Case Study: Adaptive Load Shedding in Critical Industrial Facilities

Edson Hernandez and Bob Hughes
Schweitzer Engineering Laboratories, Inc.

José de Jesús Durón-Mendoza
Grupo Zener S.C.

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CASE STUDY: ADAPTIVE LOAD SHEDDING IN CRITICAL INDUSTRIAL FACILITIES

***Edson Hernandez*[1*]*, Bob Hughes*[1]*, José de Jesús Durón-Mendoza*[2]**

[1]*Schweitzer Engineering Laboratories, Inc., Pullman, Washington, USA*
[2]*Grupo Zener S.C., Ciudad Madero, Mexico*
**edson_hernandez@selinc.com*

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Abstract

Industrial plant activities involve critical processes, especially those that include the use of toxic gases. In the event of a loss of electricity supply, such processes can fail and cause lethal health risks to those near the plants. In industrial plants that rely on their own power generation and are interconnected to an electric utility for energy backup, both the power system topology and the importance and criticality of the electrical loads across these plants change dynamically as processes and operations are initiated or stopped. In the event of a fault, an effective load-shedding scheme that adapts automatically to changes in system topology, such as islanded and non-islanded conditions, is key to compensate for lost generation, maintain power system stability, and avoid blackouts. This paper describes the design, implementation, and operational results of an in-service load-shedding scheme for a large chemical industrial complex in Mexico. The proposed load-shedding scheme uses high-speed IEC 61850 Generic Object-Oriented Substation Event (GOOSE) messages and synchrophasors, which provide apparatus monitoring and control, remote load shedding, and monitoring of power measurements for onsite generators and the interconnection with the electric utility system.

1 Introduction

An important chemical industrial complex in Mexico is composed of three different processes, which are identified in this paper as Plant A (power generation), Plant B (gas generation), and Plant C (chemical processes) because of a confidentiality agreement. Plant A generates electric power with two gas-turbine units, Plant B produces different types of gases that are consumed by both the two gas-turbine units in Plant A and processes in Plant C, and Plant C consumes both the electric power generated by Plant A and some of the gases produced by Plant B for its processes. Fig. 1 shows the relationship between the chemical industrial complex processes. The industrial complex is designed to operate under balanced generation-load conditions and is only interconnected to the local utility for backup purposes.

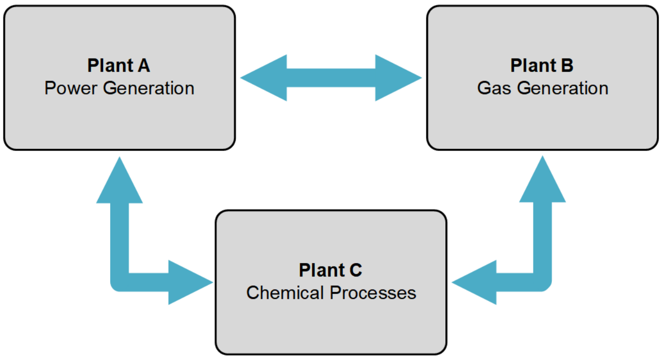

Fig. 1. Chemical industrial complex process relationships.

Before the expansion project, Plant C had a simple and rudimentary load-shedding scheme. For faults occurring in the 115 kV utility transmission line, the step-down transformers connected to the transmission line, or the gas-turbine generators, the load-shedding scheme would trip specific and important loads distributed across Plant B and Plant C, interrupting the production processes and causing considerable economic loss. The industrial complex was formerly tied to the 115 kV utility transmission line in a tap connection. Because the transmission line was experiencing frequent faults, this configuration caused the industrial complex to suffer from continuous process interruptions, which needed to be addressed in an urgent manner.

2 The Expansion Project

In 2015, the industrial complex began an expansion project to increase Plant C production, which involved the addition of a second production line and the installation of a third gas-turbine generator in Plant A to support the power demand from the new line. As part of the expansion project, a stability study of the new industrial complex power system was required, in addition to the design of a new load-shedding scheme that would replace the existing one.

2.1 The Power System

The new power system consists of three gas-turbine generators and two step-down transformers tied in a tap configuration to a 115 kV transmission line from a local utility, as shown in Fig. 2. All the energy surplus is sold to the utility.

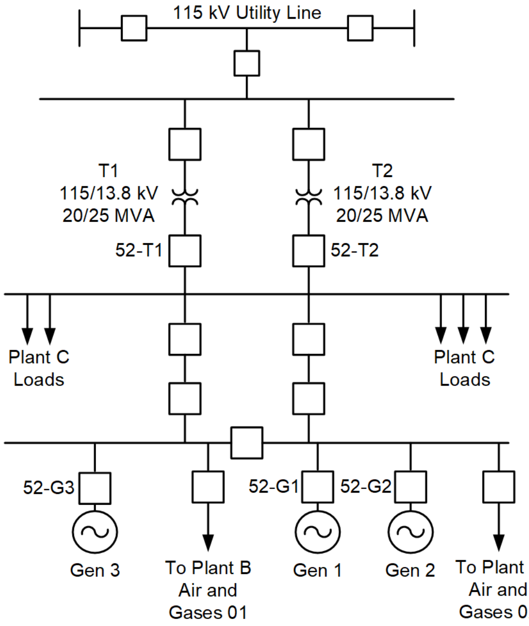

Fig. 2. Single-line diagram of the industrial power system.

2.2 *Transient Stability Study for the New Power System*

A power flow study determined the load power demand in each operation site and its relationship with the power system installed capacity. The transient stability study focused on the effects the loads would induce in the system if a loss of supply from the utility interconnection or the gas-turbine generators occurred. The goal was to determine the loads to shed and the maximum load-shedding time before the system becomes unstable.

The study results defined eight production sites distributed across Plant B and Plant C that included a total of 17 loads to trip (see Fig. 3). The study also determined the conditions for the load-shedding scheme operation: a total of 20 contingencies and a maximum load-shedding time of 100 ms.

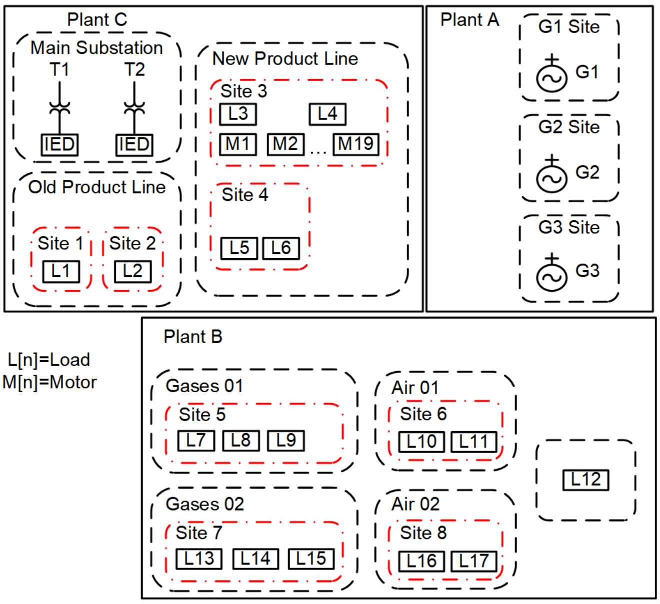

Fig. 3. Industrial complex production sites and load distribution.

2.3 *Load-Shedding Requirements*

The new load-shedding scheme has the following requirements:

- Prioritize and guarantee by any means the safe shutdown of the processes using chlorine and other toxic gases that may cause lethal health risks to those near the plants in case of a major power loss.
- Prevent unnecessary process shutdowns by shedding only a group of non-critical loads located in Plant B and Plant C.
- Shed the preselected loads as established for each of the 20 contingencies in less than 100 ms. By operating within the given time frame, the impact of power system disturbances is reduced significantly so system stability is guaranteed; the load power demand is controlled before the transformer and gas-turbine generator protection schemes operate, avoiding cascading outages and blackouts in the industrial complex [1] [2].

3 The Load-Shedding Scheme

3.1 *Initial Proposal*

Initially, the stability study proposed a load-shedding scheme in which a predefined group of strategically preselected loads were shed by considering the configuration of the system based on the position of the five breakers 52-T1, 52-T2, 52-G1, 52-G2, and 52-G3, as seen in Fig. 2. This solution assumed the power consumption of each of the eight production sites and the capacity of the step-down transformers and gas-turbine generators to be known. Hence, the power system stability could be maintained by simply shedding the loads required to reduce the power demand of the system and restore the generation-load balance. The proposed design assumed that the industrial complex would always be operating with all power sources connected to the system, but never considered any other operational situations such as maintenance, process shutdowns, or islanded operation.

3.2 *A New Proposal: Contingency-Based Adaptive Load-Shedding Algorithm*

Leveraging the initial study and the proposed 20 contingencies, a new adaptive algorithm was designed to reflect the normal operation of the complex and was proposed to the end user as the solution for the initial proposal deficiencies. The new algorithm would be able to detect whether the system operates as an islanded or non-islanded system by monitoring the status of the transformer breakers and comparing the active power measurements from these sources. In addition, the algorithm would be able to switch between islanded and non-islanded profiles, recalculate contingencies and required loads to shed per profile automatically, and be able to be activated or deactivated based on predefined power system level thresholds, which will avoid unnecessary operations and/or blackouts. The algorithm would also be able to make tripping decisions based on a comparison of generation capacity and demand rather than relying only on breaker status, which causes the algorithm to adapt automatically to any operating condition, such as total or partial shutdowns and maintenance.

3.3 Adaptive Load-Shedding Algorithm, System Physical Architecture, Design, and Operation

3.3.1 Main Components

The load-shedding scheme can be described as a set of two major architectures, the load-shedding data acquisition architecture and the load-shedding distributed tripping physical architecture.

The load-shedding data acquisition architecture is implemented by a distributed mesh of intelligent electronic devices (IEDs) installed throughout the industrial complex. Fig. 4 depicts the conceptual load-shedding data acquisition architecture. Inside Plant C, the main substation houses a panel that contains one industrial-grade Global Positioning System (GPS) clock, two industrial-grade revenue meters, one industrial-grade Ethernet switch, and an industrial-grade automation controller that serves as a load-shedding processor (LSP). Inside Plant A, three distributed sites house identical panels that contain one industrial-grade GPS clock and one industrial-grade revenue meter each.

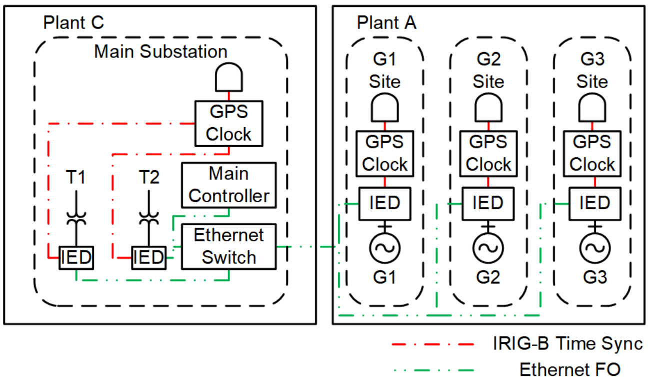

Fig. 4. Load-shedding data acquisition architecture.

The LSP is an industrial-grade real-time automation controller that acts as a communications processor that collects data from the remote IEDs, either serially or through Ethernet. The automation controller supports the IEC 61131 programmable logic, which provides the capability to manipulate and process the data concentrated from the IEDs. The automation controller supports multiple communications protocols and can function as a gateway by converting data between multiple protocols. The LSP processes the IED data and transmits the resulting load-shedding signals to the remote input/output (I/O) modules installed throughout the complex.

The automation controller uses high-speed Ethernet communications via fiber-optic cables to monitor the status of the power system [3] [4]. Each revenue meter reports apparatus status by publishing a Generic Object-Oriented Substation Event (GOOSE) message and the power measurements of the system using the IEEE C37.118 protocol (synchrophasors). The LSP is then subscribed to the published GOOSE messages and is connected to the IEEE C37.118 servers to concentrate apparatus status data and system power measurements [3]. The LSP processes and manipulates the collected data, evaluates the contingencies, and sends the load-shedding signals to the I/O modules.

The load-shedding distributed tripping physical architecture is implemented with a collection of distributed I/O modules installed in different sites throughout Plant B and Plant C that communicate with the LSP using a fiber-optic network.

Considering that many of the existing apparatuses in the distributed sites do not allow for remote control over a network with long distances from the LSP to the distributed sites, these remote I/O modules are used to receive the load-shedding digital signals from the LSP and convert them to physical tripping signals of the selected loads. Different protocols were used to communicate the I/O modules with the LSP by considering the number or the physical arrangements of loads to shed and if an exchange of information between the LSP and the I/O modules was required. A protection-oriented protocol was used for tripping loads physically located in the same control house and that were also required to be monitored remotely and exchange information with the LSP [5]. IEC 61850 GOOSE messages were used when only a remote reception of the load-shedding tripping signal was required, such as for the 19 motor protection relays located in Site 3 inside of Plant C, which subscribed to a GOOSE message from the LSP in which the load-shedding tripping signal is published.

3.3.2 Operation Principles

The load-shedding algorithm has two operational functions: pre-event calculations and event actions [5]. The algorithm performs pre-event calculations to dynamically change between predefined profiles determined by the power system topology and to update the load-shedding contingencies matrix. The algorithm monitors the contingency triggers and generates the load-shedding signals if the demand exceeds the power system capacity. Fig. 5 illustrates the conceptual design.

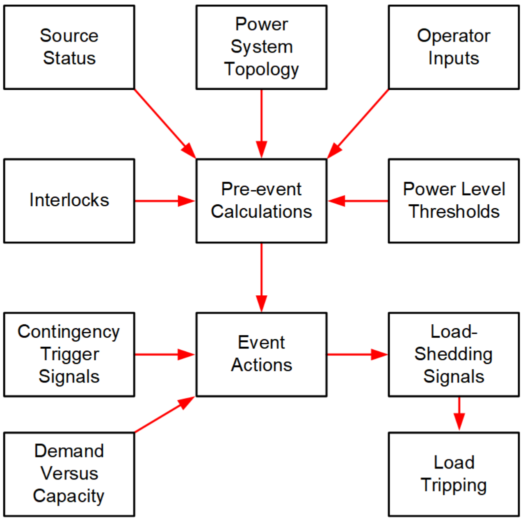

Fig. 5. Load-shedding algorithm conceptual architecture.

The load-shedding algorithm is programmed to perform the following functions (see Fig. 6).

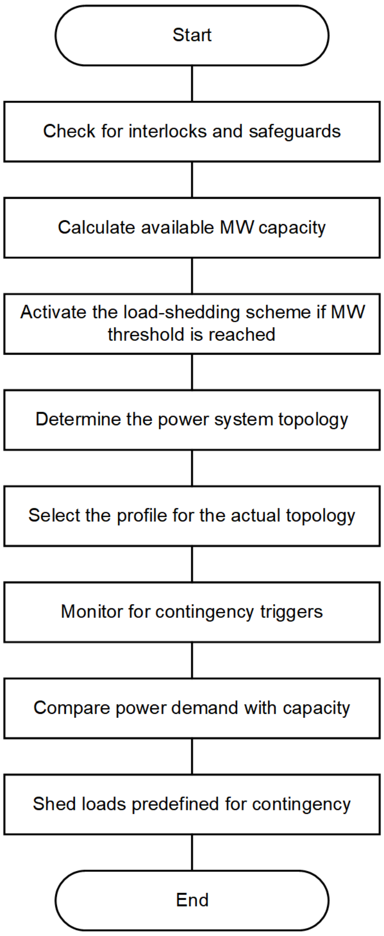

Fig. 6. Load-shedding algorithm flow diagram.

The algorithm evaluates whether the load-shedding scheme is enabled and ensures that no interlocks or safeguards are present in the system. It measures the total available capacity in the power system and evaluates whether the available capacity is greater than or equal to an initial preset threshold of 42 MW. The value of the threshold is calculated from the total power that generators G1, G2, and G3 will contribute to the system because it is assumed that the industrial complex is always operating in a balanced generation/load condition. If the conditions are met, the load-shedding scheme will be armed and ready to operate.

The algorithm monitors the power system topology in real time, which could correspond to an islanded or non-islanded system. The algorithm evaluates whether the system is in islanded or non-islanded mode and dynamically loads a preconfigured profile for the current system mode. The algorithm contains two profiles, one for islanded mode and one for non-islanded mode. Each profile contains a preconfigured matrix that contains a set of contingencies and the loads to shed in each contingency. The algorithm monitors the contingency trigger signals (the opening of a breaker) that initiate the load-shedding operation. With the load shedding initiated, the algorithm determines the contingency to select by analyzing the current source status based on the status of the breakers in the system. With the contingency detected and the loads to be shed selected, the algorithm waits for the demand to exceed the capacity to issue the tripping command to the selected loads.

3.3.3 Load-Shedding Scheme: Operation and Safeguards (Interlocks)

The load-shedding scheme is designed in such a way that it can be controlled manually, either through a local or remote control. This control provides flexibility to enable or block the load-shedding scheme when required by the industrial complex operation conditions. Locally, a panel installed in the main substation of Plant C contains buttons that allow load shedding to be either enabled or blocked. These buttons are wired to an I/O module that transmits the state of the buttons to the LSP. Remotely, the Plant A supervisory control and data acquisition (SCADA) system can enable or block the load-shedding scheme by sending Modbus control signals to the LSP. As a safeguard, the load-shedding scheme will be enabled only when both the local control and the remote control have enabled the load-shedding scheme.

In addition to the manual control, a series of interlocks were programmed to block the load-shedding scheme to guarantee that it does not operate under false conditions. The interlocks are the following:

- Block by loss of the GOOSE messages to which the LSP is subscribed.
- Block by failure in the synchrophasor communications.
- Block by errors in the synchrophasor communications.
- Block by errors in the breaker status signaling.
- Block by loss of potential in the breakers.

3.3.4 System Monitoring, Engineering Access, and SCADA Integration

Because the load-shedding scheme directly affects all areas of the complex, a very important aspect to consider is the need for SCADA integration, engineering access, and remote IED access to provide the plant operators with real time information about power system status, alarms, and warnings. Engineering access allows Plant C operators to view and download historical alarms, sequence of event (SOE) reports, and event files from the IEDs that are part of the load-shedding scheme. The LSP provides the integration of the load-shedding information to the SCADA systems distributed through the industrial complex.

Fast Ethernet communications over optical fiber are used to provide engineering access to the LSP, the remote revenue meters, the remote I/O modules, and the SCADA integration to the human-machine interfaces (HMIs) in the industrial complex [4].

Leveraging the data processing capabilities in the LSP, an IEC 61131 logic program running in the LSP concentrates power system current, voltage, and power measurements; status of the 52-T1, 52-T2, 52-G1, 52-G2, and 52-G3 breakers; status of communication between the revenue meters and I/O modules with the LSP; alarms, warnings, and interlock status of the load-shedding scheme; and external signals that enable/block the load-shedding scheme. The LSP assigns each value of the monitored signals to different internal variables that are used later to report to the connected system clients. Three clients are connected to the LSP: a SCADA system in

Plant A that monitors the power system, provides control access to enable or block the load-shedding scheme, and communicates with the LSP through Modbus TCP; a SCADA system located in the new site that hosts the gas-turbine generator G3 communication with the LSP through Modbus RTU to monitor the power system; and operator engineering consoles that communicate with the LSP embedded HMI through the LSP web interface. All the load-shedding alarms, events, and operations are logged in the LSP so that the operators can view the historic events at any time to analyze power system events [1].

4 Commissioning

Site acceptance testing (SAT) was required by the end user to guarantee that the load-shedding scheme operated under the requirements established at the beginning of the project. The nature of the distributed system in which the power sources and loads are located across the industrial complex presented a difficulty to the testing setup and procedure during commissioning. To overcome this challenge, three relay test sets synchronized to a GPS clock were used to simulate the 20 contingencies that could possibly initiate the load-shedding scheme as determined by the stability study.

One test set was placed in the main substation of Plant C to simulate the status and power measurements of transformers T1 and T2. A second test set simulating the status and power measurements of gas-turbine generators G1 and G2 was placed inside the metal-clad room in Plant A that houses the revenue meters of generators G1 and G2. The last test set was placed in the multipurpose building of Plant C to simulate the status and power measurements of generator G3. To simulate remote I/O modules that do not provide SOE recording capabilities, external I/O modules synchronized to a GPS clock were used during the test to monitor the time required for those modules to close their physical contacts upon reception of load-shedding signals.

The test set reports, the SOE reports of the remote I/O modules, and the time reports captured by the I/O modules were used to generate the SAT report after all contingencies were tested.

All 20 contingency cases were thoroughly tested. One SAT result corresponding to Contingency 01 is described in this section. Table 1 shows the initial state in the power system and the events that trigger Contingency 01.

Table 1 Pre-event state of the power system and trigger conditions for Contingency 01

Contingency 01	
Initial Power System State	**Contingency Trigger**
T1, T2, G2, and G3 online; G1 offline.	T1 and T2 fail, system transitions to islanded mode.

Before the event, the industrial complex operated in a non-islanded topology in which T1, T2, G2, and G3 were connected and supplying power to the system, and G1 was offline. The contingency initiated when T1 and T2 were tripped to clear a fault in the transmission line and the topology changed to an islanded system with only G2 and G3 supplying power to the system.

52-T1 breaker trips at 20:00:30.986 and is followed by 52-T2 breaker, which trips 37 ms later at 20:00:31.023. The load-shedding algorithm detects the contingency and processes the received data to evaluate if the demand has surpassed the installed capacity. Because the demand exceeded the installed capacity, the algorithm makes the decision to shed the preselected loads for Contingency 01.

The load-shedding signal is received 20 ms later by the relay associated to Breaker 52-B8 at 20:00:31.043, which processes the signal and closes the output contact that trips the breaker at the same time. The total operation time, from the time the contingency was detected to the load tripping, was 57 ms [2], which demonstrates that the load-shedding algorithm operates within the established time of less than 100 ms. The graphic event timeline for Contingency 01 is shown in Fig. 7.

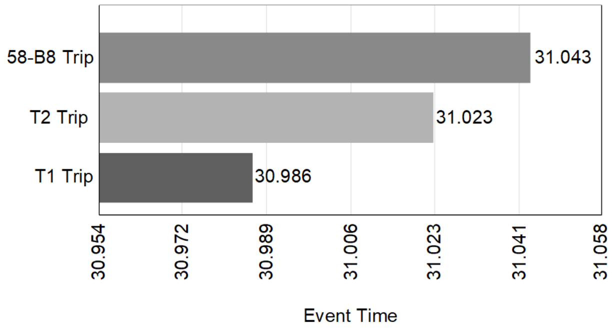

Fig. 7. SAT event timeline results for Contingency 01.

5 Operational Results

The contingency-based load-shedding scheme has shown its dependability by operating successfully several times since its commissioning in April 2016, primarily because of faults occurring in the 115 kV utility transmission line. Based on the information collected from the real-life events, the reported operating times of the load-shedding scheme were between 50 and 70 ms. The frequent power system faults and the correct operations of the load-shedding scheme have provided the plant operators with valuable information that helped to feed the algorithm with new contingencies and perform refinements to the initial values for the power source capacity, the power demand per site, and the number of loads to shed that were provided by the stability study, which yielded very conservative values.

From the several real-life events that the system has experienced, one event of particular interest is included as an operational result in this paper. This real-life event consists of a double contingency in the industrial complex that initiated as a Contingency 09 and evolved to a Contingency 17, which can be seen in Table 2 and Table 3, respectively.

Table 2 Pre-event state of the power system and trigger conditions for Contingency 09

Contingency 09	
Initial Power System State	**Contingency Trigger**
T1, T2, G1, and G2 online; G3 offline.	G1 fails, system continues in non-islanded mode.

Table 3 Pre-event state of the power system and trigger conditions for Contingency 17

Contingency 17	
Initial Power System State	**Contingency Trigger**
T1, T2, G1, and G2 online; G3 offline.	G1 and G2 fail, system continues in non-islanded mode.

Before the event, the industrial complex operated in a non-islanded topology in which T1, T2, G1, and G2 were connected and supplied power to the system, and G3 was offline. The first contingency occurred when G1 tripped at 18:36:14.860. T1 became slightly overloaded because of the loss of power contributed by G1 88 ms later, at 18:36:14.948. The algorithm detected the contingency but did not operate because the capacity exceeded the demand. The algorithm continued evaluating the same contingency for six more minutes without operating until G2 tripped, generating the second contingency at 18:36:21.240. The algorithm detected the second contingency, and because the demand exceeded the capacity, it made the decision to operate. The load-shedding signal was received 44 ms later by the relay associated to Breaker 52-B8 at 18:36:21.284, and 3 ms later in the relay associated to Breaker 52-A6 at 18:36:21.287. GOOSE messages with the load-shedding signals were received 4 ms later by the I/O modules via the Ethernet network. The graphic event timeline for the double contingency event is shown in Fig. 8.

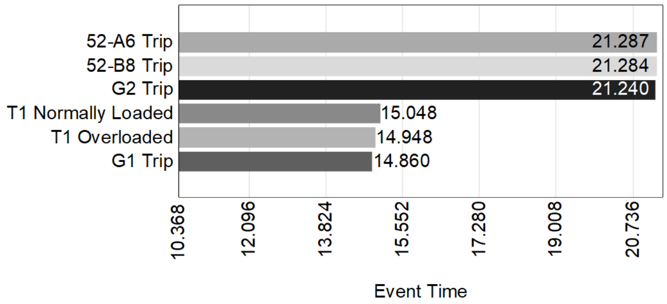

Fig. 8. Real event timeline for a double contingency, initiated as Contingency 09 and evolving to Contingency 17.

6 Conclusion

This paper describes a high-speed load-shedding scheme operating in an industrial complex in Mexico. The engineering solution proposed a load-shedding scheme that adapts to islanded and non-islanded topologies, is flexible, and considers the different operative modes that the industrial complex may experience. The load-shedding scheme helped increase the industrial complex power system reliability, which prevents constant and unnecessary stoppages in the process lines, increases production rates, and provides a safer environment by guaranteeing continuous power to achieve a safe shutdown of chlorine and other toxic gas processes.

Finally, by leveraging the installed Ethernet network, there is an opportunity to grow and improve the load-shedding scheme architecture by installing more I/O modules. These modules will use the existing GOOSE messages programmed in the LSP that transmit the load-shedding signals to have better selective control and granularity in the loads to be shed.

7 References

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