# Applying Intelligent Fast Load Shed Using IEC 61850 GOOSE

JC (Jacobus) Theron
GE Grid Solutions
650 Markland Street
Markham, ON L6C0M1
Canada
Jacobus.Theron@ge.com

Troy Wilsey
Ameresco
111 Speen St., Ste 410
Framingham, MA 01701
USA
twilsey@ameresco.com

Anthony Colonnese
Ameresco
111 Speen St., Ste 410
Framingham, MA 01701
USA
acolonnese@ameresco.com

Russell Gagner
Civilian, Naval Facilities
Engineering Command
Portsmouth naval shipyard
Bldg. 43, PWD-Maine
Kittery, ME 03804 USA
russell.gagner@navy.mil

Steven Rowe
GE Grid Solutions
7246 E 800 North
Syracuse, IN 46567
USA
Stevend.Rowe@ge.com

***Abstract –*** Industrial facilities with co-generation are in critical need of load shedding to prevent collapse of the cogeneration assets. Load shedding should be sub-cycle speed to manage thousands of distributed loads within a facility. This paper describes the capabilities of such a fast load shedding scheme spanning across a wide array of relays provided by various vendors and potentially a large quantity, and a case study system and experience of applying such a system. The fast load shed scheme described in this paper utilizes a proven system and makes it easy to configure larger and more complex load shed schemes. The paper describes the proposed architecture of a centralized fast load shed controller-based scheme interfaced with local generator/feeder/transformer/motor protection relays over IEC 61850 GOOSE. A major challenge of such a large-scale load shed scheme deployment is the configuration of devices, especially the IEC 61850 GOOSE engineering process which may add further complexity. This paper also discusses IEC 61850 GOOSE scheme configuration with high-speed performance requirements. Lessons learned from the case study fast load shed scheme deployment, testing and operations are also discussed.

*Index Terms* — Fast Load Shed (FLS), GOOSE (Generic Object Oriented Substation Event), Quality of Service (QoS), Fast Load Shed Controller (FLSC), Fast Load Shed Aggregator (FLSA), IED (Intelligent Electronic Device), Rate of Change of Frequency (ROCOF), HMI (Human Machine Interface), DCS (Distributed Control System), Infeed, Load Group.

## I. INTRODUCTION

Industrial facilities, such as petrochemical, oil & gas, pulp and paper mills and refineries, often rely on on-site generation. When an imbalance exists between the load, and the available generation due to loss of generation/utility supply, the frequency of the system will decay as the local generators begin to slow down due to the excessive load. As the frequency decays, the efficiency of the generators is affected and the ability to run the generator auxiliary system can also contribute to the problem. The frequency decay in industrial power systems with cogeneration is much faster than in traditional transmission systems. If load isn't rapidly removed from the system, a cascading effect could occur and the whole system could collapse [1], [2]. Fast Load Shed (FLS) is a special protection scheme that, in a contingency, initiates shedding of loads as required to preserve system load/generation balance thereby avoiding a complete system collapse. A contingency is the loss of one or more infeeds (local generators or incomers from the local grid). Unlike traditional under voltage, under frequency or frequency rate of change load shedding schemes, a fast load shedding scheme can initiate load shedding before the system frequency or system voltage declines significantly. The ability to shed load before the system frequency starts to decay can help the system maintain its stability. Less critical loads are shed so that more critical loads are maintained, and the industrial process suffers the minimum impact possible.

This paper will describe the capabilities of such a fast load shed system, how it was implemented in an actual system as a case study and some lessons learnt during deployment and operation of this implemented Fast Load Shed (FLS) system.

## II. IEC 61850 FAST LOAD SHED ARCHITECTURE

The capabilities of the FLS system under consideration [4], [6], [7], is a system consisting of one Fast Load Shed Controller (FLSC), zero or multiple Fast Load Shed Aggregators (FLSA) (if more than 64 infeeds and loads must be monitored), an Ethernet network and IEC 61850-8-1-capable end devices to provide fast load shedding including breaker tripping. The goal of the FLS is to re-establish power balance when source/load balance is disrupted. End devices are protective relays or meters with IEC 61850-8-1 GOOSE support. This means that the end-device must be capable of transmitting analog and digital values and receiving digital commands via IEC 61850 GOOSE.

The FLS system is a scalable architecture that can expand as the industrial facility grows and changes. The system is comprised of a main FLS controller and aggregators. A system overview and communications architecture of the FLS is shown in Fig. 1.

The FLSC is the main decision point of the system where all the calculations and intelligent commands are performed. It is a substation-hardened device with a real-time operating system that is highly reliable and accurate. The present system power flows and contingencies (active power value and offline status) is communicated to the FLSC via data messages from end devices, aggregators or both via analog/digital IEC 61850 GOOSE, of each data unit (infeeds and load groups). Each data unit represents either an infeed or a load data with power and offline status. It is capable of handling up to 32 loads/load groups and 32 infeeds, and makes the final decision to shed load in real time. Each load group can consist of one or multiple loads. The load shed commands are issued via IEC 61850 GOOSE messages to end devices.

The FLSA is an extension of the FLSC allowing for aggregation of load data and is a load shed data concentrator. It combines load data from end devices and sends this data as analog/digital IEC 61850 GOOSE to the FLSC. The FLSA does not make load shed decisions. It merely allows the FLSC to handle more than 64 data units. Each FLSA supports 64 data units acquired from end devices that are part of up to 32 load groups. Note: FLSA supports only load data units and not infeeds. Each load group can consist of multiple loads, and can be acquired via various FLSA's; not necessarily by the same FLSA. Infeeds must be configured directly to the FLSC. By connecting the aggregators in a tree-like matrix, the number of loads controlled with this scheme can reach over 2500.

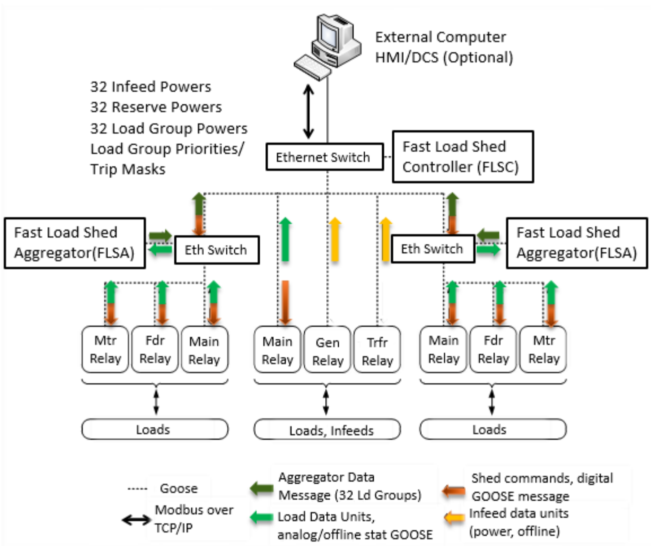


Fig. 1 – Typical FLS Scheme Communications

An FLSC is configured to shed load groups in the event of a contingency according to a set of priorities. For the purposes described here, a contingency is the loss of any one or more infeeds. A load group is a number of individual loads that are treated by the fast load shedding scheme as a single unit, allowing the FLSC to handle thousands of individual loads with a manageable number of settings. The information received by a FLSC or by FLSA in a data message about a load, an infeed or an aggregator is referred to as a data unit.

Based on settings, the information in data units, and the present priorities, the FLSC generates shed requests indicating which load groups are required to be shed by the end devices. The shed requests are transmitted to the end devices in a shed command message and the end devices do the actual breaker tripping.

The FLS system is expandable. The addition of another aggregator or FLSA connected to the FLSC extends the system by an additional 64 load data units which are part of up to 32 load groups. As an example, with 12 infeeds, 18 loads and 40 aggregators (64 loads each), the system can support 12 infeeds and 18+(64*40)=2578 shed-able loads. Minimal re-configuration is necessary in the case of system expansion.

End devices send up to six data units in a single IEC 61850 GOOSE data message to an FLSC or an FLSA. Not all the data units in a data message must be used. Infeed data units contain the measured real power flowing out of the infeed and the offline status of the infeed. Change of offline status from "Off" to "On" is an indication of the loss or imminent loss of that infeed; which is, a contingency. Load data units contain the measured real power flowing into the load and the availability status of the load for fast load shedding. Loads with availability status false are not included when calculating the amount of shed-able load in a load group. Data messages with infeed data units are sent directly to the FLSC for optimized performance and cannot be transported via an FLSA. Infeed data units trigger the FLS, hence must communicate directly with the FLSC with no additional time delay.

End devices use a configurable GOOSE message to publish data from at least one and up to six infeed or load data units. Data messages with infeed data units use fast transmission configurable GOOSE messages for fastest contingency detection at the FLSC when an infeed is lost. End devices interfacing to shed-able loads use a configurable GOOSE to subscribe to shed commands.

FLSA's send to the FLSC (or conceivably to another higher-level aggregator) a single data message. FLSA data messages contain up to 32 load group powers from up to 64 data units. Each load group power is the sum of the powers of the load data units that are available for shedding and are aggregated by that aggregator to that load group.

The FLSC sends back down an individual shed request operand for each of the load groups used by the application to the end devices, typically all in a single shed command. The shed commands are sent directly via the switched Ethernet network to all end devices and not via any of the FLSA's.

A simplified view of information exchange of the system with reference to Fig. 1 is as follows:

a) *Modbus Over TCP/IP (⟷)*. This is the communications between an optional HMI computer system, typically used to write and change load group priorities in the FLSC, and to retrieve event and operations data from the FLSC in the event of a FLS system operation. This data-exchange does not need to be fast.

b) *Infeed GOOSE Messages* ( ). This is the power (kW) and offline status of all system sources or infeeds communicated directly from generators/transformers/ feeder protection relays or meters directly to the FLSC as a IEC 61850 GOOSE message. This must be set to aggressive to ensure an offline status change will reach the FLSC as quick as possible to ensure fast action is taken when a main power source or infeed is lost.

c) *Load GOOSE Message* ( ). This is the power (kW) and offline status of all shed-able loads (doesn't have to be all loads) communicated from motors/transformers/ feeders/loads protection relays or meters directly to the FLSC or to an FLSA as a IEC 61850 GOOSE message. This data is not required to be very fast; typically, transmission time is once per second to ensure the Ethernet network won't be bogged down, and the system power loads doesn't change that quickly.

d) *FLSA GOOSE Messages* ( ). This is the power (kW) and offline status of all aggregated shed-able loads (up to 32 load groups) communicated from FLSA directly to the FLSC as a IEC 61850 GOOSE message. This message is also transmitted at once per second.

e) *Shed GOOSE Messages* ( ). This is the digital shed GOOSE command communicated from FLSC directly to all motors/transformers/ feeders/loads protection relays or meters associated with loads to be shed, to close its tripping contacts to accomplish shedding. This must be set aggressively to perform as fast as possible, since it would trigger the shedding of load.

## III. CASE STUDY FAST LOAD SHED SYSTEM ARCHITECTURE

The case study Fast Load Shed system consists of a FLSC, 38 Data Units (11 infeeds, 18 load groups) and 8 end devices located at 3 substations that publish between 3 and 5 data units each to the FLSC. Since the total number of data units is less than 64 (including allowing for a significant system expansion), an FLSA is not needed. Some end devices publish a mix of load and infeed data units (4), where others publish only load data units (4). End devices were added as part of the FLS system, since the existing protection and control (P&C) devices did not have any IEC 61850 capabilities; hence added Intelligent Electronic Device (IED)s did not perform any P&C functionalities and only FLS. The system also has an HMI which is used to change load group priorities, pull metering data from IEDs (using Distributed Network Protocol (DNP)) for system views/status and has the needed software to retrieve event files from end devices for system operational analysis. Communications architecture is as follows in Fig. 2 and simplified single line in Fig. 3. The system has 2 utility supplies from the local distribution utility, 2 gas turbines (5 MW each) and 2 diesel generators (1.8 MW each) and a battery back-up system (500 kW) installed at the power plant. Normally at least one of the gas turbines will be operational, however the diesel generators are synchronized only during islanded conditions or during testing. Total system load varied around 8 to 12 MW. Shedable loads are at the power plant and substation 2. In this scheme, some loads are automatically shed during an islanding condition since their data was not integrated into this phase of the fast load shed implementation.

## IV. DYNAMIC SOURCE/LOAD POWER BALANCING

The physics of electrical systems forces the sum of the real power generated by local generation and the real power imported/exported from the grid to precisely equal the sum of the real power consumed by the loads, always and at every instant. If a local generator is tripped, or a grid incomer is lost, the physics forces additional power to be drawn from the remaining grid incomers and local generators to match the load. Increased power flow through an incomer can overload it, causing it to trip and leading to cascading tripping and total collapse of the distribution system. Increased power flow out of a generator can cause it to slow down if the turbine/machine driving the generator cannot provide additional mechanical power rapidly enough, it will lead to frequency collapse of the industrial distribution system.

The Fast Load Shed system normally triggers if any grid incomer or co-generator trips, hence long before the system frequency or voltage can be affected by the loss of a major portion of power; hence is much more pro-active in performance to voltage and frequency based tripping schemes which are reactive.

The case study Fast Load Shed system described in Section III triggers only if both the grid incomers are lost, hence excess load will slow remaining generators down and will cause a system collapse if load is not tripped rapidly.

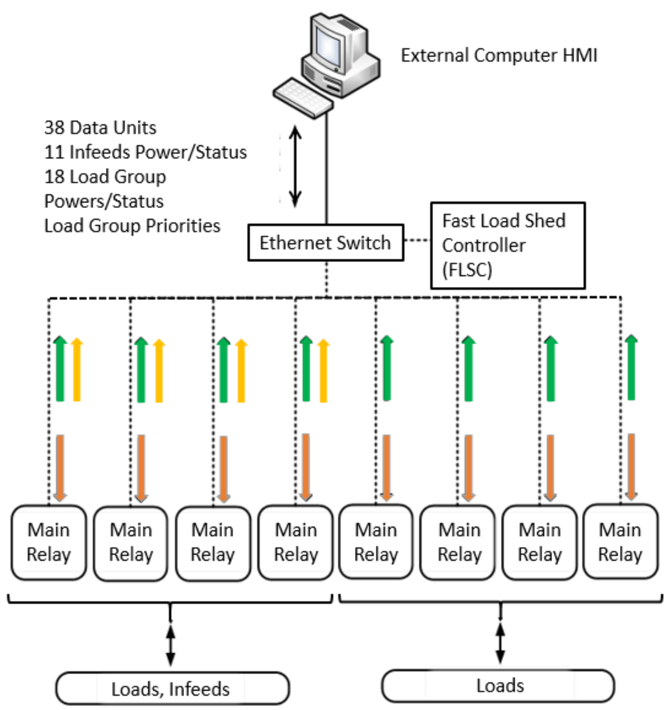


Fig. 2 – Actual FLS Scheme Communications

## V. CONTINGENCY OPERATION

When a contingency operation is triggered (by a loss of an infeed), the fast load shed controller checks if grid incomer power lost exceeds remaining generation reserve. If this situation occurs, then load shedding is performed.

The FLSC continuously calculates the load available for shedding in each load group. This value is the sum of the power of all data units that are mapped to the load group and have their availability for shedding status true (i.e. is online), plus the sum of the corresponding power values of all aggregator data units.

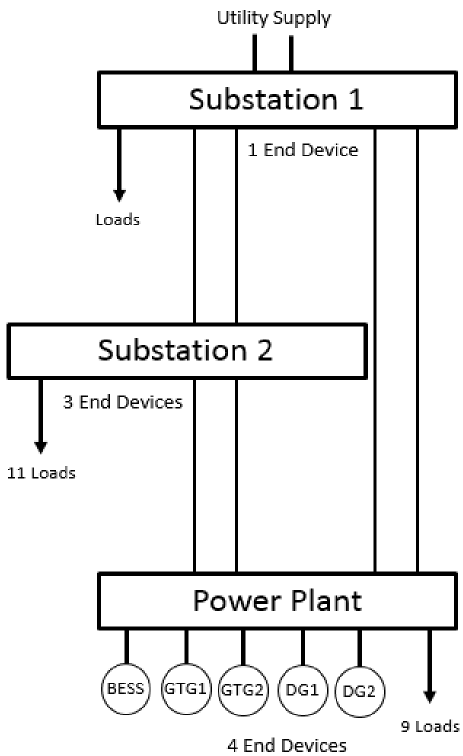


Fig. 3 – Simplified System Single Line

Using the power values of data units mapped to infeeds and various infeed settings, the FLS scheme estimates the amount of additional power (that is, reserve power) each infeed can deliver in event of a contingency. Depending on the settings, the estimation can be either based on the infeed being able to immediately supply its maximum power, or its increase by some fraction of its present power.

The steady state value of the load, infeed and reserve is estimated using the average of each of these quantities over a 10 second period. Analog values from the infeeds and load groups are typically communicated once per second to the FLSC. These steady state values are latched (frozen) when a contingency is first declared, and the latched values are used until the contingency is over and the power system is assumed to have reached a new steady state. This allows the FLSC to achieve a steady state balance between shed-able loads and infeeds. Instantaneous measurement values leading up to and during the contingency may contain unsustainable transients. For example, should an incomer open at the utility's end, and the FLSC see its power already at zero when the incomer breaker opened, the estimate of power lost would be zero were instantaneous power measurements is used.

A contingency is declared when any infeed is lost or when any programmed scenarios must trigger the FLS (For example under frequency). An infeed is deemed lost when its offline status transitions from "Off" to "On" (i.e. breaker tripped), other than due to loss of communications.

Both the infeed lost and the programmed scenario occurred creates a latched condition until the end of the contingency. Each time an infeed is initially lost or a programmed scenario initially occurs, the contingency timer is triggered or re-triggered. The contingency lasts until the contingency timer finally times out. The contingency timer has a dropout setting intended to be set long enough that on timeout the power system should be in a new stable state. Dynamic system studies might be necessary to determine how much time the local power system would need to re-establish balance, before the FLS is allowed to re-trigger.

The FLSC moment-by-moment calculates the amount of load of each load group and monitors each infeed to determine if shedding is required if an infeed is lost, which is called the load shed value. A load shed value is calculated when the FLS gets triggered due to the loss of one or multiple infeeds, and is the sum of the steady state values of all lost infeed powers, less the sum of the steady-state reserves of all infeeds not lost. The load shed value is the amount of load shedding required to restore the balance between infeeds and loads. A load shed value less than zero indicates no shedding is required, and typically occurs in an over-generated islanding condition.

When an infeed is lost, sufficient shed requests are set and latched by the FLSC, such that the sum of the latched steady state load group load values just exceeds the load shed value. Load groups with lower priorities are shed in preference to load groups with higher priorities. Load groups with priority set to zero are not used, hence not shed. Load groups having the same priority are all shed when any needs to be shed. If a second infeed is lost (that is, should there be a multiple or evolving contingency), the above calculations will result in the load shed order increasing, and in general the number of shed requests also increase.

The FLS algorithm does not need to monitor non-shed-able loads. However, all infeeds whose loss can cause a significant power imbalance or that can supply significant reserve should be monitored.

The shed requests are sent to the end devices in the shed command IEC 61850 GOOSE messages described earlier and the end devices shed the loads in the requested load groups by initiating breaker tripping. When no new infeeds have been lost and no new scenarios detected for a period of time (that is, when the contingency timer expires), the above-mentioned latches are reset, terminating the shed requests.

Load group priority changes and their writable actual values received during a contingency are not implemented and used by the FLS until the contingency is over. Implementing any changes would result in both the shedding called for in the pre-update settings and the shedding called for in the updated settings being requested, which could possibly cause more load shedding than necessary.

In case of generation loss or power unbalance, IEC 61850 GOOSE messages are sent to shed enough load per pre-defined priorities greater than available generation reserve.

Load priorities can be changed or updated via an HMI within one second. The pre-defined priorities of the load shed system basically consist of a table that defines the order in which loads should be shed. This allows the system to prioritize the loads to be shed between non-essential and essential process loads.

Priorities are numbers assigned to each load group used by the FLSC on the relative importance of the load groups; highest priority number would be shed first. The ability to change the load priorities allows the user the flexibility of dynamically changing the priorities based on the priority of each facility processes during normal system conditions.

Fig. 4 is a simplified system example illustrating the load shed priorities and how shedding is determined.

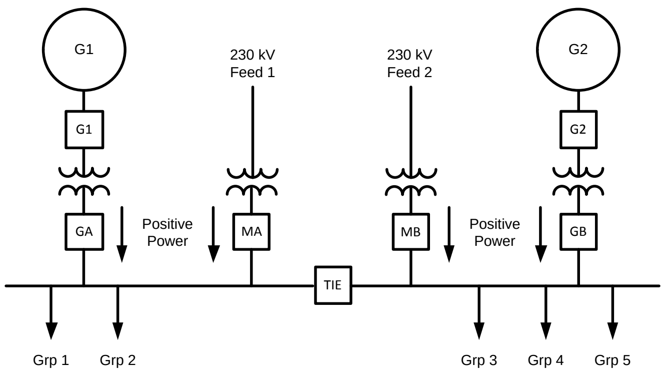


Fig. 4 – Simplified Source-Load Example

In Fig. 4, the total system load equals the sum of all the system power loads (PGrp1 + PGrp2 + PGrp3 + PGrp4 + PGrp5). The total source/generation equals the sum of system sources (PG1 + PG2 + PMA + PMB).

For example, if the industrial facility were to set the load group priorities shown in Table I and a loss of 9MW of generation with no generation reserve, the scheme will trip load groups 3 and 5 for a total of 10MW.

TABLE I
LOAD GROUP PRIORITIZATION FOR SIMPLFIED SOURCE-LOAD EXAMPLE

| Asset | Value | Priority/Status (user set) |
|---|---|---|
| Group 1 | 10 MW | 1 (highest priority) |
| Group 2 | 10 MW | 0 (do not shed) |
| Group 3 | 5 MW | 128 (lowest priority) |
| Group 4 | 20 MW | 2 |
| Group 5 | 5 MW | 3 |

* Load Prioritization (as set by end-user) – higher numbers mean lower priority loads.

If the industrial facility were to set the load group priorities shown in Table I and a loss of 40 MW of generation with 15 MW of generation reserve (at least 25 MW must be shed), the scheme will trip load groups 3, 5 and 4 (priorities 128, 3 and 2) for a total of 30MW. Shedding of all these load groups will be simultaneous.

IEC 61850 GOOSE data message to be received by the FLSC are monitored by the FLSC by maintaining a "Time-Allowed-To-Live" timer for each of the data unit messages expected to be received. This timer is reset to the "Time-Allowed-To-Live" value received in each data message containing that data unit. A loss of connection is declared if this timer ever times out, and the FLS initiates a communications trouble alarm, sets status operands to "On" and sets the data unit power value to zero in the event that communications was lost with an end-unit. The FLSC uses the values of the communications trouble alarm and the resulting change of offline status to "On" (i.e. declare it as unavailable) to inhibit a contingency, hence ensuring no shedding due to loss of communications. Remote device off-line and or communications trouble alarm could be used to annunciate FLS scheme trouble conditions, and perhaps even to block the FLS scheme.

## VI. FAST SPEED

Conventional frequency and voltage load shedding schemes operate typically in 250 ms to seconds. Contingency PLC-based load shedding schemes are typically faster, at 160 to 400 ms, depending on both system architecture and communications employed. Both these scheme types are too slow for industrial cogeneration applications, such as pulp and paper mills and refineries, where very fast load shedding is required to ensure power system and critical processes integrity.

The speed of fast load shedding including internal processing or execution time is shown in Table II, which illustrates the FLS system by order of magnitude faster executes in less than 20 ms. The total operating time of the FLS must include the end load device breaker operating time which is typically 3-5 cycles for a medium voltage industrial feeder breaker. Thus, the total operating time of the FLS scheme shown in Table II is approximately 100 ms.

TABLE II
EXAMPLE OF TYPICAL FAST LOAD SHED TIMING

| Time | Event |
|---|---|
| t = 0 | End device detects trip/breaker operation |
| 3 ms | GOOSE message with change of online state sent by end device (3 ms) |
| 3.2 ms | GOOSE message passed through multiple LAN Ethernet switches (0.2 ms) |
| 6.2 ms | FLSC processing and calculations from received GOOSE message (3 ms) |
| 7.2 ms | Shed command GOOSE message composed by FLSC (1 ms) |
| 7.7 ms | FLSC GOOSE message is sent through LAN Ethernet switches (0.5 ms) |
| 10.7 ms | Shed command GOOSE message parsed by end load devices (3 ms) |
| 14.7 ms | End load device calculations and processing (4 ms) |
| 16.7 ms | Trip contact output closes on end load devices (2 ms) |
| 16.7 ms | Total FLS execution time |
| 67-100 ms | End device load breakers open (3-5 cycle breaker) |

Table III shows some test results from a fast load shed scheme operation in conjunction with backup df/dt (ROCOF – rate of change of frequency) and under frequency load shedding, illustrating operating speed of each system at the facility under review, that was islanded as a 1 MW underpowered island. In this case, the FLS scheme operated in 15 ms, including trip command to shedding load breakers. The total operating time of the FLS scheme including the end load device breaker operating time (2 cycles for a medium voltage industrial feeder breaker) is 46 ms. In this situation, rate of change of frequency and underfrequency would have operated much slower than the FLS scheme.

TABLE III
CASE STUDY FAST LOAD SHED PERFORMANCE RESULTS

| Time | Event |
|---|---|
| 0 ms | Utility Breaker opened by protection |
| 2 ms | Breaker status open after de-bounced, island detected (1.05MW under generation), priorities 32, 18, 17,16, 15, 14 and 12 load group shed sent by FLSC (1.148MW) |
| 13 ms | Shed command message received at load devices |
| 15 ms | Trip coils energized |
| 46 ms | Shed breaker open – load disconnected (Breaker time 31ms) by FLS scheme |
| 64 ms | ROCOF (df/dt) trigger (typical) |
| 106 ms | Under frequency load shed trigger (typical) |

* Refer to Fig. 4 for one-line diagram

## VII. LESSONS LEARNED

During system installation, testing, commissioning and case study system operations, various aspects were observed of the FLS system and end-device configurations and hence improvements/changes were implemented. Some of these include the following:

### *A. Testing*

Testing of the fast load shed scheme occurred during a factory acceptance testing (FAT), site acceptance testing (SAT) and commissioning. The challenge with FAT and sometimes SAT is that not all end devices might be available, or its settings might not be finalized. Live system testing was performed during commissioning, first while the system was isolated from actual tripping (blocking switches were open), and then actual live system islanding operations, during an over-generated islanding condition (proving non-operation of the FLS system), and then during an under-generated islanding condition (proving correct scheme operation, shedding of load and maintaining of the local power system).

Each contingency that could affect the initialization of the scheme, was tested live to prove correct scheme initialization.

All testing was executed with a very detailed test plan since 3 teams were required at 3 different locations.

### *B. Scheme Initialization*

During live activation and monitoring of the system over the demonstration period it was discovered that activating all infeeds including the gas turbines and diesel generators as initiators had an undesired outcome. The undesired result, was that an inadvertent shedding of load took place during the monthly cycling of an emergency diesel generator while on its maintenance run. Reserve on all infeeds were set to zero, which caused the FLS to initiate when the diesel generator tripped.

FLS initialization was changed to ensure the scheme can only be initialized upon islanding of the industrial system via the grid incomer by eliminating the local generators breaker tripping from initiating the FLS scheme.

### *C. Post-Operation Analysis and Challenges*

After actual FLS scheme operations, when the Industrial plant lost its connection to the local utility grid (due to a system fault on the utility-side) and FLS occurred, trouble shooting was challenging due to the following:

*1) Event Report Analysis:* The FLSC did trigger and capture a detailed FLS report, sequence of events (SOE) report and end devices did trigger all SOE but not all waveforms, however not all end device functionalities were visible in the SOE and waveforms captured. Some functions such as contact input and output events were not enabled in a few end devices. This made tracking, when some load breakers that tripped and then opened during the fast load shed event, hard to identify.

Some end devices waveform capture did not include all needed analog and digital channels did not trigger during a shedding event, eg. it is essential to have all powers assigned as analog channels, shed commands, breakers trip and open indications assigned to waveform capture. Furthermore, it was necessary to change some of the waveform triggering logic to ensure waveforms are always triggered during a FLS event.

It is recommended to use SOE and waveform reports during all system testing, and reviewed during any P&C commissioning or maintenance testing. Some of these reports were not triggered or available during some system tests.

*2) Time Synchronization:* All end devices and the FLSC were time-synchronized via simple network time protocol (SNTP) from the human-machine interface (HMI), however daylight savings time was not correctly implemented in all end devices, and corrected.

Using SNTP is sufficient, however this can still have a time discrepancy of 10ms, which must be considered during system event analysis. IRIG-B or precision time protocol (PTP) would be a better choices as means of time synchronization since it would ensure that all captured events and records would be within 1ms accuracy, where only a 10ms accuracy can be achieved with SNTP.

*3) Disable/Reset of FLS Scheme:* Initially, the FLS scheme could be enabled/disabled only from the HMI. The danger with this scenario is that the scheme can't be easily disabled if communications is lost between the HMI and FLSC or the HMI is lost. A local control push button was assigned on one of the end devices near the control room to allow locally disabling the scheme.

Each load shed trip command is implemented as a latch function in all end device which performs direct breaker tripping. Resetting each trip signal in the end devices (IEDs) that tripped the load breakers during a shedding event was initially on a per-breaker basis from the HMI. This was enhanced to allow one global reset command in the HMI to reset all trip signals. These trip signals are latched and reside in the end devices, not the FLSC to ensure signals will be maintained even during the loss of communications during a shedding event.

*4) Local Generator Protection Coordination:* In some of the events where a system fault occurred, the fault was on the distribution feeder (utility supply) in excess of 0.6 seconds before the local system was islanded and distribution feeder tripped. The local generator protection of the gas turbine did unfortunately also operate for this system fault at about the same time the FLS system shed the needed load; so, in this case the whole system was lost. The FLS system did operate in about 15ms and some load breakers opened around 46ms after the system was islanded, however with such a long-lasting feeder fault, the generator protection operated too.

Proper protection coordination between the feeder protection (utility supply) and local generator protection thus needs to be re-evaluated. Directional overcurrent or distance protection elements can aid in protection coordination between the utility feeder and local generators.

Further analysis pointed out that during some utility supply faults external to the local system, islanding would not take place until the under voltage (ANSI 27) operated at the point of common coupling (PCC). 27 typically could only pick up if the local generation did trip too, meaning that local generation is lost when the fast load shed is initiated; consequently, the local system will be lost even if FLS occurred correctly. During one of the system fault events, the fault was very close to the PCC (on the utility side) and the neutral over voltage (59N) did operate much quicker. During this event the local generation was maintained; the fast load shed operated and the local system did stabilize as an island.

To rectify the under voltage (27) dilemma, transfer tripping from the utility-end to the PCC is explored to ensure much quicker islanding during a system (utility) feeder fault.

*5) Use of Synchrophasors:* During an actual FLS event, some of the dynamic changes in the local system, such as frequency and voltages, could only be observed at the update capabilities of the end devices; and doesn't show the fast-dynamic response needed for detailed analysis, especially the frequency response which is tied to the IED frequency tracking.

Synchrophasors or the measurements and monitoring of fast changing voltage and frequency is recommended to be used to enhance system analysis and observation capabilities. This would allow to monitor system stability performance, to determine system stability limits.

## VIII. ENHANCEMENTS OVER TRADITIONAL SYSTEMS

The fast load shed scheme offers many benefits over traditional systems beyond its speed improvements. Additional enhancements include: future proof (the scheme is based on universal communications protocols and architectures used by multiple vendors making it vendor neutral), reduction of hardware, redundancy for added security and utilization of existing Ethernet networks.

Hardware can be reduced because additional transducers are unnecessary since existing IEDs are used and they utilize the existing current and voltage transformer circuits and measurement algorithms. Additionally, since the information is sent as a GOOSE message over the existing Ethernet network, the wiring associated with the transduced signals is eliminated. The reduction in wiring not only simplifies this architecture, provides additional immunity to electromagnetic interferences (EMI) since fiber is used as communications medium, but it also gives the system the ability to be much larger with more measured loads. It would become very difficult to accommodate and manage a large system with wired transduced signals. When these signals are communicated, as in this architecture, the FLS system becomes much more manageable as it expands in sources and loads.

Programmable logic controller (PLC) based systems are unable to provide such fast operation that is achieved using IEC 61850 GOOSE messaging. In addition, PLC based schemes require significant custom programming unlike a pre-developed algorithm within the FLS, which avoids over-shed or under-shed situations.

PLC based systems count on a lot of hardwired interactions between process plant where the tripping takes place and control decisions occur. Using IEC 61850-based Ethernet fiber-based communications, much less copper wiring is needed exposing the whole system much less to EMI.

Since this fast load shed scheme operates based on a loss in power balance, (shedding only the amount of shedable load needed to re-establish system balance), this system is much more pro-active compared to traditional systems based on voltage and/or frequency, and much more dynamic than a PLC-based system that typically sheds loads on a specific tripping matrix to be incorporated with end devices for a specific contingency.

When industrial facilities consider an upgrade to their electrical system, it is advised to consider IEC 61850 based protective relays and meters, so these same devices can be used for protective functions, metering, data gathering and load shed. These IEDs should be designed with three phase currents, three phase voltage connections and power measurement, breaker/contactor status, trip/start and close/stop functionality and network connectivity. With this design approach, a fast load shed scheme can be easily implemented at a minimal cost, which is a large advantage over PLC-based FLS systems.

This case study system was relatively small compared to the actual capability this system can be expanded to, however this does not have an impact on expected system performance of a much larger system. The reason behind this is that the shed-command is sent directly from the FLSC to all loads to be shed directly and not via any aggregators. This is possible since thousands of devices can subscribe to a single IEC 61850 dataset message from a single device; in this case the shed-command from the FLSC.

## IX. HMI AND DCS INVOLVEMENT

Load shed priorities of the FLS may contain permanent setting values, or an external computer, or HMI (Human Machine Interface) or DCS (Distributed Control System) can be set up to continuously adjust the priorities as required by changing process needs. These adjustments include the permission and blocking for smoothly incorporating the production process needs, i.e. some loads may not be allowed to be shed during specific times of day. Modbus RTU TCP/IP protocol is used by the external computer, HMI or DCS. Fig. 2 shows the integration of an external computer with HMI communicating into the FLS scheme.

## X. CONCLUSION

Fast Load shed is a necessary requirement with facilities that have co-generation capability, such as industrial, pulp and paper mills and refineries that will incur significant process or manufacturing losses if all power is lost. This allows the facility to shed loads to prevent loss of the complete facility when the load exceeds the generation capacity through a contingency event such as loss of a utility main. The biggest advantage for using a 61850 FLS scheme is the speed by which it will transfer load compared to conventional schemes. Other benefits of this FLS system includes a much easier implementation using off-the-shelf available technology (e.g. in IEDs and networking equipment capable of IEC 61850 communications), expandable up to 2500 different loads, reduction in the use of copper with the use of more fiber for communications, shedding of load is calculated dynamically to ensure no excessive shedding occurs and this system can easily be expanded or redundancy added. One operation of the FLS system can pay for itself if it saved the industrial system from complete collapse. The case study system described in this paper utilizes a proven fast load shed system that has several advantages over existing systems and makes larger more complex or more configurable load shed schemes possible.

## XI. REFERENCES


[1] IEEE Std. C37.117-2007, *IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration*, New York, NY: IEEE.

[2] S. Shookooh, T. Khandelwal, F Shokooh, J. Tastet and JJ. Dai, "Intelligent Load Shedding Need for a Fast and Optimal Solution", IEEE PCIC Europe, 2005.

[3] C. Wester and M. Adamiak, "Practical Applications of Ethernet in Substations and Industrial Facilities", IEEE Pulp and Paper Industry Conference, June 2011.

[4] C. Wester and M. Adamiak, "Practical Applications of Peer-to-Peer Messaging in Industrial Facilities", IEEE Pulp and Paper Industry Conference, June 2012.

[5] C. Wester, T Smith, JC Theron and David McGinn, "Developments in Fast Load Shedding", Texas A&M Protective Relay Conference, April 2014.

[6] J. Sykes, M. Adamiak and G. Brunello, "Implementation and Operational Experience of a Wide Area Special Protection Scheme on the SRP System", Georgia Tech Protective Relay Conference, April 2005.

[7] G. Schauerman, M Schiefen, M. Adamiak and B. Gable, "Design of a Priority-Based Load Shed Scheme and Operation Tests", *in IEEE Conference Record, 2010,* PCIC-2010-44.

[8] C90Plus Automation Logic Controller Instruction Manua*l*, GE Publication GEK-113466.


## XII. VITAE

JC (Jacobus) Theron is Technical Applications Engineer for Grid Automation division of GE Grid Solutions. He received the degree of Electrical and Electronic Engineer from the University of Johannesburg, South Africa in 1991. Mr. Theron has 25 years of engineering experience; 6 years with Eskom (South Africa) as Protection / Control and Metering Engineer, 12 years with GE Multilin (Canada) as Product / Technical support / Protective Relaying Consultant/Protection and Systems Engineer leading the Project and Consulting Engineering team and as Product Manager, 2 years with Alstom T&D (USA) as Senior Systems Engineer and 5 years with Hydro One as Operations Assessment Engineer / P&C Technical Services Manager. He specializes in transmission, distribution, bus and rotating machines applications support and Fast Load Shed Systems, system designs and transient system testing.

Anthony (Tony) Colonnese is Sr Director of Engineering Services for Ameresco, Inc. He received a BS in Mechanical Engineering from Brown University in 1979 and has over 30 years' experience related to energy efficiency, distributed generation, and renewable energy. He oversees the proposal and development of large-scale energy projects, including new business ventures, to assure that they are technically sound and commercially competitive while mitigating business risk, and meeting the client's long-term needs. Throughout his career, he has been responsible for all aspects of projects including energy auditing, design, financial modeling, contract negotiation, and monitoring and verification.

Troy Wilsey is an engineer with extensive experience in developing projects for the U.S. Department of Defense (DoD) via Energy Savings Performance Contracts (ESPC), specializing in microgrid controls, energy storage, distributed generation, and O&M. Serving as co-principal investigator for a DoD grant demonstrating microgrid and energy storage technologies; he has been integral to the design, technology selection, grant proposal writing, and contract negotiations, as well as overseeing construction, commissioning, testing, data analysis, and reporting. The demonstration provides islanding capability to the Navy shipyard while creating a new revenue stream through participation in the ISO New England Regulation market under FERC Order 755. As of December 2015 the system has been fully commissioned and is actively operating. He is also responsible for maintaining relationships and cross pricing technologies with industry leading energy storage manufacturers and modeling payback performance periods on candidate projects. His work supports business development efforts to build out a portfolio of systems which offer energy security, savings in utility demand charges, and revenue from electricity markets in territories such as PJM, ISO-NE, and CAISO, as well as international markets such as Canada, Central America, and the UK. In addition, he offers engineering support to Ameresco's Federal Group; technologies include CHP, Solar Thermal, Solar PV, LED lighting, HVAC, and Water Conservation.

Russell Gagner is the Production Division Director at PWD-Maine, Naval Facilities Engineering Command, Mid-Atlantic (NAVFAC MIDLANT). In this capacity, he is responsible for executing utility and energy management engineering, sales and services; facilities management services and transportation services. Mr. Gagner is also senior electrical engineer at PWD-Maine. He graduated from the University of Lowell (Massachusetts) in 1989 with a Bachelor of Science degree in Electrical Engineering. Mr. Gagner has been a registered Professional Engineer in Pennsylvania since 1994. In 1989, Mr. Gagner began his career with the Public Works Department located at the Naval Education and Training Center, Newport, Rhode Island as an electrical power engineer. In 1992, Mr. Gagner worked for Quad Three Group, Inc. located in Wilkes-Barre, PA, responsible for the design and project management of electrical projects including electrical transmission and distribution systems, substation systems, and industrial control systems. In 1998, Mr. Gagner brought his expertise to PWD-Maine to provide operations, design, and maintenance support to the generation and distribution of power at the Shipyard. In 2006 he was promoted to the Electrical/Mechanical Engineering Division Head and to Production Division Director in 2010.