Case Study: An Adaptive Underfrequency Load-Shedding System

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CASE STUDY: AN ADAPTIVE UNDERFREQUENCY LOAD-SHEDDING SYSTEM

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Abstract—Underfrequency (UF) schemes are implemented in nearly every power system and are deemed critical methods to avert system-wide blackouts. Unfortunately, UF-based schemes are often ineffective for industrial power systems.

Traditional UF schemes are implemented in either discrete electromechanical relays or microprocessor-based multifunction relays. Individual loads or feeders are most commonly shed by relays working autonomously. The UF in each relay is set in a staggered fashion, using different timers and UF thresholds. Sometimes, dω/dt elements are used to select larger blocks of load to shed. Unfortunately, no traditional schemes take into account load-level changes, system inertia changes, changes in load composition, governor response characteristics, or changes in system topology.

This paper explains an adaptive method that overcomes known UF scheme problems by using communication between remote protective relays and a centralized UF appliance. This method continuously keeps track of dynamically changing load levels, system topology, and load composition. The theory behind the improved scheme is explained using modeling results from a real power system.

Index Terms—Reliability, dynamic stability, blackout, incremental reserve margin, generation shedding, spinning reserve, load shedding, ICLT.

I. INTRODUCTION

Power unbalances of power supply versus load in ac electric power systems often lead to blackouts. Blackouts affect utilities, ships, refineries, mines, data centers, industrial processes, military installations, and basically every power system in the world. A historical method for detecting power unbalances is to detect a fall or rise in the frequency of the power system voltage fundamental. The crossing of a level of underfrequency (UF) or overfrequency (OF) in a power system is then used to trigger the shedding (dropping) of loads or generators to rebalance the power system. Several present day methods exist for such UF load-shedding and OF generation-shedding schemes. This paper explains a new method of providing a unified UF load-shedding and OF generation-shedding system for any power system size. The algorithm used operates by monitoring time-synchronized measurements of angle and frequency to identify any number of islands in a power system. Load-shedding processing is based on the total inertia of each islanded system, combined with the frequency rate of change. For the purposes of this paper, this new scheme is designated as an inertia compensation and load-tracking (ICLT) system. This approach has made practical the development of an ICLT appliance for use on power systems around the world. The new system is easy to use for all engineers, even those with minimal experience.

II. BACKGROUND

In order to explain the impact of the new method, this section discusses the basis of the problems associated with load-shedding systems today.

A. Island Tracking

Island tracking is also known as "topology tracking." Load-shedding systems must track the power system topology to relate the trigger (UF or otherwise) to sheddable loads. Fig. 1 illustrates the problem with topology tracking. UF triggers are derived from the 132 kV busbars. However, the sheddable loads are downstream at the 13.8 kV, 4 kV, and 480 V busbars. Because this facility can be broken into multiple islands, a load-shedding system must track the status of all the breakers and disconnects between the 132 kV, 13.8 kV, 4 kV, and 480 V busbars in order to constantly compute the real-time topology.

Fig. 1 includes an example topology configuration showing two possible simultaneous islands, one black and one gray. Many more island combinations exist in this buswork, namely if lower-voltage bus-tie breakers are closed and incoming breakers are opened. For a medium-sized installation, topology tracking scenarios number in the tens of thousands.

The effort and cost of tracking the topology of a complex plant can be significant. Take into account that I/O modules must be placed throughout the plant to track the open and close status of all breakers and disconnects. These I/O modules require fiber-optic communication to travel the long distances between substations, which can commonly be several kilometers away in a petrochemical, natural gas liquid (NGL), or refinery facility. The user must also take into

account the cost of engineering and technician labor to configure, install, test, maintain, and monitor the equipment.

The ICLT method eliminates the need for any topology tracking, thereby greatly reducing the complexity, cost, and maintenance and greatly increasing the reliability of load-shedding systems.
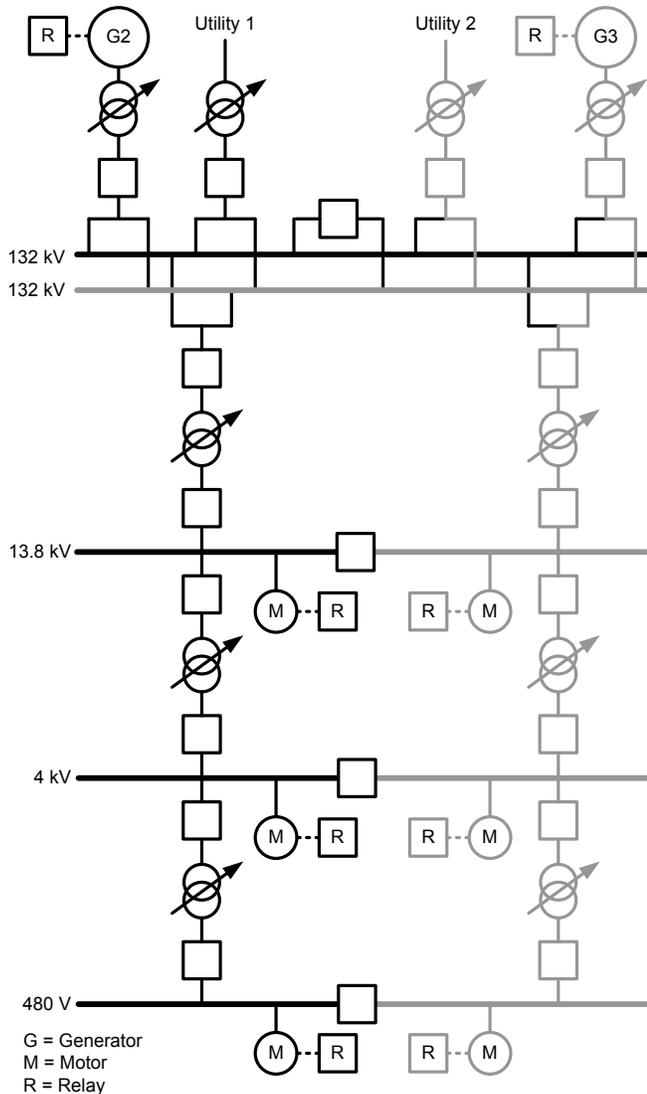

Fig. 1   Topology Tracking Example

B. System Inertia "H" Tracking

Rotating inertia, J, as taught in basic physics, is the effect of mass spinning at a radius. It is described by the following equation:

$$J = mass \cdot radius\ of\ rotation\ squared \qquad (1)$$

where:

J is expressed in units of kg-m^2.
Mass is expressed in kilograms.
Radius of rotation squared is in meters^2.

The inertia of electric power system apparatus, such as generators, motors, and turbines, is defined as:

$$H = \frac{J \cdot \omega_{om}^{2}}{2 \cdot VA_{rating}} \qquad (2)$$

where:

H is expressed in seconds.

ω_{om} is the rated machine speed (in radians per second).

VA_{rating} is the total rating of the machinery or system. It is used to put H in terms of per unit (pu).

H is most commonly used to describe the relationship between generator speed, the mechanical power from a turbine, and the electric power out of a generator per (3). The units of H are sometimes also referred to as seconds.

$$2H\omega \cdot \frac{d\omega}{dt} = P_{m} - P_{elec} = P_{acc} \qquad (3)$$

where:

ω is the generator speed expressed in pu of the rated speed.

P_{m} is the mechanical power out of a turbine (in pu).

P_{elec} is the electric power out of a generator (in pu).

P_{acc} is the acceleration power of the combined turbine and generator system.

For a generator and turbine combination, H becomes the time (in seconds) required for a machine to change 1 pu speed given full mechanical power from the turbine and a short-circuit condition on the generator terminals. Note that short-circuited generators supply no electric power, and thus the generator and turbine rotational speed (and hence electric frequency) accelerates. Considerations must be made in any inertia calculation to include generator pole count and mechanical gearing between a turbine and generator (such as is common in some microturbines). For the remainder of this paper, assume direct shaft coupling and that all electric machines are four-pole construction.

Note that (3) identifies the general power balance equation that must be satisfied by any load-shedding system. After an event, an optimal load- and/or generation-shedding system will trip enough load or generation such that the P_{acc} term is equal to near zero.

Table I quantifies large, medium, and small system relative inertias from the authors' experience. It is interesting to note that many large and small electric machines and utility grids have similar H values but radically different J values. For example, per Table I, the inertia of a large utility power system, as shown in (4), can easily be 160 times bigger than that of a large oil refinery. Note that the $2/\omega_{om}^{2}$ term is omitted in (5) because the variables cancel each other out.

$$J = \frac{H\left(2 \cdot VA_{rating}\right)}{\omega_{om}^{2}} \qquad (4)$$

$$\frac{8 \cdot 10,000}{4 \cdot 125} = 160 \qquad (5)$$

2

TABLE I
REPRESENTATIVE INERTIA VALUES FOR
ELECTRIC POWER SYSTEMS

System	H (seconds)	MVA$_{rating}$
Direct-on-line (DOL) induction motor (IM) and compressor	1	0.15
DOL IM and conveyor	0.6	0.15
DOL synchronous motor (SM) and compressor	1	0.6
Variable speed drive (VSD)	0	0.5
Pipe heaters	0	NA
Lighting	0	NA
Single-shaft industrial gas turbine (GT) and steam turbine (ST)	4.5	100
Aero-derivative industrial GT and ST	2.5	15
Diesel generator set	2	5
Steam extraction turbine and ST	3.5	35
Combined cycle and ST	5.5	150
Dynamic positioning vessel	2.5	15
Offshore oil rig	3	25
Large fertilizer plant	4	200
Large oil refinery	4	125
Large utility	8	10,000

Total power system inertia greatly impacts the performance of any UF load-shedding system. As shown in (3), the power disparity (mismatch) and inertia of a power system define how fast the frequency falls. For example, consider that the power system in Fig. 1 is a large oil refinery with total on-site generation of 125 MW and a total electric system inertia as shown in (6).

$$J = \frac{2 \cdot 4 \text{ seconds} \cdot (125 \cdot 10^6 \text{ VA})}{(2 \cdot \pi \cdot 60 \text{ radians per second})^2} = 7{,}036 \text{ kg-m}^2 \quad (6)$$

It is noteworthy that the cumulative sum of on-site generators, their turbines, motors, loads, and the like adds to the overall inertia of a power system. Assuming the utility tie is opened while importing 25 MW, the expected rate of change of frequency (dω/dt) decay is shown in (7). Note that (7) is a manipulation of (3), and 25/125 puts P$_{acc}$ into pu.

$$\frac{d\omega}{dt} = \frac{\left(\frac{25 \text{ MW}}{125 \text{ MVA}}\right)}{2 \cdot 4 \text{ seconds}} = 0.025 \text{ pu per second} \quad (7)$$

For a 50 Hz system, this translates to:

$$0.025 \text{ pu per second} \cdot 50 \text{ Hz} = 1.25 \text{ Hz per second} \quad (8)$$

Now, consider the same power system split in two under the same condition. With half the inertia but the same power unbalance, the decay rate is double, or 2.5 Hz per second. With half the inertia and double the decay rate, a load-shedding system must still trip 25 MW of load to operate correctly.

Some load-shedding schemes implemented today shed more load (MW) with higher dω/dt rates. However, without tracking H, they all would misoperate under one of the two scenarios described. For example, a traditional dω/dt scheme set up for an inertia of 7,036 kg-m^2 could be properly configured to shed 25 MW at 1.25 Hz per second. However, the same scheme would erroneously shed 50 MW at 2.5 Hz per second. Traditional UF systems do not track H and therefore will commonly misoperate. It is important to note that a contingency-based load-shedding system does have this information. Contingency-based schemes are vastly more sophisticated, complicated, and costly than UF-based schemes and are therefore not in the scope of this paper. The ICLT scheme presented in this paper replaces contingency-based systems for many locations. In other locations, this ICLT scheme acts as a backup to a contingency-based system.

The ICLT method explained later in this paper is revolutionary because it is the first load-shedding system in the world that adaptively tracks power system inertia.

C. Changing Load Levels

Many UF load-shedding schemes do not adjust tripping based upon present measured load levels. To do so would increase the complexity of the system to an unmanageable level. For example, most utility UF schemes trip load feeders at predetermined frequency levels. They do not shed more feeders or fewer feeders should feeder loading (MW) conditions change. This commonly results in serious overshedding or undershedding of megawatts, thereby not correctly balancing (3). Because of system inertia and frequency decay rates, this is sometimes an acceptable solution for massive power utilities. However, it is rarely an acceptable solution for islanded industrial power systems.

The ICLT method explained in this paper selects an amount of load to shed (MW) based upon the P$_{acc}$ term. This megawatts-to-shed number is then used to select an appropriate amount of load based upon real-time load megawatt measurements. This is done with priority or action table techniques, similar to contingency load-shedding processor (CLSP) schemes. The unique innovations of this new solution are its elegance and simplicity, which make it affordable and easy to apply.

D. Load Composition

After H, governor and prime mover characteristics and load composition are the next largest contributors to system frequency decay characteristics. Governor and prime mover responsiveness is a topic for other papers, but basically, UF schemes must be coordinated with these devices. The new

adaptive method does not provide any significant improvement in this coordination because this coordination is dependent on the skill of the protection engineer configuring the system. Load composition, however, is tracked in the new method.

The frequency versus power consumption characteristic of a load predicates how far the frequency falls in a power system for a load disparity. Therefore, this load characteristic determines how hard a governor must work to correct for off-nominal frequency conditions.

Electronic loads such as VSDs continue to consume full power as the frequency falls; therefore, VSDs make a governor work harder and increase frequency excursions. Spinning loads attached to DOL IMs and SMs reduce their power consumption as frequency decays; therefore, these items naturally keep the power system frequency constant and reduce the burden on governors.

Fig. 2 shows a simple case in which the governors controlling the turbine (shown later in Fig. 4) were prevented from acting upon frequency excursions by placing them in locked valve control. The tie line was then opened while exporting 25 MW. Three cases were then run: mostly DOL IMs, mostly VSDs, and an equal mixture of VSD and DOL IM loads. As expected, the VSD-dominated load caused the largest frequency excursion. Note that Fig. 2 was obtained for analysis purposes with all network and machine protection disabled.
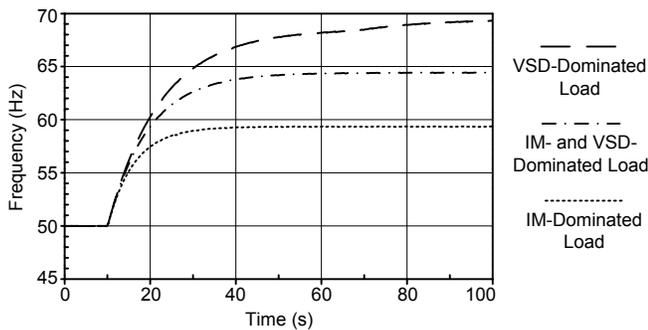

Fig. 2   Frequency Response Load Composition Influence

III. SYSTEM RELIABILITY

This section summarizes the most modern methods available to create a physical load-shedding system, starting with design principles and progressing on to describe the architecture and data flow for a load-shedding scheme at a large refinery. This background is necessary to understand state-of-the-art systems and their limitations. It also helps the user understand the simple elegance of the new ICLT method.

A. Reliability Design Principles

A properly designed load-shedding system incorporates the principles of design described in the following subsections. An ICLT system addresses all of these principles.

1) Simplified User Interface

Most important for the long-term maintainability and operation of any complex system is a simple and elegant user interface. This user interface must be capable of providing all troubleshooting for the communications and hardware health of all subsystems. It must also provide event diagnostic tools, such as log files, to capture each load-shedding event and sequence of events. Both event records and log files must have 1-millisecond-or-better accuracy and 0.1-millisecond-or-better resolution of all events. Log files must include enough information for the manufacturer to debug all of the systems, and they must also contain a simple-to-read summary of every event action that is easily understandable to untrained operators or maintenance personnel.

The load-shedding systems must work without the user interface functioning. No critical path components should be based on Windows® operating systems due to performance restrictions, processing jitter, and cybersecurity vulnerabilities. All critical path components must be embedded controllers with strong security measures taken to prevent misoperation.

2) Commissionability

Load-shedding systems are often commissioned with live plants, generators, and utility ties. The reputations of some companies have been damaged by having a single trip contact in a load-shedding system close incorrectly on a live plant during test. It is therefore critical that all trip output contacts have blade disconnects. It is also imperative that the system design prevent all possible communications hardware failures, I/O hardware failures, processor failures, power supply failures, and the like from causing a misoperation.

3) Expandability

As plants grow, their load-shedding system must also grow. Any reliably designed system must be capable of expansion with zero process outages to the existing in-service plant. The controllers and relays must never be taken out of service to perform upgrades. New settings should be downloaded with little or no gap in protection during the download process, just like with any other modern protective relay.

4) Testability

The system architecture must allow a controller sitting on an engineering desk to be fully tested under all scenarios. With the ICLT system, large numbers of panels populated with racks of I/O and relays are not necessary as part of a complete factory acceptance test. Rather, a comprehensive factory acceptance test can include two controllers being fed data by simulation equipment, which actively produces real-time scenarios for the controller.

5) Redundancy

Redundancy should never be less than dual primary. Hot standby is inadequate for a blackout prevention scheme. Dual primary redundancy is the world standard for transmission-level protection, and therefore, the user should require a set of controllers that are constantly active and racing each other (i.e., dual primary redundancy). No controller should ever be used in a master or slave mode.

6) Minimal Equipment

The larger the equipment count, the lower the overall system reliability. This stems both from the increase in unavailability through fault tree analysis and from the eventual cost-cutting measures of adding low-cost, unmonitored equipment into the scheme.

Noteworthy unreliable equipment includes items such as low-level transducers and interposing relays; neither should ever be allowed in a modern system. All outputs to trip load breakers must be initiated by direct hard-wiring to trip-rated output contacts embedded into protective relays or I/O modules. No interposing relays should be allowed in any circuit. Low-level signals do not contain the necessary quality of information; therefore, all systems must employ only modern digital metering equipment with direct communication to the central decision-making controller.

B. System Self-Monitoring

All equipment in a system must be monitored to prevent hidden failures. It is best to remove all devices without self-diagnostics to eliminate hidden failures. Each self-diagnostic device should identify its health status to the master controller. Any equipment without self-monitoring must be monitored with additional equipment. Adding diagnostics and monitoring information for all equipment in a large system adds significant complexity, furthering the rational for reducing the equipment count.

C. Architecture and Data Flow for an ICLT System

To accomplish the reliability design principles outlined in Section III, Subsection A, the ICLT scheme is to operate as a standalone scheme or as a completely independent backup to a contingency-based scheme. It is necessary for the ICLT system to function on independent hardware, protocols, and communications channels and to function with a completely different algorithm from contingency-based load-shedding systems. This is accomplished with the physical architecture shown in Fig. 3.
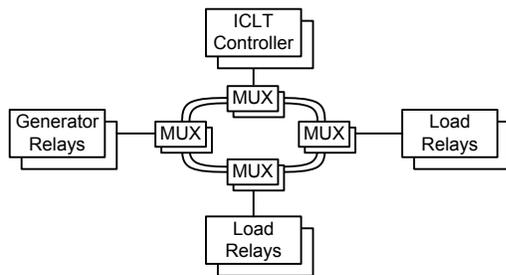

Fig. 3 System Architecture of Dual Primary ICLT System

It is noteworthy that the ICLT controller communicates directly to the generator relays and sheddable load relays. Every generator and load on the system must have a relay or mitigation device communicating to the ICLT controller.

A modern, encrypted MUX is used to route point-to-point direct communication from the relays to the ICLT controller. This allows the ICLT controller, generator relays, and load

relays to be thousands of kilometers apart without any degradation in timing or performance. Note that two MUXs and their associated rings are used to avoid single points of failure.

Logic for tripping is performed within relays, and the status is extracted directly from relays, so there is a significant danger of the system being disabled mistakenly if the relay settings are modified by personnel who are not aware of the tight integration with the load-shedding system. In the new ICLT method, this is prevented by having relay settings templates, which make critical load-shedding settings available only to administrative users.

D. Factory Acceptance Testing

Comprehensive factory acceptance tests are required to create a reliable contingency-based load-shedding system. The tests must include dynamic simulation of the power system in question in a real-time environment. The load-shedding controllers in the test must therefore be attached directly to the real-time simulation with real data updated to the controller at intervals of 1 millisecond or less.

If both a contingency system and UF load-shedding system are to operate on a power system, a dynamic simulation is mandatory. For some situations that require only a UF-based system, dynamic simulation is not required when the new ICLT adaptive method is used. Traditional UF-based schemes must be simulated extensively. Because modeling and simulation are not required, the new method provides a tremendous cost savings to some users.

E. Contingency Versus Underfrequency

For all power systems, a UF load-shedding system only detects a frequency decay after the initiating condition of a power deficit. As shown in [1], this delayed response time can frequently result in a cascading blackout. For this reason, most industrial end users require a contingency-based scheme.

Various signals have been used over the years to initiate a load-shedding contingency. These signals include breaker contacts (52a and 52b contacts), 86 lockout contacts, current thresholds, out-of-step (OOS) conditions, protective relaying trip signals, synchrophasor phase angle deflection [2], thermal limits on generators, transformer overloads, voltage depressions, and more. All of these terms are collectively called "contingencies" in order to differentiate them from UF techniques. Each of the aforementioned contingency-triggering conditions has an impact on the overall system shedding time and the operational security of the overall scheme.

A UF load-shedding scheme is commonly employed in industrial power systems as a backup to a contingency-based load-shedding system. In addition to transient inhibit periods, maintenance issues, such as equipment failures, broken wiring, shorted current transformer (CT) windings, and dc battery failures, can cause a contingency-based load-shedding protection system to fail to operate when needed. Clamping and slew rate limiters in governors, fuel problems, or air flow problems are other situations in which a

contingency-based load-shedding protection system will not operate. Improper installation or commissioning of protection equipment can also cause a contingency-based system to not react when needed. All of these reasons make it mandatory that a backup UF-based load-shedding system be employed to supplement a contingency-based system.

Unfortunately, there are severe limitations in traditional UF load-shedding protection systems, primarily because this type of system only reacts after the system is in a state of decay due to overload. These limitations have caused load-shedding systems to gain the bad reputation of being untrustworthy.

It is the authors' experience that systems based on single-function UF relays have an approximately 50 percent likelihood of rescuing a power system from decay. The new adaptive UF-based system is calculated to improve the success rate of UF load shedding significantly.

F. dω/dt Elements

dω/dt elements require supervision from pure UF elements to prevent spurious misoperations. Calculations of dω/dt within a digital relay must include very sophisticated infinite impulse response (IIR) and finite impulse response (FIR) digital filtering methods and off-nominal frequency elimination techniques, such as cosine filtering [3]. All the aforementioned methods must match unerringly between the digital relays, and therefore, identical relays must be used.

IV. CASE STUDIES OF MULTIPLE IN-SERVICE LOAD-SHEDDING SCHEMES

This section relates experiences from dozens of facilities and blackouts into simple, tangible, easy-to-understand dynamic stability phenomena. The intent of this section is to show the philosophy of setting systems for a wide variety of end users. The new ICLT system easily adapts to all of these situations.

A. UF System Acting as a Backup Steam Load-Shedding System

At one facility, on-site exothermic processes were used as the primary steam providers for two on-site 75 MW steam turbines. These steam turbine-driven generators provided electric power to the entire facility, and at times, power was sold to the local utility grid. Fig. 4 shows the system.
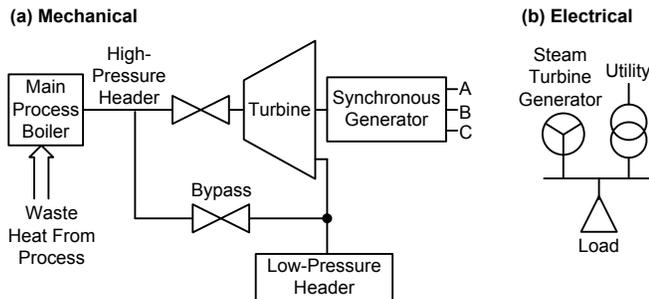

Fig. 4   Typical Fertilizer Plant

Fig. 5 identifies the settings and behavior of the on-site load-shedding system. At frequencies above 61.5 Hz and below 58 Hz, the generators trip offline for self-preservation. Under scenarios of exporting power, the grid tie line opens and the system naturally drives to OF. This happens because the main governor control valve only closes after a frequency disturbance occurs and the time constant on this is approximately 1 second. To prevent this, the steam bypass valve shown in Fig. 4 is opened within 100 milliseconds, thereby quickly diverting the steam flow around the turbine and preventing overspeed (OF) of the electric grid.
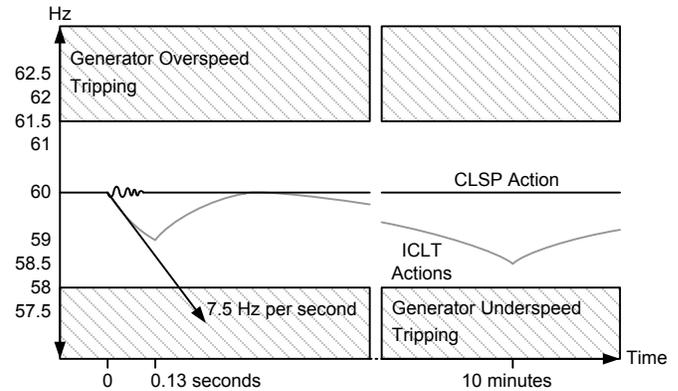

Fig. 5   Fertilizer Plant Recovery With an ICLT System

For scenarios where the plant is importing power from the utility grid, the worst-case frequency descent was determined to be 7.5 Hz per second, as shown in Fig. 5. Also shown on the plot in Fig. 5 are the system responses in frequency to CLSP and ICLT load-shedding operations. Note that the CLSP action has minimal effect on frequency and the power system permanently recovers.

An ICLT action assumes there has been no contingency action. Therefore, there is an initial system frequency recovery as the governor opens its control valve wide open and load is shed at the first UF level of 59 Hz. Of note and concern is the slow decay several seconds after the ICLT operation. This is caused by the main high-pressure header reducing in pressure because the turbine is extracting more steam than what is being produced by the exothermic process. This occurs because the ICLT scheme does not perfectly balance the P_{acc} term and the steam header pressure starts decaying as the tons per hour consumed by the turbine exceed that produced by the process.

This slow decay is arrested by further ICLT load-shedding tripping at the second level of 58.5 Hz. In this way, the electric load is reduced, thereby reducing the requirements for steam demand from the primary boilers. ICLT load shedding therefore acts as a boiler or steam preservation backup system.

In this facility, excessive load shedding is acceptable because OF situations are dealt with quickly with a fast turbine valve closing and the opening of the steam bypass valve. Because the system handles OF conditions so well, the loads selected for tripping for each level are customarily set larger than normal.

B. Load-Shedding Scheme at a Large Refinery

A classic problem is having UF triggers at multiple central locations and having hundreds of sheddable loads spread out at low-voltage locations. In one facility from the authors' experience, shown in Fig. 6, six different island scenarios can occur, each with sufficient generation to support the islanded loads.

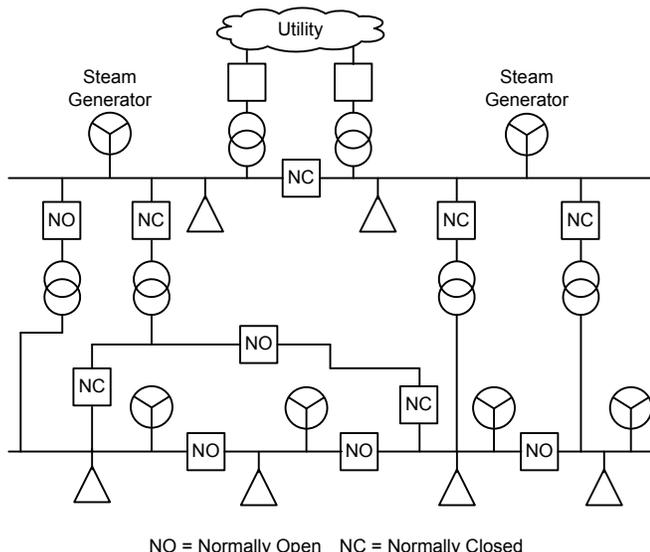NO = Normally Open   NC = Normally Closed

Fig. 6   Complex Topology Tracking

The sheddable loads have dozens of paths from which power can flow at these UF locations. This creates the unenviable problem of having to keep track of thousands of disconnects and breakers in order to properly select loads on the correct bus. To accomplish this, topology tracking algorithms are employed to monitor every island occurrence and then allocate all sheddable loads to each island. As can be expected, this requires extensive equipment, processing power, code, and testing [4] (and was previously referred to as a topology tracking problem). Because the UF triggers had to be combined with a topology tracking algorithm typically reserved for CLSPs, this form of UF load shedding is referred to as hybridized UF. The ICLT method provides superior functionality for sites such as this and can provide labor and cost savings.

V. ICLT ALGORITHM

This section explains how the ICLT method works.

In Fig. 1, identical multifunction relays are located at each generator and sheddable load. All multifunction relays are set with the same UF and OF set points and time delay, which means that all relays have identical UF and OF settings.

There are two UF levels, two OF levels, three $d\omega/dt$ negative levels, and three $d\omega/dt$ positive levels, as shown in Table II (and later in Fig. 7). All relays communicate the detection of any UF event to a centralized ICLT controller. Inside this controller, all UF events are queued and buffered into an array and then examined by their time of event. The

subsequent events are sent to a load reduction calculation. Because the load-shedding scheme must be able to operate in a few power system cycles, this scheme necessitates that all UF trigger information be updated at the controller at a minimum sample frequency of 250 Hz (4-millisecond sample time). The UF events must also be time-tagged by the multifunction relays, and all the relays must be time-synchronized to 1 millisecond or better.

TABLE II
DISCRIMINATION TABLE

Supervision Level	$< (d\omega/dt)d1$	$< (d\omega/dt)d2$ & $> (d\omega/dt)d1$	$> (d\omega/dt)d2$	$< (d\omega/dt)u1$	$< (d\omega/dt)u2$ & $> (d\omega/dt)u1$	$> (d\omega/dt)u2$
UF1	K	J	I	NA	NA	NA
UF2	N	M	L	NA	NA	NA
OF1	NA	NA	NA	H	G	F
OF2	NA	NA	NA	E	D	C

The theory of this operation is based on the principle that the decay rates of islanded segments of power systems are all different. For example, if a power system islands into two pieces, the probability of both pieces decaying identically in frequency is remote because this requires perfectly matched generation and load difference. Often, one island goes up in frequency and the other down. If both islands decrease in frequency, their rate of change is different. The likelihood of both systems crossing the same UF boundary at the same millisecond time interval is even more remote. Thus, through proper time-stamping and rapid data acquisition, the centralized controller discriminates which loads are together on the same island. Therefore, this system provides guaranteed identification of loads and allocation to the proper island.

To make the allocation of loads to the proper island guaranteed, time-synchronized phasor measurements, such as IEEE C37.118 synchrophasors, are optionally used. Thus the synchrophasor angle of each load is sent to the centralized controller, and all the power system islands are positively identified [5]. This island discrimination technique further supervises the selection of loads to shed in the controller. Synchrophasor load angle is mandatory for a large utility application of this new scheme because of the large impedance, power transfers, and inertias involved. Smaller islanded power systems do not typically require this additional sophistication. This ICLT method expands the already large usage of synchrophasor technology [2].

H tracking of the power system is estimated by the summation of the inertia of the largest-inertia devices in a system. The H of a power system is grossly dominated by the inertia of the generators and large sheddable loads. By positively identifying which generator and load are attached to each islanded grid section, the algorithm determines the approximate power system inertia and then solves (3) based upon the trigger information coming from the protective relay.

Load composition tracking is accomplished by user-entered percentages of load type (IMs, SMs, VSDs, electronics, and so on), which are further allocated to each sheddable load. The accumulation of sheddable loads that are triggered then identifies the average load composition.

Incremental reserve margin (IRM) values from each generator are accumulated to determine a total IRM value for the island in question. This allows the algorithm to shed less load than that required to satisfy (3) and still guarantee frequency recovery. The concept of IRM is especially critical for many industrial power systems [1].

Two implementations of this ICLT scheme are available: a digital formulation and a hybrid synchrophasor formulation. The remainder of this paper focuses on the digital formulation of the controller because the synchrophasor formulation will more commonly be used at the utility level and the digital at the industrial level.

Note that only a small amount of data is required: eight status bits from relays monitoring generators and six status bits from relays monitoring sheddable loads. Relays at the generators have two UF levels for H tracking of load shedding. They also have three $d\omega/dt$ elements that are supervised by two OF elements for generation shedding. Relays at the sheddable loads have three $d\omega/dt$ levels that are supervised by two UF levels. All relays have a single trip signal coming from the ICLT controller.

The load reduction calculation then takes into account the amount of load to be shed (MW) for each level based on the solution of (3). Once the amount of load (MW) to shed is selected for any event, the load to shed is selected based upon the priority of loads and the current power consumption of each load (MW). The user can alternatively enter MW values into the algorithm should dynamic metering not be possible (as is common in partially commissioned plants that are just starting up). From this calculation, an array of loads is selected to be shed and the loads are tripped by communicating back to the relays that detected the UF or OF. The whole sequence of operation, from event detection to tripping contacts closed, takes less than 20 milliseconds for most systems.

Generation shedding and/or the runback decision process is similar to that of load shedding, with the exceptions that action table techniques instead of direct priority lists are most commonly used and that OF instead of UF triggers are employed.

A. Practical Setting of dω/dt and 81 Elements for an Islanded Power System

Fig. 7 depicts the most common method for setting this ICLT appliance. These settings are for an industrial power system with a utility tie and on-site generation.

Above 62.5 Hz and below 57.5 Hz, generators, VSDs, and large DOL motors trip offline. Between 59 Hz and 61 Hz, the connection to the utility is maintained and no load shedding is desired. Below 59 Hz and above 61 Hz, the industrial plant separates from the utility and goes into a self-imposed island condition. This relies on the ICLT appliance to shed or run back generation between 61 Hz and 62.5 Hz (labeled A in

Fig. 7). This also relies on the appliance to shed load between 57.5 Hz and 59 Hz (labeled B).
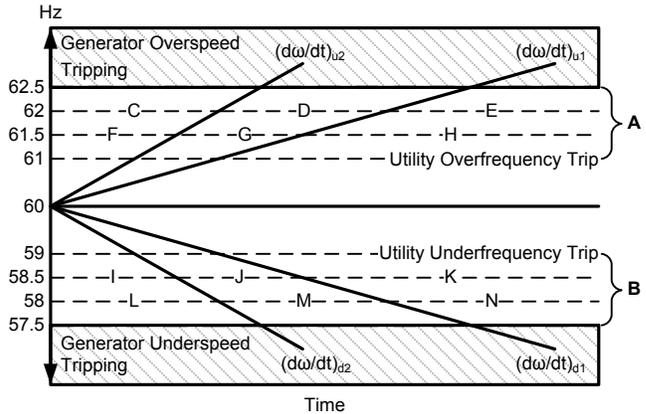
Fig. 7   Typical Industrial Settings for the ICLT Appliance

As shown in Table II and Fig. 7, the UF and OF zones are segmented by three $d\omega/dt$ zones each. More are possible, but they do not add much value, in the authors' experience. Based on practical limitations in the certainty of the $d\omega/dt$ measurement, these three zones need to be equally spaced apart (the $d\omega/dt$ levels must not be close to each other).

Generic $d\omega/dt$ settings are provided for large-, medium-, and small-sized facilities; however, these $d\omega/dt$ settings can be highly refined by dynamic stability studies. Detailed guidelines for setting UF and $d\omega/dt$ levels are provided by the ICLT system manufacturer.

There are two UF thresholds and two OF thresholds to prevent misoperation and to drive frequency lockouts. These thresholds are best selected to be equally spaced in the A and B windows of operation shown in Fig. 7. The supervision levels must not be close to the upper or lower boundaries of operation, and they cannot be close to each other.

Note that large numbers of UF and OF threshold levels are appropriate for large-inertia, slow-moving systems only. Industrial systems with fast frequency decay rates gain nothing by having more than two levels, especially considering the inertia and load composition tracking of the algorithm.

B. Implementation at Medium-Voltage (MV) and Low-Voltage (LV) Buswork and VSD

Each large, multimegawatt DOL machine has a significant protective relay with UF and $d\omega/dt$ elements. This protective relay should be used to protect the machine and provide ICLT protection.

For LV loads, load metering has become increasingly less expensive with the recent innovations in smart motor control center (MCC) devices. Better-quality, more programmable LV relays are increasingly available on the market. Use LV relays to gather load MW information, and use a single relay at each LV incoming bus to capture the UF and $d\omega/dt$ signals.

VSDs at both MV and LV are common sheddable loads. Place a protective relay upstream from the VSD to monitor frequency and $d\omega/dt$. A trip contact output from this relay is

then wired directly to the emergency "stop" input command on the VSDs. Should the user have a field-oriented controlled VSD with regenerative braking, the load energy can be added into the IRM availability calculation within the controller.

C. Relay Selection

For the scheme to work reliably, all relays used to trigger the UF signals must come from a single manufacturer and from a single generation of relaying product. The filtering and frequency tracking of relays from different manufacturers, and even between products from a single manufacturer, can be very different. Results from the authors' past relay evaluations are typified in Fig. 8.
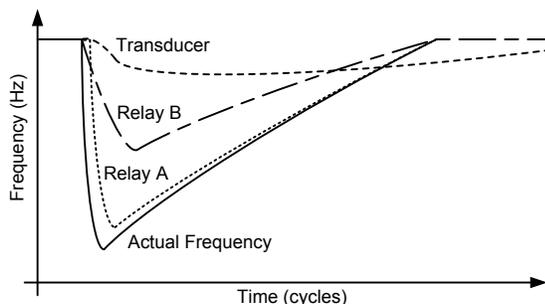

Fig. 8 Example of How Frequency Tracking Varies by Manufacturer

VI. CONCLUSION

The following points capture the essential takeaways about the ICLT method for preventing blackouts:

- The total cost of an ICLT system is significantly less than a comparable contingency-based scheme.
- An ICLT scheme universally sheds load and generation as required to prevent blackouts.
- All UF, OF, and dω/dt elements and pickup times are identical in all of the relays. They never need coordination or changing.
- An ICLT system requires no topology tracking because of frequency-based island detection.
- Modifying the priority of loads and generators to shed is a simple matter.
- An ICLT system accurately determines load- and generation-shedding amounts with dynamic inertia and load composition tracking.
- An ICLT system acts as a steam load-shedding preservation system.
- Placing protective relays at every sheddable load and generator provides a complete ICLT system.
- An ICLT system uses completely independent algorithms and hardware from contingency-based load-shedding schemes.
- Industrial facilities that require minimal frequency deviations still require a contingency-based load-shedding scheme.
- An ICLT scheme is acceptable as a standalone load- and generation-shedding scheme for an end user that can tolerate larger frequency swings.

VII. REFERENCES

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VIII. VITAE

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