DEVELOPMENTS IN FAST LOAD SHEDDING

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Abstract – This paper describes a smart load shedding scheme that monitors plant loads, plant generation and generation/utility supply reserve to select the minimum number and lowest priority loads for shedding. The paper first gives an overview of industrial power system dynamics undergoing loss of supply contingencies and existing load shed practices, such as undervoltage, underfrequency, frequency rate of change or contingency based load shedding. It will examine the impact of speed of load shedding on stability. The paper goes on to describe a load shed system that continuously calculates the generation reserve available and shed-able load available in real time by acquiring analog power measurements from generators and utility supplies through IEC61850 GOOSE (Generic Object Oriented Substation Event) messaging. This fast load shed scheme uses the reliability and redundancy of modern Ethernet networks and has simplicity compared to traditional systems. Application solutions are presented and analyzed that handle the required data acquisition using communications and protection devices typically present at an industrial facility, along with means to disseminate load shedding commands with sub-cycle speed to thousands of shed-able loads. Actual performance results from such a load shed system are presented.

Index Terms — Fast Load Shed (FLS), GOOSE (Generic Object Oriented Substation Event), VLAN (Virtual Local Area Network), 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).

I. INTRODUCTION

Industrial facilities, such as 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 slow down as the 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. Fast Load Shed (FLS) is a remedial action scheme that, in a contingency, initiates shedding of loads as required to preserve system load/generation balance thereby avoiding this complete system collapse. A contingency is the loss of one or more infeeds (local generators or incomers from the grid). Unlike traditional undervoltage, underfrequency 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. 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 manufacturing process suffers the minimum impact possible.

II. SCALABLE ARCHITECTURE

Fast Load Shed (FLS) is a system consisting of one controller, one or more aggregators (if more than 64 infeeds and load end devices exist), an Ethernet network and IEC61850-8-1-capable end devices that 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 IEC61850-8-1 GOOSE support.

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

The Fast Load Shed Controller (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 controller is informed of present system power flows and of contingencies via data messages received from end devices, aggregators or both via analog/digital IEC61850 GOOSE. It handles up to 32 loads/load groups and 32 sources/infeeds, and makes the final decision to shed load in real time. The load shed commands are issued via IEC61850 GOOSE messages to end devices.

The Fast Load Shed Aggregator (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 IEC61850 GOOSE to the FLSC. The aggregator or FLSA does not make load shed decisions. It merely allows the FLS controller (FLSC) to handle more than 64 infeeds and loads. Each FLSA supports 64 end devices and up to 32 load groups. By connecting the aggregators in a tree-like matrix, the number of loads controlled with this scheme can reach over 2500.

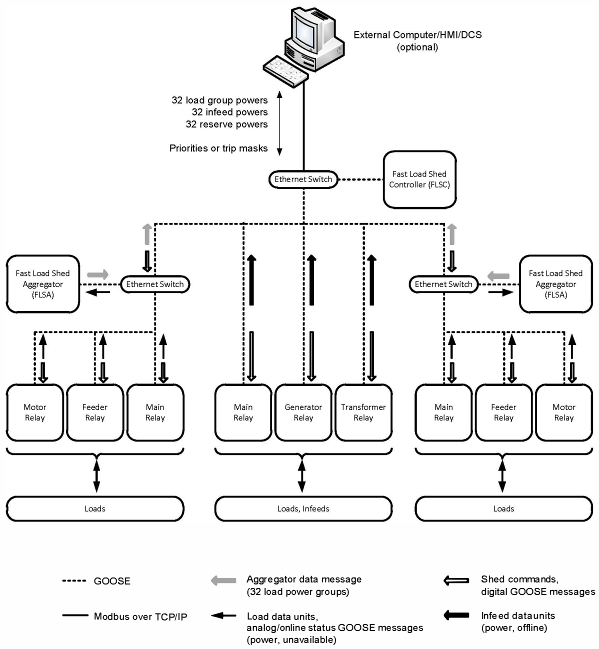

Fig. 1 – FLS Scheme Communications

An FLSC is configured to shed load groups in the event of a contingency according to a set of priorities or trip masks. For the purposes described here, a contingency is the loss of any one or more infeeds or a pre-defined scenario. 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, on the information in data units, and on the present priorities or trip masks values, 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 end devices and up to 32 load groups. With 12 infeeds, 18 loads and 40 aggregators (64 loads each), the system can support 12 infeeds and 2578 shed-able loads. Minimal re-configuration is necessary in the case of system expansion.

End devices send to an FLSC or an FLSA six data units in a single data message. Not all of the data units in a data message have to 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 eminent loss of that infeed; which is, a contingency. Load data units contain the measured real power flowing into the load and the unavailability status of the load for fast load shedding. Loads with unavailability status 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.

End devices use a configurable GOOSE message to publish data for each six of its infeed or load data units. Data messages with infeed data units use fast transmission configurable GOOSE messages for fastest contingency detection at the FLSC. End devices interfacing to infeeds 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 32 load group powers. 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 to the end devices an individual shed request operand for each of the load groups used by the application, typically all in a single shed command. The shed commands are sent directly to all end devices via the switched Ethernet network.

III. 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, at all times 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, and if the prime mover cannot provide additional mechanical power rapidly enough, lead to frequency collapse of the industrial distribution system.

When a contingency operation is triggered (either by a loss of an infeed or a programmed scenario), the fast load shed controller checks if generation 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 unavailability for shedding status false, plus the sum of the corresponding power values of all aggregator data units.

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 jump to its maximum power, or its increase being 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 load/infeed balance. Instantaneous measurement values leading up to and during the contingency may contain unsustainable transients. For instance, should an incomer open at the utility's end, and the FLSC see its power as zero when the offline status becomes true, the estimate of power lost would be zero were instantaneous power measurements used.

A contingency is declared when any infeed is lost or when any programmed scenarios occurs. An infeed is deemed lost when its offline status transitions from "Off" to "On", other than due to loss of communications. A programmed scenario is deemed to have occurred when its scenario operand transitions from "Off" to "On".

Both the infeed lost condition and the programmed scenario occurred conditions are latched 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.

The FLSC moment-by-moment calculates the amount of load shedding required, which is called the load shed value. A load shed value is continuously calculated as 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 load/infeed balance. A load shed value less than zero indicates no shedding is required.

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 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 increasing.

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.

For a programmed scenario, each load group's shed request operand is set and latched by the FLSC every 1 ms when one of the 32 programmed scenarios is true and the bit in that scenario's trip mask corresponding to that load group is a true. The scenario operand values are determined by user configurable logic. Each scenario's trip mask has 32 bits, one for each load group. An external computer system is typically responsible for ensuring the trip masks have the appropriate values pre-contingency, although the trip masks may also be set manually through the FLS software.

The shed requests are sent to the end devices in the shed command IEC61850 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.

Change requests for priorities and trip masks and for their writable actual values received during a contingency are not implemented until the contingency is over. Implementing the update 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 produce more load shedding than necessary.

In case of generation loss or power unbalance, IEC61850 GOOSE messages are sent to shed enough load per pre-defined priorities above available generation reserve. Alternatively for fixed pre-set contingencies, a predefined shedding scenario can be executed upon each defined contingency.

Load priorities can be changed or updated via a device 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. The ability to change the load priorities allows the user the flexibility of dynamical changing the priorities based on the profitability of each facility processes.

Below Figure 2 is a simplified system illustrating the load shed priorities and how shedding is determined.

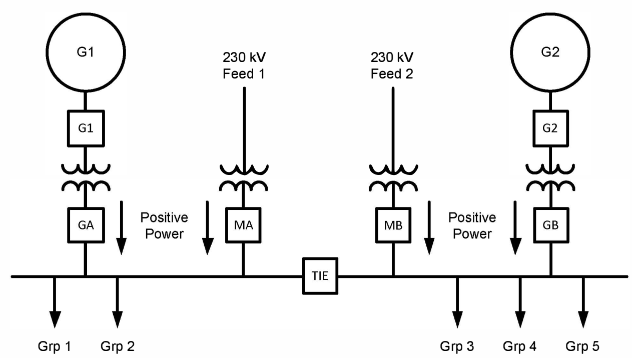

Fig. 2 – Simplified Source-Load Example

In Figure 2, 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 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 PRIORITATION 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, the scheme will trip load groups 3, 4 and 5 for a total of 30MW.

Data message monitoring of the FLSC is accomplished by maintaining a "Time-Allowed-To-Live" timer for each of the data units. 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" from initiating 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.

IV. FAST SPEED

Conventional frequency and voltage load shedding schemes operate typically in 250 ms to seconds. Contingency 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 quickly 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 FAST LOAD SHED TIMING

Execution Time	Event
t = 0	End device detects trip/breaker operation
3000 μs	GOOSE message with change of online state sent by end device
200 μs	GOOSE message passed through multiple LAN Ethernet switches
3000 μs	FLSC processing and calculations from received GOOSE message
1000 μs	Shed command GOOSE message composed by FLSC
500 μs	FLSC GOOSE message is sent through LAN Ethernet switches
3000 μs	Shed command GOOSE message parsed by end load devices
4000 μs	End load device calculations and processing
2000 μs	Trip contact output closes on end load devices
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 a petrochemical facility that was islanded as a 4.5MW underpowered island. In this case, the FLS scheme operated in 13 ms, including trip command to shedding load breakers. The total scheme operating time of the FLS scheme including the end load device breaker operating time (3 cycles for a medium voltage industrial feeder breaker) is 63 ms. In this situation, rate of change of frequency and underfrequency would have operated some time later than the FLS scheme.

TABLE III
ACTUAL FAST LOAD SHED PERFORMANCE RESULTS

Time	Event
0 ms	Breaker MB opened manually
8 ms	Breaker open de-bounded, island detected, priorities 1 , 2 and 3 load shed sent by FLSC
10 ms	Shed message received at load devices
13 ms	Trip coils energized
63 ms	Shed breaker open – load shed (assuming 3 cycle breaker) by FLS scheme
64 ms	ROCOF (df/dt) trigger
106 ms	Underfrequency load shed trigger

* Refer to Figure 2 for one-line diagram

V. RELIABILITY/REDUNDANCY, NETWORK ADVANTAGES

As stated earlier, an Ethernet network is a key component of the fast load shed scheme. A reliable Ethernet network can be created by using a ring Ethernet network architecture. An Ethernet ring architecture uses rapid spanning tree protocol to quickly recover for a ring break. This recovery time is very fast at 5 milliseconds per Ethernet switch or hop.

Tagged VLANs (Virtual Local Area Network) and priority (Quality of Service) are used within IEC61850 GOOSE messaging to provide fast IEC61850 GOOSE message delivery. Two advantages of VLANs are the separation of network traffic and security. Quality of Service (QoS) provides the ability to prioritize IEC61850 GOOSE messages on an Ethernet network. QoS has a priority setting with eight levels (0 to 7) of priority. Prioritizing traffic into different classes is important to ensure critical data is processed first (i.e. protection traffic before data, voice or video).

For the FLS, the power analog data information from generators and infeeds are transmitted as "Analog data" within the GOOSE messages and the trip commands are transmitted as "Digital data" within the GOOSE messages. The GOOSE message is primarily sent on detection of a change of state of a contained data item. With binary/digital values, change detect is a False-to-True or True-to-False transition. With analog measurements, IEC61850 typically defines a "dead band" whereby if the analog value changes greater than the dead band value, a GOOSE message with the changed analog value is sent. For Fast Load Shed, power analogs are typically transmitted once per second, not just on change of state.

To meet the reliability criteria, the IEC61850 protocol automatically repeats the GOOSE message several times in quick succession. As such, if the first GOOSE message gets lost (corrupted), there is a very high probability that the next message (e.g. 4ms later) or the next or the next (e.g. 8ms later) will be properly received. As stated earlier, the GOOSE message is primarily sent on detection of a change of state of a contained data item. Table IV shows an aggressive GOOSE retransmission scheme within a FLS controller, aggregator, or end device.

TABLE IV
AN AGGRESSIVE GOOSE RETRANSMISSION SCHEME

Sequence Number	Time From The Event	Time Between Messages	Comment
0	0 ms	0 ms	Event
1	4 ms	4 ms	T1
2	8 ms	4 ms	T1
3	16 ms	8 ms	T2
4	Heartbeat	Heartbeat	T0
5	Heartbeat	Heartbeat	T0

VI. DEVICE INTEROPERABILITY/INTERCHANGEABILITY

The end devices send their load data and receive load shed commands via the IEC61850 GOOSE messaging protocol. The IEC61850 GOOSE protocol is meant to be an open and interoperable standard. This means that any manufacturer's equipment can be used for the end devices as long as the IED (Intelligent Electronic Device) supports analog and digital GOOSE messaging. This IEC61850 standard also increases the longevity of the system because if devices are replaced or added in the future, they will still work within the system as long as they support this protocol.

Since the IEC61850 GOOSE messaging protocol is a publisher subscriber protocol, it makes changes to IEDs in the future easier. The device that sends data is the publisher. The receiving device, or subscriber, only has to "listen" for network messages that it subscribes to. Thus, changes in the future to the publisher merely mean that the publisher's settings that define the data header are the same as the previous IED, with no changes necessary in the subscriber. Changes to the subscriber (the FLSA or FLSC) are necessary when the system is expanded or altered and publisher IEDs are added or removed from the FLS system.

VII. ENHANCEMENTS OVER EXISTING SYSTEMS

The fast load shed scheme offers many benefits over traditional systems beyond its speed improvements. Additional enhancements include: future proof, reduction of hardware, 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, 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 loads.

PLC (programmable logic controller) based systems are unable to provide the fast operation that is achieved using IEC61850 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.

When industrial facilities consider an upgrade to their electrical system, it is advised to consider IEC61850 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 and three phase voltage measurement connections, 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.

VIII. 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/trip mask as required by changing process needs. These adjustments include the permission and blocking for smoothly incorporating the production process needs. Modbus RTU TCP/IP protocol is used by the external computer, HMI or DCS. Figure 1 shows the integration of an external computer, HMI or DCS communicating into the FLS scheme.

IX. CONCLUSIONS

Load shed is a necessary requirement with facilities that have co-generation capability, such as pulp and paper mills and refineries. This allows the facility to shed loads to prevent loss of the facility when the load exceeds the generation capacity through a contingency event such as loss of a utility main. The 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.

X. REFERENCES

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XI. VITA

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