured at the particular substation during very cold weather in February 1989 and December 1990.

The load shedding program will be implemented by mid-November 1991. The 15% of total load amounts to about 1800 MW during peak winter load conditions.

Puget Sound area utilities have prepared a "superbase" case for simulation of voltage stability. The case includes expanded subtransmission representation of the Puget Sound area, the Vancouver, British Columbia area, and the western Oregon area (about 2750 busses). The total number of western interconnection busses represented is about 5000. LOADSYN is used for load modeling. For load shedding program evaluation, we are using the superbase power flow case with a beta version of the EPRI/Ontario Hydro ETMSP longer-term dynamics program. Preliminary cases run at Ontario Hydro represented 60 induction motor equivalents, and 728 loads regulated by on-load tap changers and thermostats. Modifications to the load shedding program resulting from this very detailed simulation study will be reported at a later date.

Mr. Mittelstadt also asks about other methods to improve voltage stability. Using value-based planning, undervoltage load shedding could be a primary solution when the joint probability of an infrequent disturbance and a highly stressed operating condition is very low. Other low-cost controls could complement undervoltage load shedding. Transmission reinforcements would then be added when required for improved performance during more normal conditions; e.g., line additions when transmission losses become excessive, or when voltage changes during reactive switching ( $\Delta V/\Delta Q$ ) become large. For large voltage changes, SVCs may also be justified.

I am not aware of use of demand-side management for rapid load control during emergencies. Many utilities, however, use voltage reduction to obtain load relief during voltage emergencies. To be effective for classical



voltage stability (time frame of one to five minutes—Appendix B of paper), the emergency action must be quickly initiated, with relatively fast communications and actuators. Using value-based planning, I think use of sufficiently reliable distribution automation controls would often be acceptable. In some cases, demand side management results in rate structure changes. Following a large disturbance, emergency load shedding would typically be in effect for ten to fifteen minutes—until operators bring gas turbines on line, reschedule generation, restore transmission, etc.

Mr. Henville's discussion is valuable. For the Puget Sound area undervoltage load shedding, commercially available, three-phase, microprocessor-based relays are being installed. The relay measuring accuracy is  $\pm 1\%$ . The relay has internal timers. With voltage decay to a level close to the setpoint, the undervoltage elements may pickup and dropout several times, but chattering of electromechanical output contacts will not be a problem.

The relay as configured will prevent tripping due to loss of power supply.

The comment about positive sequence filtering is germane. Rather than positive sequence filtering, the microprocessor relay blocks tripping for detection of unbalanced fault.

Regarding the relay application, it's of interest that several of the Puget Sound area utilities are installing relays to trip non-critical 115-kV lines. The lines have tapped loads with generation sources at both ends. Misoperation or undesirable operation of one relay will trip only one source so that no load is lost.

I thank the discussers for their interest and their comments.

Manuscript received August 16, 1991.