

The Application of a Redundant Load-Shedding System for Islanded Power Plants

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Abstract—In order to maintain power system stability and process survivability for major system faults under a variety of system configuration topologies, the implementation of a load-shedding scheme is essential. Islanded power systems present very distinct challenges, whereby the lack of a utility interconnection hinders the system’s ability to recover from a loss of generation. In order to maintain power system stability in an islanded configuration, fast tripping and shedding of strategically selected loads in response to a specific event in the plant are the key factors governing plant survivability.

The load-shedding application presented in this paper involves a large petrochemical facility. The load-shedding system covers two process plants, one newly constructed and one existing, connected by a 12 km, 115 kV transmission line. The system contains 12 sheddable loads and can be broken into various topologies. All selectable, sheddable loads are large (approximately 15 MW) synchronous motors.

As specified by the end user, the load-shedding system has three requirements.

- Minimize process disruption
- Work under all system topologies (bus configurations)
- Operate in 60 ms or less

The load-shedding system also contains a backup, frequency-based algorithm. The combination of the two systems provides a complete solution for contingency- and noncontingency-based events.

The primary scheme uses a comprehensive power management system (PMS) that calculates predicted power deficits resulting from predetermined events (contingency based), using system inertia and governor response models for system generators. The secondary scheme is based on the pickup of underfrequency relays (conventional, frequency based). The objective of the secondary scheme is to operate based on levels of underfrequency if the system frequency drops below operator-defined thresholds.

I. INTRODUCTION

Presently, it is very challenging to control system-wide disturbances in power systems, either in utilities or industrial facilities. The objective of a power management system (PMS) is to avoid system degradation via active and reactive system controls and, accordingly, minimize the impact of system disturbances. In previous decades, load-shedding logic and subsequent control responses were ineffective due to technological limitations.

A load-shedding system requires accurate logic and control actions to achieve fast operation, particularly in islanded operation mode. Slow responses may lead to cascading outages and ultimately to total blackouts. Conventional,

frequency-based schemes act more slowly because they depend on the frequency decaying to some threshold before they operate. In some operational scenarios, the system may not be stable or able to recover the nominal frequency due to the slow response. Accordingly, blackouts may occur.

In general, the speed of any implemented load-shedding system in islanded operation mode is the key design parameter because of two main factors: system inertia and generator operating points. Because the inertia of an islanded system is relatively low, compared to a utility, a system disturbance will have a greater impact on the system frequency. Equation (1) represents the relationship of inertia to frequency in a synchronous machine.

$$J \frac{d\omega_m}{dt} = T_m - T_e \quad (1)$$

where:

J = combined moment of inertia

ω_m = angular velocity of the rotor

T_m = mechanical torque

T_e = electrical torque

Equation (1) shows that the rate of change of the frequency, or angular acceleration, is inversely proportional to the inertia, so the lower the inertia, the greater the rate of change of frequency, given a torque imbalance due to a system disturbance.

In the case of load shedding, the torque imbalance would occur because of the power imbalance caused by a loss of generation, as shown in (2).

$$\left(\frac{P_m - P_e}{\omega} \right) = T_m - T_e \quad (2)$$

The total electrical torque would be roughly equal to the mechanical torque in a steady-state system. A loss of generation would cause an increase in load on the remaining generator(s), which would increase the mechanical torque on the system. At the instant the disturbance happened, the mechanical torque would remain constant until the governor controllers started to react. This time depends on the tuning parameters of the governor control system. Accordingly, before the governor controllers start to react, a net decelerating torque (T_a), as shown in (3), will be present on the system, and the frequency will begin to decay.

$$\frac{d\omega_m}{dt} = \frac{T_a}{J} \quad (3)$$

where:

$$T_a = T_m - T_e = \text{net accelerating torque.}$$

From (3), the inertia of the power system (J) dictates the rate at which the frequency will decay—the larger the inertia, the slower the decay.

Despite the fact that inertia does play a role in power system stability, it is not simple or economical to manipulate. The most economical way of improving system stability is to equalize the generation to load (via load shedding), thereby minimizing the disturbance impact to the power system.

Using high-speed governors and turbines with quick reaction time is another method to mitigate power deficiencies; however, this is not a cost-effective solution. Further proactive techniques consist of a variety of methods to maintain capacity reserve margins, ensuring that the protective systems have enough time to react to disturbances, thereby preventing system instability.

II. ELECTRICAL NETWORK

The existing electrical network (Plant A) is isolated from any utility and consists of four combustion gas turbines and large-, medium-, and small-size compressors and pumps. The existing load-shedding scheme is a conventional, frequency-based design, where the sheddable loads are only the large-size compressors.

The new electrical network (Plant B) consists of three combustion gas turbines and large-, medium-, and small-size compressors and pumps. The two networks are connected by a 12 km, 115 kV transmission line, constituting an isolated electrical grid. Fig. 1 shows the subject electrical network.

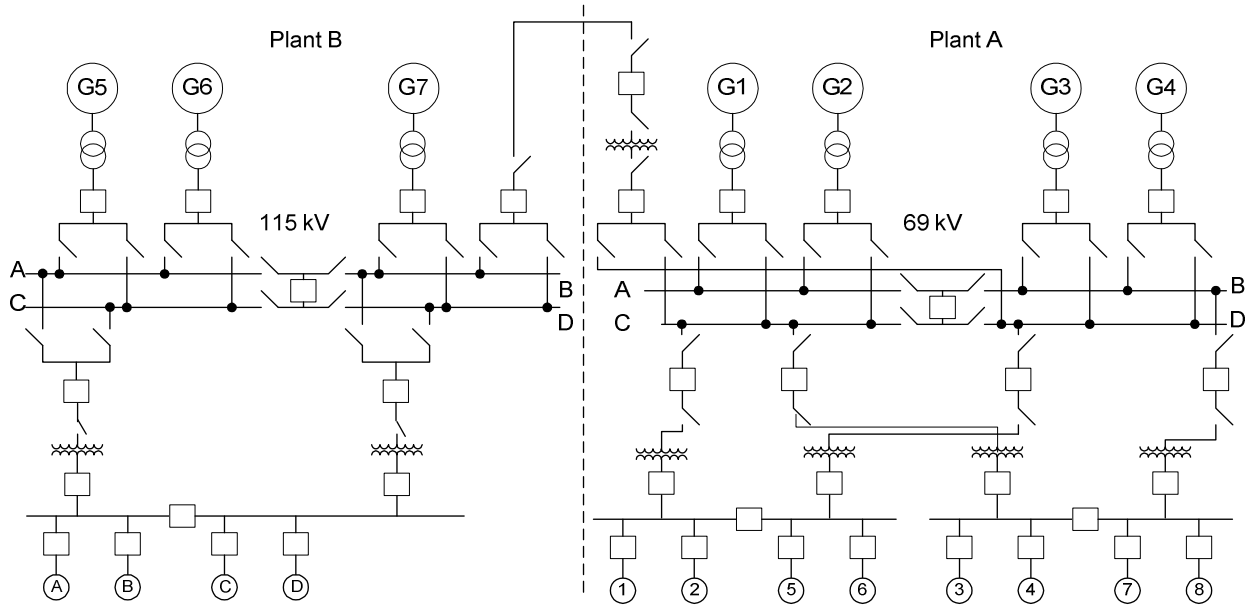


Fig. 1. Electrical Network Under Review

In order to maintain the new system's stability and reliability, a PMS was proposed. One of the system's roles is to implement an integrated load-shedding scheme. The objective of this scheme is to maintain the power supply to the plant's critical loads. In order to achieve this objective, the following design criteria were adopted:

- Fast load shedding to avoid frequency excursions at levels that cannot be recovered.
- Selectable load shedding to shed loads in the same disturbed facility. For instance, if a disturbance occurs in Plant A, load will be shed in the same plant to facilitate operational coordination.

Based on the design criteria, a contingency-based load-shedding system was adopted as a primary defense. The contingencies are primarily established based on the loss of generation unit, transmission tie line, or the bus coupler between the two buses.

The existing power plant (Plant A) has an underfrequency-based load-shedding system. This existing system was modified to coordinate with the new contingency-based system in terms of load-shedding steps and underfrequency set points.

III. CONTINGENCY-BASED PRIMARY LOAD-SHEDDING SCHEME

The primary load-shedding scheme implemented in the PMS dynamically calculates the load-shedding amounts for each predetermined event (contingency) and selects the individual loads to shed based on settable priorities, measured power consumption, and the present configuration of the power system. Each contingency has its own set of priorities.

A. Conceptual Architecture

The primary load-shedding scheme was designed based on the design requirements, predetermined events, and a contingency load priority list. Fig. 2 illustrates the conceptual architecture of the primary load-shedding system.

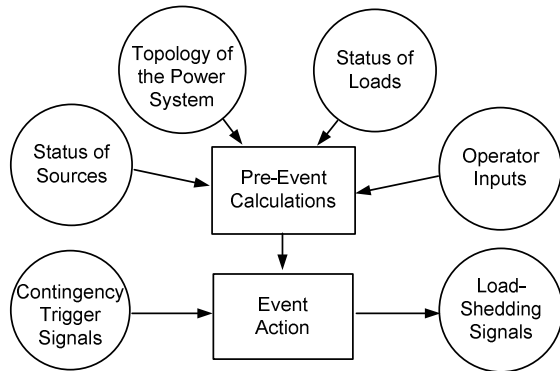


Fig. 2. Conceptual Architecture

B. Load-Shedding Contingencies

The load-shedding system was developed to respond on loss of generation, tie line, or bus coupler breakers. These events are termed contingencies and are initiated by the change of state of the breakers, trip signals, or lockout relay operation. When a contingency breaker opens under load, power may be lost to some portion of the system. In this project, the system was identified in terms of the number of contingencies that needed to be addressed. Each contingency then had its own priority list of sheddable loads. These sheddable loads were identified previously and chosen so that they would have minimal impact on the system processes, while still being large enough to adequately satisfy the load-reduction needs of the system to ensure stability. Referring to Fig. 1, a total of ten contingencies were identified:

- Generator breaker (G1 through G7, a total of 7)
- Bus-coupler breakers (2)
- Tie-line breaker (1)

Fig. 3 shows the human-machine interface (HMI) that the operators use to set load priorities for the system. In Fig. 3, each row in the DESCRIPTION column lists the loads that are available to shed. Under LOAD SHEDDING PRIORITY, each column corresponds to a contingency that the load-shedding system is monitoring. The highlighted boxes contain a number that indicates the shedding priority of the motor load for that particular contingency. This number is settable by the operator.

BREAKER NUMBER	DESCRIPTION	LOAD STATUS	LOAD SHEDDING PRIORITY																			
			BA	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10									
S20-0335	SEPAN0008 HP GAS COMPRESSOR	NORMAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
S20-0336	SEPAN0006 HP GAS COMPRESSOR	NORMAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S20-0337	SEPAN0005 HP GAS COMPRESSOR	NORMAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S20-0338	SEPAN0004 HP GAS COMPRESSOR	NORMAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S20-0339	SEPAN0003 HP GAS COMPRESSOR	NORMAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S20-0340	SEPAN0002 HP GAS COMPRESSOR	NORMAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S20-0341	SEPAN0001 HP GAS COMPRESSOR	NORMAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S20-0342	SEPAN0011 HP GAS COMPRESSOR	NORMAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S20-0343	SEPAN0004 HP GAS COMPRESSOR	NORMAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S20-0344	SEPAN0005 HP GAS COMPRESSOR	NORMAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S20-0345	SEPAN0006 HP GAS COMPRESSOR	NORMAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S20-0346	SEPAN0008 HP GAS COMPRESSOR	NORMAL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Fig. 3. HMI Load Priority Screen

C. Determination of Load-Shedding Amount

One of the most important factors in any load-shedding system is determining how much load to shed. Conventional, frequency-based schemes are inaccurate in the amount they shed because they do not consider the amount of lost generation, only the level of the system frequency. Accordingly, these schemes may not operate quickly enough, and may result in a system blackout. Alternately, the newly implemented system accurately calculates the amount of load to shed, thereby minimizing the impact on the process plants and shedding specific loads that will allow the system to recover.

The response of the remaining generation units must also be taken into account when determining the amount of load required to shed. Each generator's step-load capability must be factored in to the load-shedding algorithm. This step-load capability is determined by modeling the generator governor and simulating its step-load response to various sized load increases.

In addition, the current operating point of the generator needs to be monitored to ensure that the load-shedding system considers the active and reactive power output capabilities of the remaining generators in its algorithm. In particular, each generator has an output limit governed by the capability of the machine and the prime mover.

IV. UNDERFREQUENCY-BASED SECONDARY LOAD-SHEDDING SCHEME

As a backup system, the underfrequency load-shedding scheme is applied by using the pickup of underfrequency relays. If the system frequency falls below a certain threshold, load shedding will be initiated via pickup of the underfrequency relays.

A. Existing Load-Shedding Scheme

The existing load-shedding system in Plant A is conventional, where frequency relays at the incoming switchgear are used to execute the required load shedding. The load-shedding scheme in Plant A can be summarized as shown in Table I.

TABLE I
LOAD-SHEDDING SEQUENCE IN PLANT A

Load-Shedding Step	Load	Underfrequency Trip Level	Time Delay
1	Motor 6 Motor 5	59 Hz	No time delay
2	Motor 4 Motor 3 Motor 2 Motor 1	58.7 Hz	No time delay

For the selection of the underfrequency load-shedding scheme, a trial-and-error procedure was applied to develop the best combination of number and size of loads to shed. One combination of the load-shedding amounts and underfrequency settings was studied through dynamic simulation.

Considering both upper and lower thresholds, this scheme evenly divides each motor load into 4 groups and evenly divides the thresholds between minimum and maximum levels.

The selection of underfrequency delay (or pickup) times is primarily based on the security, accuracy, and noise levels in the frequency measurement. Secondly, the minimum underfrequency delay time is selected based on the short duration frequency disturbances caused by short-circuit and motor-starting conditions. The upper constraint on the selection of pickup time is predicated by system inertia and the frequency band between pickup levels. Based upon these considerations, if both power plants operate separately, the pickup time of 0.1 seconds for all load-shedding steps is proposed through the simulation case studies.

In addition, the proposed underfrequency load-shedding scheme of Plant B could be integrated with the existing load-shedding system in Plant A. In this case, the scheme had been designed to assign two different time delays in Plant B based on whether the tie-line breaker connecting the two plants is closed or opened. If the tie-line breaker is closed, paralleling Plant B with Plant A, then the pickup time is set to 0.3 seconds to coordinate with the backup underfrequency load-shedding scheme in Plant A.

Table II illustrates the selected load-shedding scheme to protect overload condition and accordingly maintain system stability whether the two plants are separated or connected.

TABLE II
UPDATED LOAD-SHEDDING SEQUENCE FOR BOTH PLANTS

Freq. Pickup (Hz)	Plant A		Plant B		
	Sheddable Load (Syn. Motors)	Time Delay (s)	Sheddable Load (Syn. Motors)	Time Delay (s)	
				Tie CB Open	Tie CB Close
59.0	Motor 4	0.1	Motor D	0.1	0.3
58.7	Motor 3	0.1	Motor C	0.1	0.3
58.3	Motor 2	0.1	Motor B	0.1	0.3
58.0	Motor 1	0.1	Motor A	0.1	0.3

B. Updated Load-Shedding Scheme

The incremental load-shedding amounts and underfrequency settings were determined through case studies to ensure the best probability that the system would remain stable. The amount of load shedding was decided based on the system overload conditions with respect to system operation conditions.

The underfrequency load-shedding scheme must be coordinated within the operating limitations of the generator and motor loads with respect to low-frequency operation. The continuous operating condition of the gas turbine is between 59 and 61 Hz, and the lower threshold for underfrequency step selection must be greater than the generator protection setting (57.5 Hz). It must also be greater than the damage point of all synchronous and induction motors. The lowest and last step of underfrequency load shedding should be set at least 0.5 Hz above the damage point of all synchronous and induction motors. Accordingly, this criterion selects the lowest step at an underfrequency level of 58 Hz.

The upper threshold for underfrequency step selection must be properly coordinated with the incremental reserve margins of the primary (contingency-based) load-shedding system. Accordingly, 59 Hz is selected as the upper threshold.

V. COMMUNICATION FOR CONTINGENCY-BASED LOAD SHEDDING

As technology expands and the speed of communication becomes faster and more reliable, industries that are not in a position to be on the experimental edge continue to adopt time-proven methods. The proven technologies tend to stay static for years before their once experimental phase matures into the robust and reliable phase. This point tends to become a major paradigm shift for companies that have relied on one set of technologies and realized a new set of technologies can accomplish the same job more efficiently. The recent introduction of the IEC 61850 standard has become the latest turning point at which the tried and true serial communications are often successfully supplanted by Ethernet-based technologies. The utility community is seeing a growing acceptance of Ethernet communications and IEC 61850 throughout the substation for data acquisition, automation, and some protection functions.

A. High-Speed Data

High-speed data need to be communicated every 2 ms. High-speed data involve all information concerned with the trip signals or breaker operations that isolate generation from the system, as well as the trip signals initiated to trip load offline. Consider the operation of a generation breaker. When this breaker operates, generation is immediately lost, and the system capacity is reduced by roughly the amount the generator was supplying to the system. Once this generation is lost, it is of the utmost importance that enough load be removed from the system to maintain system frequency. Given this requirement, it becomes obvious that both the indication that generation has been lost and the corresponding trip signals to the loads selected to shed must be transmitted quickly and securely. If the loss of generation is not detected quickly enough or the trip signals are slow to arrive at the chosen loads, then the system may not be able to recover, or, more likely, an underfrequency backup scheme will operate.

B. Low-Speed Data

Low-speed data are communicated about every 1 second. Low-speed data encompass all information that, while important for calculation of various set points within the load-shedding system, does not change frequently enough nor suddenly enough to warrant the need for high-speed transmission. These values include MW flow, disconnect switch status, load consumption, etc. These values are used to arm the load-shedding system, but the high-speed data actually trigger the system to operate. Because these low-speed data play no role in the triggering of the load shedding, they can be updated less periodically.

C. Engineering Access Traffic

Engineering access traffic is information that is not associated with the actual real-time operation of the load-shedding system but permits the retrieval of historical monitoring and configuration information from the system. These data are not speed-critical but can require a higher bandwidth due to the amount of information being transferred. Frequently used engineering access traffic includes event report retrieval, Telnet access to individual relays within the system, remote desktop services, and ad hoc diagnostics.

D. Combining the Three Types

Traditional serial communications require three separate communications channels to transport the three separate types of necessary data. Not to mention, when dealing with systems that are as critical as a load-shedding system, redundancy is nearly always required. This means a minimum of six communications channels with the proper redundancy must be available for the load-shedding system to be functional. For communications channels within a substation, adding more channels is as easy as running a cable to each device. When building a substation from the ground up, proper planning and system specifications make this issue a triviality compared to the overall system. However, as was the case with this project, communication between substations becomes more of a challenge.

With two substations separated by 12 km, more communications channels mean more cable runs or fiber over those 12 km of transmission line. This is often not feasible, and, as was the case with this particular project, only two pairs of fiber were allotted for all communications between the two substations. Given this restriction and the original intent of using high-speed serial communications for the high-speed data, the obvious choice was to install a multiplexer to combine the different data and send one data stream across a pair of fiber. Using this method, installing two multiplexers at each end carrying identical data streams across the two pairs of fiber allowed for redundancy of the system. See Fig. 4 for the serial communications architecture of a nonredundant system. A redundant system would have a total of two multiplexers on each end, and each device would be connected to both.

VI. SERIAL COMMUNICATIONS

While this architecture was, at least on paper, a viable option, an uncomfortable uncertainty existed with regard to the use of multiplexers. Two concerns immediately came to the surface—determinism and reliability. Reliability always plays an important role when it comes to designing systems, especially systems for refineries, where massive amounts of money are dependant, to a large extent, on the ability to keep the electricity flowing. Multiplexers are largely used for communications purposes that can rarely be classified as critical and are designed and manufactured accordingly. To that extent, serial multiplexers are efficacious in what they are designed for, but what they are designed for, in most instances, does not include high reliability within extreme environments. Not to mention, with the current trend of Ethernet and other high-speed data communications, serial communications products are becoming less and less available.

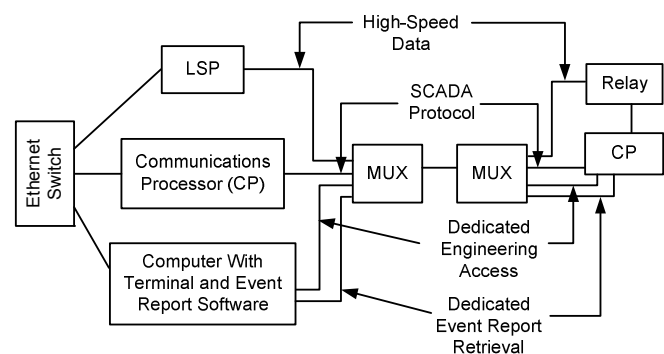


Fig. 4. Nonredundant System Architecture

Determinism was also a very important consideration. It is extremely important that when high-speed data are sent from one end or the other, the data arrive at the other end 100 percent of the time, without worry of retransmissions, being held in queue, or simply getting lost or corrupted. If high-speed information is sent, then it must, under all circumstances, make it to the other end reliably and in a timely fashion. This takes extensive testing and collaboration with

the multiplexer manufacturer in order to guarantee the performance required for the system.

Considering all of these requirements, multiplexers have still found their way into the utility protection arena and have performed as well as could be expected. However, Ethernet communications have begun to reach a maturity where utilities are more accepting and able to rely on their performance, and, therefore, are making them a larger piece of their system communications schemes.

VII. ETHERNET COMMUNICATIONS

While serial communications remain widely used throughout the communications world, Ethernet communications are becoming more prevalent for substation communications. Serial communications are sure to remain because dedicated point-to-point, high-speed, secure, low-overhead protocols are still the preferred standard for protection communications. However, Ethernet is taking hold in this realm as well.

The IEC 61850 standard includes a high-speed, multicast protocol: GOOSE messaging. GOOSE messaging is an Intranet-only routable, OSI Layer 2, broadcast/subscription, Ethernet-based protocol that evolved from the UCA2 GOOSE messaging protocol. GOOSE is not an IP (Internet Protocol) message. It is restricted to routing among network addresses on a LAN or Intranet. GOOSE cannot be routed between networks across a WAN or Internet. It can be deployed similar to traditional point-to-point protocols or among switched Ethernet LANs and is very useful in some protection-type applications. In particular, it is ideally suited for this load-shedding application, because it is sufficiently fast and, being an Ethernet protocol, it can run on the same communications line with several other protocols.

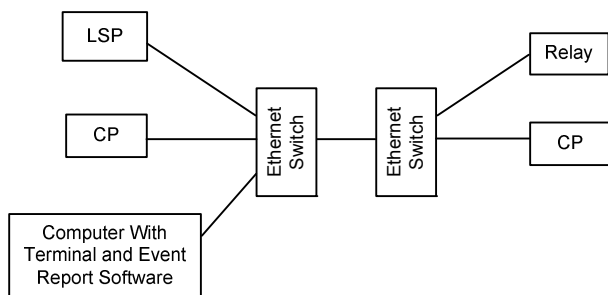


Fig. 5. Ethernet Network

VIII. THE DECISION BETWEEN SERIAL AND ETHERNET

The proposed load-shedding system called for redundant communications. For this redundant communications ring, we were provided with two pairs of optical fiber. With this in mind, we were restricted in that all communications had to use one communications path. Considering this, we were faced with two options, multiplexing the serial data or changing over to Ethernet.

It is important to note that other options do exist, namely wireless, for the transmission of data over 12 km. The two substations are within line-of-sight with no obstructions, so this would be an ideal application for spread-spectrum radio or similar technologies. However, in this particular case, the area may encounter sand storms, which would be more than enough to disrupt the signal and stop communications. Considering this possibility, the system architecture was limited to wired communications solutions only.

Economically speaking, the multiplexed serial data would have required the purchase of four multiplexers, as opposed to Ethernet, where there were already switches installed at each substation. However, each switch would need to be supplied with cards for 9-micron fiber-optic cable connections. Regardless, the Ethernet cards were roughly one-fourth of the cost of the multiplexers. In terms of reliability, the addition of more hardware inherently decreases the reliability of the system.

While the addition of the 9-micron Ethernet cards to the switch was technically no different than adding multiplexers to the system, in terms of the hardware added, the Ethernet cards are rated for extreme environmental conditions, whereas the multiplexers are not. In the end, in terms of both reliability and cost, moving to Ethernet communications not only became a feasible alternative, it looked to be a better alternative than the original design, considering the limitation of the physical communications paths that was allotted.

IX. SYSTEM ARCHITECTURE

The system is segregated into two halves, local and remote. As mentioned earlier, the remote substation is located 12 km away from the local substation. The load-shedding system algorithm is centralized on a computer with a Linux[®] operating system, referred to hereafter as the LSP (load-shed processor), at the local substation. Data collected from the field intelligent electronic devices (IEDs) are concentrated in a communications processor and sent via unsolicited messaging to the LSP. These data consist of the low-speed data discussed earlier, breaker and disconnect switch statuses, and meter analog values. These data are gathered by the LSP and used to perform system calculations to decide if generation is lost on the system, how much, if any, load should be shed, and which loads are selected. Low-speed data (data sent by the communications processors) are essentially used to calculate the reaction in the event of lost generation. High-speed data communicate what event has occurred (the tripping of a generation breaker, tie line, etc.) and send the commands to trip the required load.

Because the LSP resides in the local substation, all relays communicating these high-speed “event” data can communicate serially. Premade fiber-optic patch cable can be used between the local relays and the LSP, making it possible to connect all the relays providing high-speed data. These serial connections were one of the preexisting design choices that did not need to change. However, the need for the high-speed Ethernet GOOSE protocol became evident when gathering and transmitting high-speed data from the remote substation.

Because these low- and high-speed data, along with Telnet-type engineering access traffic, can coexist on the same communications line, Ethernet is the prime choice for this application. See Fig. 6 for the Ethernet system architecture.

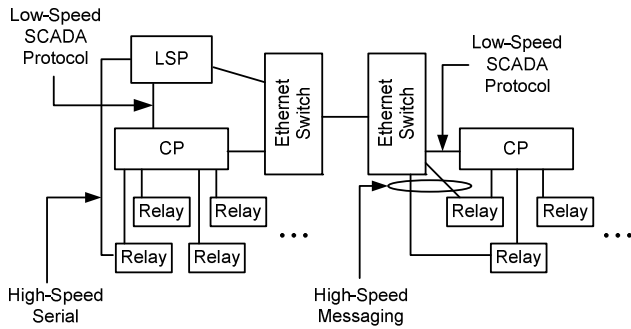


Fig. 6. Ethernet System Architecture

The sequence of events for a typical load-shedding event would initiate upon the opening of a generation breaker or the receipt of a trip signal from the tripping relay associated with a generation breaker. This breaker status, or trip status, would be sent via high-speed serial communications in the case of an event occurring in the local substation and via Ethernet GOOSE in the case of the remote substation, and then received at the LSP. The LSP receives and processes this signal and issues **TRIP** commands to the relay outputs of the loads that have been selected to shed. Fig. 7 is typical of the local substation where the high-speed serial communications are used.

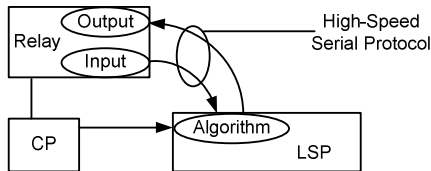


Fig. 7. Basic Function of the LSP

Fig. 8 illustrates the path the trip signals originating from the remote substation must follow. Because of the intermediary Ethernet link, the data path is not as direct as within the local substation. This Ethernet segment, while still fast enough for our application, does slow the overall response of the load-shedding system. This issue will be addressed later.

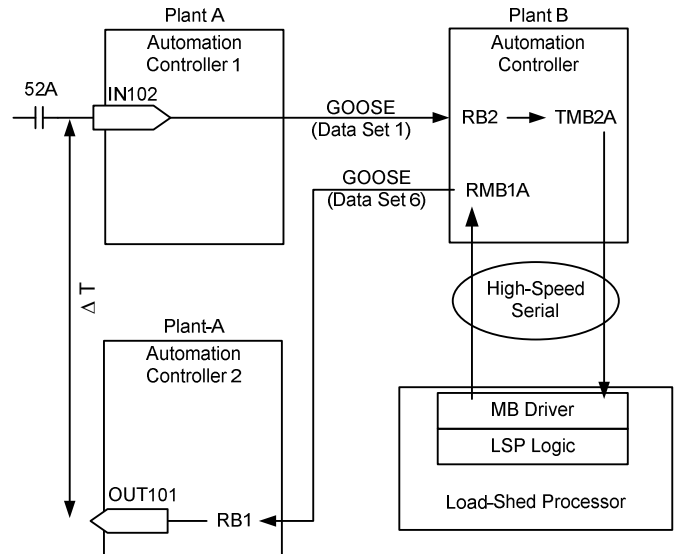


Fig. 8. General Architecture

A. Why Timing Is Critical

Load shedding is becoming a more popular protection-type functionality. Until recently, load shedding was not capable of being done quickly by today’s standards, but faster computer processors and data communications have allowed industries to begin investigating subcycle load shedding.

The purpose of load shedding is to protect a system in the event of lost generation and help the system to maintain stability and system frequency. When generation is lost, if the remaining generation is not capable of outputting additional power to make up for the deficit, the system frequency will eventually decay beyond recovery and collapse. However, if a system is in place that can calculate exactly how much power will be lost and how much the remaining generation can supply in addition to what it is currently supplying, the LSP can then calculate how much load must be shed in order for system frequency to maintain stability. This is the essence of a load-shedding system: to calculate the effect a loss of generation would have on a system and then determine how much, if any, load should be shed to maintain stability.

In a modern, high-speed, load-shedding system, the load-shedding algorithm is being processed quickly enough that dynamic system decisions can be processed and operate in times under 16 ms. Not only can it be processed in under 16 ms, but the trigger that initiates the process, the process itself, and the receipt of the output of the process are transmitted in less than one power cycle. Traditional automated systems would require significantly longer times to process data and make a dynamic decision based on these data. Technology now allows us to not only process this information but communicate it to the necessary hardware, which could be separated by larger distances, to take corrective action. Such technological capability becomes a veritable panacea for power stability related issues.

In the case of load shedding in particular, the load-shedding system must be coordinated with backup under-frequency protection schemes so that the system frequency never falls below the underfrequency threshold. The time that

it takes for the system frequency to decay to this point is largely dependent on the system makeup. Systems with large system inertia and a large composition of synchronous machines have the benefit of their system frequency being held up by the sheer inertia behind those machines. Therefore, the frequency with large system inertia will not decay as quickly as a system with smaller generators, induction motor loads, and resistive loads.

Load-shedding systems act as large, wide-area, protective relays, thereby blurring the line between automation and protection systems. Not very long ago, automation and protection were completely separate functions. An automation group at an industrial plant or utility would work on applications involving remote control of the system and data acquisition, and the protection group would focus on high-speed protection of the system assets. Now, automation schemes are being coordinated with protection schemes, bringing both groups together. In the case of load shedding in particular, the protection engineers complete detailed studies of how robust the system is in response to a loss of generation. The automation engineers use that information to determine what to expect of each generator when writing the LSP algorithms.

B. Time Tests

The load-shedding system presented here has two components: a serial side and an Ethernet side. Below we will compare the performance of the two different communications types and discover how they compete with each other. As mentioned before, the Ethernet communications scheme does add time to the performance, which should be no surprise, because it is an additional path that the serial communications side does not encounter.

For an illustration of the test setup, refer to Fig. 8. Input IN102 detects a trip signal from a generator breaker. IN102 is part of a GOOSE messaging data set that triggers on change. The changing state of IN102 causes a change of state GOOSE message to be issued. The receiving device has mapped the GOOSE message to local bit RB02, which is subsequently mapped to the high-speed serial protocol transmit bit. This bit is transmitted to the LSP where it is then processed and, in turn, issues a **TRIP** command via the high-speed serial protocol. That **TRIP** command is received by the sending device and mapped to a GOOSE message to be transmitted over the Ethernet network. Once transmitted, the receiving device detects the GOOSE message, processes it, and asserts an output to trip the selected load. This whole process takes, as shown in Table III, an average of 40 ms, roughly two-and-a-half cycles. Observed timing with time-synchronized Sequential Events Recorder (SER) records has ranged from 35 ms to 42 ms.

TABLE III
ETHERNET PATH
(REFER TO FIG. 8. TIMING INDICATIVE OF AVERAGE TIMES RECORDED)

Action	Time Duration Since Previous Action	Time Duration Since Start
Trigger and GOOSE Message Publication at Plant A AC1	Start	Start
Wide-Area GOOSE Trigger Transmission		
GOOSE Trigger Message Receipt at Plant B AC	11 ms	11 ms
GOOSE-to-Serial LSP Interface		
Subsequent Serial Message Publication to LSP Within Plant B AC	4 ms	15 ms
LSP Algorithm Processing		
Receipt of Serial Message From LSP at Plant B AC	12 ms	27 ms
Wide-Area GOOSE Trip Transmission		
GOOSE Trip Message Receipt at Plant B AC	10 ms	37 ms
Trip Control Output at Plant A AC2	4 ms	41 ms

In Table IV, we eliminated the Ethernet side of the communications and rely completely on the serial communications. See Fig. 7 for a basic illustration of the test setup. An input is received and transmitted via a high-speed serial protocol to the LSP. The LSP processes the input and issues a **TRIP** command. The **TRIP** command is received by the tripping device and asserts an output. Taking out the Ethernet loop, we see greatly improved performance. We measure 13 ms from input to LSP decision to output. With the direct serial communications, we were well under one cycle.

TABLE IV
SERIAL PATH
(REFER TO FIG. 7. TIMING INDICATIVE OF AVERAGE TIMES RECORDED)

Action	Time Duration Since Previous Action	Time Duration Since Start
Trigger and Serial Message Publication at Plant A Relay	Start	Start
Wide-Area Serial Trigger Transmission		
Serial Trigger Message Receipt at Plant B LSP	5 ms	5 ms
LSP Algorithm Processing Plus Wide-Area Serial Trip Transmission		
Receipt of Serial Trip Message From LSP at Plant A Relay AC	4 ms	9 ms
Trip Control Output at Plant A Relay	4 ms	13 ms

X. CONCLUSIONS

This paper proposed and demonstrated a redundant load-shedding scheme for islanded power plants. Contingency-based load shedding is an important tool for use in a PMS. When done properly, it provides an added layer of protection that cannot be matched by conventional, frequency-based schemes. Given the current technologies available to the industry, there is a wide array of methods by which to implement such a scheme.

In addition to the primary contingency-based load-shedding scheme, the application of underfrequency relays acts as a secure secondary load-shedding scheme in the event that the primary scheme is unavailable.

Ethernet communications are becoming a viable option for protection-related automation schemes. While, with this scheme, the direct serial communications operated in one-third the time the Ethernet scheme took to operate, it should be noted that the GOOSE messages were preprocessed by another device, relieving the LSP of this processing burden. However, in distributing the processing burden, additional time was added to the overall round-trip timing. Taking the preprocessing equipment out of the equation takes 8 ms out of the transfer time for the Ethernet-based scheme. This brings the time comparisons a little closer. Where the serial communications system operates in less than one cycle, the Ethernet system operates in approximately two cycles. Both times met the specification, and the Ethernet system adds flexibility to the system and requires fewer communications lines because it is part of the Ethernet network. However, the obvious drawbacks to Ethernet-based systems are slower responses, larger computational requirements, and possibly less security.

The most important design element to keep in mind is that the hybrid serial and Ethernet system met previously set design criteria. Ethernet for remote communications provides a robust, inexpensive, and reliable method to transport high-speed, low-speed, and engineering data between stations. The Ethernet solution dovetailed into the existing system and also met the timing requirements. Future refinements may further improve timing and simplify communications, but this design satisfies all the acceptance criteria.

While it is important to address the options available within certain constraints and how this project is similar to any number of projects currently under development, it is interesting to note the paradigm shift that is occurring within the industry.

XI. FURTHER READING

N. Seeley, "Automation at Protection Speeds: IEC 61850 GOOSE Messaging as a Reliable, High-Speed Alternative to Serial Communications," proceedings of the 10th Annual Western Power Delivery Automation Conference, Spokane, WA, April 2008. Available at <http://www.selinc.com/techpprs.htm>.

R. Jenkins, D. Dolezilek, and M. Gugerty, "Case Study Comparison of Serial and Ethernet Digital Communications Technologies for Transfer of Relay Quantities," proceedings of the 33rd Annual Western Protective Relay Conference, Spokane, WA, October 2006. Available at <http://www.selinc.com/techpprs.htm>.

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XII. BIOGRAPHIES

Boungwook Cho received his BSEE degree in 1981 and his MSEE degree in 1985 from Seoul National University. He is a registered professional engineer in Korea. He has more than 20 years experience in the design, analysis, and application of power plants. He was recently involved in the design of a power management and load-shedding system for the Shaybah project for Saudi Aramco in Saudi Arabia. He joined Hyundai Engineering Company in 1985, and he is currently responsible for the electrical department of power plants group.

Heechul Kim received his BSEE degree in 1997 and his MSEE degree in 1999 from Myongji University. He has over 10 years experience in the electrical design, analysis, and application of power generation plants. He was recently involved in the design of a power management and load-shedding system for the Shaybah project for Saudi Aramco in Saudi Arabia. He joined Hyundai Engineering Company in 1999, and he is currently an electrical engineer with the electrical department of power plants group.

Musaab M. Almulla graduated from King Fahd University of Petroleum & Minerals in 1998 with a BS degree in Electrical Engineering. After graduation, Musaab joined Saudi Aramco in the power distribution department, where he was responsible for the engineering, operation, and maintenance work related to power generation and distribution at Saudi Aramco facilities, focusing mainly on relay coordination studies and generation control. In 2002, Musaab graduated from Arizona State University with a MS degree in Electrical Engineering/Power Area. In 2005, he joined the project management team at Saudi Aramco, where he has been involved in the development, design, construction, and commissioning of all electrical activities related to the power generation facilities in the Shaybah Expansion Project.

Nicholas C. Seeley graduated from the University of Akron in 2002 with a B.S. degree in Electrical Engineering. After graduation, Nic began working at American Electric Power in Columbus, Ohio, for the Station Projects Engineering group, where he focused on substation design work. In June 2004, Nic was hired at Schweitzer Engineering Laboratories, Inc. in the Engineering Services division, where he is currently an automation engineer involved in the development, design, implementation, and commissioning of numerous automation-based projects.