Operations and Maintenance Considerations for Underfrequency Relaying Design

Edsel Atienza, *Schweitzer Engineering Laboratories, Inc.*

***Abstract*—In the past, dedicated single-function relays were required to implement underfrequency load shedding (UFLS) associated with North American Electric Reliability Corporation (NERC) PRC-006-0, NERC PRC-007-0, and regional requirements. Microprocessors have allowed the integration of underfrequency relaying into bus relays, transformer relays, feeder relays, and phasor measurement units. This integration provides added benefits with respect to planning, implementing, documenting, maintaining, and providing post-event analysis of underfrequency systems associated with NERC PRC-009-0. Incorporating synchrophasor data becomes especially important because this provides real-time indication of the power system state before, during, and after underfrequency events.**

In general, relay schemes operated and maintained by transmission operators trip transmission equipment, and relay schemes operated and maintained by distribution providers trip distribution equipment. Unlike most other relay schemes, the responsibilities of maintaining and operating UFLS systems frequently span between transmission operators and distribution providers, making all aspects more difficult (design, maintenance, analysis, and reporting).

Both the division of responsibilities and the integration of UFLS into other systems affect the total operating costs of underfrequency designs. This paper presents best practices and lessons learned for the design, maintenance, analysis, and reporting for UFLS implemented in microprocessor-based relays.

I. Introduction

Large system disturbances such as faults can result in mismatches between load and generation. These mismatches result in frequency deviations that can have adverse effects, such as overexcitation of transformers and system instability. In large, interconnected systems, areas loosely tied together may separate into islands; these smaller islands do not necessarily have balanced load and generation. Even in smaller, tightly interconnected systems, large system disturbances can lead to mismatches between load and generation and frequency deviations without separation into islands. Underfrequency load-shedding (UFLS) programs are used to recover from frequency deviations in a system lacking sufficient generation [1] [2].

A number of North American Electric Reliability Corporation (NERC) PRC standards identify various entities involved in UFLS programs. NERC PRC-006-1 requires planning coordinators to perform studies, identify potential islands, and develop a UFLS program [3]. From these studies, load-shedding schedules are developed and included in regional reliability standards. These schedules are implemented by transmission operators, transmission owners, distribution providers, and load-serving entities as owners and operators of UFLS programs, as required by regional reliability organizations per NERC PRC-007-0 [4].

II. Implementation of Load-Shedding Schedules

Load-shedding schedules typically include multiple stages. Each stage identifies a frequency level and time delay associated with shedding a percentage of the system load, as shown in Table I. Loads can be shed at multiple voltage levels by tripping transmission lines, transformers, distribution feeders, reclosers, or circuit switchers. Transmission operators and distribution providers must prioritize and assign loads to each load-shedding stage based on the schedule.

A. Metering of Loads

Accurate and current metering data are necessary to assign loads to load-shedding stages and to document compliance to NERC and regional standards. The metering infrastructure can significantly affect the long-term operational costs of a UFLS program. A simple electromechanical power meter at each load may be sufficient to determine the seasonal peak of each load, but the labor required to read, record, and reset the meter on a regular basis must be considered. Digital meters, communications, and automatic meter reading systems increase the initial material and installation costs but reduce the labor involved in obtaining periodic meter readings. Reoccurring communications and software support agreements must be considered in the costs of automatic meter reading systems.

B. Assigning of Loads to UFLS Stages

UFLS stages vary by frequency level and time delay. Stages with higher frequency levels and shorter time delays are typically assigned lower-priority loads. Stages with lower frequency levels and longer time delays are typically assigned higher-priority loads. The following four main criteria should be considered when prioritizing and assigning loads to UFLS stages: interruptible loads, size of loads, critical loads, and location of loads.

1) Interruptible Loads

Many larger power consumers are given the option to become interruptible loads. Under abnormal system conditions, these loads are tripped first in exchange for lower power prices. They are usually the first loads to be shed during a UFLS event.

TABLE I
EXAMPLE FLORIDA RELIABILITY COORDINATING COUNCIL (FRCC) UFLS IMPLEMENTATION SCHEDULE [5]

UFLS Step	Frequency (Hz)	Time Delay (s)	Amount of Load (% of member system)	Cumulative Amount of Load (%)	Acceptable Range for Total Cumulative Amount of Load (%)
A	59.7	0.28	9	9	8 to 12
B	59.4	0.28	7	16	15 to 19
C	59.1	0.28	7	23	22 to 26
D	58.8	0.28	6	29	28 to 32
E	58.5	0.28	5	34	33 to 37
F	58.2	0.28	7	41	40 to 44
L	59.4	10.0	5	46	45 to 49
M	59.7	12.0	5	51	50 to 54
N	59.1	8.0	5	56	55 to 59

2) *Size of Loads*

Tripping larger blocks of loads, such as entire transmission lines, substations, and transformers, reduces the amount of metering and relaying equipment installed and maintained for a UFLS program. Although tripping smaller blocks of loads at lower voltage levels increases the complexity of UFLS programs, it is done to prevent tripping of critical loads.

3) *Critical Loads*

Critical loads, such as emergency services, life support systems, or sensitive production facilities, may be left out of UFLS stages or assigned to stages with lower frequency thresholds and longer time delays. Reclosers with digital multifunction controllers can be used to shed load beyond a critical load.

4) *Locations of Loads*

Reducing power transfer between areas of the system reduces stress on the transmission system and aids in the recovery following a major system event. During underfrequency conditions, shedding loads at dense load concentrations remote from generation reduces local load/generation mismatches, resulting in reduced power transfer between areas. Shedding loads near generation may further offset the local balance between load and generation, increasing stress on the system. Regional standards may designate some UFLS stages to include loads only from specific locations.

III. SUBSTATION UNDERFREQUENCY RELAY ARCHITECTURES

Early underfrequency relay schemes were implemented using single-function relays. An underfrequency relay, timing relay, and lockout relay were required for each UFLS stage implemented within the substation. To minimize equipment costs and maintenance, multiple feeders within the same substation were typically assigned to the same UFLS stage and lockout relays were wired to trip multiple feeder breakers.

A. *Electromechanical Reclosing Relays*

The feeder relaying package must be considered when using a centralized underfrequency relay to trip multiple feeders. Electromechanical reclosing relays are typically initiated using breaker auxiliary contacts. This results in initiation of the reclosing relay for both feeder overcurrent trips and underfrequency trips. Normally closed contacts from the underfrequency lockout relay must be wired to each feeder breaker to block automatic reclose during an underfrequency event, as shown in Fig. 1.

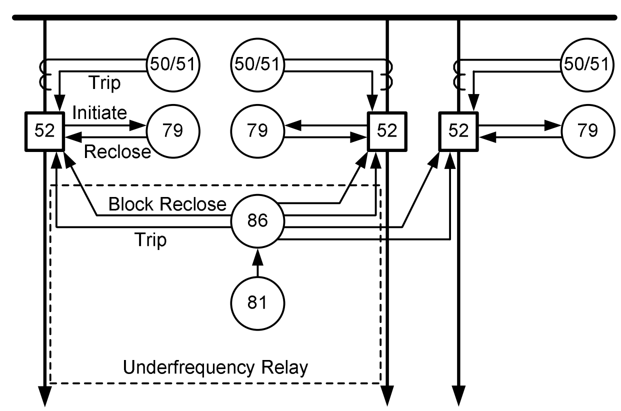

Fig. 1. Centralized Underfrequency Relay With Electromechanical Feeder Relays

Test switches or cutout switches connected to the output contacts of the underfrequency lockout relay allow the underfrequency relaying system to be tested without the tripping of breakers. Under test conditions, underfrequency trips are opened using the switches, and block close contacts can be shorted to allow feeder breaker reclosing. Block close contacts left open during maintenance activities prevent automatic reclosing of feeder breakers for temporary faults and can delay restoration efforts.

B. Centralized Underfrequency With Digital Feeder Relays

Reclosing functions integrated into digital feeder relays have programmable initiate conditions. Instead of initiating based on breaker auxiliary contacts, the reclosing function can be programmed to be initiated only by the feeder protection elements and not by the underfrequency trip. This eliminates the need to wire contacts from underfrequency lockouts to block the closing of feeder breakers, as shown in Fig. 2. If the underfrequency relay includes sufficient contacts for tripping, the lockout relay can even be eliminated.

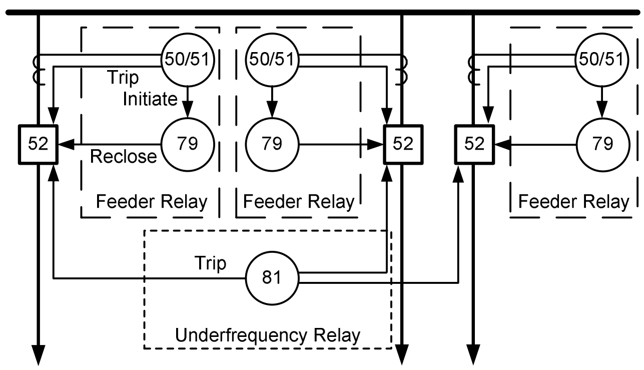

Fig. 2. Centralized Underfrequency Relay With Digital Multifunction Feeder Relays

C. Digital Feeder Relays With Underfrequency Elements

Many digital feeder relays include integrated voltage elements, frequency elements, and comprehensive metering. Logic settings within the relay allow the initiation of the reclosing element only by the overcurrent elements and/or allow the underfrequency element to drive the reclosing relay to lockout, as shown in Fig. 3.

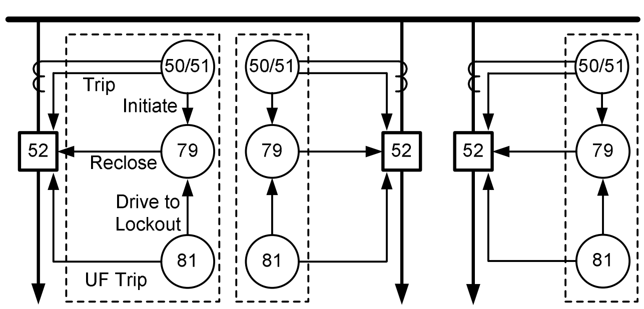

Fig. 3. Digital Feeder Relays With Integrated Underfrequency (UF) Tripping

There are several tradeoffs when choosing between centralized underfrequency relaying and distributed underfrequency relaying.

The disadvantages of distributed underfrequency relaying are as follows:

- Voltages must be wired to each feeder relay.
- A larger quantity of relays may need to be included in the underfrequency test program.
- Depending on utility operations procedures, feeder breakers may need to be taken out of service when the feeder relay is tested.

The advantages of distributed underfrequency relaying are as follows:

- Existing microprocessor-based relays will likely already have underfrequency capabilities.
- Wiring from a central underfrequency relay to feeder breaker trip circuits is eliminated.
- Each feeder can be set to different UFLS stages without additional wiring.
- Feeder relays can be programmed to switch among different UFLS stage assignments through supervisory control and data acquisition (SCADA) without settings changes.
- The failure of a single UFLS relay only affects a single feeder.
- The comprehensive metering and load profile capabilities of some digital relays eliminate the need for a dedicated meter on the feeder.
- Feeder oscillograph records from underfrequency events show voltage, frequency, and current for post-event analysis and compliance documentation.

The importance of each of these advantages and disadvantages of distributed underfrequency relaying depends on the maintenance requirements and division of responsibilities in planning, operating, and maintaining the UFLS program.

IV. MAINTENANCE PROGRAMS

NERC PRC-008-0 requires that each transmission owner and distribution provider have a UFLS equipment maintenance and testing program [6]. The number of devices that need to be included in this program can vary widely based on the architecture used. For centralized underfrequency relaying, the number of relays to include in the UFLS maintenance program is typically reduced. When only a single UFLS stage is implemented at a location, testing and documenting just a single centralized relay are less expensive than including every feeder relay in the UFLS maintenance program. When multiple UFLS stages must be implemented at the same location, the centralized underfrequency relaying offers little maintenance benefit over the distributed system, as long as sufficient redundancy and/or test capabilities are included in the feeder relays.

V. DIVISION OF RESPONSIBILITIES

Larger distribution providers with hundreds or thousands of feeders typically install, own, operate, and maintain their own UFLS systems. The load on each feeder breaker and possibly on each transformer is smaller than the load to be shed for each underfrequency stage. Multiple feeder breakers and possibly transformer breakers at several locations must be tripped for each UFLS stage. Using integrated underfrequency elements in digital feeder relays eliminates the need to install additional equipment-dedicated underfrequency relays but increases the number of relays included in UFLS maintenance programs. When all feeders fed by a single transformer can be included in the same UFLS stage, using integrated underfrequency elements in the transformer relay can reduce the amount of UFLS equipment to maintain. If the quantity and size of substations provide sufficient flexibility to meet UFLS schedules, the reduced maintenance of centralized underfrequency relaying may outweigh the flexibility of distributed feeder-based underfrequency relaying.

For medium-sized distribution providers with few substations that require just one or two feeders to meet each UFLS stage, multiple UFLS stages may need to be implemented at each substation. Centralized underfrequency relaying becomes more complicated for these systems and offers little maintenance advantage over distributed underfrequency relaying. In these systems, the flexibility of the distributed underfrequency relaying is a significant advantage over centralized underfrequency relaying.

For small distribution providers with few feeders, each UFLS stage may be smaller than the load shed by tripping a single breaker. For these small distribution providers, complying with regional UFLS schedules on their own can be difficult and expensive, requiring line reclosers and circuit switchers to shed smaller blocks of load. Many of these smaller distribution providers rely on their transmission operator to install, own, operate, and maintain the UFLS program. To meet regional requirements, these transmission operators assign loads from multiple distribution providers to UFLS stages. This typically reduces the number of UFLS stages each distribution provider is required to implement. With few UFLS stages to implement at each location, centralized underfrequency and maintenance simplify installation for the transmission operator.

Although a transmission operator may own and operate the UFLS equipment, the responsibilities of the distribution provider for complying with UFLS standards are not completely eliminated. Distribution providers must continue to meter the feeders and provide accurate load information to transmission operators. When connecting the UFLS equipment of the transmission operator to feeder breakers, the distribution provider must ensure proper wiring and settings are used in the feeder breaker and relaying package to prevent automatic reclosing of the breaker during the underfrequency event. Metering and event reporting from distribution provider equipment are essential for post-event reporting.

VI. Post-Event Reporting and Analysis

Post-event reporting and analysis required by NERC PRC-009-0 must not be ignored when designing and installing a UFLS system. Reporting includes analysis of the underfrequency events and their initiating conditions [7]. Underfrequency events typically affect large areas and can include significant changes in frequency and several seconds of system oscillations. These characteristics present challenges when analyzing underfrequency events.

A. Time Synchronization

Underfrequency events are typically triggered by significant events at transmission and generation levels. Impacts of these events are evident at all transmission, distribution, and generation voltages and throughout the interconnected system. Underfrequency records at distribution levels must be compared with time-stamped sequence of events and fault records at transmission and generation sites. Time synchronization is necessary to correlate records from multiple locations and from multiple utilities.

B. Event Duration

System oscillations following significant transmission or generation events can last several seconds. Oscillograms available from many relays at transmission and distribution levels is typically sized to less than 2 seconds in order to record the initial trip and breaker failure clearing. Long-term disturbance recording is necessary to fully analyze long-duration events.

C. Analysis Quantities

Under steady-state conditions, the frequency is common throughout the entire system and provides no indication of system topology or power flow through the system. However, underfrequency relaying does provide a reliable method to detect and act on system disturbances using local measurements. High measurement resolution and fast sampling rates are required to provide useful frequency data for analysis. Traditional SCADA systems with 1- to 5-second scan intervals do not support the sampling rates required to provide sufficient frequency data for analysis. Local recording and/or dedicated high-speed data streams are required to obtain sufficient frequency data.

Post-event analysis of system events using phasor measurement offers significant advantages over frequency measurement. Changes in system topology and power flow affect relative phase angles across the power system. Phase angles among key locations provide a direct indicator of relative strengths or weaknesses in the power system. While dedicated high-speed data streams and centralized archiving provide great benefits to analysis of phasor measurements, even phasor measurements obtained at traditional SCADA rates provide insight into power flows and system topology before and after an underfrequency event.

A wide-area monitoring system (WAMS) incorporating high-speed data streams from phasor measurement units (PMUs) and multifunction relays is the ideal solution for documenting and analyzing underfrequency events and their initiating conditions. A WAMS can incorporate frequency, voltage magnitude, and voltage phase angle from many key transmission and generation locations; is inherently time-synchronized; can include several samples per second; and can include sufficient recording capabilities to capture system oscillations following events.

NERC PRC-009-0 Requirement R1.2 indicates that owners and operators of UFLS programs must provide a review of UFLS set points and tripping times [7]. To accomplish this, time synchronization, metering of loads, and time-stamped sequence of events must be implemented at each site containing UFLS equipment. As an alternative, oscillograms obtained from digital multifunction feeder relays and transformer relays include sufficient breaker status monitoring and load data for analysis and reporting.

VII. Conclusion

As system loading, system topology, system inertia, and regional UFLS schedules change, more underfrequency relaying may need to be implemented. Understanding the impacts of NERC and regional requirements on operations and maintenance aids in the design of relaying systems. The following must be considered to minimize the total cost of ownership of underfrequency relaying designs:

- Division of ownership, operations, and maintenance responsibilities among different entities.
- Number and size of loads in relation to UFLS stages.
- Number of UFLS stages implemented at each location.
- Feeder automatic reclosing systems.
- Underfrequency relay maintenance and impact on distribution operations.
- Post-event reporting and analysis.

Digital relays and good design criteria provide opportunities to reduce the costs of implementing and complying with UFLS requirements.

VIII. References

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IX. Biography

Edsel Atienza received his BSEE from the University of Idaho in 2001. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2002 as an international field application engineer. In 2006, he joined Tampa Electric as a substation operations engineer responsible for relay testing and maintenance. He returned to SEL in 2008, serving the southeastern United States as a field application engineer.