Hardware Implementation of an Automatic Adaptive Centralized Underfrequency Load Shedding Scheme

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Abstract—The underfrequency load shedding (UFLS) mostly used in industry is a decentralized deterministic scheme designed to shed a prespecified amount of load after a predetermined time delay. It sheds the same amount of load from the same location irrespective of how fast the frequency drops and without consideration of the disturbance location or dip in bus voltage. Recent studies focused on adaptive UFLS, but these studies are still based on software simulation. This study presents an implementation of a real-time centralized adaptive UFLS scheme using industry-grade hardware. It estimates the amount of load to be shed based on the rate of frequency decline and distributes the load to be shed among the load buses based on the voltage dip at these buses. The UFLS in this study is implemented using a real-time digital simulator, phasor measurement units embedded in the relays, a global positioning system clock, and a synchrophasor vector processor. The load is modeled as a mixture of dynamic and static load. The implemented scheme restored the system frequency and voltage. The results emphasize its adaptability and suitability for implementation in industry.

Index Terms—Phasor measurement units (PMUs), real-time digital simulator (RTDS), synchrophasor vector processor (SVP), underfrequency load shedding (UFLS), voltage dip.

I. INTRODUCTION

Due to the rapid expansion of the power system to meet increased consumer demand and with more rigid economic and environmental restrictions, utilities push the power systems to operate close to their limits. Consequently, system-wide disturbances that may lead to outages and/or blackouts become more likely [1]. This increases the importance of implementing a protection scheme that preserves the system stability and security.

Underfrequency load shedding (UFLS) is an emergency protection scheme that is expected to protect the system against frequency instability that may occur when the online generators cannot supply the demanded active power. For example, this may occur due to a major outage of generation. The most commonly used UFLS in industry is the conventional UFLS. This is a distributed scheme where the settings of the frequency level, time delay, and the amount of load to be shed are prespecified set values in the distributed relays [2]. This way, the frequency setting and the amount of load to be shed in each step are fixed values regardless of disturbance location, bus voltage, and how fast the frequency declines. The conventional method of UFLS may cause further problems in the system. For example, when major generation is lost, voltage instability may result if accompanied by another contingency [3].

Due to the shortcomings of the conventional UFLS method, most of the recent research is interested in enhancing the adaptability of the conventional method by developing the adaptive UFLS. This method estimates the amount of active power imbalance based on the frequency and rate of change of frequency decline. Thus, it sheds the load adaptively, taking into consideration the disturbance location and, therefore, it sheds the load from buses with most voltage dip [3]. In this method, several approaches are used by researchers to assess the buses’ voltages. Reference [2] uses the V-Q margins as an indication of bus voltage behavior and sheds more load from the voltage-sensitive buses, [3] uses the voltage dip to determine which buses experience more voltage drop due to the disturbance, and [4] uses the rate of voltage change with respect to active power to specify the voltage-sensitive buses for load shedding. These ways of implementation maintain the frequency and load buses’ voltage stability.

The conventional UFLS is a decentralized scheme, which means each load shedding relay is only responsible for its associated load and that no data are required to be sent from system buses to a central location. However, the adaptive UFLS can be implemented centrally by sending measurements from system buses to the central processing point to assess system stability and issue the required corrective action.

The centralized load shedding scheme is one of the wide-area monitoring, protection, and control (WAMPAC) applications that are enhanced by the recent development in phasor measurement units (PMUs) technology along with the advancement in communication and processing systems. PMUs provide timestamped measurements that are synchronized with a GPS clock. The measurements taken from different remote locations in the power system are then sent to a central-processing system. Examples of such measurements are voltage phasors, frequency, and rate of change of frequency. The synchrophasor data sent from PMUs provides wide observability of system dynamics and a complete simultaneous snapshot of the power system condition, which allows greater ability to implement wide-area stability, control, and protection schemes centrally. Thus, power system grid operation, reliability, and stability can be improved considerably.
Research has been conducted recently to develop different wide-area monitoring, protection, and control applications. For the recent research to be feasible to industry, real hardware has to be involved in testing and validating the schemes. This is also important to avoid misoperation of the equipment in the field. Most of the adaptive centralized UFLS research does not involve real hardware for test and validation.

This paper presents an implementation and validity testing of a real-time centralized adaptive UFLS scheme using actual hardware of: PMUs (embedded in the protective relays), a synchrophasor vector processor (SVP), and a real-time digital simulator. The aim of the implemented scheme is to restore system frequency stability and improve voltage at affected buses after a major system disturbance caused by loss of generation. The scheme estimates the total amount of load to be shed from the system based on the rate of change of frequency, distributes this amount among load buses based on voltage dip of these buses, and sends appropriate load shedding signals back to PMUs (relays) to shed specific loads at their associated buses, and, thus, restores frequency stability and helps prevent probable consequent frequency and voltage instability.

II. IMPLEMENTATION OF THE CENTRALIZED ADAPTIVE UFLS SCHEME

In this study, the implementation and testing of the centralized load shedding scheme is performed using actual industrial grade equipment. Fig. 1 illustrates the implemented system configuration and shows the IEEE 9-bus system inside the real-time simulator, which is the system used in this study to test and validate the load shedding scheme. The actual laboratory setup is shown in Fig. 2.

The real-time digital simulator (eMEGAsim OPAL-RT HILbox OP5600) enables the power system model to interact with the actual hardware (relays, PMUs, SVP, and GPS) in real time. The voltage/current amplifiers (Omicron CMS 156 and Doble F6350) connect the real-time simulator’s analog signals to the relays. PMUs gather synchronized real-time measurements from multiple locations on the power system modeled in the real-time simulator and send it to the SVP. The SVP, which serves as a central location, processes the data received from the PMUs, calculates the amount of load to be shed, and then sends signals back to the relays to shed the load from specific buses in the system. The GPS provides the time reference for PMU’s operation.

The power system model used to test the scheme is simulated in real time using the OPAL-RT real-time simulator. The PMUs are connected to generator buses and important load buses in the simulated power system model through the simulator’s analog output port and voltage amplifiers to measure the voltage and frequency at these buses. The PMUs’ stream of synchrophasor data, such as the rate of change of frequency and voltages, are sent to the SVP. The SVP uses the data received from PMUs and performs the load shedding algorithm when it senses any generation-load unbalance that may cause frequency instability. The programmed algorithm estimates how many megawatts to be shed from the system in order to restore system stability, determines the appropriate candidate buses for load shedding, calculates the amount of the load to be shed at each candidate bus, and then sends a specific number of trip signals back to the PMUs to shed specific amounts of load at their associated buses.

A. RTDS

The RTDS enables efficient modeling and simulation of electrical power systems and provides a platform to test real equipment with a modeled system using hardware-in-the-loop (HIL) simulation technique. HIL enables testing protection devices and controllers under real system constraints by connecting the devices to the simulated model through the simulator’s input and output signals that show the same time-dependent values as in a real process. These devices will behave like they are connected to the real physical system, which increases the realism of the test. Thus, real-time simulation with the HIL capability is an effective way to design, test, verify, and certify the functionality and performance of protection devices and schemes.

In this project, OPAL-RT eMEGAsim Real Time Simulator-OP5600 was used to simulate the power system model in real time. The simulator contains a powerful real-time target computer equipped with up to 12, 3.3-GHz processor cores with a real-time operating system from QNX and Red Hat Linux.

RT-LAB software is a distributed real-time platform fully integrated with MATLAB/Simulink; it is the software that is used to conduct real-time simulation of Simulink models in an OPAL-RT RTDS. It provides tools to compile, distribute, and execute the model on multiple target processors of the simulator.

B. Amplifiers

The amplifiers are used to amplify the output voltage signals from the analog output port of the real-time simulator from low-level voltage signals to the rated secondary values of the relays (PMUs) since the maximum possible output voltage from the simulator is only 16 V. Omicron CMS 156 and Doble F6350 amplifiers are used for this. The Omicron CMS 156 has three output voltage channels and a fixed voltage amplification factor of 50 V/1 V. The Doble F6350 has up to six output voltage channels and three ranges of voltage outputs: 75 V/6.7 V, 150 V/6.7 V, and 300 V/6.7 V.
C. PMUs

Six SEL-487E relays are used as PMUs. These relays are connected to a GPS signal utilizing a satellite-synchronized clock which provides the time reference for synchrophasor operation. The PMUs gather system information from the buses that they are connected to in the modeled system, and send the synchrophasor measurements, such as voltages at load buses and the rate of change of frequency at generator buses, to the SVP, which is also connected to the same GPS clock. The communication between these relays and the SVP was performed using a local-area network (LAN) Ethernet connection utilizing the IEEE C37.118 communication protocol. The synchrophasor data are sent from PMUs to SVP at a rate of 60 messages/s. All of the required settings and configurations for the PMUs to make them able to send synchrophasor data to the SVP and receive commands from SVP are performed using SEL-AcSELerator Quick Set software.

D. SVP

In this project the SVP—SEL 3378 represents the CPU and considered the brain of this load shedding scheme. It collects, time correlates, and processes synchrophasor messages with flexible programming capability.

The proposed load shedding algorithm was programmed in the SVP using the SVP Configurator software, which supports all programming languages described by the IEC 61131-3 standard language: Instruction List (IL), Structured Text (ST), Sequential Function Chart (SFC), Function Block Diagram (FBD), and Ladder Diagram (LD). In this project, ST language is used to program the function blocks and the Continuous Function Chart Editor graphical language is used to assemble the function blocks that carry out the required data receiving process, load shedding algorithm calculations, decision making, and sending the load shedding commands.

The programmed algorithm first time correlates the data received from PMUs using the Time Alignment Client Server (TCS) functionality, then performs the algorithm calculations that estimate the total amount of load to be shed from the system in order to restore system stability in case of generation-load unbalance, calculates the load to be curtailed at each candidate bus for load shedding according to voltage dip of that bus due to the disturbance, and, finally, sends a specific number of trip signals back to PMUs, using the “Fast Operate Commands” utilizing the SEL relays’ remote bits, to trip specific load feeders at their associated buses.

In this paper, the SVP is located on the same rack with the PMUs in the laboratory. In a large-scale network, the SVP can be placed in the Load Dispatch Center, phasor data concentrators (PDCs) can be used in a large-scale network to collect synchrophasors data from multiple groups of generators’ PMUs; the generators in a large system can be grouped based on geographical areas as an example.

III. ALGORITHM IMPLEMENTATION

The aim of the implemented centralized load shedding scheme is to restore frequency stability and help preventing the probable consequent voltage instability that can occur after a major disturbance caused by a generator outage. The implemented algorithm uses frequency and voltage variables gathered from different locations of the power system to decide the optimum amounts and locations of load to be shed in order to restore system stability adaptively.

The proposed load-shedding algorithm monitors the system frequency and voltages at load buses continuously. When it senses any generation load unbalance that may lead to frequency instability, it performs the following steps:

- estimates how much load (MW) must be shed from the system in order to restore system frequency stability;
- calculates the amount of load to be shed at each candidate load bus;
- sends a specific number of trip signals back to the PMUs, and the PMUs (relays) trip specific amount of loads in their associated buses according to these signals.
A. Estimation of the Total Load to be Shed

The magnitude of the disturbance power is the amount of unbalance between the generated and demanded active power. The disturbance power or power mismatch for each generator in the system is calculated using the generator swing equation

$$\Delta P_i = p_{m,i} - p_{r,i} = \frac{2H_i df_i}{f_n} \frac{df_i}{dt}$$  \hspace{1cm} (1)

$$\Delta P_i$$: power mismatch of generator $i$ in per unit;
$p_{m,i}$: mechanical turbine power of generator $i$ in per unit;
$p_{r,i}$: electrical power of generator $i$ in per unit;
$H_i$: inertia constant of generator $i$ in seconds;
$f_n$: system-rated frequency in hertz;
$f_i$: generator $i$ frequency in hertz.

The total disturbance power in the system that has generators is equal to the addition of all online generators’ disturbance power and is represented by

$$\Delta P = \sum_{i=1}^{N} \Delta P_i = 2 \sum_{i=1}^{N} H_i \times \frac{df_i}{f_n}$$  \hspace{1cm} (2)

$\Delta P$: total disturbance power in the system (in per unit);
$f_c$: center of inertia (COI) frequency in hertz.

$$f_c = \frac{\sum_{i}^{N} H_{i \rightarrow \text{sys}} f_i}{\sum_{i}^{N} H_{i \rightarrow \text{sys}}}$$  \hspace{1cm} (3)

$H_{i \rightarrow \text{sys}}$: inertia constant of generator $i$ in seconds based on a common system base.

$$H_{i \rightarrow \text{sys}} = H_i \times S_i / S_{\text{base} \rightarrow \text{sys}}$$  \hspace{1cm} (4)

$S_i$: apparent power of generator $i$ in megavolt-ampere;
$S_{\text{base} \rightarrow \text{sys}}$: system base in megavolt-ampere.

The COI frequency is the frequency of the equivalent system inertia. It is an important parameter since each machine (with a different inertia) responds differently immediately after the disturbance occurrence. Thus, COI frequency gives global state information of the system when each generator has a different frequency [5].

B. Calculation of the Amount of Load to be Shed at Each Candidate Load Bus

The total amount of overload is relieved from the system by distributing it among different candidate buses for load shedding. Buses should be ranked according to their voltage dips after the disturbance in larger systems; the higher-ranked buses are selected to share the disturbance power. Shedding the load from the buses that experienced voltage problems can, in turn, help prevent further voltage deterioration in these buses. Since the studied system is small (only three load buses), all load buses are considered candidate buses for load shedding.

At any instant of time, the algorithm records the last 60 messages of the load buses’ voltages (1 s) in a set of matrices (predisturbance voltage matrices). When the algorithm senses a disturbance that causes the center of inertia frequency to drop below 59.97 Hz, it stops recording the voltages in the aforementioned matrices, starts recording load buses’ voltages for 1.12 s in another set of matrices (postdisturbance voltage matrices), and calculates the system total power mismatch. From the average values of voltages in the two sets of matrices, the voltage dips are calculated and will be used to distribute the total amount of power to be shed among load buses. The trip commands will be sent when the frequency drops below 58.5 Hz and after voltage recording and dips calculation processes have been completed.

The amount of load to be shed at each candidate bus $i$, $(P_{\text{shed},i})$, is calculated using (5) and is proportional to the voltage dip of that bus due to the disturbance (the greater the voltage drop a bus has experienced, the more load will be shed at that bus)

$$P_{\text{shed},i} = \left( \frac{\Delta V_i}{\sum_{i \in N_L} \Delta V_i} \right) \times \Delta P$$  \hspace{1cm} (5)

$P_{\text{shed},i}$: power to be shed from the load bus $i$;
$\Delta P$: total amount of power to be shed from the system;
$N_L$: number of load buses;
$\Delta V_i$: voltage dip at the load bus $i$.

C. Shedding the Specific Amount of Load Decided by the Algorithm from Selected Load Buses

The SVP’s “Fast Operate Commands” utilizing the SEL relay’s remote bits are used to send shedding signals from the SVP to the PMUs to shed the load decided by the SVP’s programmed algorithm.

Fast operate “set” commands sent from the SVP to the PMU (relay) are used to assert the relay’s remote bits. The relay settings are configured to close a specific number of contacts upon receiving these remote bits to shed specific loads, and by deasserting these bits using fast operate “clear” commands, the relay opens and resets these contacts after load shedding.

At each load bus in the simulated model, the total load is divided into feeders, each carrying 10 MW. The feeders’ breakers in the modeled system are linked to digital inputs of the simulator’s digital input port and when the digital input is energized, the breaker opens and trips that feeder. When the input is de-energized, the breaker stays closed. The digital inputs are connected to the relays’ contacts and the relay closes a contact and energizes a digital input when it receives a fast operate command from the SVP that set a remote bit. For instance, when the SVP decides to shed 10 MW from a specific load bus, it will
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Fig. 3. IEEE 9-bus system single-line diagram.

TABLE I
LOAD DIVISIONS AT EACH LOAD BUS

<table>
<thead>
<tr>
<th>Load bus</th>
<th>Large induction motor load (MW+MVAR)</th>
<th>Small induction motor load (MW+MVAR)</th>
<th>Static load (MW+MVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus-5</td>
<td>25+j10</td>
<td>56.25+j22.5</td>
<td>43.75+j17.5</td>
</tr>
<tr>
<td>Bus-6</td>
<td>18+j6</td>
<td>40.5+j13.5</td>
<td>31.5+j10.5</td>
</tr>
<tr>
<td>Bus-8</td>
<td>20+j7</td>
<td>45.5+j15.75</td>
<td>35+j12.25</td>
</tr>
</tbody>
</table>

To run the model in the OPAL-RT RTDS, the model is divided into subsystems so that each subsystem can be assigned to one of the simulator’s 12 processor cores. The model was divided into four subsystems because of the large number of motors and to avoid overruns that can occur when the simulator operations are not all achieved within the fixed timestep and, thus, the real-time simulation is considered erroneous.

One subsystem is the master, two are slave subsystems, and one is the console subsystem. The console subsystem provides access to the model for monitoring and control while the simulation is running in real time. The simulation is set to run in real time in a fixed timestep of 40 μs.

V. RESULTS AND DISCUSSION

Different cases of generator outage disturbance have been studied to test the functionality, performance, and adaptability of the implemented centralized load shedding scheme. These different cases were performed by tripping a generator’s breaker while the simulated system model is running in real time in the steady state. Different combinations of location and loading of the tripped generator have been tested.

The same cases were tested on the decentralized conventional UFLS to compare the performance of the two load shedding schemes.

Table II shows the frequency settings and time delays for levels 1–3 of the decentralized UFLS relays at load buses 5, 6, and 8. Each level for each relay sheds one feeder (10 MW).

Sample cases:
- Case (A): Generator-1 Outage while supplying 109 MW;
- Case (B-1): Generator-1 Outage while supplying 80 MW;
- Case (B-2): Generator-2 Outage while supplying 80 MW;
- Case (B-3): Generator-3 Outage while supplying 80 MW.

A. Case (A): Generator-1 Tripping While Supplying 109 MW

The main purpose of this case is to test and validate the functionality of the implemented centralized scheme regarding its ability to restore system frequency stability and to improve voltages at affected load buses.

1) Synchrophasor Vector Processor Decisions:
   a) Disturbance Power: In this case, the SVP’s programmed algorithm determined that the total power to be shed from the system is to be 88 MW.

Fig. 4 shows plots using Matlab for the power mismatch of generator 2, 3 and the sum of them, which is the total disturbance power in the system. Fig. 5 is a zoom-in of a few seconds at the beginning of the disturbance. From the graphs, the initial value of the disturbance power directly after generator-1 tripping is about 80 MW, which is close to that determined by the SVP.
**Figs. 6 and 7 show the rate of change of frequency (df/dt) of generator-2 recorded using Matlab (Fig. 6) and using SEL-5078 Synchrowave central software (Fig. 7) that is used for PMUs data visualization and analysis.**

The two graphs, Figs. 6 and 7, are quite similar but not identical, which indicates that the data sent from PMUs reflects the behavior of the simulated system model correctly, but also shows the importance of involving real hardware in studies since such differences between the findings from a pure simulation environment and the one that utilizes actual hardware can be considerable.

Fig. 6 is recorded inside the simulation environment; each point in the graph is recorded every 40 μs as the simulation is set to run in a 40-μs timestep. On the other hand, Fig. 7 is recorded form the actual synchrophasors’ data sent from the relays; each point in the graph is recorded every 16.667 ms since the message rate of PMUs is set to 60 messages/s; this is one of the main reasons that causes the difference between the two graphs.

**b) Distribution of the Amount of Load to be Shed Among Load Buses:** Fig. 8 shows the part of the SVP program that distributes among load buses the total power to be shed which is calculated in a previous step of the program. This step calculates the amount of load to be shed from each load bus according to the voltage dip of that bus.

The inputs to this set of function blocks are the total load to be shed and the average voltages of load buses before and after the disturbance, which are also recorded in a previous step of the program, from which the voltage dips are calculated. The outputs are nine Boolean variables, three of them for each load bus, and these output variables are used with the “Fast Operate Commands” to send shedding signals to PMUs to trip the number of their associated feeders. The number of the Boolean output variables for each load bus that will become “True” and assert a “Fast Operate Command” is determined by the amount of load to be shed from that bus. For example, if 10 MW is determined to be shed from a load bus, only one output variable associated with that bus will become true and one “Fast Operate Commands” will be sent since each load feeder is 10 MW. Rounding is used for amounts that are not multiples of 10. For example, for 27 MW to be shed, three output variables will become “true” to trip three feeders and for 24 MW, two output variables will become “true” and trip two feeders.

In this test case, the total amount of power determined by the SVP to be shed from the system in order to restore frequency stability is 88 MW, and this amount is distributed among load buses (5, 6, and 8) and calculated by the SVP to be as follows: 34 MW from bus-5, 33 MW from bus-6, and 21 MW from bus-8. According to this distribution, eight Fast Operate Commands have been issued. Three of these commands have been sent to bus-5 PMU to trip three feeders: three to bus-6, and for bus-8 PMU, two commands have been sent to it to trip two feeders. Notice that because buses 5 and 6 are very close to the tripped generator, more load was required to be shed from them than that from bus-8.

For this test case, the three levels of the decentralized conventional UFLS relays operated and tripped nine feeders (for a total of 90 MW); three feeders from each load bus, which is higher by one feeder from that shed by the centralized scheme.

**2) Frequency:** Fig. 9(a)(b)–(c) shows the system frequency response when applying the centralized UFLS, the decentralized
UFLS, and without applying any load shedding, respectively. It is clear from the graphs that by using the implemented centralized scheme or the decentralized scheme the frequency remains at or above 57.75 Hz and recovers to approximately the nominal value; both schemes are able to regain system stability, but the proposed centralized scheme is able to do so with lower load curtailment by considering voltage variations in load buses. Without applying any load shedding, the frequency dropped to less than 50 Hz and settled below 54 Hz which could lead to further generator outages that may be initiated by the generators’ and turbines’ speed protection if the system continued to operate at this low frequency.

From Figs. 5, 6, and 9(a), it can be observed that generator-1 trips at 30 s and the load shedding signals are issued at 31.33 s, a frequency of 57.8 Hz, and a value of $-1.448)$ and $-1.605)$ for $\frac{df}{dt}$ of generator 2 and 3, respectively. As mentioned before, the tripping signals are issued when the frequency goes below 58.5 Hz and 1.2-s voltage recording time has elapsed from the instant that the frequency drops to less than 59.97 Hz.

3) Voltages at Load Buses: Fig. 10(a)–(c) shows the line-line voltages of load buses-5 (red color), bus-6 (blue), and bus-8 (black) when applying the centralized UFLS, the decentralized UFLS, and without applying any load shedding, respectively.

It can be noticed from the graphs that before the loss of generator-1, all bus voltages were within the nominal operating values (230 kV). When generator-1 tripped the voltage of all load buses dropped and the voltage of closer buses to the tripped generator, buses 5 and 6 experienced a voltage drop of more than the further bus 8.

In Fig. 10(a), just before the load shedding scheme operated, the voltages at load buses 5, 6, and 8 drop to 182.8, 185.2, and 200.7 kV (line-line), respectively. The voltage dips that were recorded by the algorithm can be observed from Fig. 8; the algorithm recorded the average value of line-to-ground voltages before the disturbance to be 132.399, 132.834, and 132.442 kV, and after the disturbance to be 110.592, 111.694, and 120.112 kV at buses 5, 6, and 8, respectively. According to this, the line-to-neutral voltage dips were calculated by the algorithm to be 21.8, 21.14, and 13.33 kV, which is equivalent to 37.7, 36.6, and 23 kV (line-line) for buses 5, 6, and 8, respectively.

As shown in Fig. 10(a) and (b), the implemented centralized scheme and the decentralized scheme are able to recover the voltages at load buses close to the rated values, but the decentralized scheme sheds more load from bus-8 than what was actually needed to recover system frequency and voltage. Without applying any load shedding, as shown in Fig. 10(c), the voltages
at load buses settled with considerable drop—especially buses 5 and 6 which stabilized at 210 kV. If the system continues to operate with this voltage drop, there is a possibility of consequent voltage stability problems considering other factors that are not simulated in this paper, such as transformers’ automatic voltage regulators at load buses. These regulators will try to increase the voltage in their low-voltage distribution side by changing the transformers taps, and this may cause the demand for reactive power in the system to increase, leading to a further drop in voltage at the transmission buses. Also, if the reactive power demands from the remaining online generators reach their limits, the situation may become worse.

B. Cases (B):

Case (B-1): Generator-1 Outage while supplying 80 MW.

Case (B-2): Generator-2 Outage while supplying 80 MW.

Case (B-3): Generator-3 Outage while supplying 80 MW.

Although in each case the same amount of generation is lost from the system, the expectation is that the disturbance power will be different in each case due to the differences in each machine’s inertias and relative location of the disturbance. Also, the expectation is that in each case, the load buses will experience a different voltage drop, which requires different decisions to be taken by the centralized load shedding algorithm on the amount of load to be shed from each individual bus. Thus, by testing these cases, the performance of the implemented centralized load shedding scheme can be compared to the conventional scheme, and its adaptability and ability to help prevent probable voltage problems that may occur after a major generation outage can be verified.

Tables III and IV show a summary of the results obtained from cases (B) testing by applying the implemented centralized and decentralized schemes, respectively. From the tables, it can be noticed that the implemented centralized scheme sheds less load from the system to recover frequency stability, and it distributes this load among load buses adaptively by taking into consideration voltage variation at these buses due to the disturbance. On the other hand, the conventional decentralized relays behave the same way each time irrespective of the disturbance location and voltage dips at the load buses.

The simulated test system in this paper is very small (only three load buses); in a larger power system, it is expected that the difference between the deterministic nature of the decentralized scheme and the adaptable behavior of the centralized scheme is to be more pronounced.
TABLE IV
RESULTS SUMMARY FOR CASES (B) TESTING BY APPLYING THE DECENTRALIZED UFLS

<table>
<thead>
<tr>
<th>Case</th>
<th>B-1</th>
<th>B-2</th>
<th>B-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tripped Generator</td>
<td>G1 80MW</td>
<td>G2 80MW</td>
<td>G3 80MW</td>
</tr>
<tr>
<td>Number of 10MW load feeders shed from load buses</td>
<td>Bus-5</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Bus-6</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Bus-8</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Actual power shed from the system (MW)</td>
<td>60</td>
<td>90</td>
<td>60</td>
</tr>
<tr>
<td>Final value of system frequency after load shedding (HZ)</td>
<td>60.04</td>
<td>60.16</td>
<td>59.94</td>
</tr>
<tr>
<td>Final value of line-line voltages at load buses (KV)</td>
<td>Bus-5</td>
<td>222.3</td>
<td>232.9</td>
</tr>
<tr>
<td></td>
<td>Bus-6</td>
<td>223.7</td>
<td>234.3</td>
</tr>
<tr>
<td></td>
<td>Bus-8</td>
<td>232.1</td>
<td>232.9</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

The hardware used in the implementation responded as expected with the programmed algorithm. The phasor measurement units (PMUs) successfully sent the synchronized real-time data for the measurements received from the eMEGAsim digital simulator’s analog output port to the SVP. The SVP received these measurements, performed the programmed load shedding algorithm, and issued the appropriate shedding signals accordingly. The interactions among all hardware together with the algorithm led to satisfactory performance. Furthermore, the SVP decisions were able to restore system frequency to a safe level and improve voltage level at the load buses for each disturbance. The SVP was able to distribute the amount of power to be shed according to voltage dips of the affected load buses for the different disturbance locations and this emphasizes the algorithm adaptability and its suitability for the implementation in industry. In addition, the load model was able to reflect the load dependency on the voltage and frequency variations.

Recommendations and Future Work: Since this study might be a starting point for using industrial-grade hardware in the implementation of other WAMPAC applications, there are several improvements and developments that could be accomplished, some of which are as follows.

1) Due to the limited system size utilized for this study, there was no need to investigate PMUs placement algorithms. However, it may not be economically feasible to have a PMU on each bus for a larger system. Thus, a next step would be to investigate different PMUs placement algorithms and compare their optimal monitoring of the system.

2) The test system can be upgraded to a bigger system, such as the IEEE 39-bus 10-generator New England system that is widely used in power system stability studies, and use it for further validation of the implemented scheme.

3) Reference [1] reported that the cause of recent major blackouts was due to voltage problems. The demand of implementing undervoltage load shedding (UVLS) and underfrequency load shedding schemes has increased. Consequently, this guarantees wider protection of the system against frequency and voltage instabilities [6]. Hence, implementing a UVLS algorithm in conjunction with this centralized adaptive UFLS would detect system voltage problems from a disturbance that does not affect system frequency.

4) The GPS clock is of great importance. Any obstacles that interfere with the GPS clock reception would result in problems, such as system freezes, PMUs not measuring and sending, and the SVP not receiving and processing. Special attention must be given to the GPS clocks since this could result in significant negative consequences in the field.

5) The time lags of PMU’s streams due to communication channels’ latency are not studied in this paper. More research is needed to carry out and study the effect of the communication channels’ time lag on such schemes.

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REFERENCES


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