An Intelligent Load Shedding (ILS) System Application in a Large Industrial Facility

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***Abstract* — Conventional methods of system load shedding are too slow and do not effectively calculate the correct amount of load to be shed. This results in either excessive or insufficient load reduction. In recent years, load shedding systems have been repackaged using conventional under-frequency relay and/or breaker interlocks schemes integrated with Programmable Logic Controllers to give a new look to an antiquated load preservation methodology. A truly modern and intelligent load shedding system with a computerized power management system should provide fast and optimal load management by utilizing system topology and actual operating conditions tempered with knowledge of past system disturbances. This paper demonstrates the need for a modern load shedding scheme and introduces the new technology of intelligent load shedding. Comparisons of intelligent load shedding with conventional load shedding methods are made from perspectives of system design, system engineering, project implementation, and system operation. A case study of the application of an intelligent load shedding scheme in a large industrial facility is provided.**

***Index Terms* — Load Shedding, Intelligent Load Shedding, Power System Monitoring and Simulation, Frequency Relay, PLC, ILS.**

I. Introduction and Background

In general, load shedding can be defined as the amount of load that must almost instantly be removed from a power system to keep the remaining portion of the system operational. This load reduction is in response to a system disturbance (and consequent possible additional disturbances) that results in a generation deficiency condition. Common disturbances that can cause this condition to occur include faults, loss of generation, switching errors, lightning strikes, etc.

When a power system is exposed to a disturbance, its dynamics and transient responses are mainly controlled through two major dynamic loops. One is the excitation (including AVR) loop that will control the generator reactive power and system voltage. Another is the prime-mover loop, which will control the generator active power and system frequency. A brief discussion of these two dynamic loops is given below.

A. Excitation / Generator – Reactive Power – Voltage

During a fault condition, one of the direct effects of a fault current is the drainage of reactive power from the system. This reactive power is essential for the transfer of mechanical energy to electrical energy (and vice versa) in the rotating machines (generators and motors). After the fault clearance, system is faced with partially collapsed flux energy in the rotating machines and has to balance its generation and load levels while rebuilding its magnetic energy. During this time, depending on the motor residual back emf, the system is also faced with an additional reactive power demand from the motor loads under reacceleration conditions.

The voltage regulation and operating voltage of the overall system will directly depend on the amount of reactive power that the generators could deliver to the system. On severe disturbances, the generators may automatically call upon its over-excitation capability (ceiling voltage), which help in recovering the system stability.

B. Prime Mover / Generator – Real Power - Frequency

Turbine governors and the type of prime movers also have a dramatic impact on the performance of the power system during major disturbances.

The frequency conditions of the overall system directly depend on the amount of real power that the generator prime movers can deliver to the system. Also, the mechanical energy available to help the generators prime mover ride through a fault or other disturbances plays an important role on the system behavior. This stored energy varies dramatically between that of a gas turbine, steam turbine, and hydro units. As a consequence, the performance of power systems supplied by different types of prime movers and governors will behave very differently under both steady-state and transient conditions.

In addition to system upsets caused by faults, there are disturbances caused by switching surges or lightning strikes. As an example, some switching disturbances can result in a loss of generation or cause a system to separate from the utility grid (system islanding condition). This condition can

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cause the power system to collapse and will be adversely impacted by inappropriate load reduction caused by an improper load shedding scheme. For some switching disturbances (that results in a loss of generation or system islanding condition), the cascading effects may be of the primary concern if the load shedding action is not set correctly and/or timed properly.

Moreover, the type of disturbance impacts the dynamic response of the prime mover. For instance, a short circuit at the power station busbar may result in acceleration of the generator prime mover. When this occurs the speed regulator will then initiate closing of the fuel or gas inlet valve. After the fault has been cleared, the turbines face the impact of the load still connected. At this time their fuel or gas inlet valves are closed resulting in difficult reacceleration conditions.

II. Conventional Implementation of Load Shedding

This section is a review of a number of load shedding techniques that have been previously devised. Each system has its own set of applications and drawbacks.

A. Breaker Interlock Scheme

This is the simplest method of carrying out load shedding. For example a source breaker would be interlocked via hardwired or remote signals to a set of load breakers that have been pre-selected to trip. When a generator breaker or a grid connection is lost for any reason, signals are automatically sent to load breakers to open. This system is very fast since there is no processing required and all decisions about the amount of load to be shed were made long before the fault occurred.

In Fig. 1, the load is supplied by a combination of a generator and a power grid. A disturbance outside the facility causes the main breaker to operate and open. This would isolate the system from the power grid causing the system load to be supplied solely by the local generator (STG1). The opening of the main breaker (MainBreaker) would signal the interlocked load breakers (LoadCB_1…n) to trip without any intentional time delay. This pre-selected breaker interlock list is typically determined without any knowledge of system transient response and is often too conservative, resulting in unnecessary load shedding.

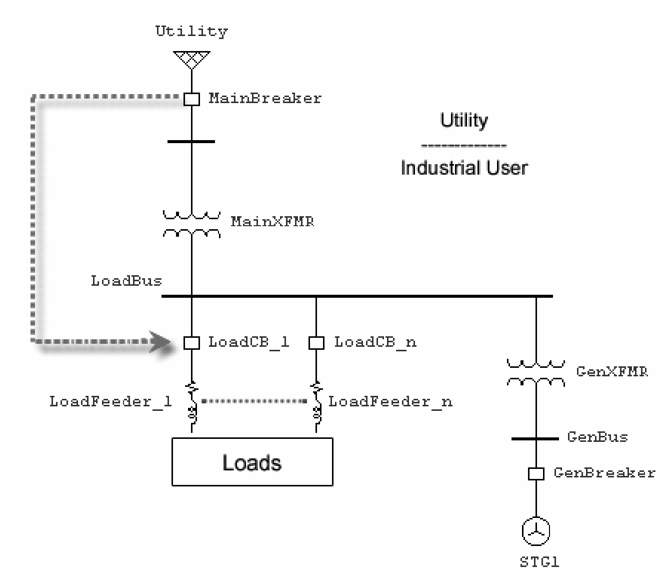

Fig. 1. Breaker Interlock Load Shedding Scheme

In addition, the breaker interlock scheme has other inherent drawbacks:

- Difficult to change load priority since the actions for load shedding are hardwired and amount of load shedding is calculated for the worst-case scenario.
- Only one stage of load shedding is available.
- More loads are shed than necessary.
- The operation of this type of load shedding system will most likely shut the entire industrial facility down in a non-orderly way. This unplanned outage may result in processing equipment damage, reduced equipment lifetime, or worse.
- Plant restarting may be delayed because of the requirement to shut down and then restart other remote facilities that have been affected by the loss of the main facility, before the main facility can be started.

B. Under Frequency Relay (ANSI Device 81) Scheme

Frequency relays do not detect disturbances but react to the disturbances. They detect either a rapid change in frequency or gradual frequency deterioration and initiate staged operation of interlocked breakers. When the first stage is reached, the relay waits a predetermined amount of time, to avoid nuisance tripping, and then trips one or more load breakers. This is done to allow the frequency to recover. If the frequency continues to decay, the relay will wait for the next stage to be reached and after an additional time delay, opens other load breakers. For the system shown in Fig. 2, the frequency relay (FreqRelay) detects the first load shedding stage and the interlocked load circuit breakers (LoadCB_1 to LoadCB_i) are tripped accordingly, which will reduce the real and reactive power demand on the generator. If the frequency continues to decay then subsequent load shedding stages will be reached and additional load breakers (LoadCB_j to LoadCB_k) will be tripped until frequency returns to normal.

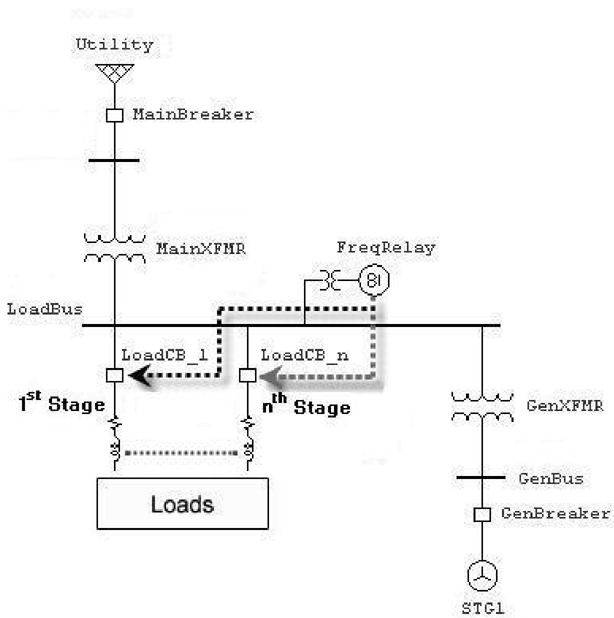

Fig. 2. Under Frequency Relay (81) Load Shedding Scheme

The load shedding schemes that use only conventional frequency relays are primarily used for static control of system loads. The frequency relay based load shedding scheme has a number of inherent drawbacks as listed below.

1) Slow Response Time of Frequency Relays

Frequency relays must be slow to avoid nuisance trips. In addition to the time it takes for the frequency to reach relay settings, there is an intentional time delay setting to prevent nuisance tripping during frequency spikes and transient deviations. Due to the fact that disturbances like three-phase faults that prevent flow of real power, this time delay may be further prolonged due to the overfrequency condition that can occur during the fault.

As shown in Fig. 3, when a three-phase fault occurs in this system, frequency initially increases. The fault is cleared when the MainBreaker trips and opens. System separation eliminates utility real power support and as frequency decays, underfrequency relay set point is reached at 0.15 seconds (9 cycles). An intentional time delay of 0.15 seconds is introduced in the frequency relay to avoid any nuisance tripping. The first set of breakers trip in 30 cycles after the onset of the fault, resulting in a total load shedding time of 0.583 seconds.

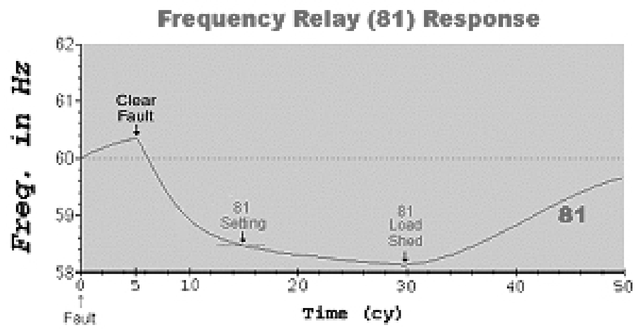

Fig. 3 System Frequency Response Depicting Stage 1 Frequency Setting

During this period of time, the generators are faced with a continuous overload condition. The fault causes the system to be drained of reactive power before load shedding can relieve the strain on the system and prevent further instability. Table I outlines the settings for the various frequency relay stages and the corresponding amount of load to be shed for each stage.

TABLE I
LOAD SHED TABLE FOR CASE 2

Stage	Frequency	Delay (seconds)	MW Shed
Stage 1	58.5 Hz	0.25	10
Stage 2	57.5 Hz	2.00	30

If the amount of load shed in the first stage is insufficient and the frequency continues to decay, the system frequency will reach the next set point and additional load shedding will be initiated. The next block of load is shed with additional time delay. Hence each additional stage introduces delay in the load shedding process.

2) Incorrect Load may be Dropped Causing Undesirable Blackouts

The settings of a frequency relay are usually determined by the most severe disturbance conditions and the minimum amount of local generation. This type of relay setting will result in excessive load shedding for other faults that are not as severe. Low system frequency signal to the frequency relay does not provide other pertinent information such as the type and location of the disturbance. In addition, the electrical distance between generators and loads are unknown.

In response to a frequency mandated operation, frequency relays operate a set of fixed circuit breaker, independent of their actual operating load. The operating load on the breakers may be different than the loading used to determine frequency relay settings. Additionally, the sequence of operation of the breakers may not be correct and/or optimal. Modification cost is high since it may require field changing of hardware.

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2) *Analysis Knowledge is Lost*

Conventional load shedding systems that rely solely on frequency measuring systems cannot be programmed with the knowledge gained by the power system designers. The system engineer must perform numerous system studies that include all of the conceivable system operating conditions and configurations to correctly design the power system. Unfortunately, the engineer's knowledge of the system, which is gained through the studies are not utilized fully. Additionally, most data and study results are simply lost. This unavailability of information for future changes and enhancement of the system will significantly reduce the protection system performance.

C. Programmable Logic Controller-Based Load Shedding

The use of Programmable Logic Controllers (PLCs) for automatic sequencing of load has become an important part of substation automation in recent years. The application of PLCs in industrial load management and curtailment schemes started in the early 1980s. However, it wasn't until power management systems were combined with microprocessor based PLCs that distributed fast load shedding systems became a reality.

With a common type of PLC-based load shedding scheme, load shedding is initiated based on the system frequency deviations and/or other triggers. The circuit breaker tripping can be programmed based on the system loading, available generation, and other specific logics. Each subsystem is equipped with a PLC that is programmed to shed a preset sequence of loads. This static sequence is continued until the frequency returns to a normal condition. Modification of the logic requires changing of the latter-logics that are programmed in the PLCs.

PLC-based load shedding scheme offers many advantages over the frequency-based scheme since they have access to information about the actual operating status of the power system. However monitoring of the power system is limited to the sections of the system that are connected to the data acquisition system. This drawback is further compounded by the implementation of pre-defined load priority tables in the PLC. These load reduction tables are executed sequentially to curtail blocks of load until a preset load shedding level is achieved. This process may be independent of the dynamic changes in the system loading, generation, or operating configuration. The system-wide operating conditions are often missing from the PLC's decision-making process resulting in insufficient or excessive load shedding. In addition, the load shedding systems response time (time period for which the load shedding trigger is detected by the PLC or relay up to the time when the trip signal is received by the circuit breaker) during transient disturbances is often too long requiring for even more load to be dropped.

The state-of-the-art load shedding system uses real-time system-wide data acquisition that continually updates a computer based real-time system model. This system produces the optimum solution for system preservation by shedding only the necessary amount of load and is called Intelligent Load Shedding.

III. INTELLIGENT LOAD SHEDDING (ILS)

A. The Need for ILS

Due to the inherent drawbacks of existing load shedding methods, an intelligent load shedding system is necessary to improve the response time, accurately predict the system frequency decay, and make a fast, optimum, and reliable load shedding decision. This system must have the following capabilities:

- Able to map a very complex and nonlinear power system with a limited number of data collection points to a finite space.
- Automatically remember the system configuration, operation conditions as load is added or removed, and the system response to disturbances with all of the system configurations.
- Recognize different system patterns in order to predict system response for different disturbances.
- Utilize a built-in knowledge base trainable by user-defined cases.
- Adaptive self-learning and automatic training of system knowledge base due to system changes.
- Make fast, correct, and reliable decisions on load shedding priority based on the actual loading status of each breaker.
- Shed the minimum amount of load to maintain system stability and nominal frequency.
- Shed the optimal combinations of load breakers with complete knowledge of system dependencies.

In addition to having the above list of capabilities, ILS system must have a dynamic knowledge base. For the knowledge base to be affective, it must be able to capture the key system parameters that have a direct impact on the system frequency response following disturbances. These parameters include:

- Power exchanged between the system and the grid both pre and post disturbance.
- Generation available before and after disturbances.
- On-site generator dynamics.
- Updated status and actual loading of each sheddable load.
- The dynamic characteristics of the system loads. This includes rotating machines, constant impedance loads, constant current loads, constant power loads, frequency dependent loads, or other types of loads.

B. Additional Requirements for ILS System

Some additional requirements must be met during the designing and tuning of an ILS scheme:

- Carefully selected and configured knowledge base cases.
- Ability to prepare and generate sufficient training cases for the system knowledge base to insure accuracy and completeness.
- Ability to insure that the system knowledge base is complete, correct, and tested.
- Ability to add user-defined logics.
- Ability to add system dependencies.
- To have an online monitoring system that is able to coherently acquire real-time system data.
- The ability to run in a preventive and predictive mode so that it can generate a dynamic load shedding table that corresponds to the system configuration changes and pre-specified disturbances (triggering).
- A centralized distributed local control system for the power system that ILS system supervises.

C. Function Block Diagram of the ILS

In Fig. 4, the system knowledge base is pre-trained by using carefully selected input and output databases from offline system studies and simulations. System dynamic responses, including frequency variation, are among the outputs of the knowledge base.

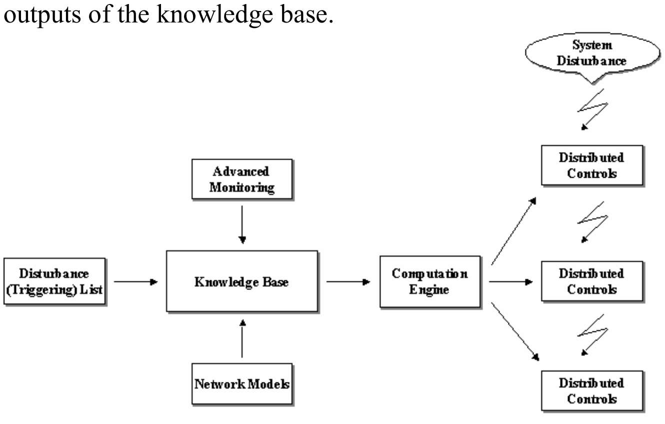

Fig. 4. Function Block Diagram of the ILS Scheme

The trained knowledge base runs in the background of an advanced monitoring system, which constantly monitoring all of the system operating conditions. The network models and the knowledge base provide power system topology, connection information, and electric properties of the system component for ILS. The disturbance list is prepared for all pre-specified system disturbances (triggers). Based on the input data and system updates, the knowledge base periodically sends requests to the ILS computation engine to update the load shedding tables, thus ensuring that the optimum load will be shed should a disturbance occur. The load shedding tables in turn are downloaded to the Distributed Controls that are located close to each sheddable load. When a disturbance occurs, fast load shedding action can be taken.

D. Implementation Configuration of ILS

ILS knowledge base and computation engine reside in an ILS server computer. The server interfaces with an advanced real-time power system monitoring and simulation system that continuously acquires real-time system data. Based on ILS calculations, the server dynamically updates the load shedding tables and downloads that information to the distributed PLCs. Upon detection of any disturbance by the PLCs, load shedding is initiated. The load circuit breakers will be tripped based on the pre-generated optimal load shedding tables. This is shown in Fig. 5.

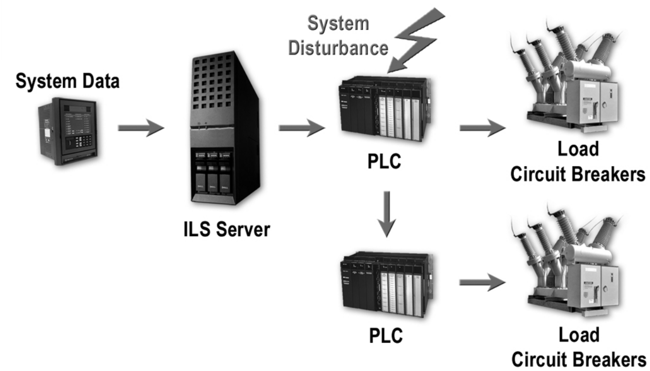

Fig. 5. ILS Implementation Diagram

E. Comparison with Conventional ILS Schemes

A comparison of ILS system response time with that of frequency relay load shedding is illustrated in Fig. 6. As shown, frequency relay load shedding will be delayed until the system frequency drops below the relay set point (Stage 1). Additional load shedding will be needed if the system frequency does not recover to normal (Stage 2). Thus the total response time for the frequency relay based load shedding is much longer than ILS system.

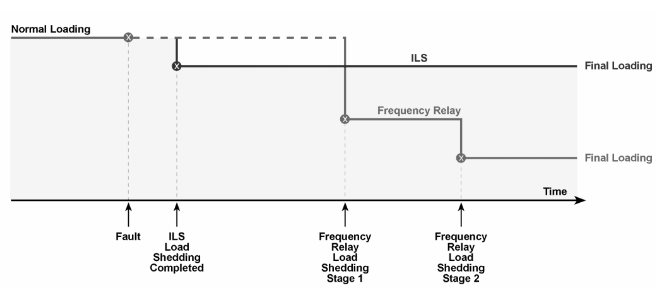

Fig. 6. ILS vs. Frequency Relay Load Shedding

ILS requires only one load shedding stage and has a much faster response time (less than 100 ms in most cases).

A comparison of ILS system response time with that of PLC-based load shedding is illustrated in Fig. 7. The PLC based load shedding will take longer time to respond to the fault due to lack overall system topology, calculation time, and time delays associated with frequency relays. These examples demonstrate the advantages of ILS over the conventional load shedding schemes.

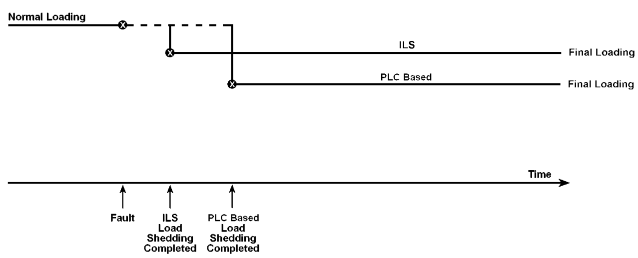

Fig. 7. ILS vs. PLC-Based Load Shedding

IV. ILS Case Study: Installation and Implementation in a Real Industry Facility

A. System Description

A working example of ILS system was recently installed at PT Newmont Batu Hijau, a mining plant in Indonesia. An overall one-line diagram is shown in Fig. 8. This islanded system draws power from four 34 MW steam turbine driven generators (STG) and nine 5.1 MW diesel engine driven generators (DG). The 11 kV generation plant supplies system load through two 150 kV transmission lines stretching 15 kilometers (10 miles). The voltage is stepped down to supply the distribution system at 33 kV. The entire system operates at 50Hz.

Under normal operation all STGs are online and maintaining an average operating load of 110 MW. The average load per generator is between 25 and 30 MW. Spinning reserve is provided by two DGs. When one STG unit goes offline, about five to seven DGs are manually brought online to carry approximately 18 to 20 MW of plant load, respectively.

Based on historical disturbances, an electrical fault on the 150 kV transmission lines would cause the generator units to trip offline, which in turn triggered the existing frequency relay load shedding scheme to operate. Due to the inherently slow speed of this scheme, too much load was often dropped resulting in significant impact on production with losses averaging USD 200,000 per day.

The system utilized a multi-stage frequency based load shedding scheme with a load shedding sequence as shown in Table II.

TABLE II
LOAD SHED TABLE

Stage	Frequency	Delay (ms)	MW Shed
Stage 1	48 Hz	1000	28
Stage 2	47.2 Hz	250	28

B. Types of Disturbances

The main disturbances considered for load shedding are:

a. Loss of generation due to electrical faults
b. Loss of generation due to boiler trip

1) One Generator Trips

The loss of a generator has tremendous effects on the system process since the electrical demand is approximately 92% of the generating capacity of the steam plant. For example, losing one STG unit reduces the generating capacity by about 20%. As a result of this condition, the two mill motors are shed. Operators then have to manually start up the diesel generators in order to restart the mill motors.

2) Two Generators Trip

When a fault occurs on the transmission line, two generators (about 45% of the generating capacity) could be tripped by the transformer protection relays. The loss of two STG units can potentially escalade very quickly to a total system shutdown if the proper amount of load is not shed before the remaining system becomes unstable.

3) Pulverizer and Boiler Trips

The powerhouse steam boilers are fired with pulverized coal. Each boiler has two pulverizes that are capable of supplying only half of the steam capacity from each pulverizer. One or both pulverizes can shut down when a mechanical problem occurs, or the supply of coal is lost. When a pulverizer is shut down for any reason, the steam generating capacity of the boiler is reduced with a reduction in electric power generating capacity. The generating capacity will not immediately fall to zero if both pulverizers are lost because of the residual capacity of the boiler. The remaining generating capacity of each boiler during upset conditions must be known so appropriate settings of the load shedding system can be made.

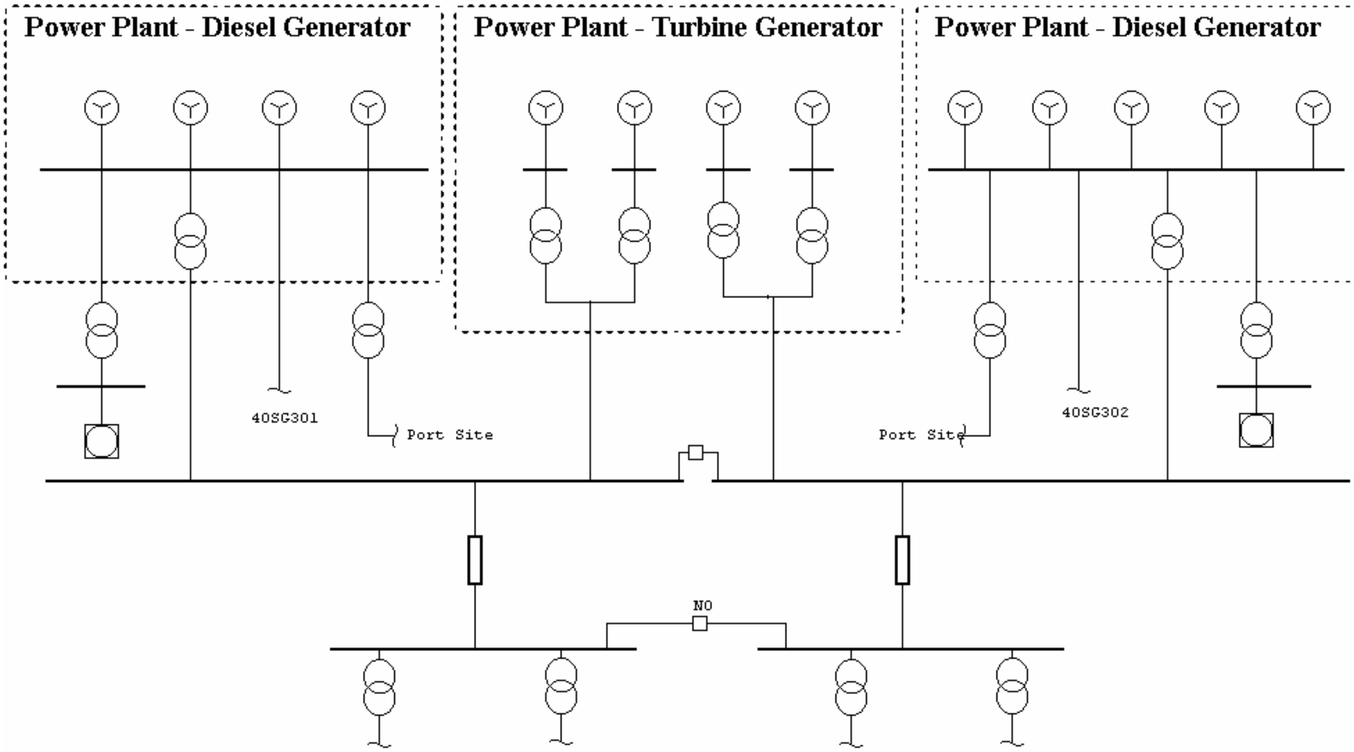

Fig. 8. Simplified One-Line Diagram for PT Newmont Nusa Tenggara

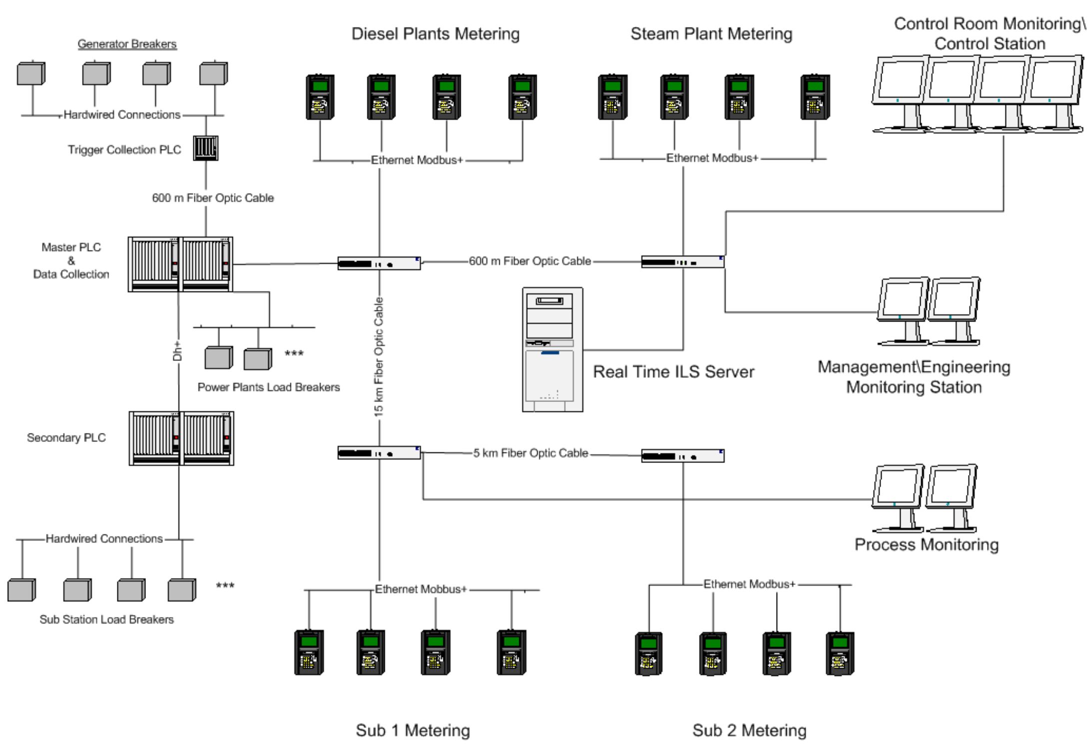

Fig. 9. ILS Communication System Architecture for PT Newmont Nusa Tenggara

C. Data Communication Architecture

As previously explained, the speed of operation and continually updated load shedding tables are what sets the ILS system apart from other types of automatic load reduction systems. The electric demand for this mining operation is fairly constant except for the small motor load that can quickly fluctuate between 3 MW to 25 MW. For the ILS to work correctly, this load swing must be included in the continual load tabulation, so a data collection server was located in the substation that supplied these loads. This allowed the ILS to continually monitor these loads.

The ILS server is installed in the power plant control room. To bring the data from the Data Collection Server (located at the load substations), fiber optic cable was chosen to be the most effective way to accomplish this task. Radio communication and other methods were evaluated, but discarded since running 15 kilometers of fiber was feasible.

Ethernet equipped smart meters or Intelligent Electronic Devices (IEDs) were used for data acquisition. Online system data combined with circuit breaker status and other pertinent information are passed to ILS server for processing and calculating the following:

- Total generation
- Total load to shed for each triggering event
- Generation capacity
- Total spin reserve
- Minimum load to be shed for each triggering event
- Optimal combination of circuit breakers

Using the above information, ILS performs all of the calculations necessary to determine the optimum load shedding tables. These tables are then downloaded to the local PLCs every 500 ms. The load shedding trigger is hardwired directly to the PLCs. This configuration produces a total response time of less than 70 ms, which is a significant improvement over the original system response time of 300 ms. In addition to an improved response time; the optimal load is now shed.

D. System Improvements Achieved with ILS

1) Reduced Response Time

ILS will significantly reduce the system load shedding time with its master/local PLC configuration. The local PLC is able to detect the operation of a STG breaker almost instantly because the trip signal is hardwired to the PLC. The local PLC then distributes this signal to all of the secondary/remote PLCs. For this system where independent triggers (isolated case disturbance) were detected, the response time was measure around 20 ms. In order to distinguish between isolated case disturbance and subsequent contingencies, an intentional delay of 50 ms was introduced prior to sending the trip signals to the load breakers. This is illustrated in Fig. 10.

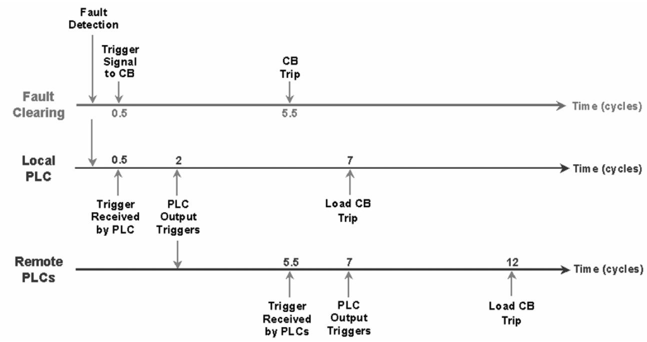

Fig. 10. ILS Response Time with Intentional Delay

2) Optimal Load Shedding

The shedabble loads are two 13 MW motors and four 7.5 MW motors. The first stage of the existing frequency based load shedding system would have shed the one 13 MW motor and two 7.5 MW motors when the system frequency fell to 47.2 Hz. If the underfrequency condition persisted below 48 Hz for an additional 750 ms, the remaining 13 MW motor and two 7.5 MW motors would be shed. This means a total response time of about 1000 ms after the main breaker tripped. This scheme ensured that sufficient load would be shed to maintain system stability. Less critical loads, such as the mine loads are not considered as sheddable loads since their loading can vary between 3 to 25 MW during normal mining operation.

The original frequency relay scheme for a specific disturbance is achieved by dropping Load 1 through Load 4 as shown in Table III. For the same disturbance, ILS monitors pre-disturbance generation level of about 25 MW and spinning reserve of about 19 MW. Based on these inputs and additional system data, ILS calculates the required load to be shed equal to 7.0 MW, thereby, selecting Load 2 as the optimal load to be dropped.

TABLE III
LOAD SHED TABLE FOR FREQUENCY RELAY SCHEME

Load ID	Group Priory	Quantity	Operating MW
Load 1	1	1	13
Load 2	1	2	7.5
Load 3	2	1	13
Load 4	2	2	7.5

A comparison between ILS and the frequency relay scheme for one generating unit trip is shown in Table IV. ILS will shed an optimal (minimum) load of 7.5 MW in 75 ms vs. 28 MW in 300 ms when using the original frequency relay load shedding scheme for one generator unit tripping. The comparisons show a significant improvement in both load shedding response time and reduction in the amount of load shedding when utilizing ILS technology.

TABLE IV
COMPARISON BETWEEN ILS AND FREQUENCY RELAY SCHEMES (1 Unit Trip)

	MW Shed	Time (ms)
ILS	7.5	75
Frequency Relay	28	250

In case of two generating units tripping at the same time, ILS monitors pre-disturbance generation level of about 50 MW and spinning reserve of about 16 MW. Based on these inputs and additional system data, ILS calculates the required load to be shed equal to 34 MW. A comparison between ILS and the frequency relay scheme for two generating units tripping is shown in Table V.

TABLE V
COMPARISON BETWEEN ILS AND FREQUENCY RELAY SCHEMES (2 Unit Trip)

	MW Shed	Time (ms)
ILS	34	75
Frequency Relay	56	1000

V. CONCLUSION

Load shedding in industrial power systems serves as the ultimate guard that protects the system from an overload induced collapse. This critical load preservation is normally done with the use of circuit breaker interlocks, under frequency relaying, and PLC-based schemes. Common drawbacks of these schemes include lack of detailed pre- and post-disturbance data, real-time system configuration, type and duration of the disturbances, as well as other important information. This paper has introduced an intelligent optimal and fast load shedding technology referred to as ILS. ILS combines system online data, equipment ratings, user-defined control parameters, a knowledge base obtained from offline system simulations, system dependencies, and continually updated dynamic load shed tables. This system can perform load shedding in less than 100 milliseconds from the initial occurrence of a disturbance. ILS technology has been successfully installed and operational at industrial facilities.

ACKNOWLEDGMENT

The authors greatly appreciate and acknowledge the engineering staff and management of PT Newmont Nusa Tenggara, Indonesia for their contribution and support in installation and testing of the ILS system at Batu Hijau mine.

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