Slope-Permissive Under-Voltage Load Shed Relay for Delayed Voltage Recovery Mitigation

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***Abstract*—In this paper, a new relay algorithm is proposed for under-voltage load shedding (UVLS) based on rate of voltage recovery and predicted time to recover above a preset voltage threshold. Simulation experience in the Southern Electric System has shown that conventional UVLS relay logic is ill-suited to the task of mitigating delayed voltage recovery and fast voltage collapse situations while maintaining compliance with existing NERC Reliability Standards. The proposed scheme continuously monitors both voltage magnitude and rate-of-change of voltage magnitude and uses these values to determine a projected voltage recovery time following a contingency event. If the projected recovery time is such that resultant system conditions are unacceptable (e.g., major load loss, loss of generation, or voltage collapse), the relay will operate to shed load at the distribution feeder level. This unique scheme has been implemented in a commercially-available programmable relay and is presently installed and active in a number of substations in Georgia Power Company.**

***Index Terms*—Fast voltage collapse, power systems, power transmission planning, under-voltage load shedding, voltage stability.**

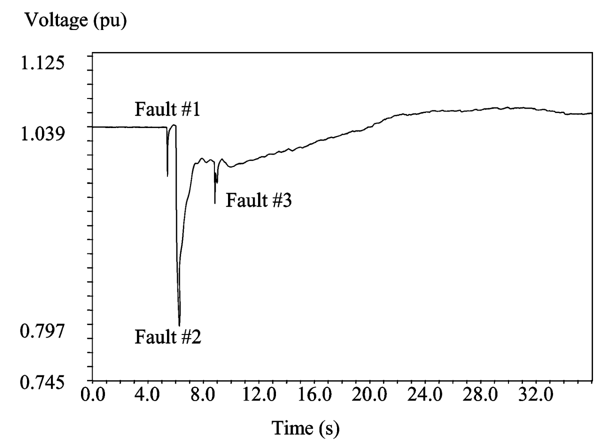

Fig. 1. Delayed voltage recovery in Atlanta, GA.

I. Introduction

FAST voltage collapse and delayed voltage recovery problems have become increasingly important over the last several years as systems become more stressed due to load growth and a general declining trend in system infrastructure investments. Numerous cases of heavily loaded systems experiencing fault-induced voltage problems have been reported in the literature and extensively studied. These studies have shown a clear link between motor load, especially smaller motors, and the tendency of system voltages to experience a fast collapse or slow recovery following fault clearing [1]–[4]. One such event occurred in 1999 in the Atlanta, Georgia area resulting in the loss of approximately 1900 MW of load in the area [5]. The recorded voltage in the area is shown in Fig. 1. Voltage recovery is almost immediate following the first fault, but increasing recovery times are clearly evident following the second and third fault events.

Since 1999, Southern Company and other utilities have vigorously pursued various strategies for identifying and mitigating the effects of such system contingencies. Various system improvement projects ranging from static var systems, local generation, and new transmission have been considered as possible solutions to this type of delayed voltage recovery problem [2], [6], [7]. Following the August 2003 blackout in the USA, the NERC Board of Trustees approved a Steering Group recommendation that all utilities should evaluate under-voltage load shedding (UVLS) schemes. This has resulted in UVLS becoming an option of significant merit in situations characterized by delayed voltage recovery. In this context, UVLS is primarily considered as aiding a slowly-recovering voltage rather than preventing all fast collapse scenarios. The use of UVLS to mitigate all fast voltage collapse scenarios is generally beyond the scope of this paper. However, the use of the approach demonstrated in this paper may result in a reduction of fast voltage collapse risk and this concept will be discussed further as appropriate in later sections.

NERC Reliability Standards do not allow the intentional loss of load for Category B events (single contingency, typically studied as a three-phase fault with normal clearing) [8]. Therefore, the system improvement options previously mentioned must be pursued to provide Category B contingency mitigation with regard to fault-induced delayed voltage recovery (FIDVR) problems. Planned load shedding is permissible under NERC Reliability Standards for Category D events (multiple contingency, typically studied as a three-phase fault with breaker failure with subsequent loss of multiple system elements) [9]. UVLS schemes, therefore, may be employed for Category C and D contingency mitigation but must not operate for Category B events [8]–[10].

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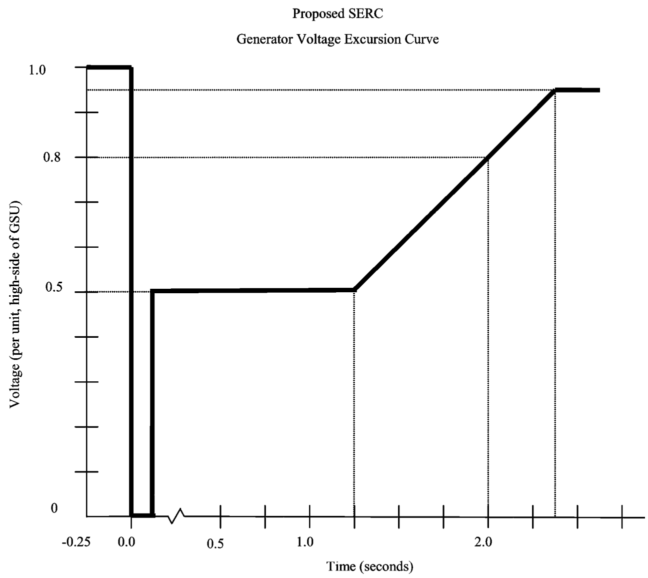

Fig. 2. Proposed SERC generator (high-side) voltage ride-through capability curve.

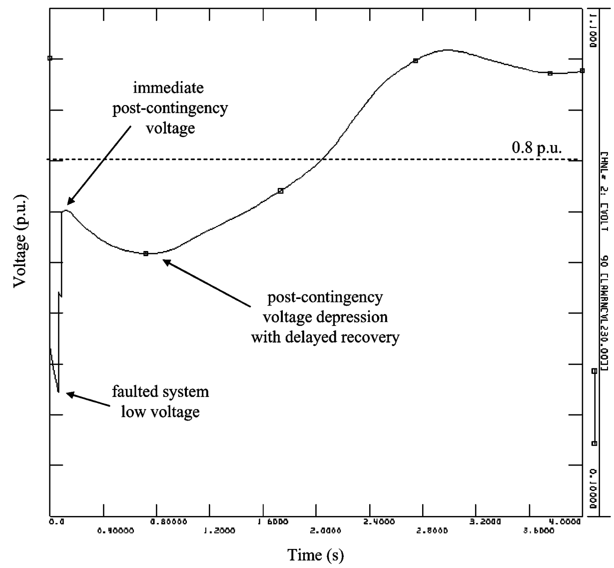

Fig. 3. Example load-serving substation voltage recovery plot.

II. UVLS Scheme Requirements

It is necessary to define performance criteria for a system-wide UVLS scheme that is both effective and secure. The operational definitions of effectiveness and security are that any scheme must prevent widespread or cascading outages and must not operate for Category B contingencies, respectively.

Static var equipment or system improvements are necessary for Category B mitigation so that load is not intentionally shed—clearly the contingency must not escalate. In general, system improvements are likely to be significantly more expensive than static var equipment and therefore static var systems are the first (preferred) option for consideration. Supplying variable amounts of reactive power quickly to motor load subjected to low voltage offers significant mitigation benefit; this fast-acting reactive power may come from either static var equipment or online generating units [2], [6], [7].

To maximize the benefit of online generation, it is necessary that Category B contingencies not result in loss of generation due to low voltage. The concept of a voltage ride-through capability curve is being considered in the NERC Reliability Standard process. As a participant in the NERC Phase III–IV Planning Standard Field Test, a SERC Reliability Corporation Task Force developed and proposed the generator (high-side) voltage ride-through capability curve shown in Fig. 2 for all generating units. Ride-through curves such as Fig. 2 will specify both the depth and duration of low-voltages which must be withstood without a generator tripping. Note that this type of curve is normally representative of the capabilities of the auxiliary equipment to withstand low voltages. The presumption is that it is the loss of auxiliaries that is most likely to lead to the loss of any particular generating unit. A further consideration that can directly impact a particular generator is the distance relaying commonly used for backup generator protection.

Using the draft curve of Fig. 2 as a guide, Southern Company has adopted a Category B contingency voltage recovery criteria as "voltage at all transmission buses must recover to above 80% voltage within 2 s of any contingency." This Category B contingency recovery criteria is conservative with respect to Fig. 2 because voltage recovery at generating plant substations will always exceed that at load-serving substations. An example simulated voltage recovery plot at a load-serving substation is shown in Fig. 3. In this case, the voltage recovery would be at the limit of acceptability.

Category D contingency mitigation can include planned load shedding via UVLS [9]. For UVLS applications, the relay input voltage will be at load points, typically remote from generating plant substations. Simulation experience has shown a reasonable correlation between generating plant substation voltages and load-serving substation voltages. As a general rule, load-serving substation voltages recover 2 s later than generating plant substation voltages. (Note that this observation reveals that there is virtually no chance of violating the draft criteria shown in Fig. 2 for Category B contingencies where load serving station voltages are assumed to recover in 2.0 s.) Therefore, the adopted UVLS application criteria for Category D contingency mitigation are as follows:

- generating plant substation (high side) voltages must recover to within 80% of pre-contingency voltage within 2.0 s;
- load-serving substation voltages must recover to within 80% of pre-contingency voltage within 4.0 s; and
- no system voltages are allowed to settle at less than 0.95 per-unit.

With regard to the first criteria, generators and their associated auxiliaries that are exposed to voltages less than 80% for more than 2.0 s could possibly be allowed to trip provided that the other criteria are met and the post-contingency system is in a secure state.

III. Specification of the UVLS Scheme

Drawing from many years of experience with under-frequency load shedding schemes and considering other schemes described in the literature [11], [12], the initial UVLS scheme was developed based on multiple load shed stages, each separated in both operating time (delay) and voltage level. The goal was to develop an effective and secure UVLS scheme that involved the minimum amount of load. Simulations quickly showed this simple type of scheme to be much too ineffective in the tightly-coupled transmission system around Atlanta, Georgia. Transmission system (230 and 500 kV) faults at locations anywhere within a 10 000 mi^2 (25 600 km^2) area resulted in faulted system voltages throughout the area of 0.1–0.4 per-unit. Analysis of subsequent simulation results using simple time-delay and voltage level based schemes revealed that the delayed voltage recovery characteristic was essentially the same over the entire area. The result would be significant over-shedding leading to unnecessary load interruption and significant and sustained (as high as 1.2 per-unit for several seconds) post-shedding overvoltages on the bulk transmission system. It was clear that depth of voltage depression was an unsuitable variable to use for minimizing the total load in the UVLS scheme unless time delays between stages were carefully assessed.

With the only suitable variable to differentiate between UVLS stages being time, simple voltage-sensing relays could be employed to implement the UVLS scheme with each voltage relay set to operate at a different time. The next step in the evolution of the UVLS scheme was the specific development of a four-stage UVLS scheme with each stage having a specified amount of load and progressively longer time delays. An example of this early scheme is

- 1st Stage: 10% of area load shedding 2 s after initial onset of low voltage (below 0.8 per-unit);
- 2nd Stage: 5% of area load shedding 2.2 s after initial onset of low voltage (below 0.8 per-unit); and
- 3rd and 4th Stages: Identical to the second stage, except operating at 2.4 and 2.6 s, respectively.

A key feature of this scheme is the requirement that the first stage not operate before 2.0 s. This requirement is necessary because planned load shedding is not permissible for NERC Category B contingency mitigation. The selected 2.0 s recovery time at all transmission system buses for Category B contingencies effectively prevents UVLS from operating with timers set less than 2.0 s—see Fig. 2 and the associated discussion.

Recalling the Category D contingency voltage recovery criteria presented previously and the draft generator ride-through capability in Fig. 2, generators could trip if the plant (high side) bus voltage remains below 0.8 per-unit for 2.0 s or more. Clearly, initiating UVLS operation at 2.0 s will not result in immediate voltage improvements, so the likelihood of loss of generation is significant. Analysis of simulation results clearly showed unacceptably high levels of tripped generation (based on Fig. 2) for any UVLS scheme not operating before the assumed tripping time (see Fig. 2) of any units exposed to low voltage.

In order to maintain post-contingency system security, it is necessary to minimize the amount of generation lost due to undervoltage. With available undervoltage relays, however, shedding load using a simple timer starting at 2.0 s is not effective. Furthermore, to meet NERC requirements, UVLS may not operate before the selected 2.0 s recovery time requirement for Category B contingencies. An intelligent relay was required that could somehow differentiate between Category B and Category D contingencies so that UVLS operation could take place before 2.0 s for Category D contingencies but not operate at all for Category B contingencies.

IV. Slope Permissive UVLS Relay

A simple but effective solution was created using a programmable digital relay. Because other measures (e.g., static var systems) are assumed to be in place to mitigate Category B contingencies, any contingency which results in a voltage recovery (above 80%) time of 2.0 s or less at all transmission substations must be either a Category B event or a mild Category D (or C) event. Any voltage recovery (above 80%) of greater than 2 s must therefore be a Category D event and planned load shedding is permissible. Note that Southern Company has developed highly accurate methods and procedures for identifying worst-case contingencies so that mitigation measures can be designed for worst-case Category B contingencies without concern that "other more severe Category B contingencies could exist."

An algorithm which calculates the slope of the voltage recovery trajectory was created based on successive voltage values. This slope, coupled with the most recent voltage value, can be used to establish a first-order (linear) prediction of the time at which the voltage recovery is expected to reach a certain value. (Higher order trajectory approximations were also considered but not selected so as to avoid unnecessary computational burden on the relay platform.) For the Category D contingency recovery criteria presented previously, voltages at load-serving stations where UVLS relays would be located must recover above 0.8 per-unit in 4 s or less. Any slope-based prediction of a recovery time greater than 4.0 s can therefore be used to initiate UVLS operation. Note that mild Category D contingencies may result in recovery times that exceed the Category B recovery time requirement (2.0 s) but still meet the Category D recovery time requirement without UVLS operation. These mild contingencies will result in slope-based recovery time predictions between 2.0 and 4.0 s and therefore not result in UVLS operation. This margin in recovery time directly results in minimizing the expected operation of UVLS and increases the overall security of the scheme. This margin also serves to minimize potential issues (e.g., slope calculation sensitivity) in the calculation and prediction of recovery time.

Slope-based prediction of recovery time will prevent UVLS operation for Category B contingencies. Therefore, UVLS relays can securely operate in less than 2.0 s without concern of violating NERC Reliability Standards. By initiating UVLS operation, when needed, well before 2.0 s, generating plant substation voltages can more likely recover within criteria. Based on this relay algorithm, the UVLS scheme was revised as follows:

- 1st Stage: Up to 10% of area load shedding after 1.5 s following the initial onset of low voltage (below 0.8 per-unit) when predicted voltage recovery time is greater than 4.0 s;
- 2nd Stage: Up to 5% of area load shedding after 1.7 s following the initial onset of low voltage (below 0.8 per-unit) when predicted voltage recovery time is greater than 4.0 s; and
- 3rd and 4th Stages: Identical to the second stage, except operating after 1.9 and 2.1 s, respectively.

The first stage has been designed to offer a larger initial step to more quickly mitigate low voltage conditions. It is well known

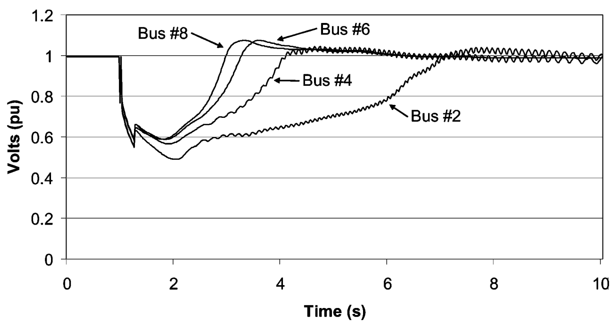

Fig. 4. Sample voltage recovery trajectories.

that motor loads will decelerate or even stall when subjected to longer lasting low voltages. Any action taken quickly will have a more beneficial effect and could lead to an overall reduction in the total amount of UVLS required.

The first stage operating time of 1.5 s was selected based on a compromise of the need for rapid operation (when required at all) and the fact that the voltage response must be sufficiently far along in its progression toward recovery (or not) to insure an accurate slope calculation. The voltage recovery must have passed its minimum value and be on an upward trajectory. Large numbers of simulations have shown that recovery trajectories reach their lowest point roughly 1.0–1.25 s after the initial fault; initiating the first stage at 1.5 s provides adequate assurance that the recovery is on an upward trajectory.

Numerous variations in load model composition (percentage motor load, model parameters, etc.) have also been considered. More pessimistic model assumptions lead to a greater simulated potential for fast collapse (no recovery), but the characteristics of voltages which do recover continue to show positive trajectory slopes from about 1.0 s onward. For all work reported in this paper, the load model was assumed to consist of 50% small motor with the remainder consisting of constant power, current, and impedance. The details of the model used and its validation using major event measurements are described in [5].

In Fig. 4 are shown simulated voltage recovery plots at four different buses numbered 2, 4, 6, and 8 in decreasing order of delayed voltage recovery severity for a fault occurring at 1.0 s. It is clear that the recovery characteristic reaches its minimum point within 1.0–1.25 s following the fault and has begun an upward trajectory of some type 1.5 s after the fault.

These curves are taken from simulation studies of the Southern Electric System including reduced representations of other systems in the Eastern Interconnection. The total model size is approximately 18 000 buses. Similar behavior to that shown in Fig. 4 is common at other buses under different system and contingency conditions. The minor oscillations shown in the traces for Buses 2 and 4 in Fig. 4 are due to a small (insignificant) hydroelectric unit losing synchronism and not being tripped in the simulation study.

Each stage becomes armed after the voltage remains below 80% for the specified time. However, an armed stage is not permitted to trip unless the slope calculation leads to a prediction of a recovery time (above 80%) greater than 4.0 s. Depending on the recovery trajectory, a particular UVLS relay may operate immediately after the specified time delay or at any time

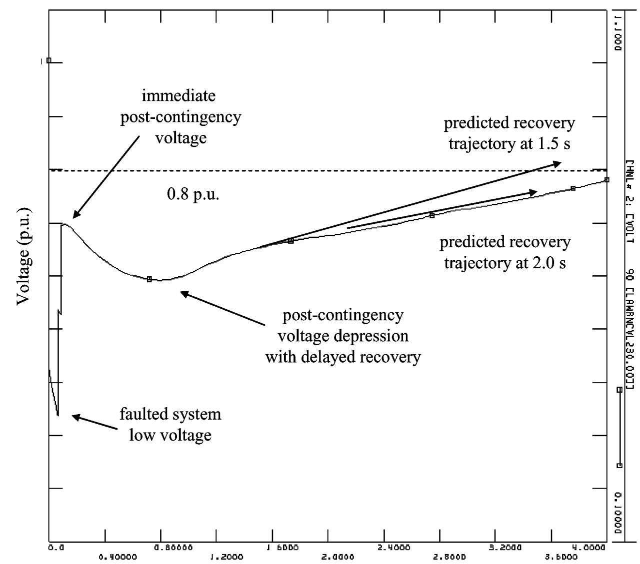

Fig. 5. Example voltage recovery characteristic with slope-based recovery time prediction.

thereafter whenever the slope-based recovery time prediction becomes greater than 4.0 s. Full relay reset occurs at any time voltage recovers above 80%.

In Fig. 5 is shown a simulated recovery characteristic including slope-based recovery time projections at 1.5 and 2.0 s. Assuming this recovery characteristic is seen by a Stage 1 UVLS relay, the relay would become armed at 1.5 s. Tripping would not occur at 1.5 s because the recovery time (above 80%) projection at 1.5 s is less than 4 s. However, the relay would remain armed and tripping would occur at some point between 1.5 and 2.0 s as the slope-based recovery time (above 80%) prediction begins to exceed 4.0 s due to changes in the voltage recovery trajectory. This ability to continue to track the recovery characteristic allows the scheme to be less dependent on modeling assumptions. For example, it is possible (even likely in some cases) for motor load to stall a short time after a fault thereby worsening the entire situation. If the situation degrades, the predicted recovery could exceed 4.0 s thus activating the relay.

V. Example UVLS Demonstration

For illustration purposes only, the operating times of the four-stage UVLS scheme described previously were lengthened to 2.0, 2.2, 2.4, and 2.6 s to more clearly show the operation of the four independent stages. If the slope-based recovery time prediction exceeds 4 s, UVLS relays will operate at (or after) the indicated time delay. In Fig. 6 is shown an example of the artificially-modified scheme.

It is interesting to note in Fig. 6 that at 2.0 s, the slope of the recovery trajectory is almost negative (predicted recovery time would approach ∞ and could be indicative of a fast collapse rather than a delayed recovery)—all Stage 1 UVLS relays operate and the voltage is immediately increased. After Stage 1 operation, however, the trajectory slope is clearly negative (predicted recovery time would be ∞) and the second stage immediately operates after the 2.2 s time delay. After Stage 2 operation, the recovery slope is positive but clearly not sufficient to

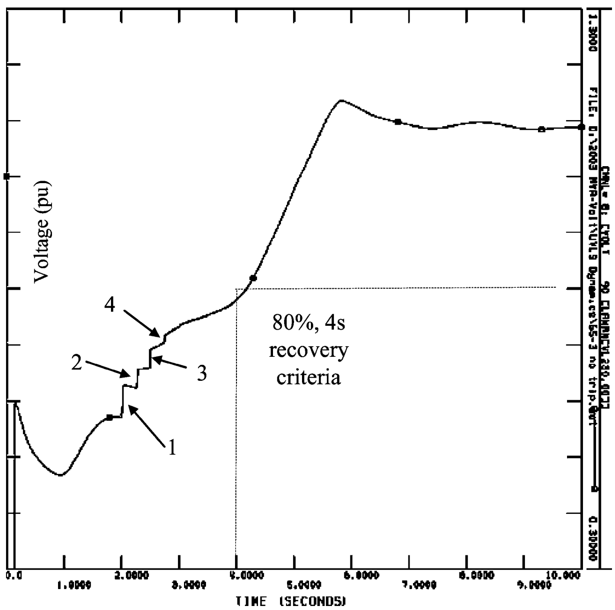

Fig. 6. Example recovery characteristic showing four stages of UVLS operation (with modified timing).

predict a recovery time (above 80%) within 4 s—the Stage 3 relays operate immediately after the 2.4 s time delay. After Stage 3 operation, the recovery trajectory slope is more positive and a prediction of recovery time would be slightly greater than 4.0 s. As a result, Stage 4 relays operate as designed. It is important to note that the slope-based UVLS scheme almost meets the 80%, 4.0 s recovery time criteria even with artificially-long time delays. However, such a delayed scheme would not meet generating plant substation recovery requirements and therefore could not be used in practice.

VI. Implementation and Field Installation

During the design stage, great emphasis was placed on security against unnecessary load loss. This meant guarding against undesired operation of the relay, premature load shedding or shedding load that would have little or no effect on system recovery.

A commercially-available programmable relay containing both voltage and current inputs was selected based on ease to program, oscillographical capability and mathematical processing power. The scheme consists of one relay per selected distribution transformer that trips multiple distribution feeders supplied by the transformer. The relay monitors both the load current through the transformer and the three phase voltages on either the high side or low side busses. Preference is given to high side voltage monitoring so as to eliminate many coordination issues with existing distribution system protection practices.

The relay is blocked from tripping load if the measured current is less than a predetermined value. Tripping lightly loaded feeders would have little or no effect on system recovery. A negative sequence inhibitor and dead bus detector was programmed to block tripping for values of negative sequence voltage greater than a preset percentage of positive sequence voltage and for voltages below a certain value. This was done to guard against

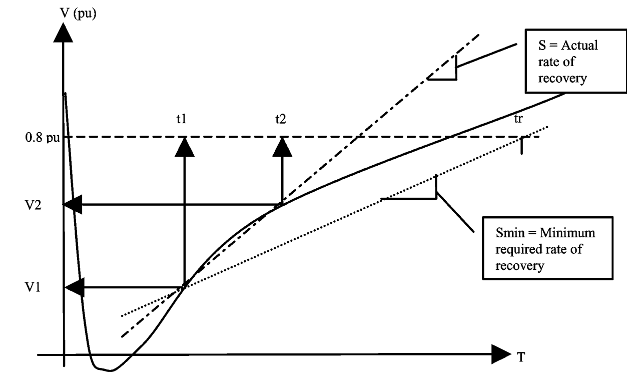

Fig. 7. Evaluating the rate of recovery.

operating during most fault conditions and potential transformer secondary fuse failures. Should the measured voltages return to a specified value for more than a predefined time period, the relay will reset the stage timer and subsequent voltage depressions will be considered new events.

Once the scheme has been armed and an undervoltage condition occurs (excluding the inhibiting criteria mentioned previously), the relay will wait for the preset stage time to pass. It continuously calculates rate of voltage recovery and compares the result to the minimum required rate of recovery. The relay can act on the result of the comparison only after this stage time has passed. The basic slope calculating principles programmed in the relay are illustrated in Fig. 7 and the equations that follow.

This relay stores the previous voltage V_1 and compares it to the current voltage V_2 and then determines if

$$S = \frac{(V_2 - V_1)}{\Delta t} < S_{\min}$$

where

S	voltage recovery slope;
$S_{\min}$	minimum required voltage recovery slope;
V_1	voltage (rms magnitude) at time t_1;
V_2	voltage (rms magnitude) at time t_2;
t_1	begin time;
t_2	end time;
Δt	$t_2 - t_1$.

The minimum required voltage recovery slope is calculated as follows:

$$S_{\min} = \frac{(V_R - V_1)}{(t_R - t_1)}$$

where V_R is the predetermined voltage recovery target (0.8 pu in this scheme) and t_R is the predetermined recovery time (4.0 s in this scheme).

Once a voltage depression has lasted longer than a defined stage time, the relay captures a recording of the voltage spanning 5 s. The recording includes 2 s of pre-triggered cycled memory. This captured data will allow post mortem analysis of any future local voltage depressions. At the same time the relay will send an alarm to the system operator. This type of alarm monitoring was dubbed "near miss or close call alarming" since alarming for every voltage depression of short duration is unwanted. If the relay should progress to actual shedding of load, a second alarm would be sent to the system operator indicating UVLS operation.

The relay utilizes typical sampling (16 samples per 60 Hz cycle) and filtering (cosine) techniques for digital relays. These time-tested techniques minimize the potential for mis-operation due to numerical issues. To verify reliable operation, multiple relays with their trip elements disabled were placed in service for several months for monitoring purposes. No problems were identified during the monitoring period and the relays were subsequently made fully active.

The UVLS relay is armed and disarmed remotely either as part of a group or individually by the system operator. Restoration of load after an operation is also achieved by remote control. The system operator has a choice of restoring a single feeder or whole substations at once depending on system conditions.

VII. Conclusions

A new algorithm for undervoltage load shedding has been presented in this paper. The algorithm has been implemented in commercially-available programmable relays and has been deployed in Georgia Power Company These relays allow the four stage undervoltage load shedding scheme developed by Southern Company to be set so as to minimize the total load in the scheme as well as to maximize relay security.

The algorithm used in the relays is based on a slope of voltage recovery calculation. With this calculation, the relays can operate more rapidly than conventional undervoltage relays that use basic "time at level" or "inverse time" (or similar) trip logic. This rapid operation is essential to mitigate fault-induced delayed voltage recovery conditions while maintaining compliance with applicable NERC Reliability Standards regarding permissible (planned) load shedding for contingency mitigation.

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