Fast and Reliable Load-Shedding Scheme for Wastewater Treatment Plant – A Case Study

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Fast and Reliable Load-Shedding Scheme for Wastewater Treatment Plant – A Case Study

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***Abstract*—Innovations in the fields of automation and networking have helped traditional power system substations evolve. Intelligent electronic devices (IEDs) accompanied by optimized and smartly engineered communications networks have provided engineers with opportunities to better design and implement various algorithms. Therefore, in the event of a disturbance or fault, the power system stability and process survivability are maintained.**

Power systems are proven to have more stable operation while connected to a utility; however, the challenge arises when the power system is islanded and suffers from a loss or an excess of generation. In an islanded configuration, fast and selective shedding of loads and/or generators based on system topology is critical in responding to system disturbances to avoid blackouts and ensure minimum process downtime.

This paper presents a real-world implemented load-shedding scheme (LSS) for a North American wastewater treatment plant. The LSS was deployed in two tiers of primary and secondary controls via redundant substation-hardened controllers. The primary shedding system is based on calculation of a predictive power deficit or surplus for various predetermined contingency events. The primary system issues shedding decisions upon contingency detection, whereas the secondary shedding system is based on triggers asserted by underfrequency and/or overfrequency protective relays.

The paper also provides an overview of the implemented network scheme; however, a detailed discussion regarding engineering and performance will be included in the authors' future work.

Keywords—fast load shedding, contingency, underfrequency, software-defined networking, power management and control system, frequency response, wastewater treatment plant

I. INTRODUCTION

A power monitoring and control system (PMCS) is defined in [1] as:

> *A PMCS is ideal for industries with onsite generation and/or that are grid connected. It contains automated control functions specifically designed to prevent, detect, and mitigate system blackouts in either grid-connected or islanded mode. Automated functions within a PMCS control major power system assets for optimal economic operation. By properly collecting, processing, and presenting power system data as usable information, the PMCS system enables operators, maintenance personnel, and engineering staff to diagnose system events, predict equipment failures, and minimize unnecessary maintenance [1].*

This paper presents a case study for one of the largest wastewater treatment plants in North America. The plant under consideration was constructed in 1932 and has had various updates during its life span. In 2017, the plant went through a major electrical infrastructure upgrade with the installation of a PMCS to ensure robust, reliable, and operator-friendly control and monitoring of the power system in the facility. As part of the complete PMCS suite, one important feature was to implement a fast, reliable, and robust load-shedding system that would guarantee power system stability and process survivability. In addition, it was essential to recognize that any misoperation could lead to the release of toxic waste or untreated water into the downstream river, posing a serious health and safety hazard for the public.

The paper describes the load-shedding scheme (LSS) implemented to meet the project requirements using the field proven engineering algorithms, design techniques, and testing methodologies. Section II examines the simplified power system of the wastewater treatment facility. Section III provides an overview of the implemented system architecture using software-defined networking (SDN). Section IV presents the details of the two types of high-speed load-shedding algorithms and their implementation using the defined system architecture. Section V explores implementation details for intelligent and selective load shedding. Section VI evaluates testing scenarios and associated results.

II. OVERVIEW OF FACILITY POWER SYSTEM

The power system for the wastewater treatment plant is an industrial microgrid with multiple power sources, including onsite power generation and numerous high- and low-voltage buses distributed throughout the facility.

The plant is interconnected to the electrical utility via two 13.2 kV primary voltage service feeders. In addition to the utility feeders, there is 8.8 MW of onsite cogeneration, which includes three 4.16 kV/1.6 MW reciprocating engines and one 4.16 kV/4 MW gas-fired combustion turbine generator (GEN).

The 13.2 kV utility feed is transformed down to 4.16 kV at two different switchgears. These two switchgears are the primary sources of high-voltage distribution to the various areas of the plant. Major process loads are fed at 600 V, except for the aeration blowers in the plant, which are fed at 4.16 kV. The 13.2 kV, 4.16 kV, and 600 V switchgears throughout the plant are configured as double-ended main-tie-main systems. Fig. 1 provides a simplified version of the facility power system as an overview for readers; however, to maintain the end user's system confidentiality, the asset tags and details have not been disclosed.

III. SIMPLIFIED SYSTEM ARCHITECTURE BASED UPON SDN TECHNOLOGY

Modern numerical relays and metering IEDs not only protect and monitor the plant power system, but also form the foundation of a load-shedding system. The IEDs are networked over Ethernet communications using two independent networks in a ring configuration utilizing parallel redundancy protocol (PRP) based on SDN technology.

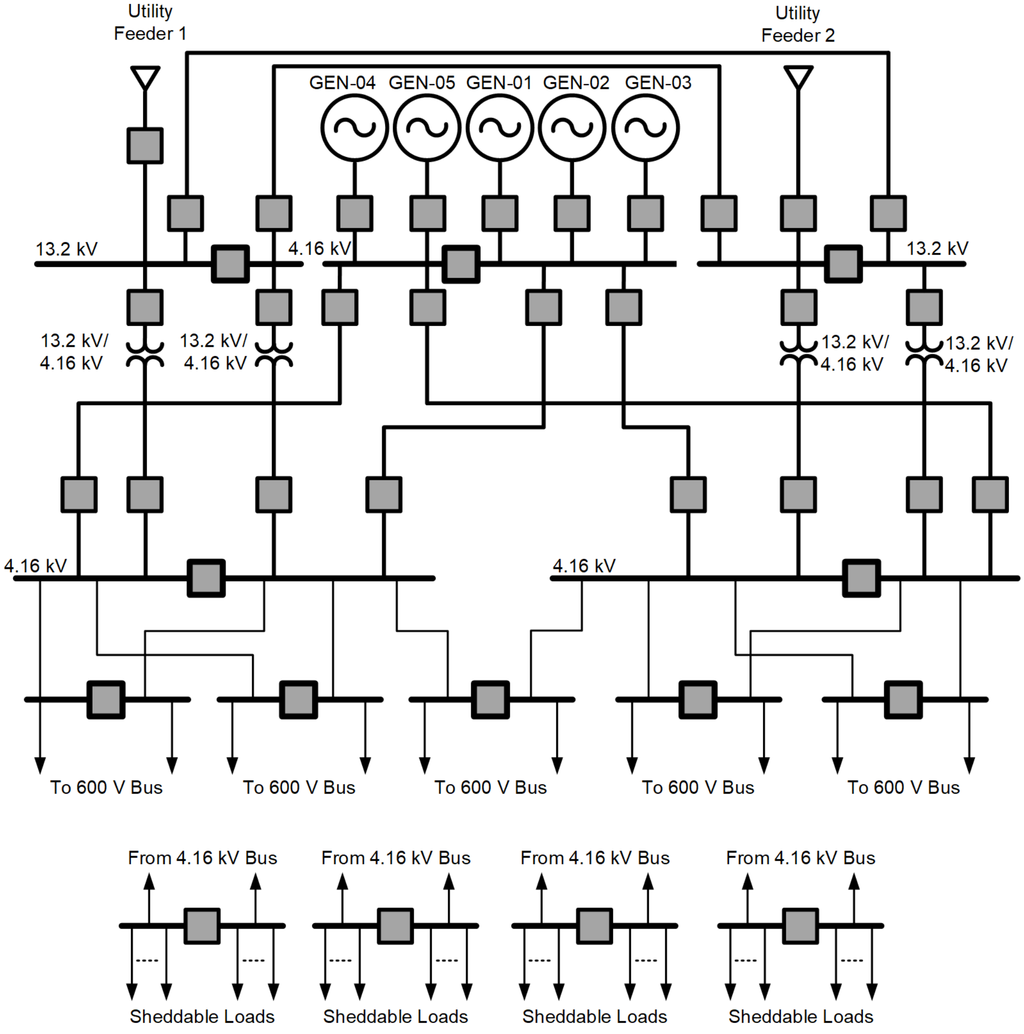

Fig. 1. Simplified Single-Line Diagram of the Power System for the Wastewater Treatment Plant

Data for load-shedding purposes are gathered by local relays, installed on various equipment across the power system. These data are then sent via International Electrotechnical Commission (IEC) 61850 Manufacturer Messaging Specification (MMS) and Generic Object-Oriented Substation Event (GOOSE) communications protocols over the Ethernet network to data concentrators (DCONs) that operate on redundant hardware as A and B devices. DCON-A and DCON-B are installed in two physically distant locations. These DCONs then distribute data to centralized controllers, which operate on redundant hardware installed in the same locations as DCON-A and DCON-B, respectively. Data are sent to the fast load-shedding (FLS) controllers by DCONs via User Datagram Protocol (UDP) over the Ethernet network. Each of the controllers performs its specific functions and outputs control signals. These control outputs are distributed through the DCONs via UDP communications protocol. From the DCONs, the signals are sent via IEC 61850 GOOSE signals over the Ethernet network to relays and trip units. From the relays, hardwired output contacts transmit controls directly to the desired control point.

Fig. 2 presents a simplified version of the system architecture used for implementation of an FLS system.

IV. High-Speed Load Shedding – Functional Overview

“High-speed [load-]*shedding control functions are required to mitigate power system unbalance and prevent blackout*[s]*”* [1]. The main purpose of these control functions is to maintain balance between power generation and demand and/or load by intelligently selecting and tripping load breakers based on a triggered contingency that may include a generator, utility tie line, and bus tie.

For the wastewater treatment plant under discussion, two types of FLS schemes have been designed and deployed. The primary FLS scheme is called contingency-based load shedding (CLS); whereas, the secondary FLS scheme is called underfrequency-based load shedding (UFLS). The details of both types of load-shed schemes are explained in the following subsections.

A. Contingency-Based Load-Shedding Scheme

“A CLS algorithm sheds load to maintain the power system balance by reducing the total plant electrical load to less than the calculated available turbine and generator capacity after a contingency occurs” [1]. A contingency is defined as the opening of a breaker that interrupts system power flow. Contingency triggers are communicated from protective relays to the DCONs using GOOSE messages.

When a contingency breaker opens, the CLS controller triggers load shed *“based on the contingency status and metering, user-settable load-shedding priorities, user-settable incremental reserve margin (IRM) values, topology status, load status, and metering. The CLS controller sends the load trip signals to the respective”* intelligent electronic devices (IEDs,) via DCONs, using GOOSE messages, *“the output contacts of which are wired to trip coils of the breakers”* [1] Fig. 3 shows the overall CLS algorithm.

The algorithm runs on real-time automation controllers, in advance of the event trigger taking place; therefore, the power deficit can be seen by the operator before any event occurs. If there is not sufficient plant load to balance the loss of power from a contingency source, an alarm will convey this to the operator, which allows the operator to take corrective action for avoiding an operation state that is vulnerable to a blackout.

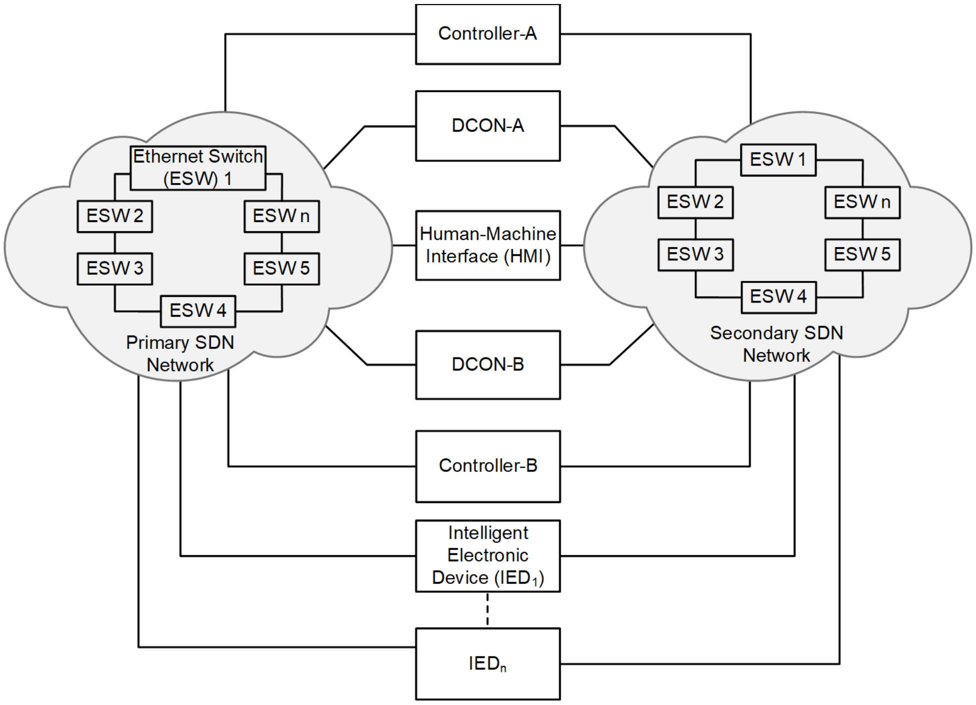

Fig. 2. Simplified System Architecture Based on SDN Technology

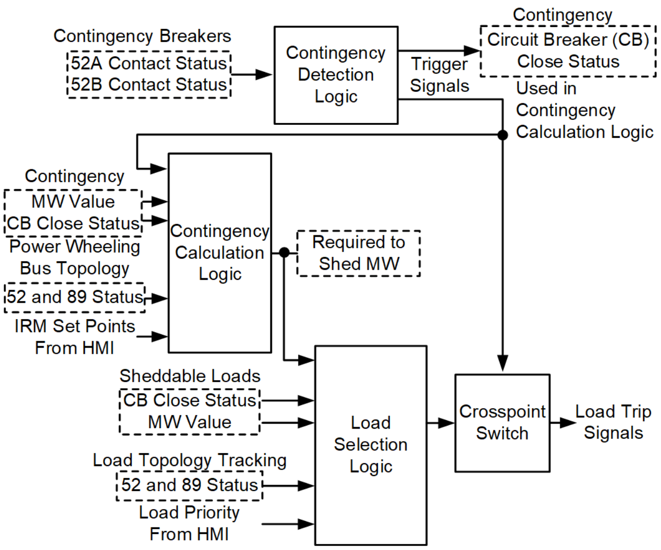

Fig. 3. Block Diagram for Contingency Load-Shed Algorithm

For the operator to understand the expected loads to be shed, based on the prospective contingency trigger, a crosspoint switch is populated and displayed to the operator by means of a human-machine interface (HMI). Fig. 4 shows a simplified version of the crosspoint logic. A crosspoint switch matrix is essentially a table constructed as contingency versus load.

Each contingency has an associated trigger. Trigger 1 corresponds with Contingency 1, and so forth. Each load is selected based on contingency and may be preselected for multiple contingencies. However, if a load was shed in one contingency, it will be inhibited from being selected for shedding by any other contingencies. The result of the crosspoint switch multiplication is trip signals that are sent directly to the DCONs at various locations. From there, they are sent to the field IEDs with output contacts wired to the trip coil of the associated load.

B. *Underfrequency-Based Load-Shedding Scheme*

According to [1], a UFLS scheme is an FLS:

> *algorithm that maintains the power system balance by reducing the total plant load by fixed amounts of load power at [four] separate underfrequency (UF) levels. The UF level detection occurs in [protective] relays located at each bus/generator.*
>
> *When the [relay] detects a UF event, it sends a high-speed signal to the UFLS system. The UFLS controller determines the load to shed based on the UF trip level, user-settable load-shedding priorities, topology status, load status, and metering. The UFLS system sends the load trip signals to [the] IED[s. The] output contacts of [the IEDs] are wired to trip coils of the breakers [1].*

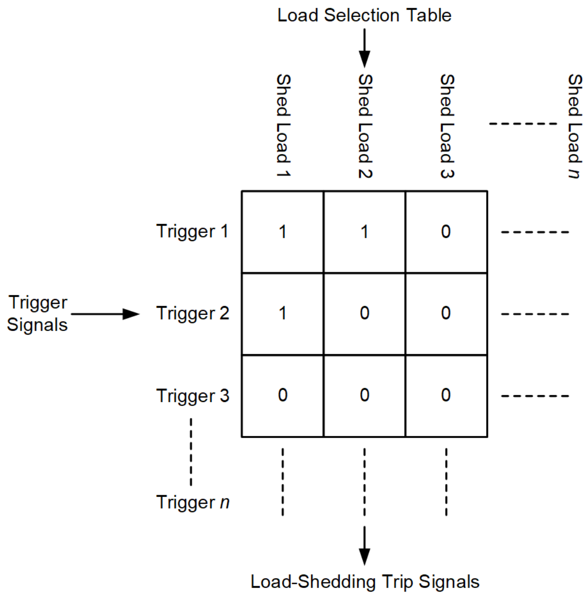

Fig. 4. Crosspoint Switch Matrix

This scheme backs up the primary CLS scheme by detecting frequency decay that was not prevented by the CLS, which was due to an alarmed breaker opening, overestimated generator IRM, or a load-shedding failure due to wiring and/or trip coil issues.

An added benefit of this centralized underfrequency load-shedding scheme is the ability to isolate events on an island-by-island basis. This ensures that only relevant loads are shed for frequency excursions throughout the island and that other islands remain unaffected. This is in contrast to relay-based underfrequency load-shed schemes in which feeders are tripped as soon as the UF trigger asserts, without any consideration of the required amount of load to be shed. Fig. 5 explains the UFLS algorithm.

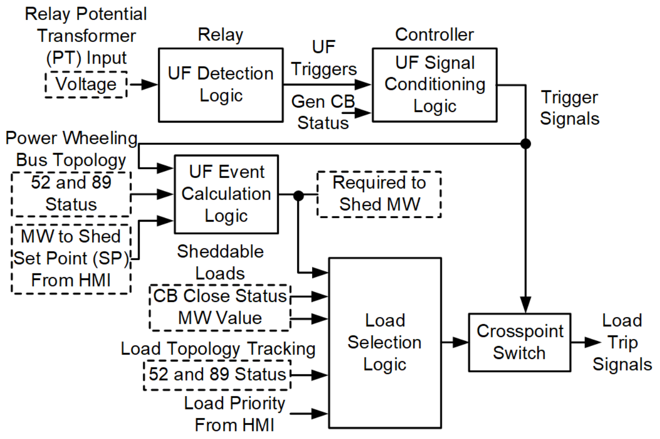

Fig. 5. Block Diagram for Contingency Load-Shed Algorithm

V. HIGH-SPEED LOAD SHEDDING – IMPLEMENTATION DETAILS

A. *Selected Contingencies for Primary CLS Scheme*

For the power system shown in Fig. 1, 27 breakers were identified that may initiate primary load-shedding contingencies. The contingencies are split into three different classifications: generator, tie line (loss of utility source), and bus coupler (loss of a link between system buses). Table I shows the contingencies identified for the specific case study.

B. *Selected Contingencies for Secondary UFLS Scheme*

The secondary LSS is based on the frequency degradation of the system and the corresponding power decrease for which it is stabilized. For the power system shown in Fig. 1, the underfrequency system operates on the 4.16 kV generator buses and will only operate when islanded from the utility. The underfrequency system will shed load based on a power setting entered for each level on the HMI. Underfrequency triggers are generated via relays that perform bus frequency measurements at generator buses. In addition, the relays installed in the 13.2 kV distribution buses are also programmed to provide underfrequency triggers to controllers for the identified underfrequency contingencies.

Table II lists the underfrequency contingencies identified for the specific case study.

C. *Underfrequency Coordination*

Fig. 6 shows a simplified visual representation of the frequency coordination for the UFLS scheme with the underfrequency protection settings of the two types of generators installed in the power system shown in Fig. 1.

The underfrequency load-shedding set points are coordinated with the utility decoupling requirements, such that the plant can ride through voltage and frequency excursions if there are disturbances on the utility network. To overcome this, the controller topology tracking informs the operator about the connected state of the utility in the plant power system. If the plant is utility connected, then the controller dynamically disables Level 1 and Level 2 of the underfrequency scheme.

TABLE I. PRIMARY CONTINGENCIES

Contingency Number	Type
1–5	Generator
6–7	Utility tie line
8–27	Bus tie

TABLE II. UNDERFREQUENCY CONTINGENCIES

Contingency Number	Bus	Underfrequency Level
1	Generator Bus-A	Level 1
2	Generator Bus-A	Level 2
3	Generator Bus-A	Level 3
4	Generator Bus-A	Level 4
5	Generator Bus-B	Level 1
6	Generator Bus-B	Level 2
7	Generator Bus-B	Level 3
8	Generator Bus-B	Level 4

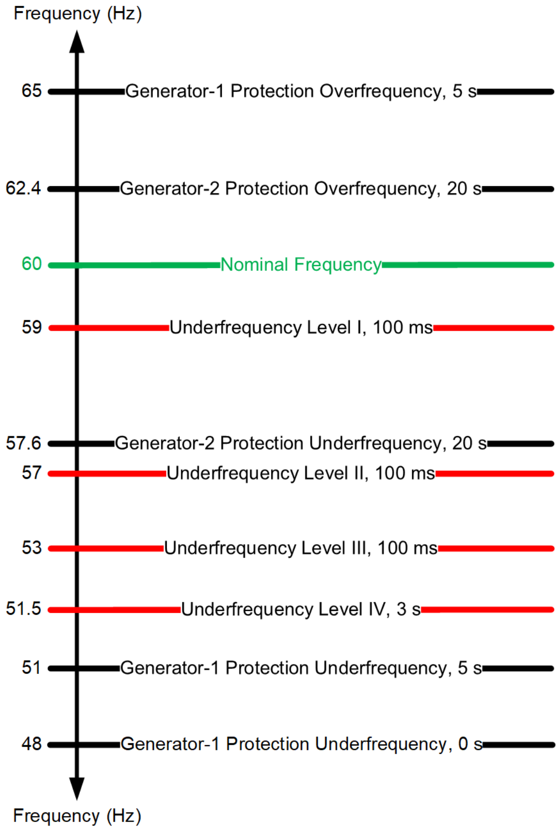

Fig. 6. Coordination Between UFLS Levels and Generator Frequency Protection Settings

Coordination of the UFLS and CLS should be performed so that when both algorithms are enabled, it would not cause any unnecessary load tripping. The CLS action takes place first; whereas, the UFLS waits for a trigger from the field. Because of the vast differences in the inertia and rating of machines, it was critical that the load-shedding system be designed to cover the maximum range of possible operation scenarios. Based on the aforementioned facts, the following conditions were established to achieve coordination between the CLS and UFLS:

- Block Underfrequency Levels 1 and 2 when the CLS is enabled. Levels 1 and 2 were designed as a backup for the CLS and will only come into effect when the primary load-shedding scheme is disabled.
- Keep Underfrequency Levels 3 and 4 active all the time, even with the CLS enabled. Levels 3 and 4 were designed to serve as a last resort for saving the system from a blackout.

D. *Sheddable Loads*

Based on recommendations from the customer's operations department, 66 loads were identified as sheddable loads for the power system shown in Fig. 1. These 66 loads are situated throughout the entire power system at voltage levels of 4.16 kV and 0.6 kV.

E. *Load Selectivity Based on Load Group Priorities*

All of the sheddable loads are organized into ten groups of loads. Each load has a group associated with it, which can be set by an operator through the HMI. The CLS and/or UFLS algorithm will try to select the optimal amount of load to satisfy each contingency. Each load within a group will have equal priority to shed. The group assigned to each load does not need to be unique.

All load-shedding actions use an optimal load selection algorithm, which tries to select minimum number of loads to satisfy a contingency. Loads are selected for shedding based on their present power and their predefined group. Loads with a power value of zero, negative power value, or group value of zero will be inhibited and not selected for shedding. Operators may set load groups to zero to intentionally inhibit them from shedding. Loads with lower numerical groups are selected for shedding first, starting with the number 1 and moving up the list as loads are available, until the total amount of load selected for shedding matches or exceeds the amount of load required for shedding.

F. *Load-Shedding Signals*

Load-shedding signals are sent out by the redundant controllers, propagated through the DCONs, sent to the field relays that are installed on load feeders, and then sent to the load trip coils. When a load is selected for shedding, the load trip signal is sent out by the controller and held for 60 seconds. This ensures that the signal is propagated through all devices and reaches the load. The trip signal is then propagated through the load-specific relay to the breaker trip coil. The average round-trip time from contingency detection to load-shed command transmit was observed to be in the range of 25–30 milliseconds in this case study. This time does not include contingency and load-breaker opening time, which can vary from 45 milliseconds (three-cycle breakers) to as much as 200 milliseconds. Fig. 7 shows a typical data flow, including detection of the contingency trigger and sending out a load-shed command.

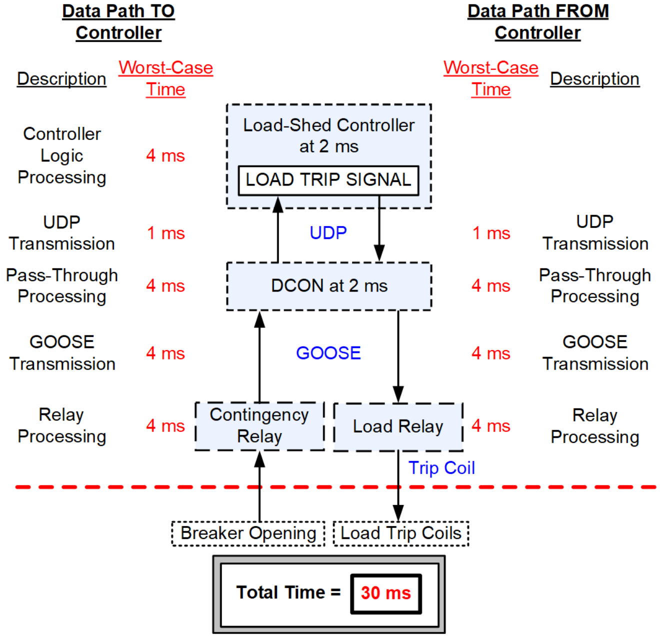

Fig. 7. Load-Shedding Timing Diagram

VI. TESTING SCENARIOS

A. *Test-1: Islanded From Utility With Three Generators Running and One Type-2 Generator Tripping*

The power system is islanded from the utility and two Type-1 generators each running at 1.15 MW and one Type-2 generator running at 3.6 MW are kept online. The UFLS is enabled, the load on the island is approximately 5.9 MW, and the Type-2 generator is tripped at t = 1 second. The frequency response of the island for the UFLS is represented by the solid blue line in the plot shown in Fig. 8. The observations are as follows:

- Level 1 was triggered at t = 1.330 seconds and UF L1 required to shed (RTS) = 1.6 MW.
- Level 2 was triggered at t = 1.417 seconds and UF L2 RTS = 2 MW.
- The minimum frequency was 53.86 Hz.
- The Type-1 generators did not trip and the remaining load on the island was 2.3 MW.

The same scenario was repeated with CLS enabled and UFLS disabled. The load on the island was approximately 5.9 MW and the Type-2 generator was tripped at t = 1 second. At t = 1.200 seconds, the CLS shed 3.6 MW of load on the island. The frequency response of the island for CLS is represented by the dashed black line in the plot shown in Fig. 8. The observations are as follows:

- The minimum frequency was 55.48 Hz.
- The Type-1 generators did not trip and the remaining load on the island was 2.3 MW.

B. *Test-2: All Generators Running With Maximum Import and an Upstream Fault on the Utility*

The power system is connected to the utility with a maximum import of 4.8 MW and all generators are kept online. The UFLS Level 1 and Level 2 are disabled and CLS is enabled.

A three-phase fault on the utility-side transmission line is simulated at t = 0.917 seconds. The transmission line breaker is opened approximately three cycles after the fault at t = 1 second to isolate the faulted section of line.

The island-side main utility breaker is opened at t = 1.115 seconds and CLS operates based on the status of this specific breaker. Two hundred milliseconds after the main breaker opened at t = 1.315 seconds, the CLS controller sheds 4.8 MW of load. The minimum frequency was 57.44 Hz.

The frequency response of the island is plotted in Fig. 9.

C. *Test-3: Islanded With Two Type-1 and One Type-2 Generators and One Steam Turbine Running, and One Type-2 Generator and a Steam Turbine Tripping With the CLS Undershedding*

The power system is islanded from the utility and two Type-1 generators each running at 1.15 MW, one Type-2 generator running at 3.6 MW, and a steam turbine running at 0.6 MW are kept online with the contingency-based load-shedding processor (CLSP) enabled and UFLS disabled. The load on the island is approximately 6.5 MW. The Type-2 generator and steam turbine are tripped at t =1 second and at t = 1.200 seconds, and the CLS shed 3.2 MW of load on the island. However, the required-to-shed amount was 4.2 MW. Therefore, undershedding by CLS caused the system frequency to decay. The frequency response of the island for CLS is represented by the dashed black line in the plot shown in Fig. 10. The observations are as follows:

- The minimum frequency was 51.27 Hz.
- At t = 2.303 seconds, UF L3 picked up with RTS = 1.2 MW, which helped with frequency recovery and saved the system from collapsing.
- The Type-1 generators did not trip and the remaining load on the island was 2.1 MW.
- The maximum frequency for this scenario was 63.84 Hz and the overfrequency protection of the Type-1 generators was 65 Hz for 5 seconds.

Based on the designed coordination between CLS and UFLS, the controller should block UF Levels 1 and 2 to prevent overshedding of the load on the island. However, Underfrequency Levels 3 and 4 should be kept active as a safety margin for the system in cases where CLS or other UFLS levels undershed loads on the island.

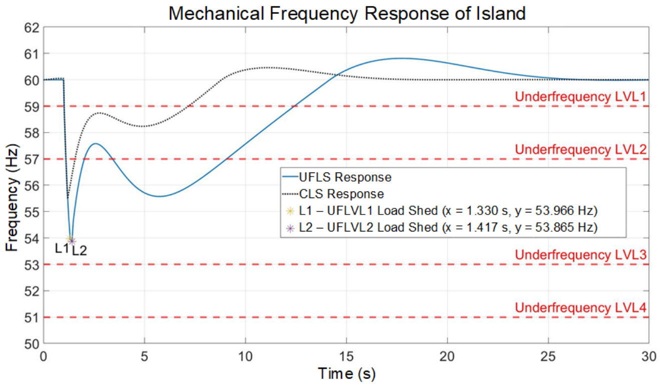

Fig. 8. System Frequency Response for Test-1

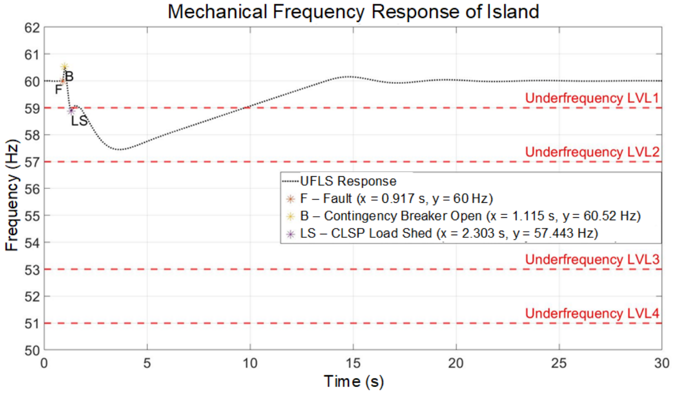

Fig. 9. System Frequency Response for Test-2

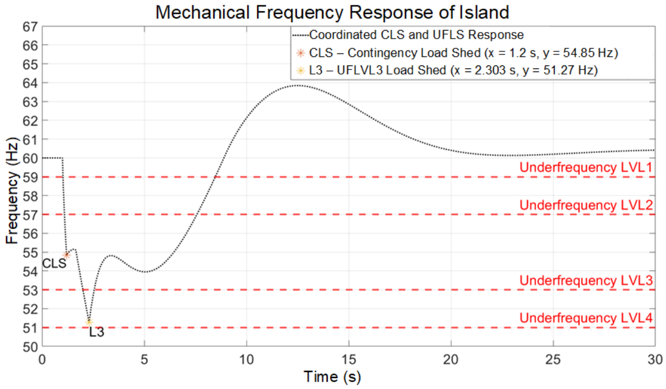

Fig. 10. System Frequency Response for Test-3

VII. CONCLUSION

A wastewater treatment plant is a critical infrastructure that is required to always operate with reliable and trusted operations. These operations can only be guaranteed with the availability of a reliable electric power system and processes. Any power system disturbance can easily destabilize the overall power system and can lead to blackout scenarios. Such blackouts can cause maloperations that can have a direct effect on the public health because usually water that is cleaned through these treatment facilities is released into river systems.

The work described in this paper explicitly focuses on the design and engineering of high-speed load-shedding systems, which are based on the latest SDN-based network infrastructure. The results presented show the significant impacts of timely load-shed actions that helped the power system survive without getting into a blackout situation.

The system developed for this plant will not only make the plant power supply more robust and reliable, but it also will allow the plant operator to make decisions in cases of natural disasters, such as flooding or hurricanes, and manage the power flow to critical loads, eventually keeping the plant running and safeguarding both the environment and public health.

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