Intelligent Electrical Load Shedding in Heavily Loaded Industrial Establishments with a Case Study

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Abstract—**The purpose of a Load Shedding Control System (LSS) is to prevent a dangerous overloading of the generators and/or a general collapse (blackout) of an electric power system due to a generator failure or any contingency which may diminish the capacity of the operational generators below the active power required by the loads. Such a state may create an imbalance in the power supply and thus lead to a frequency decay, voltage collapse and overload on all the power generation units connected to the system.**

In case the electrical supply is inadequate to meet the demand of the process loads, partial supply to certain areas can be interrupted in order to prevent the failure of the whole electrical system. This process is called load shedding. This is an entirely different concept from a power failure that may occur due to various reasons.

Load shedding is an effective method to prevent a total collapse of the electrical supply, which may have a disastrous impact on the continuity of the processes and operations. Unless power imbalances are properly managed, they may cause the entire workflow to collapse until the power to the industrial establishment is restored.

The aim of this paper is to discuss the electrical load shedding process of a refinery, which is a heavily loaded industrial establishment, in detail.

Keywords-load shedding; under-frequency load shedding; interconnected power system; islanding; Intelligent Load Shedding (ILS)

I. INTRODUCTION

Maintaining the power supply to the critical process loads is vital for an industrial cogeneration power plant, both for the continuous production and the overall safety of the plant during emergencies. A sudden interruption of the production may result in significant economic losses and even cause major safety concerns. The majority of industrial establishments that require an uninterrupted energy supply in the form of electric power and steam choose to install cogeneration units [1].

Though power systems are designed to function under normal conditions, they also include a safety margin for emergencies. The main objective of the electric utility is to operate the power system without exceeding the system constraints and operational limits. However, in certain conditions such as a sudden increase in the system demand or an unexpected power failure, system constraints and operational limits may be exceeded beyond the tolerance limits. In such cases, load shedding is considered an emergency measure to avoid cascaded tripping and a blackout [2].

One of the best known methods of load shedding is undervoltage load shedding. In case of an extreme event in a network, undervoltage load shedding can be applied as an economical method to prevent a voltage collapse and to maximize the power system's loadability. In this method, different bus voltages are considered as overloads or voltage collapse indices [3].

A second common type of load shedding is frequency load shedding. An imbalance in the active power supply may lead to frequency changes [3]. If voltage and frequency deviate outside the permissible range, the system becomes unstable. Thus, the system controllers attempt to restore the normal voltage and frequency values within the permissible range. If the disturbance is so large that the controllers cannot restore normal function, load shedding is the last resort to avoid the breakdown of the power system [4].

Load shedding is a commonly applied method in states of emergency/extreme emergency where the system is headed for a collapse. Given the appropriate conditions, the load shedding process should be started as soon as possible [5].

For this purpose, different techniques including circuit-breakers interlocking, LS based on under-frequency relays, and LSS based on PLC or micro-controllers have been developed over the years. These techniques shed a predefined amount of load (power blocks) in order to reach a balanced power state according to the available generation capacity, thereby providing faster and optimum responses during a sudden loss of power.

In this paper, we would like to present a load shedding system activated either by under-frequency or a lack of generation capacity depending on operational states.

II. SYSTEM DESCRIPTION

A simplified one-line diagram of the electrical system of a heavily loaded industrial establishment (a refinery) including a load shedding system is shown in Fig. 1

The on-site installed power generation capacity at the refinery is 120 MW (Table I) and the maximum connected load is 97.24 MW (Table II). In addition to three on-site generators, the power supply of the refinery is ensured through two 154 kV underground transmission lines connected to the Turkish national power grid. The generators are continuously operated in parallel with the national grid. The electrical system of the presented refinery includes the following individual sections [6]:

1) The main switchgear section-154 kV: The 154 kV switchgear system which is connected to the national grid through two high voltage feeders.

2) Generation section: The power generation section at 11 kV and 34.5 kV levels. This subsystem includes two 39.54 MW gas turbine driven generators and one 41.31 MW steam turbine driven generator.

3) Main distribution section: The distribution section at 34.5 kV level. This subsystem includes four incomers (two from generation bus-bar and two from the national grid through the 154/36 kV transformers, plus a number of outgoing feeders to the process substations of the refinery.

4) Substations section: Process plant substations include the step-down transformers supplied by dual 34.5 kV feeders originating from the main 34.5 the kV distribution switchgear.

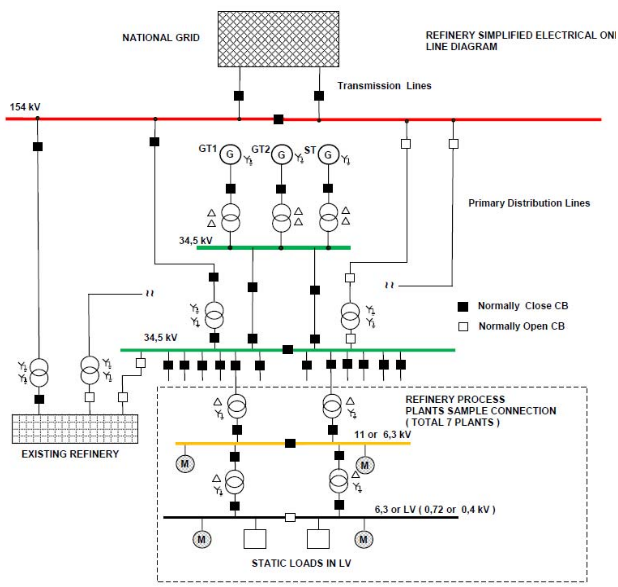

Figure 1. Simplified one-line diagram of the electric system of the refinery

III. LOAD SHEDDING PHILOSOPHY

Blackouts are one of the critical disturbances that may occur in interconnected power systems. In such cases, the frequency and voltage of the power system rapidly decline, causing the other generation units to overload. If the overloaded generation units cannot carry the extra strain, they start to fail in a cascade [4]. A state of emergency in a power system may occur due to a sudden increase in the system load, an unexpected loss of a transmission line or a generator, or a failure in any of the system components. This may lead to certain problems including overloaded lines, under-frequency, voltage collapse, or angle instability [5].

For industrial electrical systems containing stand-alone generators, appropriate islanding and load shedding system (LSS) strategies must be developed to stabilize the system and prevent a total blackout under an abnormal condition, [1].

Load shedding has two operational criteria: load shedding due to inadequate generation capacity (main) and load shedding due to under-frequency (backup). In case one of these criteria is fulfilled, a sequence of load shedding and/or alarm is triggered in order to restore the stability of the power system to maintain normal operations.

Load shedding due to inadequate generation capacity: The aim of this control is to anticipate a frequency drop, in case any change in the power system network configuration imposes a greater load on the available generation/interconnection power sources.

To detect any imbalances in the power supply, the LSS maps the power network topology (Identification of the Network Configuration – INC) verifying the status of the main circuit-breakers and thus identifying the operational status at any given moment. Load values will be calculated based on the analog signals at the 34.5kV bus bars and 11 kV generator circuit breakers.

These operational states or modes comprise all the probable operational conditions that may occur in the electric power system, monitoring the interaction between generation and load. Since several operating modes cannot be operated in this manner, load reduction or load shedding becomes necessary.

If the generated power is inadequate, the load shedding procedure starts immediately. The magnitude of the load to be shed must be based on a comparison between the capacity of the generators in operation, the maximum capacity of the interconnected power sources, final spinning reserve, and the measurement of the power required by the load. This comparison is performed for each possible network configuration and possible contingencies in advance. Thus, as soon as the load becomes larger than the generating/interconnection capacity, the LSS will order to shed pre-selected groups of loads in order to maintain the balance.

The load shedding steps are strictly in accordance with the preset load priority sequence and limited to the necessary minimum. Based on the identification of the network configuration (INC), the load shedding system selects the load, and the generation and interconnection lines to be involved in the section of the electrical system that will be affected and then maintain a stable and balanced condition

Load shedding due to under-frequency: A second common load shedding technique is frequency load shedding. Imbalanced active power in a system leads to frequency changes. Therefore, any type of active overload or generation reduction in a system will be reflected as a frequency change [3]. The aim of this control is to avoid a power system collapse due to under-frequency.

In order to detect an under-frequency, a set of protection relays installed on the power network of the refinery continuously monitor the frequency and send a signal to the LSS immediately in order to start load shedding if the frequency reaches predefined values. Three cases are possible:

Case 1*:* If under-frequency is detected while the generators and the national grid are running in parallel, decoupling relays in the relevant switchgear start the separation process from the national grid (area disconnection). For this purpose, all the interconnection lines with the national grid are disconnected. Subsequently, the load shedding process is activated based on the difference in the current generation capacity and the original network configuration.

Case 2*:* If under-frequency is detected and the refinery is disconnected from the national grid, the LSS will initiate a cascading sequence of load shedding steps in order to recover the frequency (and maintain a balance between load and the generation capacity).

Case 3: If both refineries (New and Existing) are connected only by a single 34.5 kV line and an under-frequency is detected, the load shedding procedure separates the refineries (disconnecting the remaining 34.5 kV line) and each refinery starts its own load shedding scheme.

When the refinery is connected to the national grid, the frequency will be controlled by the national grid. All the generators are adjusted in load mode or steam generation mode (if applicable).

When the electrical system of an industrial facility is disconnected from the national grid, the frequency will be managed according to the generator priority list. This list comprises all the generators.

IV. Design of Load Shedding

A. *Load Shedding Design Based on Lack of Generation Capacity (LGC)*

In order to design the different load shedding programs, it is necessary to perform a comparative evaluation of the generation/load relationship for the different operational modes. This evaluation is based on the data presented in Tables I and II including the generation limits, interconnection lines, import limits from the Public Power Network (154 kV system) and loads in substations of the refinery.

TABLE I. Plant Equipment Capacities

Equipment	Power Capacity	Description
Main Transformers	100/133 MVA	154/34,5 kV Transformers between the national grid and the plant
GTG - 1	39.27 MVA	Gas Turbine Generator - 1
GTG - 2	39.27 MVA	Gas Turbine Generator - 2
STG -1	41.3 MVA	Steam Turbine Generator - 1
Transmission lines	153.5 MVA	Transmission lines between the national grid and the plant

TABLE II. Plant Load Distribution in Substations

Substation	Load (MW)
Substation - 01	9,22
Substation - 02	21, 27
Substation - 03	5,56
Substation - 04	43,39
Substation - 05	8,89
Substation - 06	8,4
Total load	97,24

Additionally, a “Priority Load List” for different sections of the refinery based on a detailed criticality analysis of each process unit is used in the design of the load shedding system.

The first step is the evaluation of the most probable scenarios that may occur in the power network topology. In this particular case, the evaluation is carried out considering that only the generators and the total load are connected to the main or auxiliary bus-bars. Based on this assumption and several simplifications on the circuit-breakers involved in the study, a total of 256 Operational Modes were analyzed as a reference.

B. *Load Shedding Design Based on Under-Frequency Conditions (UFC)*

In order to define the load shedding schedule based on under-frequency logic, it is necessary to define different (worst case) scenarios in which a sudden power loss causes the frequency to drop ($df/dt<0$). Subsequently, the amount of the load (Power Blocks) needed to reestablish the power balance and recover the frequency is calculated.

Traditionally, under-frequency relays, breaker interlock systems and PLC-based (programmable logic controller) systems are used for load shedding. However, these load shedding systems do not take system operating information in consideration. Since these are still best-guess methods, they usually end up with excessive or inadequate load shedding at the feeders. In case of an emergency, faster and optimal load relief can be obtained with an intelligent load shedding system [7].

According to the descriptions presented in Section II, in the event of a Case 3 scenario, the LSS must operate on three levels:

- The First Level is managed by the decoupling relays. Whenever the frequency drops below a predetermined critical value (f_0) for a certain period of time (Δt) and an inverse power condition is present, these relays separate the new and existing refineries from the external power system. Once the separation is complete, this state is signaled to the LSS for initiation. To enable a timely response to grid separation and to decide whether or not to shed any plant load, it is imperative that the disconnection from the grid is detected in a timely manner. It is also vital that the external quality of the supply is monitored and islanding is initiated when the quality of supply is out of the norms [8].

- The Second Level is managed by the LSS itself, taking into account new and the existing refineries. The "system frequency tracking" will be implemented by using under-frequency relays located at the load shedding panel.
- The Third Level is managed by a set of multifunction relays that will operate by separating the new refinery from the existing refinery and tripping a set of predefined loads at the 34.5kV level as a backup system.

V. UNDER-FREQUENCY ANALYSIS

Due to the off-frequency characteristic of the generation units and the need for under-frequency load shedding, it is not possible to fully accomplish the frequency threshold defined by the Turkish Electricity Market Grid Regulation. Since the minimum frequency of the gas turbines during continuous operation is around 47.5 Hz, the power systems of the refineries must be separated from the Turkish Power Network long before the system frequency reaches this rate.

In practice, the most commonly applied load shedding scheme for islanded distribution systems is the under-frequency load shedding (UFLS) scheme [9].

To be able to define the set-points (f Pickup) at which the load shedding system will begin to operate, it is necessary to simulate different scenarios where a sudden loss of generation units produces severe under-frequency conditions. Among the various scenarios analyzed, the load shedding results of the new refinery during operation in the island mode are presented below.

Load Shedding Case Scenarios:

Case 1: Simultaneous sudden loss of the generation units: STG and GTG-2 (80.57 MW) with total load connected (100 MW).

As shown in Fig. 2, the frequency variation is observed as soon as the generation units are disconnected from the system (t_0 = 0.5 sec) while the total load remains connected, representing the maximum overload condition (about 155%).

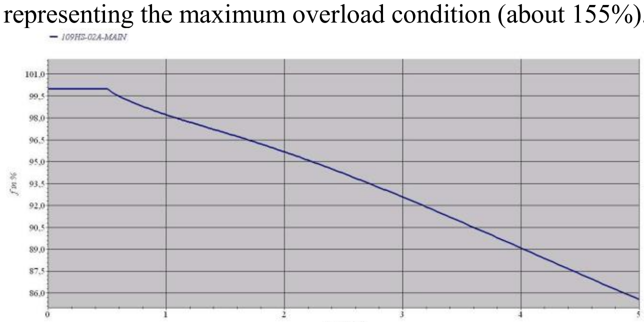

Figure 2. Frequency response without the load shedding system (loss of STG and GTG-2 = 80,57 MW – installed capacity)

LSS due to inadequate generation capacity is initiated (under the same loss of generation capacity scenario – maximum frequency deviation) in order to calculate the minimum frequency value that is reached by the system during the overall LSS operation time (250 ms) as shown in Fig. 3.

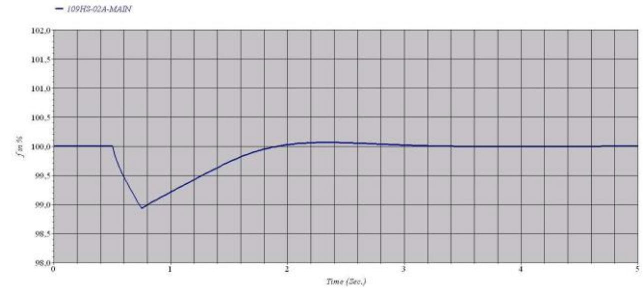

Figure 3. Frequency response during the operation of the load shedding system due to inadequate generation capacity (max. time = 250 ms) (loss of STG & GTG-2 = 80,57 MW – installed capacity)

Based on these simulations, a set of two load shedding steps were calculated:

Step 1, f_1= 48,6 Hz (97,2% f_n), load to be tripped = 29 MW time delay = 0 sec.

Step 2, f_2= 47,5 Hz (95% f_n), load to be tripped = 35,5 MW time delay = 0 sec.

If LSS is performed according to the above-mentioned frequency settings, the frequency response shown in Fig. 4 is observed.

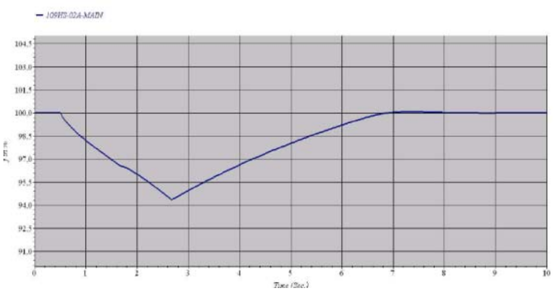

Figure 4. Frequency Response with Under-Frequency Load Shedding (due to the loss of STG & GTG-2 = 80.57 MW – Installed Capacity)

According to these calculations, a frequency recovery is possible after about 7 seconds and the frequency reaches a minimum value of 47.17 Hz, just above the minimum (47 Hz) for the steam turbine's possible operation.

The voltage and power generation responses observed during the power loss and load shedding operations are shown in Figs. 5 and 6, respectively.

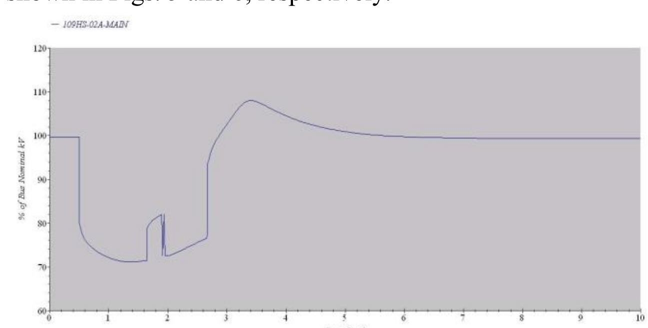

Figure 5. Voltage Response at 34.5 kV with the Under-Frequency Load shedding System

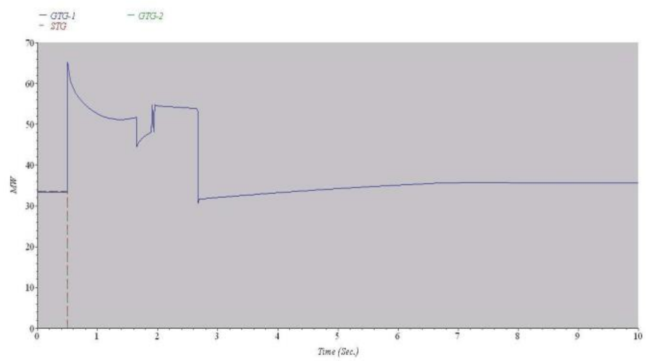

Figure 6. Electrical Power Generation variation

Similar load shedding scenarios have been analyzed for all possible operation modes and integrated into the load shedding PLC.

VI. CONCLUSION

The load shedding system is the last resort as a backup measure in cases where an electrical power system faces a disturbance that causes an imbalance between the mechanical power supplied and the power required by the load.

A rapid initiation of preventive measures and the optimum response are the key features for a successful system recovery under these conditions.

Based on the evaluation of the power generation capacity, loads, and the interconnection constraints of the new and existing refineries, it is possible to estimate the main load shedding scheme for inadequate generation capacity logic used as the main protection against islanding power imbalance conditions.

The load shedding scheme and the load priority list are used as design references in the programming process, and all the possible operational modes and load conditions that can occur in the refineries' power networks are taken into consideration.

In case of any changes in these parameters, the LSS logic should be updated in order to guarantee the proper operation of an industrial electrical system.

In addition, the LSS was also evaluated based on under-frequency conditions. This analysis has pointed to the need for different settings as a function of the power network topology (adaptive logic) due to the different frequency responses depending of the interconnection status between the new and existing refineries and the possible overload conditions.

In order to predict these frequency behaviors, a simplified equivalent model of the power systems (the new and existing refineries) has been used, which has helped define the load shedding steps in each specific case studied.

These results have demonstrated that is not possible to fully accomplish the decoupling requirements dictated by the Turkish Electricity Market Grid Regulation. Therefore, it is proposed to define a group of settings at the decoupling and under-frequency relays (f <) used in the LSS logic and its backup systems.

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