

## An approach for a multi-stage under-frequency based load shedding scheme for a power system network

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### ABSTRACT

The integration of load shedding schemes with mainstream protection in power system networks is vital. The traditional power system network incorporates different protection schemes to protect its components. Once the power network reaches its maximum limits, and the load demand continue to increase the whole system will experience power system instability. The system frequency usually drops due to the loss of substantial generation creating imbalance. The best method to recover the system from instability is by introducing an under-frequency load shedding (UFLS) scheme in parallel with the protection schemes. This paper proposed a new UFLS scheme used in power systems and industry to maintain stability. Three case studies were implemented in this paper. Multi-stage decision-making algorithms load shedding in the environment of the DIGSILENT power factory platform is developed. The proposed algorithm speeds-up the operation of the UFLS scheme. The load shedding algorithm of the proposed scheme is implemented as a systematic process to achieve stability of the power network which is exposed to different operating conditions. The flexibility of the proposed scheme is validated with the modified IEEE 39-bus New England model. The application of the proposed novel UFLS schemes will contribute further to the development of new types of engineers.

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## 1. INTRODUCTION

In power systems, if generating power decreases during an emergency condition, the system frequency will decline [1]. During this condition, the dynamic of the system changes drastically. This dynamic depends on the amount of the disturbance, the response of emergency automation, and the governor's system. When the load gradually increases the governors will sense the condition and the generators speed will start to increase which will transfer more input power to the generators. At this point, primary and secondary frequency control will be activated. In a situation where a severe disturbance occurs, it will lead to the deficiency of generation. The frequency will drop drastically and the governor's response will not be capable to recover the frequency in time, even when the other controllers are activated. When the system frequency continues to decline, the under-frequency load shedding (UFLS) is therefore needed as an emergency scheme to restore the system frequency. In some power systems, the load shedding scheme is

deployed to automatically operate through disconnecting the loads from the system. This method is implemented with a small delay depending on the scheme coordination [1].

The best method of applying load shedding is to shed the loads in different steps rather than shedding the loads in one bulk. The number of steps for load shedding depends on different utility designs. The advantage of implementing load shedding steps is that it protects the system from over shedding or under shedding. The most reliable and accurate element that is used for UFLS is the rate-of-change of frequency function. In general, the under-frequency load shedding does pose disadvantages concerning system adaptability during an emergency change of the frequency. One of the disadvantages of using under frequency load shedding (UFLS) scheme is that a pre tripping frequency setting is required. This setting is to be selected to operate when a specific emergency condition occurs. It means that its operation is effective for only the pre-calculated emergency cases [1]. Therefore, it is not possible to predict all conditions that can occur in the power system. In the cases of large interconnected power networks, a full analysis of the system behavior with different methods are required to integrate the under-frequency load shedding scheme into the power system. The under-frequency load shedding scheme is used as the last resort to restore the system frequency. In a case where the spinning reserve is activated simultaneously with the under-frequency load shedding an over frequency condition can occur. Therefore, coordination between the controllers and the UFLS is critical [1].

Various problems are associated with the power network when operating at low frequency. One of the problems is the vibratory stresses on long low-pressure turbine blades [2], [3]. The second problem is the performance of plant auxiliaries driven by induction motors. The above factors are influenced by a few parameters that need to be taken into account namely, turbine and generator parameters, the power system inertia constant, and the load-damping constant [4].

The problem for the development of load shedding schemes (LSSs) has been studied for many years in both utility power systems and industrial plants with in-house generation. In large power utilities load shedding actions are used as the last resort to control the system in emergencies. Different methods have been used to achieve LSSs in the power system networks. The following is a brief description of the algorithms that were proposed by previous researchers. [5] Developed an intelligent load shedding (ILS) which can be applied in industrial facilities. A computerized system that provided fast and optimal modern load management was developed. The scheme used the programmable logic controller (PLC) for the decision-making process. Under frequency, the relay was applied to perform the ILS. In [6], an intelligent adaptive load shedding scheme was developed that provides strategies that deal with events when the system approaches extreme disturbances. The rate of frequency decline method was used. The complete power system network was divided into controlled islands. Some of the islands were loaded rich while the others were generation rich. The scheme was simulated using the DYNRED program in a PSAPAC package and tested on a 179-bus system. The method produces results showing a stability improvement when compared to the conventional load shedding schemes.

In [7] the authors focused on adaptive UFLS integrated with a frequency estimation numerical algorithm. Their primary objectives were to protect the electric power systems from dynamic instability and frequency collapse. Non-recursive Newton-type algorithm for frequency and the rate of change of frequency estimation was used. A generator swing equation for obtaining the magnitude of disturbances was used. Pinceti [8] presented a paper that focused on a formal approach that is based on a finite state transition model to define the load-shedding actions for a medium-large size industrial plant. A method that is based on a cyclic algorithm that analyzes the plant configuration and defines the necessary actions for any possible event that may lead to a frequency crisis was proposed. A SCADA system was used to model island detection logic and calculate the average load from the raw measurements. It was proven that the proposed algorithm is more efficient for emergency Load-Shedding in industrial plants. In [9] the researchers focused on automatic load shedding in power systems. Under frequency method for load shedding scheme was proposed. A software simulation was implemented as the test bench for this scheme. The simulation results were obtained using PSCAD/EMTDC software to prove the effusiveness of the system.

In [10] presented a paper that deals with centralized adaptive load shedding methods to enhance power system voltage stability margins. Two different power networks where considered one focused on UFLS and the other one on voltage stability. The performances of these adaptive methods were compared with one another and also with the conventional method. In [11] the authors modeled and re-developed an adaptive and optimal UFLS scheme. The model used a system frequency response (SFR) method. SFR and UFLS were used to monitor the estimated disturbances and identify the changes of the system frequency. The optimal load shedding scheme that was developed was tested on the IEEE 39-bus in New England to show the performance against the random load shedding scheme. In [12] the researchers proposed a novel approach for an adaptive load shedding scheme. The novelty was based on regional coordination for UFLS for four sub-areas connected to an external system using adaptive UFLS.

In [13] a modeled and simulated an adaptive load shedding scheme was designed. The proposed distributed load shedding scheme was based on an IEEE 39 bus system. Power system simulator (PSS) was used for simulation. The adaptive load shedding scheme was compared with the conventional UFLS. The results prove that the adaptive load shedding scheme performance is better than conventional UFLS performance. The operation performance under disturbances was improved when the adaptive load shedding scheme was implemented. Karimi [14] presented a new UFLS scheme for an islanded distribution network. The UFLS scheme was based on an adaptive and ILS techniques. It was able to conserve the power system collapse even for large disturbance and events in the system. The proposed scheme was evaluated through simulation in PSCAD/EMTDC software. Manson [15] developed an adaptive method of how to overcome under frequency scheme problems. The method used communication between remote protective relays and centralized under frequency devices. This method continuously kept track of dynamically changing load levels, system topology, and load composition.

In [16] a method on how to implement a dynamic correction for the UFLS scheme was designed. The method firstly determines a comprehensive weight index that includes load characteristics and inertias of generators. Then the active-power deficit was calculated based on the low-order frequency response model, concerning the effect of voltage. Once the above was completed a dynamic correction of the load shedding was modified. The proposed method provided a new reference and an idea for the online application of frequency-control for load shedding scheme. Laghari [17] developed a technique for UFLS that used a combination of fixed and random priority of loads. The objective was to implement this scheme in the smart grid. They made use of Different scenarios considered to prove the flexibility of the proposed scheme. The technique used three modules which were the center of inertia frequency calculator module (COIFCM), load shed amount calculator module (LSACM), and optimum load shedding module (OLSM). An 11-kV Malaysia distribution network consisting of hybrid DG resources having three DG units, two Mini hydro DG units, and one Bio-Mass DG unit were considered. This network was modeled using PSCAD/EMTDC and Matlab software. It was concluded that a combination of random and fixed load priority can help to perform optimal load shedding.

Tofis [18] proposed plug-and-play selective an adaptive load shedding scheme that used a single measurement of the electric frequency of the power system. The algorithm used for the scheme approximates the online structure of the nonlinearities of the swing equation and adaptively bounds the load disturbances and the functional approximation errors of the nonlinearities. The method used a control law to cancel the nonlinearities to respond sufficiently to the load disturbances, therefore achieving the frequency stability of the system successfully.

Mollah [19] developed an adaptive load shedding scheme. The algorithm used was based on load priority index (LPI) where it was implemented in a 15-bus system. An OPAL-RT real-time simulation was used to implement the adaptive load shedding scheme. The drawback of the adaptive scheme is a network used was small and it only consisted of one generator. Where [20] proposed a UFLS scheme that used the rate of change of frequency (ROCOF) to estimate the average frequency during disturbances. An IEEE 39 bus power system was deployed to validate the algorithm. The scheme used the decentralized method where coordination of load shedding scheme and plant protection were implemented successfully [21] developed a dynamic multi-stage UFLS based on the uncertainty of generation loss. The proposed method was based on using the BONMIN solver algorithm which used the Monte Carlo simulation technique. An IEEE 39 bus power system was used for simulations. UFLS considered a practical setting under different horizons of uncertainty in generation loss. A formulated mixed-integer linear programming optimization problem was used for a probabilistic UFLS scheme to minimize the expected amount of load curtailment. [22] Proposed a two-stage load shedding scheme that was used as the secondary control in the Hierarchical operation of Islanded microgrid. The method was based on the coordinated response of inverter-based distributed energy resources (DERs) where a 6-bus system with five DERs and six aggregate loads was used. PSCAD/EMTDC software was used for simulations. The methods dealt with the power deficits caused by the microgrid islanding.

In [23] develop a centralized, adaptive load shedding scheme that is based on the combination of voltage and frequency stability issues. A centralized, adaptive load-shedding algorithm that uses global voltage stability index and SFR, model was proposed. The structure used was the IEEE 39-Bus system. The constrain is that the algorithm used is sophisticated and complex. In [24] proposed an intelligent UFLS/UVLS method that is based on the active participation for smart appliances. They used VQ margin mode algorithm is used in PSAT (power system analysis toolbox) simulator. The proposed method shows that the system frequency was able to recover although it took longer than it was expected.

In [25] proposed an improved UFLS scheme that can detect power deficit during the shedding process and accordingly adjust the amount of load shedding. They used an algorithm based on continuous monitoring of the overshooting signal of the second frequency derivative of the center of inertia.

PSCAD/EMTDC software was considered for this study. In [26] Proposed a topology based on tracking the changes of the power system to implement the adaptive under frequency loads shedding scheme. The proposed algorithm is based on identifying island conditions in an interconnected power network that comprise of several transmission power systems. PSS/E and LabVIEW were considered for this study.

The drawbacks of the current literature in development LSSs are that the researchers focused on the theory and static simulations and overlook the planning and digital simulation to prepare for the system for practical implementations. The utilities and industry prefer the feasibility study to end up with a practical implementation for testing and validating the results.

The structure of the paper is presented as follows: Proposed case studies are presented in part 3. Part 3.1 covers case study 1 and results for the investigation of the performance of the 10 generators when the loads are increased. Part 3.2 covers a case study 2 and results where comparison of the under frequency (UF) and the ROCOF algorithms of the UFLS elements of a DIgSILENT protective relay. Implantation of a multi-stage UFLS schemes in DIgSILENT power factory platform is done. Part 3.3 provides a case study 3 and results where the implantation of a multi-stage UFLS schemes in DIgSILENT power factory platform for a worst-case scenario is done. Part 4 presents the discussions and part 5 the conclusion of the paper is covered.

UFLS schemes have been proposed in the past and still have not found a good solution when the correct amount of load to be shed has to be determined, to select the load to be shed, and to reduce the execution time of the load shedding operation. The objective of this paper is to develop and implement a UFLS scheme for distribution power network by application of the proposed under frequency algorithm based on soft intelligent electronic devices (IEDs) in DIgSILENT power factory software. The proposed algorithm speeds-up the operation of the UFLS scheme.

Deliverables of the paper are as follows:

- A model of the modified IEEE 39 bus system is developed in the DIgSILENT power factory software, and load flow simulation is performed.
- A system for frequency stability analysis.
- New models of the elements of the power system are used for the development of the IEEE 39 bus system and implementation of the UFLS schemes.
- A To compare the UF and the ROCOF algorithms of the UFLS elements of a DIgSILENT protective relay and select one with the better performance
- New UFLS algorithms based on multi-stage load shedding operation and prioritization of the amount, order, and location of the loads to be shed are developed.
- Soft IEDs are developed to be implemented in the DIgSILENT power factory environment.
- Multi-stage decision-making algorithms load shedding in the environment of the DIgSILENT power factory platform are developed.
- To investigate and analyze the performance of the UFLS scheme and the behavior of the whole network under the severe contingency of loss of 4 generators

## 2. UNDER-FREQUENCY LOAD SHEDDING ALGORITHM

The basic concepts of frequency dropping are that it can be stopped either by increasing output mechanical torques of the turbines or by reducing the load demand. The increase of output mechanical torques of the turbines is not likely due to the slow reaction of the turbine governor. The second way seems to be the logical solution. This method can use the system frequency decline as the indicator to shed the part of the load through activating the UFLS scheme. During a situation where the frequency is dropping due to some contingencies, the activating of the UFLS scheme should disconnect a sufficient volume of the load. This is done to prevent the system frequency from dropping below the level which is hazardous for power system equipment. The shedding of loads due to frequency declining can be done in multiple stages. This is done to reduce the over shedding and under shedding of loads. The stages correspond to the change of frequency as it declines. This means that the stages have different frequency thresholds. Every time these thresholds are reached, a certain amount of load needs to be shed. Figure 1 represents a graphical explanation of the frequency variation during the operation of the UFLS scheme.

The x-axis on the graph above represents the time taken when the frequency drops and the y-axis represent the system frequency. The graph above shows that at  $f_{nom}$  the system is stable and operates in a normal condition. At a point where the system frequency is less than  $f_{nom}$  the system will be no longer stable. When it reaches setting  $f_{set1}$  the first level of load is shed. If the system is still experiencing instability condition, the next portion of the load is shed at  $f_{set2}$ . The method continues until a balance between the generation and load demand is achieved. In this case, the graph shows that five steps were used to shed

the loads, and when stage five was reached the system frequency was able to recover. The corresponding load-shedding algorithm is shown in Figure 2. This type of load shedding operation is implemented in power system utilities [1].

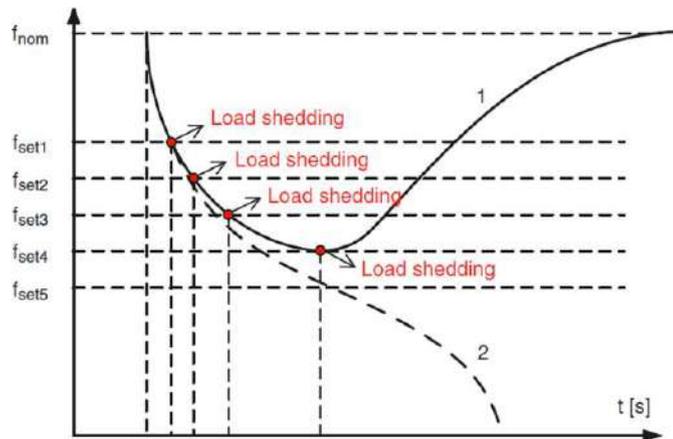


Figure 1. The power system frequency variations and the UFLS operation [1]

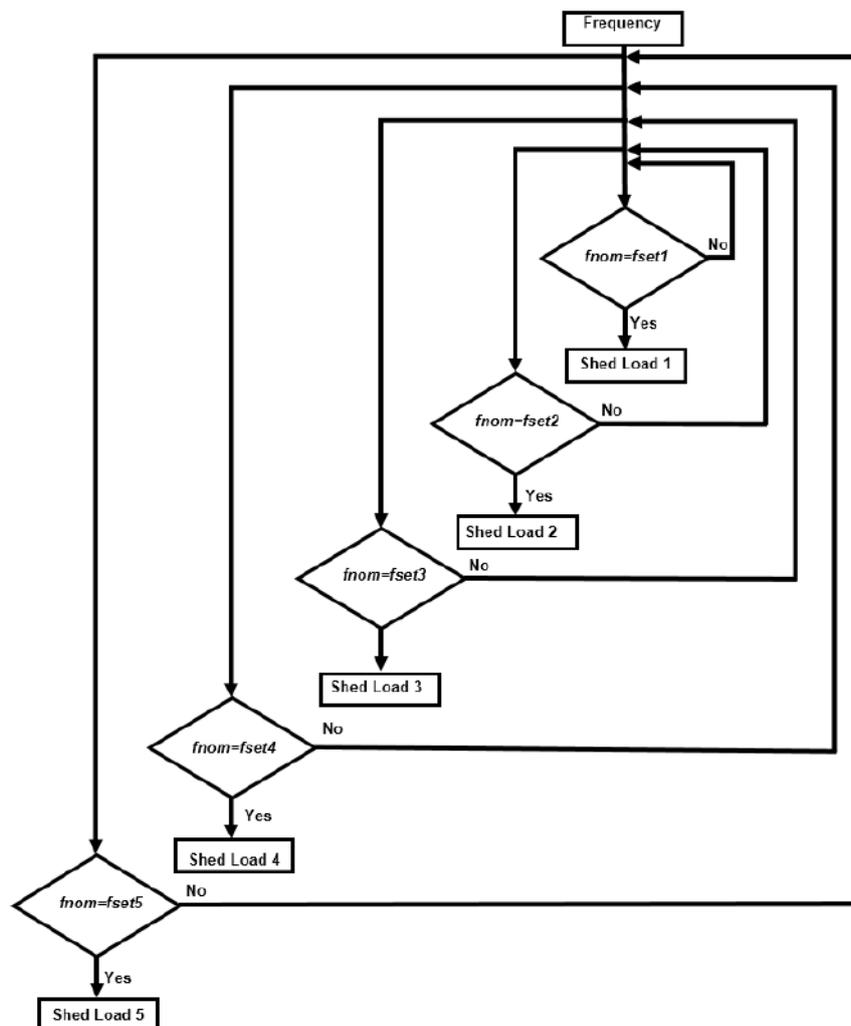


Figure 2. The flowchart of the UFLS algorithm

## 2.1. Implementation of the UFLS scheme

When developing a UFLS scheme various problem are considered. The first problem is to know which condition is creditable as the indicator when the UFLS scheme is required or triggered. Once this point is achieved, it is important to consider the following components of the load-shedding algorithm:

### a. Lower frequency settings

The first part is to identify the system frequency that the grid or supply is operating. In this case, the grid uses 60Hz. Once this part is completed lower frequency setting level is configured.

### b. Intervals between frequency settings

This part depends on the protection device used for under frequency protection. The time interval between the frequency levels setting depends on the pickup time and the breaker tripping time.

### c. Maximum capacity of loads connected

When developing the UFLS scheme the maximum capacity of the load connected to the load shedding system needs to be determined. It is necessary to know exactly how much load is shed to retain the system balance and stability.

### d. Steps for the load shedding

The number of steps depends on the amount of load that needs to be shed. All the above components need to be embedded in the algorithm when developing the UFLS scheme. Since the power system is interconnected and has different dynamics. It is important to carry out full research work to determine the possible problems that may occur. All the above depends on the diversity of the number of steps, the frequency levels and the amount of load to be shed at each step [1].

## 2.2. The establishment of the used power network system

To design a load-shedding scheme for a power network system, a model that represents the different generating machines is defined. Once that is done the load parameters and the criteria for setting the frequency relays need to be defined as well. In this paper, the IEEE 39 bus power system model is used to illustrate the proposed load-shedding scheme. The IEEE 39 bus system is divided into four areas for the research investigations, better understanding and analysis, simplicity, and as well as to establish and implement the proposed case studies. The network is divided into 4 interconnected areas, as shown in Figure 3.

The investigation is based on the assumption that the generator units are electrically connected with negligible oscillations between them and with a uniform frequency across the whole system. The loads in the network are represented as a constant power, which suggests that there is no reduction in load because of the voltage and frequency drops after a contingency situation. The simulations were implemented based on the following assumptions, the mechanical power arriving at the generators does not vary and is equal to electrical power magnitude before the contingency, and the magnitude of the loads does not vary with time, voltage, or frequency. It is only reduced by disconnecting part of the load because of the load-shedding scheme. All the above was implemented on DIgSILENT power factory software.

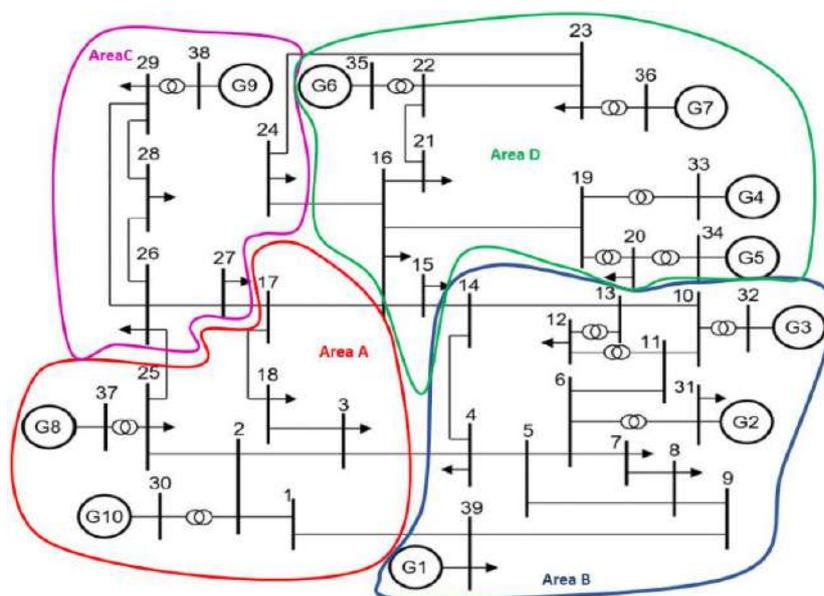


Figure 3. The IEEE 39 bus system divided into four areas [27]

### 3. PROPOSED CASE STUDIES

The paper aims to develop and implement in the DIgSILENT environment a multi-stage UFLS scheme to stabilize the system when it is overloaded or exposed to a drastic loss of generation. In the considered case studies, the implementation of the load-shedding scheme is analysed. When power system network is exposed to various contingencies such as overload or loss of generators and so on. A well-co-ordinated protection schemes is required to monitor and control the system. When the protection schemes are applied and the system continues to be unstable, a load-shedding scheme is deployed. This method is used as the last resort to stabilize the system through shedding the loads that are causing the system to be unstable. It must be noted that the power system network chosen is assumed that all 10 generators are synchronous. The penetration of non-synchronous generation sources is not considered in the case studies. Three case studies were implemented in this paper. The flowchart that represents the performed case studies aims is shown in Figure 4 and Table 1 (see Appendix) represents the summary of all of them.

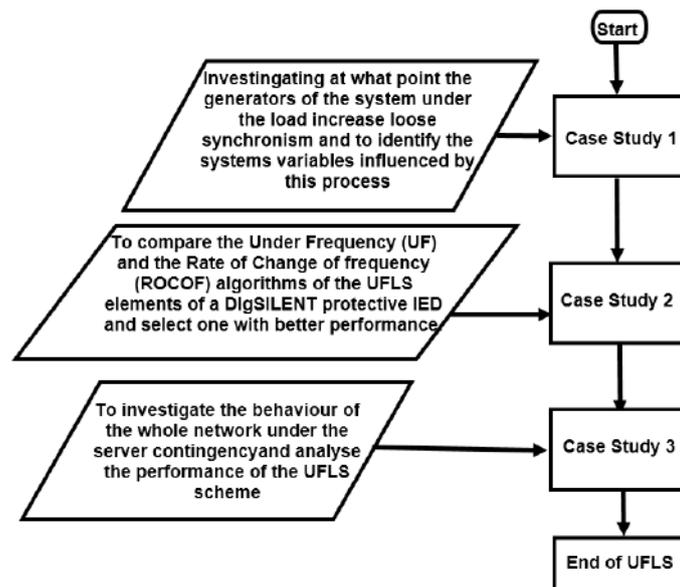


Figure 4. Case studies and their aim

#### 3.1. Case study 1 and results

This case study aimed to find out at what point the generators become out of step. The case study considered was based on the assumption that all the devices to stabilize the system were utilized. Credible contingencies were developed when load flow simulations were implemented. These contingencies were to assist the IEEE 39 bus system to reach the power stability margin. The components that were monitored during this investigation were all 10 synchronous machines that are in the network system. Basic synchronous machines have many different variables, but only critical variables were selected for monitoring such as the following: the active power (m:P:bus1) the speed (s:xspeed), the excitation voltage (s:ve) and the terminal voltage (s:ut) respectively. It must be noted that the s:ut was only considered for the simulation experiment although in the real world scenario it is not possible to access it. A DIgSILENT platform toolbox known as “Transmission Network Tools” was selected for this case study. The overall load scaling technique was considered so that the system loadability would be calculated. The algorithm is based on finding out the critical point where the generators become out of step (pole slip). This is done by increasing the power demand until the load flow calculation can no longer converge. In this case, all loads in the system were scaled simultaneously using iteration control for the load flow. During this process, an initial load scaling with a multiplication factor of one was implemented. The load scaling used an adaptive step size algorithm where the step size was defined as the initial step size of 1% for the initial active and reactive power of the loads. The maximum step size selected to be 1% and the minimum step size is 0.01% of the initial active and reactive power. All was done on maximum iterations of 100 from the initial active and reactive power.

For the experiment, the loads were gradually increased once again by an increment of 1% at every second until the maximum load margin was reached and passed to a point where the generators became out of step (pole slip) deploying the adaptive step size algorithm. Since there was no protection scheme applied

the system eventually shuts down. When the contingency such as simultaneously increasing the active power of all the loads in the system was implemented, generators at Area A, Area B, Area C, and Area D were monitored and the results were recorded as shown in Figure 5.

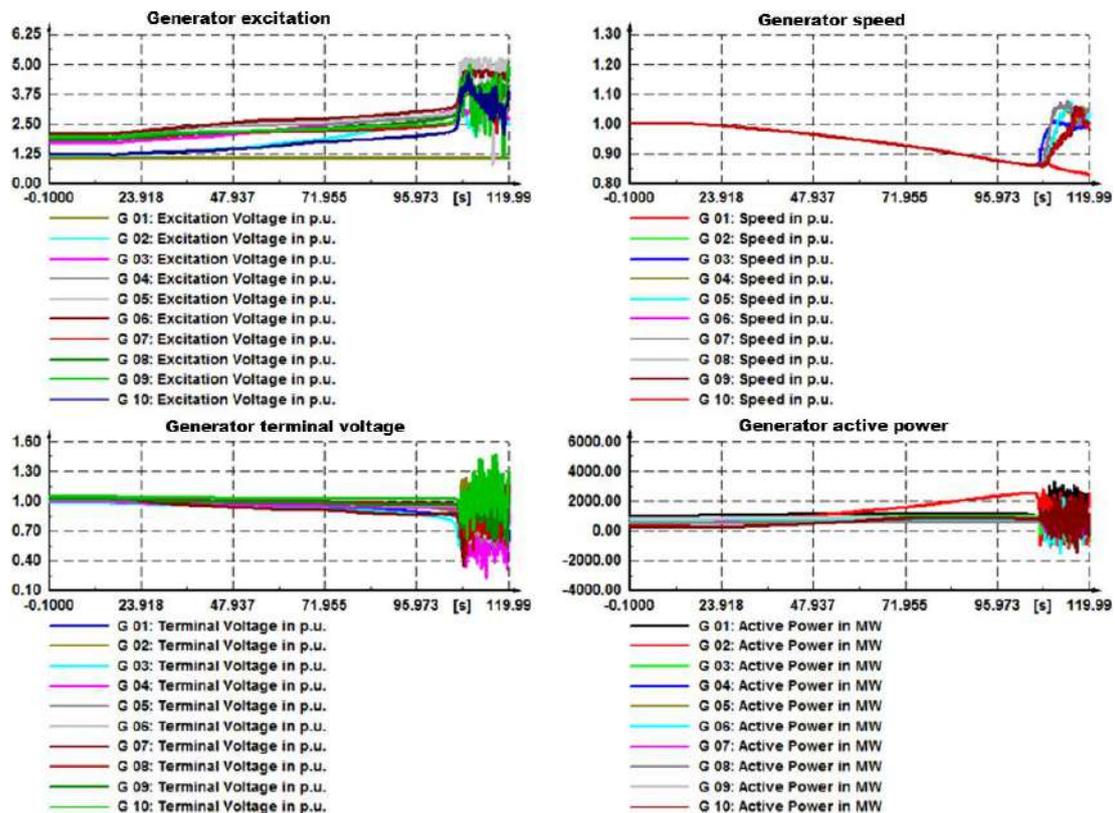


Figure 5. The magnitude of the generators excitation voltages, Speed in pu, the terminal voltages in pu and active power, in MW for all 10 generators

When the simulation was implemented the results indicated that a load event was executed at 15th second of the system operation with an increment change of active power by 1% at every 1 second. At a time of 107.18th second the generator, G01 became out of step, meaning the pole slip and it was lost. The generator G05, G09, G08 at the 107.21th seconds, later followed it. As the loads continued to increase, generators that were still in the system were experiencing an overload. The system stressed to a point where they were no longer able to contain the loads. Therefore, the generator G04 started to experience overloading as well and its pole slipped at 107.22th second. The system was on its way to a complete shut down because the generators that were left were all out of synchronization. The generator 10 whose pole slipped at 107.24th seconds later followed. At this point only the generator G6 and G7 were in operation. These generators were heavy stress and generator G06 only lasted 1 second after the generator G10 had collapsed. The last generator that was lost due to heavy loading of the system was the generator G07 that took 107.27 seconds to shut down.

The next task was to use the speed (s:xspeed) and frequency (n:fehz:bus1) variables, as the indicator when the generators approached a collapsed condition as shown in Figures 6 and 7. The last resort to maintain stability was now to use UFLS scheme. Figures 6 and 7 represent the behavior of the generators when the network was loaded. It can be seen that when the system was gradually loaded the frequency (n: fehz: bus1) and the speed (s:xspeed) also dropped. In these cases, as the frequency drops the controller devices were introduced to compensate the system until a point where it can no longer operate. At this point, a load shedding scheme was required to stabilize the system.

Traditionally when the system experience instability due to various contingencies it was discovered that two components are used as the ideal indicators. In a case where the partial loss of generation occurs within the network system. The first indicator would be a drop in bus voltages and the second indicator is the system frequency. However, when the network system was lacking the reactive power, the voltage

drops causes the system to mal-operate. On the other hand, it is generally recognized that a drop in frequency is a more reliable indication when the loss of generation occurs. In a case where a contingency such as a sudden loss of generation appears, the system frequency will have a drastic reduction. The system frequency will be reduced at a rate of change that depends on the magnitude of the resultant overload, and the inertia constant of the system.

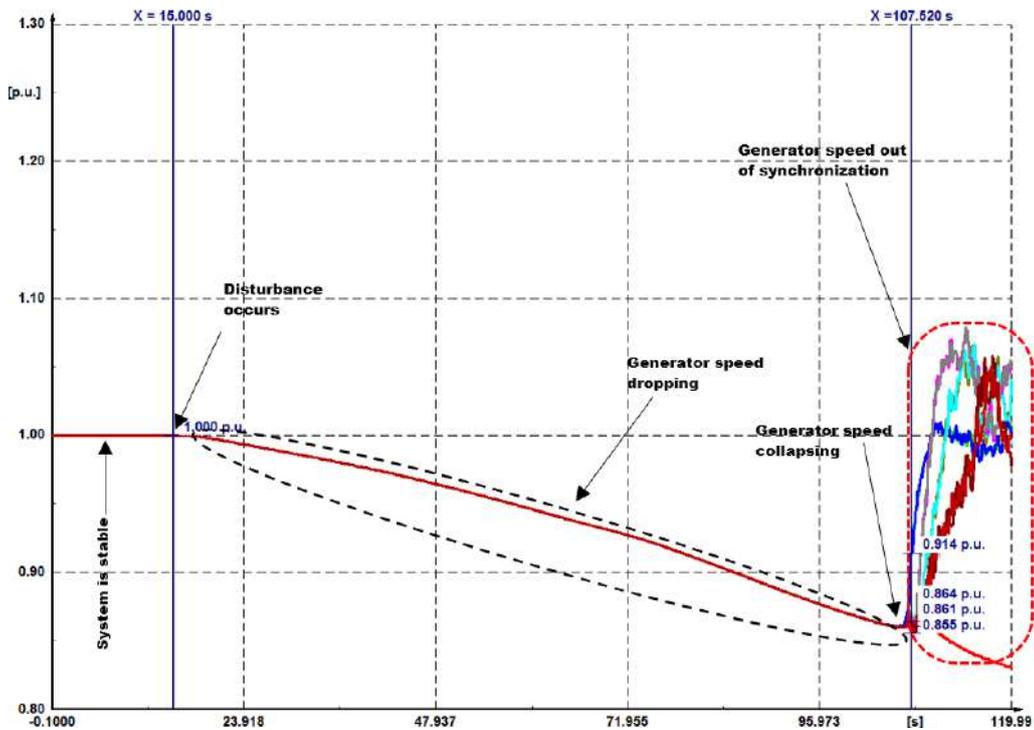


Figure 6. The speed (s:xspeed) variable behavior for all generators

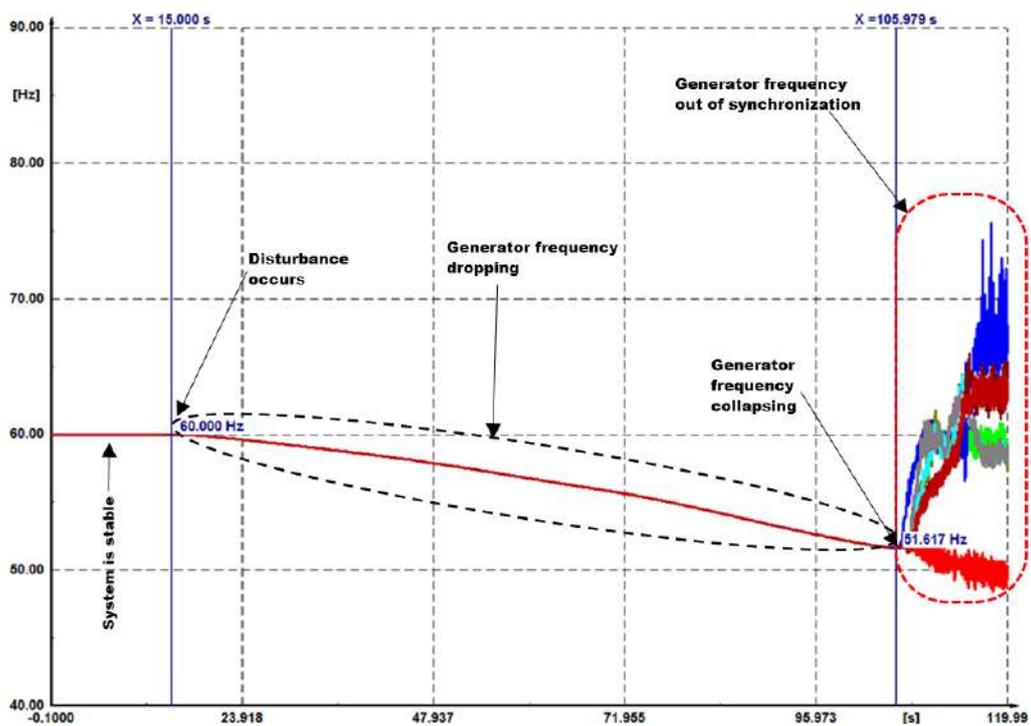


Figure 7. Frequency (n:feh:bus1) variable behavior for all generators

### 3.2. Case study 2 and results

The case study aimed to compare the two algorithms of UFLS elements that are used by the IEDs in the DIgSILENT power factory. One algorithm used an under-frequency (UF) F81 frequency element as the load shedding solution. The second algorithm used the F81R ROCOF element as the load shedding solution. The two algorithms were applied separately during this case study and the results were compared. Area A was used for the case study. Once the best algorithm was determined, it was applied to all other areas of the power system network. The investigations were done by creating various conditions on the system to fully understand and validate the performance of the two algorithms.

The ROCOF algorithm operates in such a manner that monitors system frequency fluctuation. The frequency fluctuation is caused by the oscillation of the machines when a new load condition occurs. The new load condition occurs in an event where a sudden loss of connection from a source happens. A simplified block diagram of the under frequency IED using the UF or ROCOF algorithm is shown in Figure 8. Both algorithms (UF and ROCOF) were integrated and a simulation was implemented in the DIgSILENT platform to validate the dynamic behavior of the UFLS scheme.

#### 3.2.1. Starting frequency of the load shedding system

The disconnection of loads from the network system should be set in such a manner that it would initiate the circuit breaker to operate at a value of frequency that is below the normal working system frequency. The value is normally selected at approximately 95% of the nominal system frequency. The frequency level for initiating load shedding should be below any frequency at which the system could continue to operate.

#### 3.2.2. Minimum permissible frequency

A steam turbine is designed in such a manner that when it operates at a nominal mechanical speed, it generates a nominal system frequency. While it operates under normal conditions, there are excessive vibrations and stresses in its components. However, in an abnormal condition where it operates below normal the speed caused by a reduced system frequency, cumulative damage could be produced by excessive vibrations. Therefore, it is recommended that the time limits given in Table 2 should not be exceeded. However, during transient operation and with a load below nominal, the frequency is usually reduced to 93% of rated frequency and it can still be accepted without causing damage either to the turbine or to the turbo generator auxiliary lubrication and cooling systems [1].

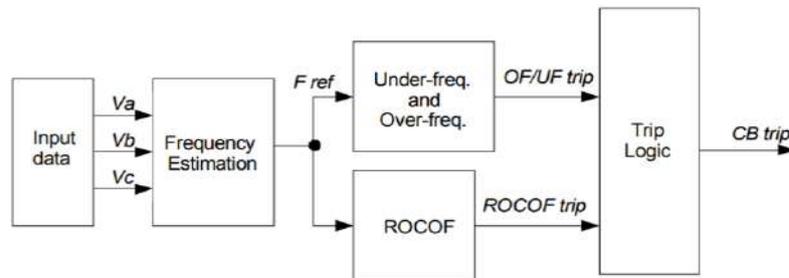


Figure 8. A simplified block structure of the relay with UF and ROCOF load shedding algorithms

Table 2. Typical times for the operation of turbines (full load)

% of rated frequency at full load	Maximum permissible time in (min)
99.0	Continuously
97.3	90
97.0	10
96.6	1

The LSSs must be properly coordinated with all the equipment operating in the system. Especially during the time where the system is operating at its maximum limits. The limitations relate to the operation of the power plant auxiliaries. A study on power plant auxiliaries for a 60Hz network system showed that their performances start to fall off and power output decreases at a frequency below 59Hz and reaches a limitation condition between 53Hz to 55Hz. The UFLS scheme needs to provide a margin where the maximum frequency decay is limited. This limit is considered before the equipment such as the turbine is damaged or

the network system can no longer recover and lead to a blackout [1]. The study for the 60Hz network system states that at least 57Hz can be selected as the margin for maximum frequency decay limit. Due to relay and circuit breaker operating times a high-frequency level is required to be 57 Hz because the frequency will continue to drop below before the load is shed.

### 3.2.3. Principles used for setting frequency elements in the IEDs

When determining the setting of the frequency elements in the IEDs, speed, and coordination requirements is taken into consideration. The coordination between IEDs must be set in such a manner that it trips successive stages to ensure that the minimum number of loads is shed, subjected to the initial overload conditions. Two parameters influence the frequency IED settings, namely the operating times and the determinations of frequency variation.

The time setting selection is based on the time intervals between the system frequencies decaying from the relay pick-up value to the point in time when the load is effectively disconnected. The pickup time included the time interval, plus the pre-set time delay of the relay, and the breaker opening time. On the other hand, it was required to determine the best combination number and size of load shedding steps that needs to correspond with the IEDs frequency settings. These IEDs frequency settings are selected in such a manner that it sheds the required load within the frequency limits which are specified for a maximum overload condition. This concept is determined in such a manner that a minimum amount of load is shed for less severe conditions.

### 3.2.4. Investigation of the performance of the UF and ROCOF algorithm in the software environment of DIgSILENT

Once all the above was considered the simulation was implemented on the IEEE 39 bus system and the results were analyzed individually for all four areas. Since the concept is the same for Area B, Area C, and Area D to avoid repetition, Area A was only considered. The initial conditions were summarised as follows:

- The total load of the system: 6070.8MW
- In-house load at Area A: 696MW
- In-house generation: G10 = 250MW and G8 = 540MW
- Total power exported: 94MW
- The system operates with automatic voltage regulators (Avr) and power system stabilizers (PSS) on service

The investigations were performed in the following order:

- a. Part 1: Load flow calculation of the Area A subsystem in the case of no disturbances

The simulation focused on the insourcing supply of Generator 08 for Loads 03, 18, and 25 respectively. In this case during the initial condition when the system is operating in normal condition G08 supplies Bus 01 through the transformer Trf 02-30. Some of the power from G10 is exported to Area B. On the other hand, G08 supplies the Bus 25 where there are three points connected Load 25 and two transmission lines. The load in this bus consumes 224MW from G08 and the two transmission lines transfer the power of 230.2 MW to the next Bus 01 and 84.2 MW to Bus 26 respectively. Since substation Bus 26 is at Area C the 84.2 MW is considered as the exported power. The load flow also shows that Bus 17 is fed with 193.4MW of power through a transmission line that comes from Area D. At the same time, Bus 17 is connected to two transmission lines where one is feeding Bus18 to which Load 08 is connected. In this case, Load 08 during normal condition is consuming 158MW. On the other hand, the second line is feeding the Bus 27 which is situated in Area C. The simulation also shows that Bus18 and Bus01 each had a transmission line that transfer powers of 396.4MW and 28.8MW to Bus 03 where Load 03 is connected. Load 03 consumes 322 MW of power during normal conditions. At this point, the load flow analysis at Area A was completed and a contingency of losing Generator 08 as the worst case for area A was implemented.

- b. Part 2: RMS/EMT simulation of the whole system in the case when generator G08 lost the automatic voltage regulators and stabilizers are not in operation. Comparison of the time for monitoring of dynamic behavior of the frequency used by UF and ROCOF

The procedure is based on a sudden loss of G08 by the opening of the circuit breaker at 15 seconds. While implementing this contingency all the generators that were still in the system were monitored. The specific element or variable that was monitored was the frequency of the generator (n: fehz: bus1). This is an experiment provided to compare how well the UF and ROCOF algorithm of the relay measures the decay of the frequency when the system operates without governors and stabilizers. At this point, the UFLS was not considered only the measurement and monitoring function of the UF, and the ROCOF algorithm is used. The results show that generator G08 was lost after 15 seconds the frequency started to decay drastically from 60Hz down to 49.870 Hz within 120 seconds. It can be seen from the results that after

a sudden loss of G08 the system frequency took 25.621s when using under frequency element (UFS) to reach the margin for maximum frequency decay limit which is 57Hz. below this point system was exposed to instability and it was approaching a point of collapsing as shown in Figure 9.

The same procedure as the above was implemented but in this case, a ROCOF element was used to measure the system frequency. The results in Figure 10 shows that after the sudden loss of G08 the system frequency took 18.209s when using UFS to reach the margin for maximum frequency decay limit which is 57Hz. In both results no loads were shed and although it was discovered that UFS took longer than the ROCOF to measure and monitor reaching of the margin for maximum frequency decay limit of 57Hz.

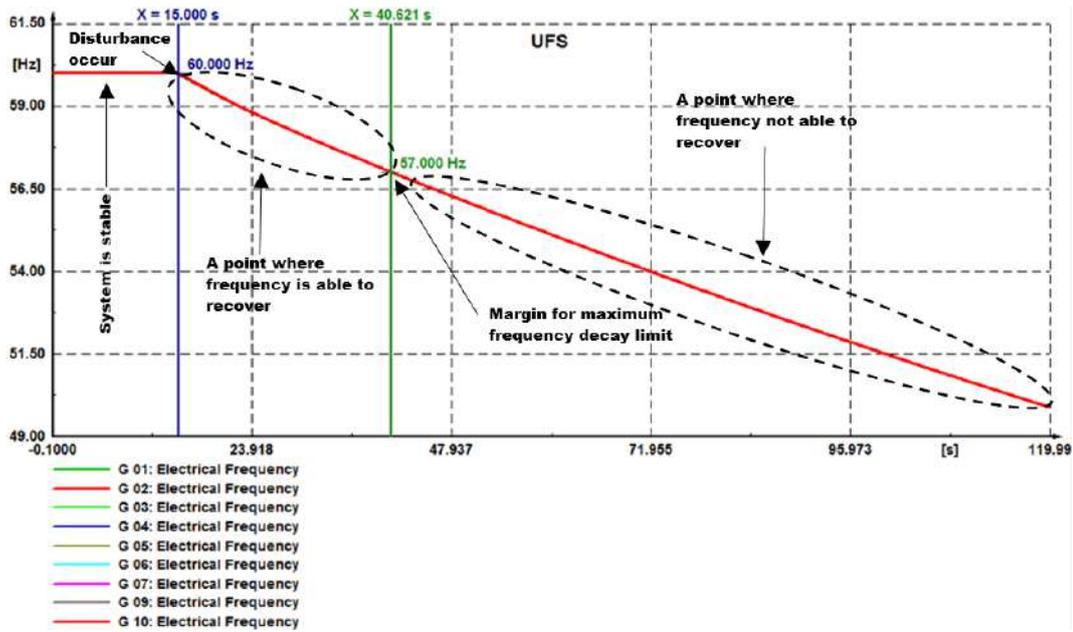


Figure 9. The Generators frequency dynamic behavior measurement using UFS for the case of generator 8 lost and without the Governor and turbine (gov) of the generators

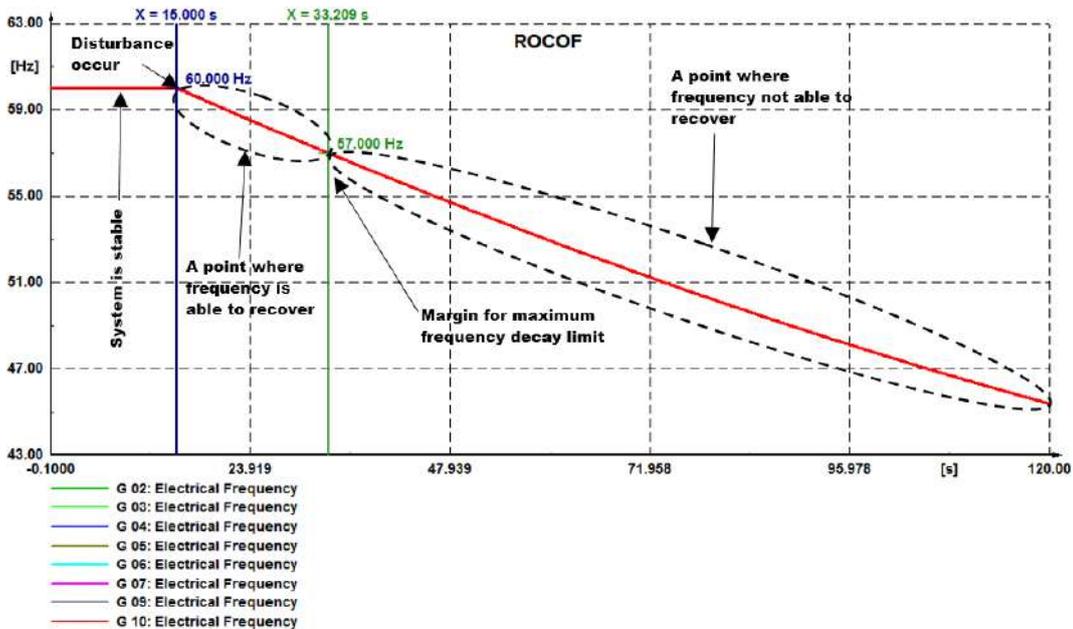


Figure 10. The generator frequency dynamic behavior measurement using ROCOF relay algorithm for the case of generator 8 lost and without the governor and turbine (gov) of the generator

- c. Part 3: RMS/EMT simulation of the whole system in the case of G08 lost and the automatic voltage regulators and stabilizers are in operation. Both UF and ROCOF algorithms are not in operation

The next step was to introduce the IEEE Type 1 Speed-Governing Model to the generators. The results in Figure 11 show the frequency of all nine generators during a condition where the generator G08 was lost after 15 seconds. In this case, both protection algorithm UFS and ROCOF for UFLS were not considered. The frequency started to decay from 60Hz to 59.358Hz within 16.858 seconds. It later recovered to 59.456Hz because of the IEEE Type 1 Speed-Governing. However, the system frequency was not able to recover back to 60 Hz. Although this contingency was not severe because the generators were still in synchronization and the frequency did not go below 57Hz which is the maximum limit. Therefore, this case was not considered the worst-case scenario. However, load shedding was still required to be implemented since if the system continues to operate under the condition it will eventually approach a critical point and end up collapsing.

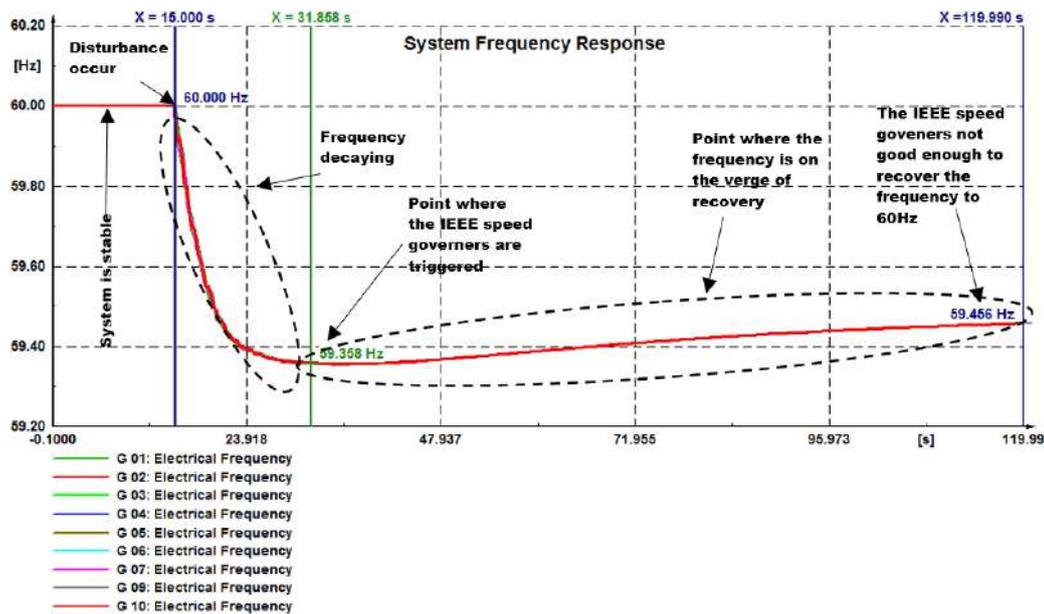


Figure 11. The system frequency dynamic behavior for all the generators in the system in a case of G08 lost and using IEEE speed governor model

- d. Part 4: RMS/EMT simulation of the whole system in the case of G08 lost, the automatic voltage regulators and stabilizers are in operation and the UFLS scheme is in operation. Comparison of the time for recovering the system frequency used by the UF and ROCOF algorithm.

When generator G08 was lost, 8.89% of the power of the whole system was lost and the system was experiencing an unbalance between the supply and the load demand. At this instant, the system frequency started to drop which indicated instability. Therefore, it was required that the system should shed at least 8.89% of the existing load to recover the system frequency back to 60Hz. When dynamic controller models were introduced, the system frequency managed to improve. But it did not recover back to 60Hz, therefore another protection scheme was required to be integrated to the system, which would be able to recover the system frequency. The UFLS was needed to be implemented in this case as the last resort to recover the system frequency back to normal. Area A was the first part to be protected.

The proposed load shedding used protective devices when applying the scheme. In a case of system frequency monitoring the load shedding scheme utilizes the UFLS scheme. The algorithm that is developed by the UFLS scheme is based on shedding first the loads where the bus voltage drop is lowest due to some system disturbances. The scheme is designed and configured to shed the loads in stages depended on the size of the disturbance. Each stage has different priorities to determine the number of loads that need to be shed. The load shedding scheme application is fully decentralized according to the load buses (can be a transmission line feeding a bulk of loads or precise portion of loads at a feeder level). Every area where there is a load bus has intelligent electronic device (IED) where the under-frequency element is programmed to operate when required. The IEDs are coordinated in a way that they shed the amount of the loads (active or reactive power) that is equal to the power that has been lost by generation. This is done to constantly to

balance and match the generation with the load demand to keep the system frequency at the nominal value. In these cases, the IEEE 39 bus system was considered as a network that was it a point where a load shedding scheme was required to stabilize the system. Under frequency LSSs were implemented into the IEEE 39 bus system. The flow chart that was used for these exercises is shown in Figure 12.

Three stages of frequency levels for load shedding were configured for this area: Stage 1: the UFLS scheme was configured that 5.3% of the total (6070.9MW) load is shed, Stage 2: another 2.6% of the total load, and at Stage 3: it was required that 0.99% of total load needed to be shed. Therefore, the total load that needed to be shed was 540MW, because the generator that was supplying 540WM suddenly was disconnected from the rest of the system

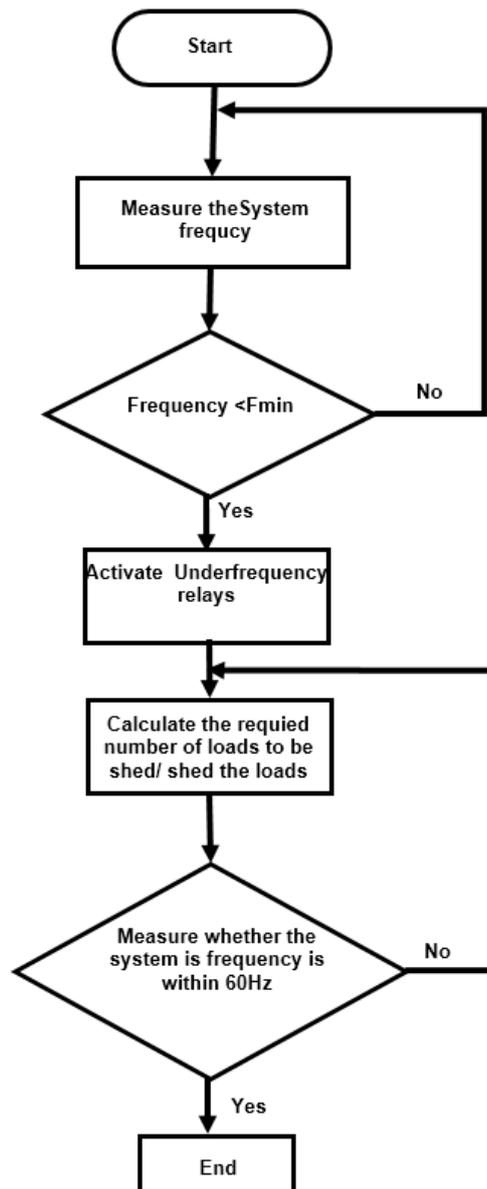


Figure 12. The flowchart of the traditional load shedding scheme

Due to the imbalance of the system after the disconnection of G08, the frequency changed from the normal condition the ROCOF needed to be calculated which depends on the amount of load that needs to be shed. There was also a need to calculate the threshold frequency where the loads need to be shed. The approximated equation that was used for calculating the ROCOF and the threshold frequency for every stage is as follows [28]:

$$\frac{df}{dt} = \frac{\Delta P \cdot f}{2 \cdot G \cdot H} \quad (1)$$

where

$\Delta P$  is the change in power output between synchronized and island operation

$f$  is the rated frequency

$G$  is the machine rating in MVA

$H$  is the inertia constant

The tripping time is calculated as follows:

$$t_{trip} = t_{pick-up} + t_{breaker} + t_{relay} \quad (2)$$

where the pick-up time is calculated as follows

$$t_{pick-up} = \frac{f_s - f_1}{\frac{df}{dt}} \quad \text{where} \quad f_s = \frac{df}{dt} t_{pick-up} + f_1 \quad (3)$$

where

$f_s$  is the system frequency

$f_1$  is the threshold frequency selected for the first stage

The threshold frequency for the second stage was calculated using the following.

$$f_2 = f_s - \frac{df}{dt} \times t_{trip1} \quad (4)$$

$$f_3 = f_s - \frac{df}{dt} \times t_{trip2} \quad (5)$$

The calculated values for the UFLS scheme when 8.89% load is shed are shown in Table 3.

The frequency elements (UFS and ROCOF) of the IED used for the UFLS scheme are simulated in moving 120 seconds windows and three consecutive results which are for stages 1, 2, and 3 were recorded and interrogated. The under-frequency relay installed in Bus 03 was deployed to shed the 5.3% of loads for stage 1. The disconnection of loads for stage 1 was calculated to be triggered when the system frequency drops below 59.82Hz. When the contingency was applied the system, frequency dropped down to a point where the pre-calculated threshold frequency was reached. At this point, the under-frequency relay is triggered and the signal was sent to the circuit breaker to trip and shed the load 03 which represents 5.3% of the system load. Figure 13 shows that when using the UFS element set in the under-frequency relay the system took 9.057 seconds to complete the protection scheme where on the other hand Figure 14 shows that the ROCOF took 18.89 seconds. When the performance of the schemes using UFS or ROCOF relay element were compared it was discovered that UFS element performed better than ROCOF one in terms of time although the ROCOF has more functional flexibility than UFS. However, the system frequency was improved but it still did not recover back to 60Hz. This means that there was still a need to improve the frequency by applying stage two of the load shedding scheme.

After interrogating the results when stage 1 has triggered, it was discovered that the system frequency was improved from 59.456Hz to 59.727Hz within 9.057 seconds. However, when the generator G08 was lost, 540 MW was required to be shed, but at this point, only 5.3% of 6070.8 MW which was calculated to be 322 MW was shed. For the system, frequency to fully recover at least another 218MW needed to be shed. Shedding 218 MW at once was avoided to limit a condition where the system over sheds, therefore another 2.6% of the load was set to be shed at stage 2. In total, the load shed at the end of stage 2 is 7.9%. The threshold frequency for stage 2 was calculated to be at 59.71Hz. The simulation case study was applied once again, and the system frequency was improved from 59.727Hz to 59.917Hz as shown in Figure 15 using UFS shedding algorithm and 59.727Hz to 59.917Hz in Figure 16 using ROCOF one. The UFS algorithm took 14.402 seconds and ROCOF took 9.356 seconds to complete the load-shedding scheme. When the UFS and the ROCOF algorithm performance was compared, it was discovered that ROCOF performed better because its response was faster by 5.046 seconds. However, at this point, the system frequency was not fully recovered and the results show that there was still a need to implement a stage 3. The stage three-parameter was also pre-defined for Area A. The threshold frequency was calculated to be 59.65Hz for stage 3. This stage was configured to shed 0.99% of the load on Bus 25 where load 25 is

situated. When stage 3 is triggered, the total load that needed to be shed added up to 8.98%, which was now equal to the amount that was suddenly lost when G08 was offline.

Table 3. The calculated values for the UFLS scheme

Stages	Threshold frequency in Hz	Tripping times in seconds	Load shed in %
Stage 1	59.82	0.2765	5.3%
Stage 2	59.71	0.2549	2.6%
Stage 3	59.65	0.322	0.99%
Total load shed			8.89%

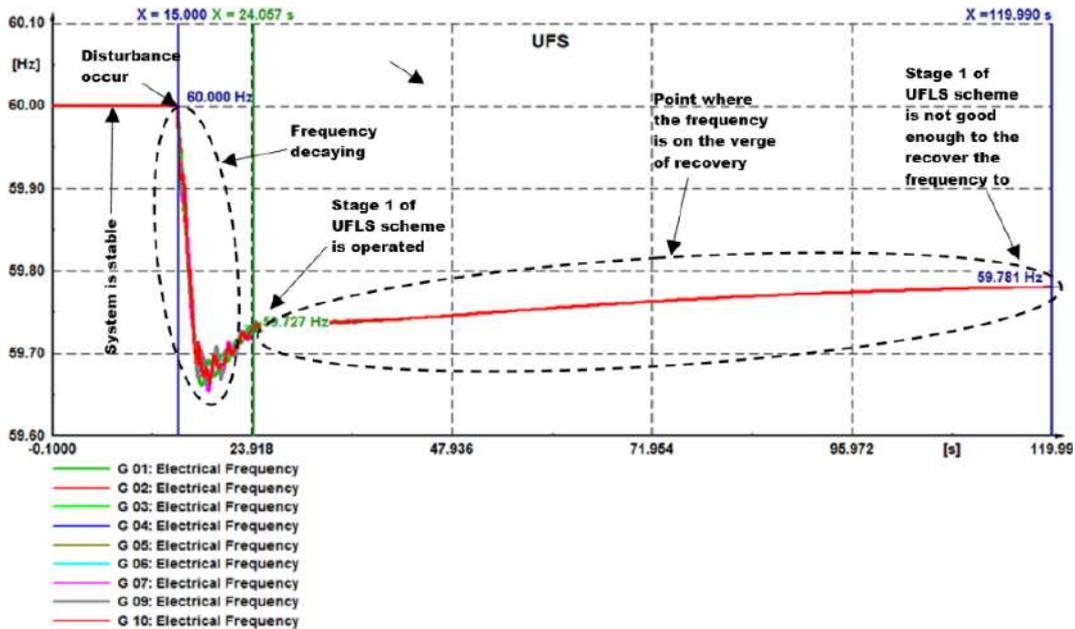


Figure 13. Frequency dynamic behaviour during stage 1 of the UFLS scheme operation using the UFS shedding algorithm element in the case of G08 lost governors operation (when 5.3% load is shed)

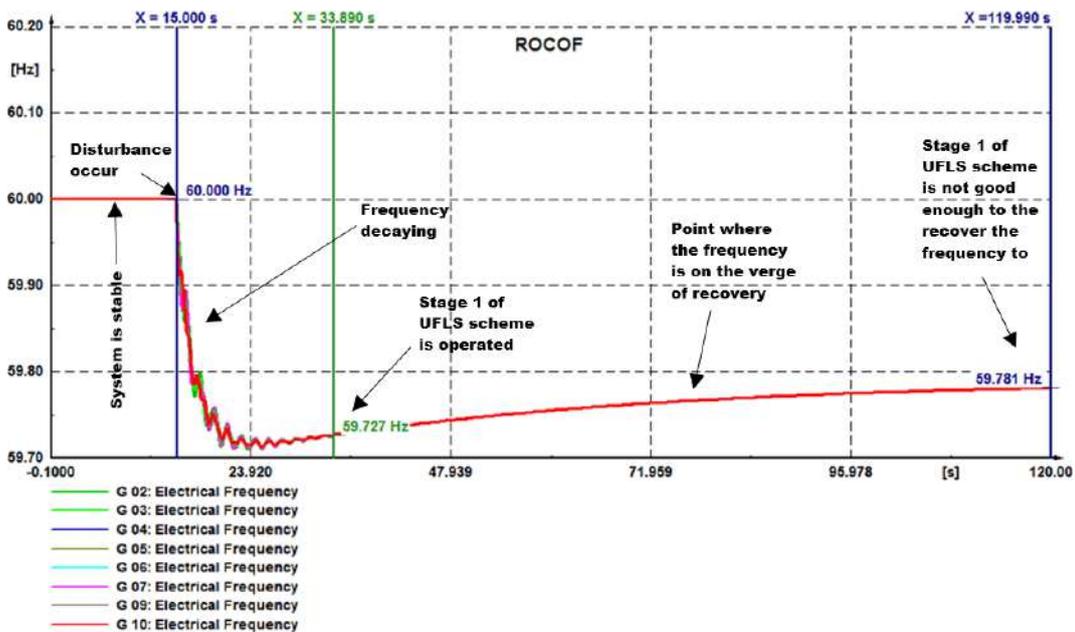


Figure 14. Frequency dynamic behaviour during stage 1 of the UFLS scheme operation using the ROCOF shedding algorithm element in the case of G08 lost governors operation (when 5.3% load is shed)

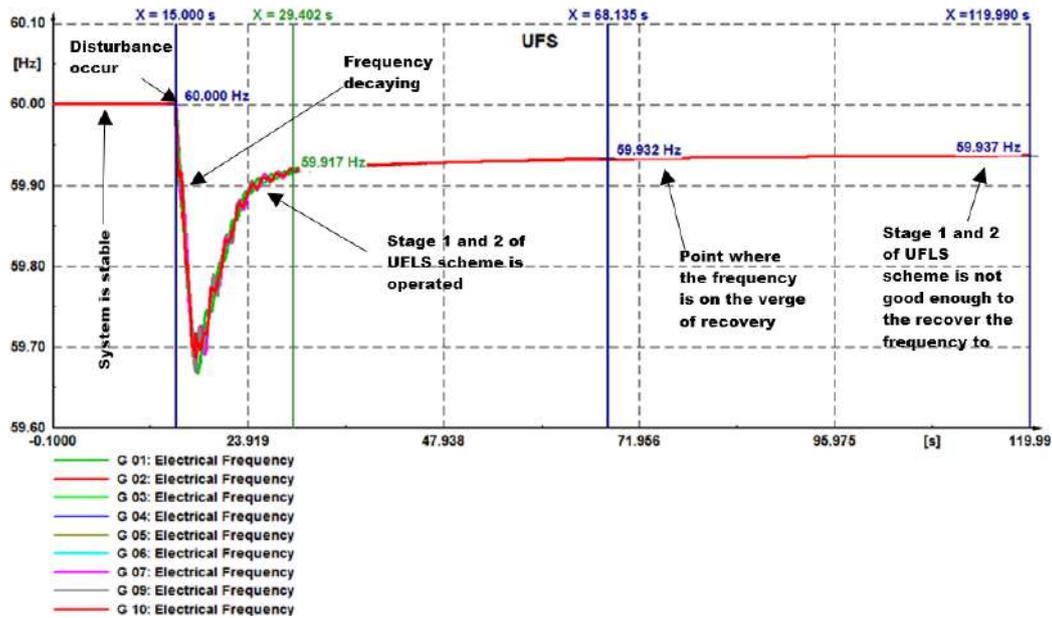


Figure 15. Frequency dynamic behaviour during stage 1 and 2 of the UFLS scheme operations using the UF algorithm when a total of 7.9% load was shed in the case of G08 lost and governors operation



Figure 16. Frequency dynamic behaviour during stage 1 and 2 of the UFLS scheme operations using the ROCOF algorithm when a total of 7.9% load was shed in the case of G08 lost and governors operation

The results shown in Figures 17 and 18 represents the complete load shedding scheme that was implemented for Area A when the G08 was lost. It can be seen from the results that the system frequency was completely recovered and the system was transferred to a new initial condition where it was defined as a stable system. Figure 17 shows that the UFS algorithm 27.451seconds to complete. On the other hand, Figure 18 shows that the ROCOF algorithm took 15.568 seconds to complete the UFLS scheme. At this point, the objective of implementing the UFLS scheme for Area A was achieved. The results show that the system frequency was able to recover back to 60Hz. However, when comparing the performance of the two algorithms it was concluded that the ROCOF performs much better than the UFS. The UFS took much longer then ROCOF to complete the recovering of the system frequency as shown in Tables 4 and 5. The ROCOF overall performance was 11.883 seconds faster than the traditional UFS algorithm.

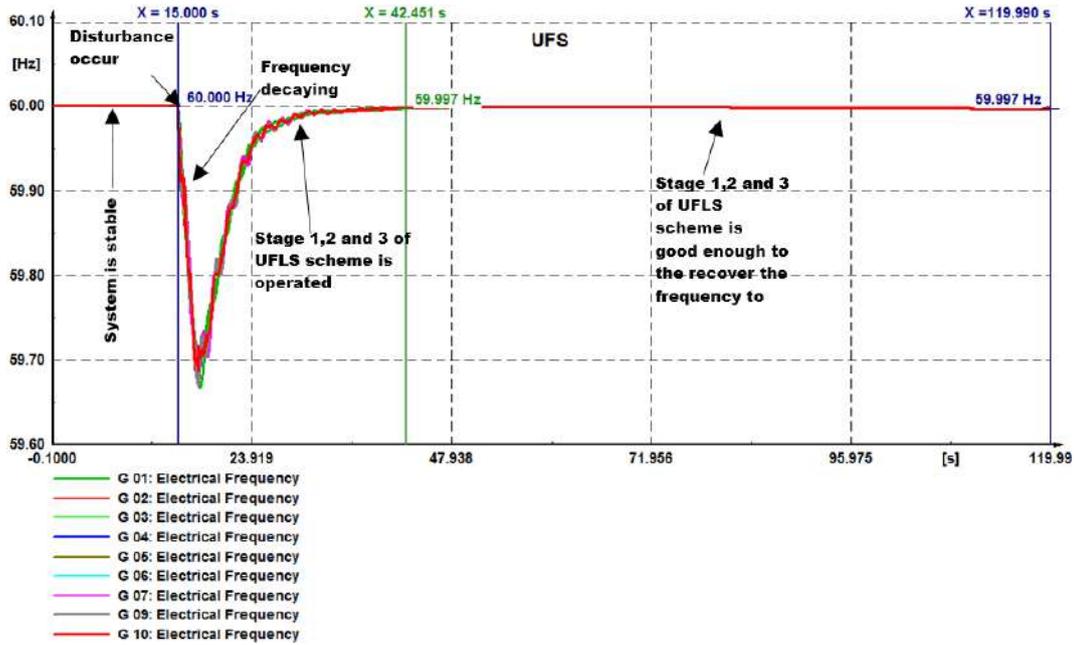


Figure 17. Frequency dynamic behaviour during stage 1,2 and 3 of the UFLS scheme operations using the UF algorithm when a total of 8.98% load was shed in the case of G08 lost and governors operation

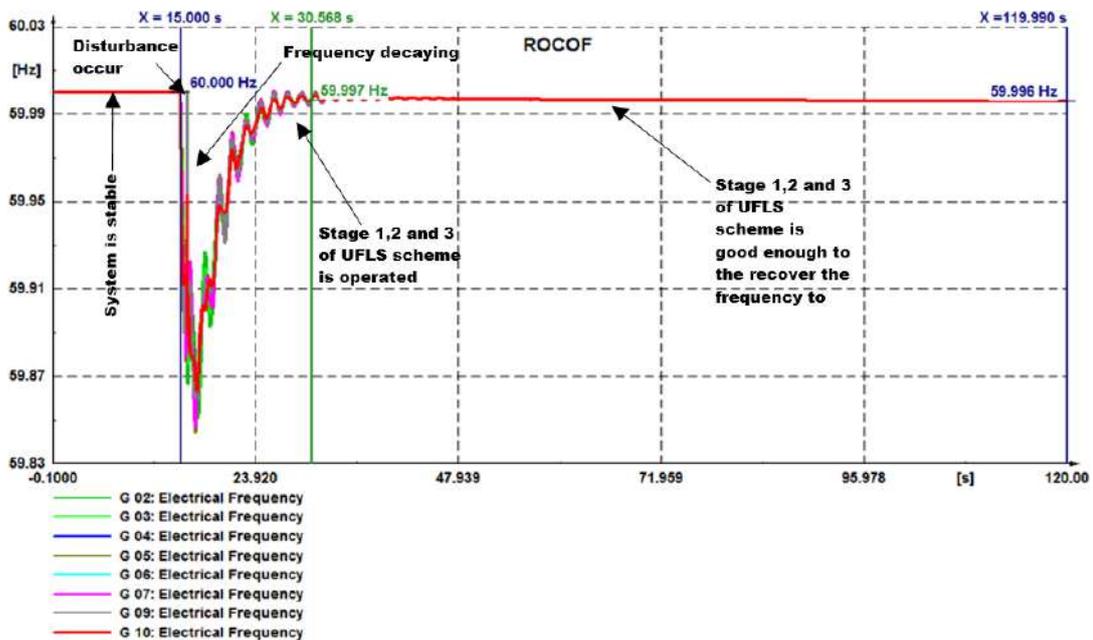


Figure 18. Frequency dynamic behaviour during stage 1, 2 and 3 of the UFLS scheme operations using the ROCOF algorithm when a total of 8.98% load was shed in the case of G08 lost and governors operation

Table 4. Summary of the results when the UFLS scheme used the UF algorithm

Stages	Initial frequency in Hz	Recovery frequency in Hz	Time is taken to recover in seconds	Load shed in %
Stage 1	60	59.727	9.057	5.3
Stage 2	60	59.917	14.402	7.9
Stage 3	60	59.997	27.45	8.89

Table 5. Summary of the results when the UFLS scheme used the ROCOF algorithm

Stages	Initial frequency in Hz	Recovery frequency in Hz	Time is taken to recover in seconds	Load shed in %
Stage 1	60	59.727	18.89	5.3
Stage 2	60	59.917	9.917	7.9
Stage 3	60	59.997	15.568	8.89

### 3.3. Case study 3 and results

The case study aims to investigate and analyse the performance of the UFLS scheme and the behaviour of the whole network when a severe contingency occurs in the system. The worst-case in this study is defined to be when roughly 50% of the supply is disconnected from the system. This is achieved by a combination of a group of generators to be disconnected from the system. Therefore, the system frequency drops drastically. All other control components were utilized to compensate for the system frequency but the system was still unstable. In this case, it was concluded that there was a need to apply the load shedding scheme as the last resort to recover the system back to stability.

The same procedure in the previous case was followed where 8.89% of the load had to be shed. However, in this case, at least 49.75% of power was lost and therefore it was considered as the worst-case scenario. The configuration procedure for setting the relays that were used for the UFLS was the same as in the previous case study. The only difference was in the parameter settings used to configure the relays. The contingency applied was:

- Sudden loss of generator G 01 situated at Area B that injects 16.47% of the power into the system
- Sudden loss of generator G 06 situated at Area D that injects 10.71% of the power into the system
- Sudden loss of generator G 08 situated at Area A that injects 8.89% of the power into the system
- Sudden loss of generator G 09 situated at Area C that injects 13.67% of the power into the system

The contingency was applied simultaneously at the 15th second as shown in Figure 19 and the system was left with 49.74% of power lost. Therefore, the load that needed to be shed was 3020 MW and this contingency was considered as the worst case.

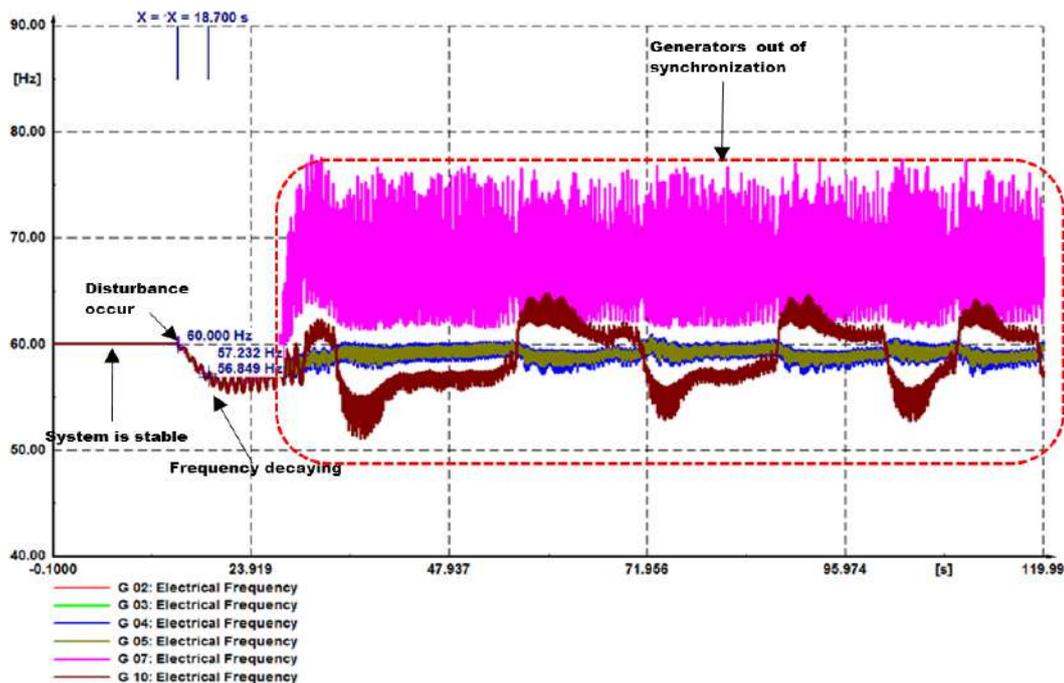


Figure 19. Frequency dynamic behaviour for the worst-case scenario where 49.74% of power is lost using a simulation window of 120 seconds the generator controllers and stabilizers not in operation

The simulation window used at first was based on the 120 seconds. It can be seen that there was a need to shorten it because already by the 30 seconds the system frequency was already below the maximum limit. On the base of this simulation, the window was reduced to at least 35-second absolute time. Figure 20 represents the same results but in this case, the simulation window used was 35-seconds. In this case, it was easy to interrogate the results and produce a better analysis.

The lost generators caused the frequency to decline which can be seen in the plot of Figure 20. The results show that when the 49.74% power was lost by the system, the frequency took 3.7 seconds to reach the limit. Since the other controls were not effective enough to compensate for the power that was lost, the system was exposed to instability. As explained earlier in the chapter the system has of 10 generators that were operating in synchronism, for this case four generators were lost and the six that were left were heavy overloads. The behaviour of the left generation in the system during the contingency is shown in Figure 21.

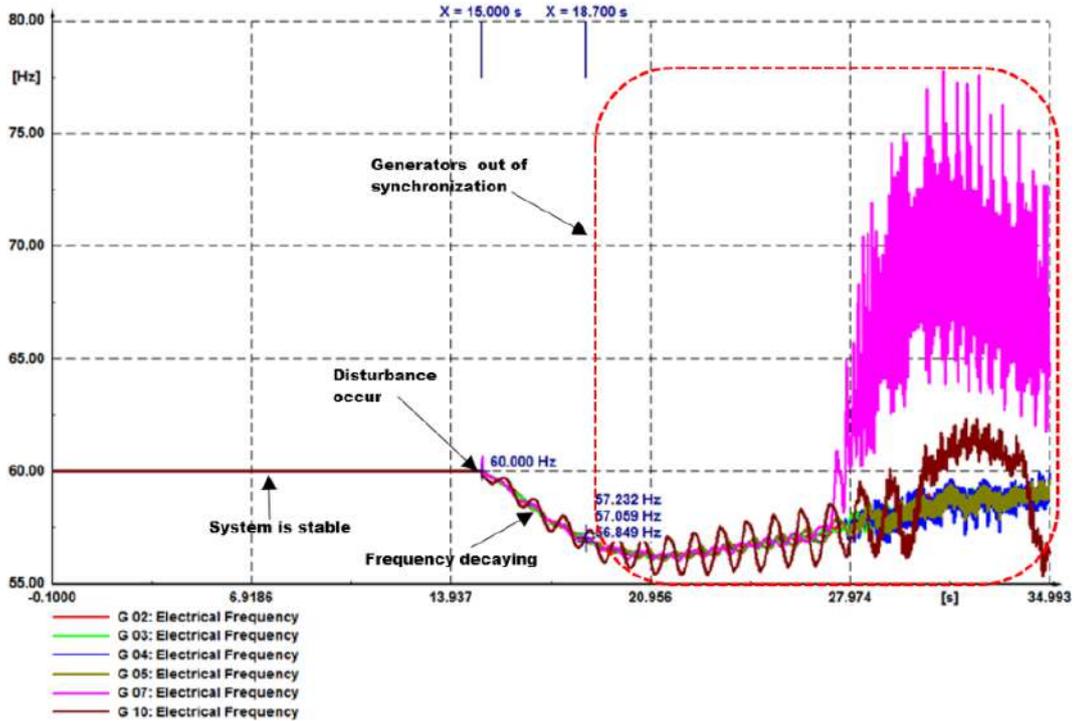


Figure 20. Frequency dynamic behaviour the worst-case scenario where 49.74% of power is lost using a simulation window of 35 seconds the generator controllers and stabilizers not in operation

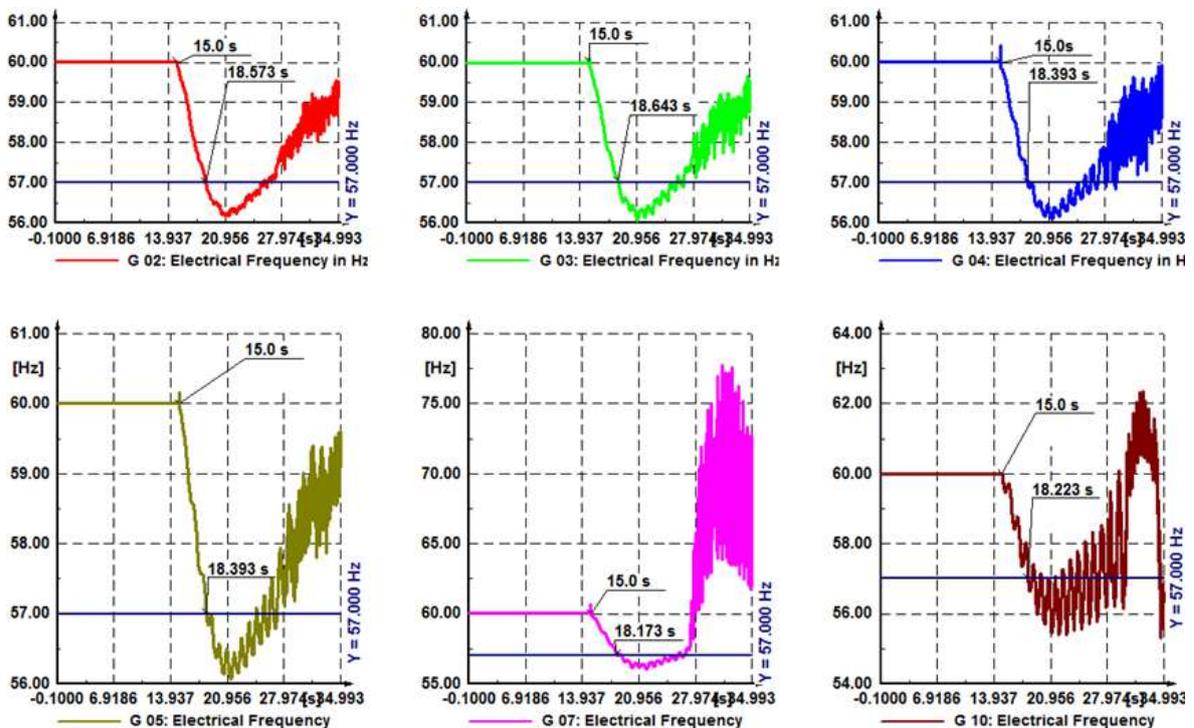


Figure 21. Dynamic behaviour of the left generators in the system during the contingency

In summary, the results for Figure 21 are shown in Table 5. It can be seen that an average of 3.3996 seconds was taken by the generators to reach the minimum limit for system frequency after the contingency. These times obtained indicates the period for the load shedding to be implemented as shown in Table 6.

The results showed that after the average of 3.3996 seconds, the generators were out of synchronization and the whole system was heavily loaded. At this point, the components in the system were operating at the critical condition and exposed to instability. Without a load-shedding scheme, not all the frequency stabilizers were able to recover the system frequency, which was lower than 57.00 Hz in this case. Thus, was necessary to recover the system from unstable to stable. The under-frequency loads shedding scheme for this case was configured to operate in 4 stages. Stage 1 was set to shed 10.06% of loads when 59.78Hz was reached, stage 2 was calculated to shed 16.64% of loads when 59.47Hz was reached, stage 3 was calculated to shed 12.87% when 58.99Hz was reached and stage 4 was calculated to shed 10.17% of loads when 58.57Hz was reached. All the steps were set in such a manner that when stage 1 was triggered, and the system frequency does not recover and continue to drop therefore stage 2 would be triggered, and so on until the system frequency recovers. The simulation was implemented using the DIGSILENT platform and the results were recorded and documented for each stage.

**3.3.1. Stage 1 results**

When all 4 generators were lost simultaneously after 15 seconds of stable operation, the system was exposed to a severe contingency and the UFLS scheme was triggered. The frequency initially experiences a decline as soon as the disturbance was applied to the system. As the frequency decreases below 59.78 Hz, stage 1 started to operate and 10.06% of the load was shed. Figure 22 represents the results of the individual generator frequency and Figure 23 represents the results of the six generator frequencies combined.

The results show the individual different times taken by the frequency as it drops. When analysing the results, it can be seen that the load shedding scheme for stage 1 shed 10.06 % of the load. However, the system frequency continued to drop until it passed the minimum limit. The frequency curves also show the time taken to reach the best frequency before it reaches the minimum limit. The summary of the results is shown in Table 7.

The table summary shows that during stage 1 of the load shedding the system continued to decline. It was also discovered that the average frequency that was obtained after stage 1 has operated settled at 56.58 Hz. The system took an average of 12.567 seconds to complete stage 1 of the UFLS scheme. However, the frequency was still below the minimum limit. The quickest generator to reach the stable zone was found to be G02, which took 9.555 seconds to stabilize. On the other hand, the longest time was 17.985 seconds. However, it was discovered that the system frequency did not recover its normal value and therefore stage 2 was required.

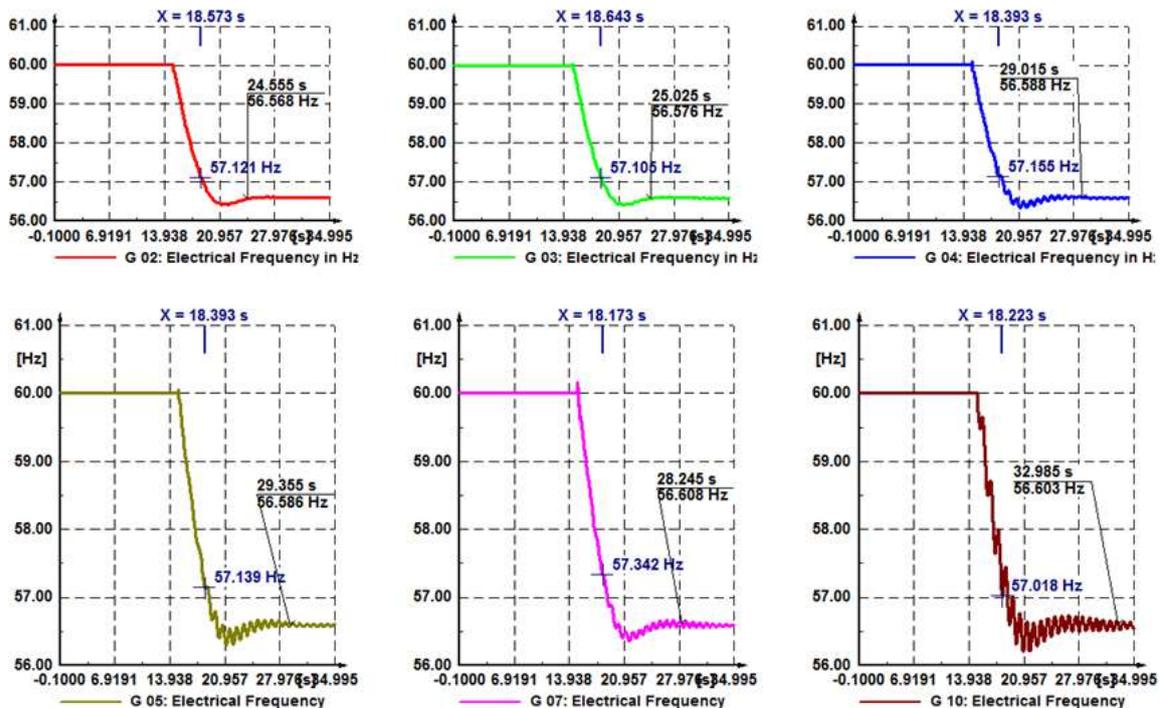


Figure 22. Individual generator frequency dynamic behaviour during the stage1 operation for the case of 4 generators lost governors and stabilizers in action

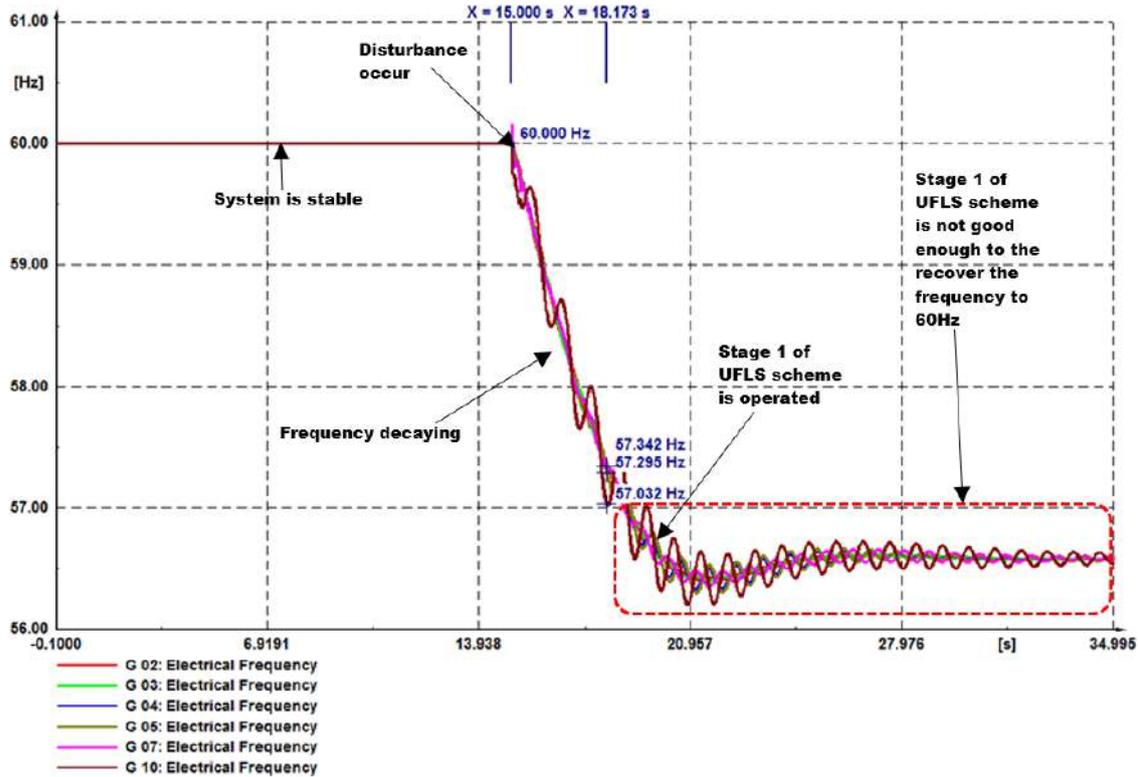


Figure 23. Six-generator frequency combined dynamic behaviour during the stage 1 operation for the case of 4 generators lost and governors and stabilizers in action

Table 6. Time is taken to reach the minimum limit of frequency

Generator name	System frequency at the initial condition in Hz	The minimum limit for system frequency in Hz	Time is taken to reach the minimum limit for system frequency in seconds
G02	60	57	3.573
G03	60	57	3.643
G04	60	57	3.393
G05	60	57	3.393
G07	60	57	3.173
G10	60	57	3.223

Table 7. The summary of the results obtained at stage 1 of the load shedding

Generator name	System frequency at the initial condition in Hz	The frequency reached after stage 1 in Hz	Time is taken to reach the system frequency in seconds
G02	60	56.568	9.555
G03	60	56.576	10.025
G04	60	56.588	14.015
G05	60	56.586	14.355
G07	60	56.608	13.245
G10	60	56.603	17.985

### 3.3.2. Stage 2 results

The system frequency was not recovered after the operation of stage 1, the UFLS scheme continued to operate and the threshold frequency of 59.465HZ was reached. Therefore, stage 2 was triggered to operate. This means that there was an additional of 16.64% of the load to be shed. Hence at this point, a total of 26.70% of the load was shed. The results in Figures 24 and 25 that the system frequency was improved although it can be seen that there was still a need for more load to be shed.

The summary in Table 8 shows that during stage 2 load shedding the system was improved. At this point system frequency was within the maximum limit. The system was able to operate although it was still in a critical zone. It was also discovered that the average frequency that was obtained after stage 2 was 57.962 Hz. It took an average of 9.124 seconds for the UFLS scheme to complete its operation. The quickest generator recovered from transient was G02, which took 8.33 seconds to stabilize. On the other hand, the slowness generator took 10.983 seconds. Although, the system was safe to operate after stage 2 was triggered as the system frequency was above the minimum limit. However, after the analysis, it was seen that the system frequency did not recover enough and therefore stage 3 was required.

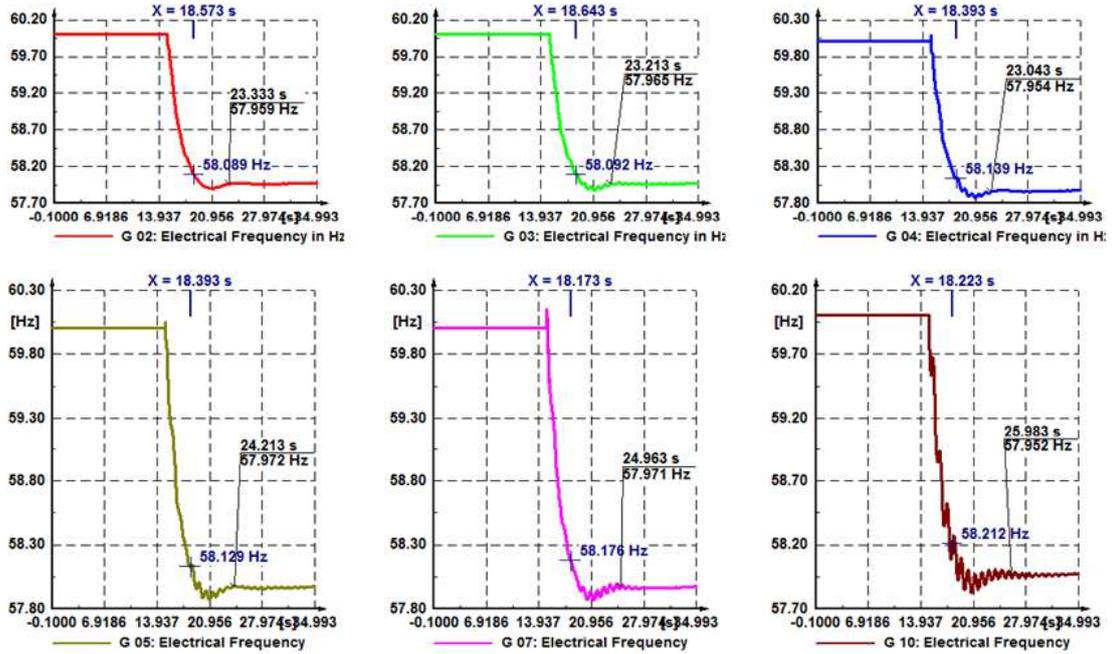


Figure 24. Individual generator frequency dynamic behavior during stages 1 and 2 for the case of 4 generators lost and the governors and stabilizers in action

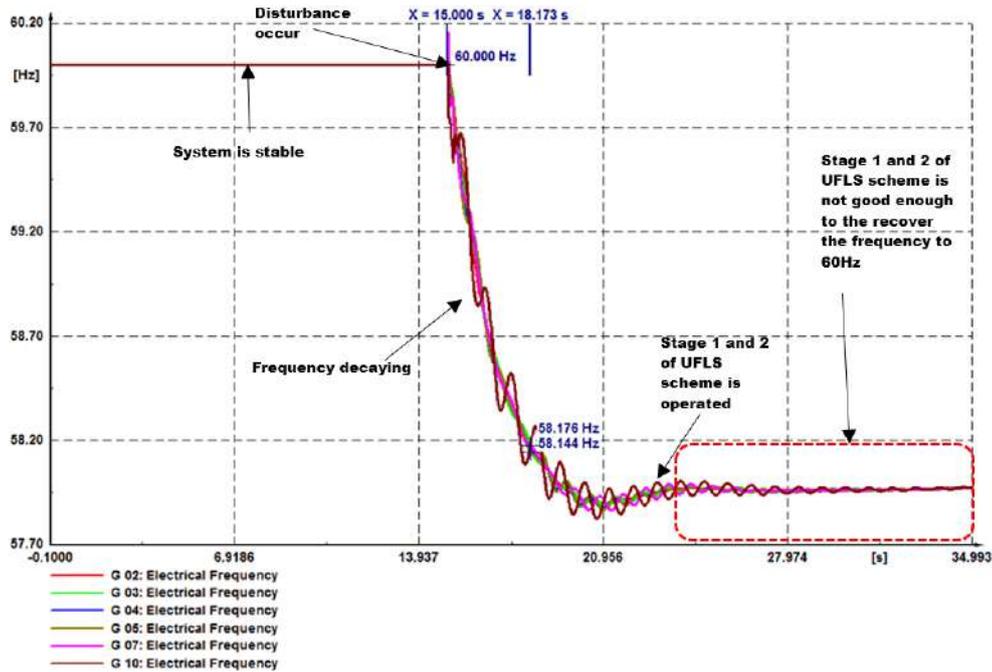


Figure 25. Six generators frequency dynamic behavior during stages 1 and 2 for the case of four generators lost, governors, and stabilizers in action

Table 8. The summary of the results obtained at stage 2 of the load shedding

Generator name	System frequency at the initial condition in Hz	The frequency reached after stage 2 in Hz	Time is taken to reach the system frequency in seconds
G02	60	57.959	8.33
G03	60	57.965	8.213
G04	60	57.954	8.043
G05	60	57.972	9.213
G07	60	57.971	9.963
G10	60	57.952	10.983

**3.3.3. Stage 3 results**

At this point stage 1, and 2 were already triggered and the system was still unstable because the system frequency was still required to be improved. When the frequency continued to drop below 58.4 Hz stage 3 was triggered. At this point, an additional 12. 87% of loads were shed and in total, 39.57% of the load was shed as shown in Figures 26 and 27.

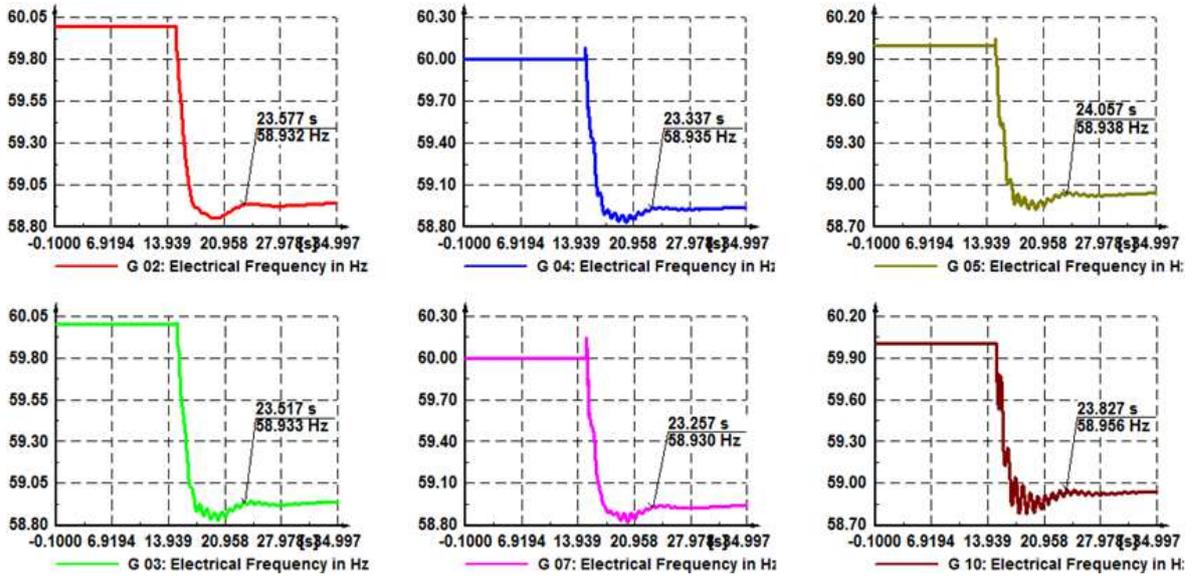


Figure 26. Individual generator frequency dynamic behavior during stage 3 for the case of 4 generators lost and the governors and stabilizers in action

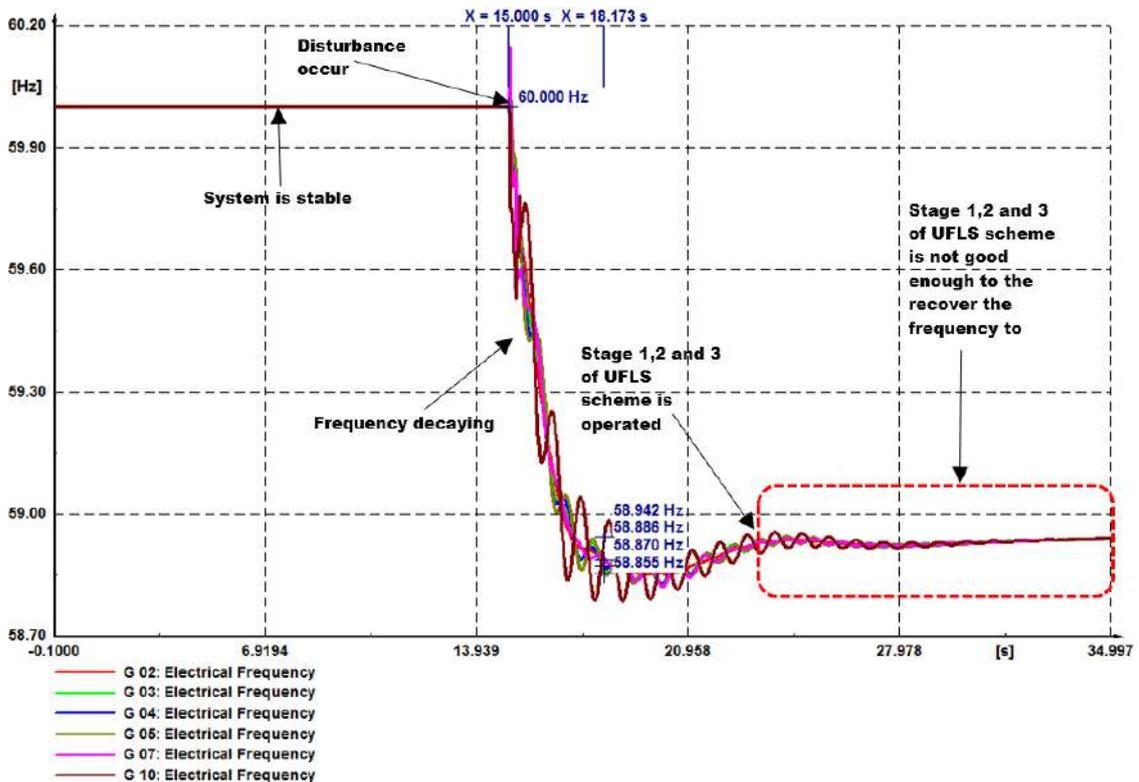


Figure 27. Six generators frequency dynamic behavior combined during stages 1, 2 and 3 for the case of 4 generators lost and the governors and stabilizers in actions

It can be seen that the system frequency was improved and it was within the maximum limit. The system was still operating at a critical zone although the system frequency was improved when compared to its values in stage 2. The results also showed that the system frequency still needed to be recovered by shedding more load. The summary in Table 9 shows that during stage 3 of the load shedding the system was improved but the frequency was still below the 60Hz. Therefore, stage 4 was required to compensate for the system frequency.

**3.3.4. Stage 4 results**

When stages 1, 2, and 3 were triggered it was found from the results that there was still a need to shed at least 10.17% of the load for the system to recover back to 60Hz. Therefore stage 4 was triggered by the UFLS scheme and an additional 10.17% of loads were shed. Therefore, all 4 stages operated and a total load of 49.74% was shed. The simulation was implemented once again and the results were recorded as shown in Figures 28 and 29 respectively. The results showed that the system frequency was improved drastically.

Table 10 shows the summary of the results obtained at stage 4 of the load-shedding scheme. At this point system frequency was improved by implementing UFLS scheme and it was able to recover back to its normal value. It was also found that the average frequency that was obtained after stage 4 was 59.999 Hz. An average of 13.044 seconds was taken by the UFLS scheme to complete its operation. The quickest generator that recovered from transient was G02, which took 12.886 seconds to stabilize. On the other hand, the slowness generator took 13.046 seconds. Based on these analyses the system was safe to operate after stage 4 load shedding was triggered because its frequency was above the minimum limit and has recovered to its normal value. The summary of all 4 stages is shown in Table 11.

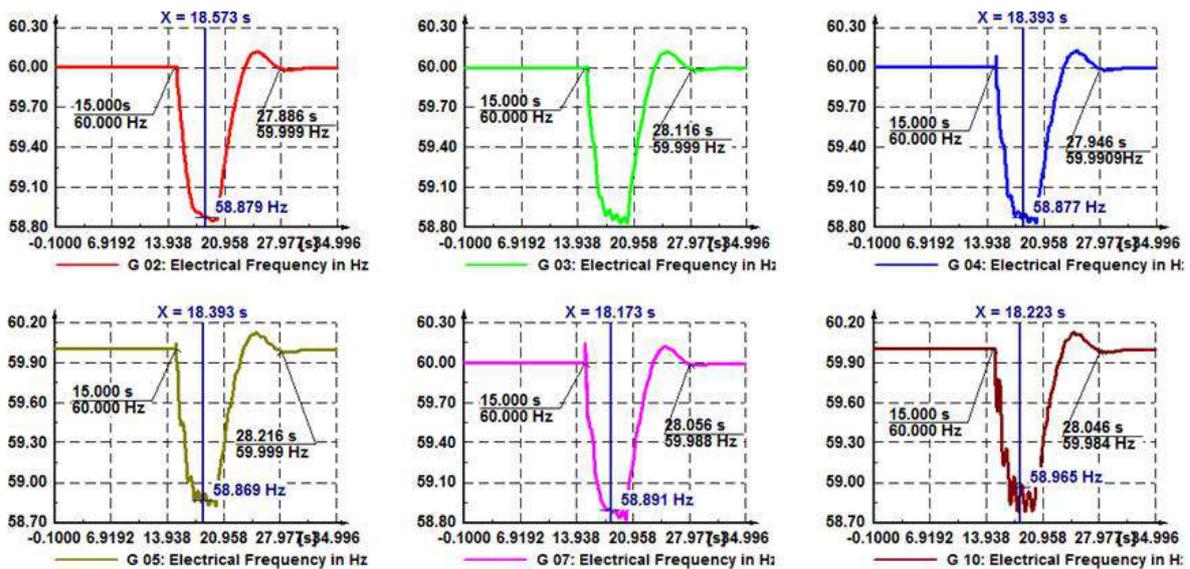


Figure 28. Individual generator frequency dynamic behavior during stages 1, 2, 3 and 4 for the case of 4 generators lost and the governors and stabilizers in action

Table 9. The summary of the results obtained at stage 3 of the load shedding

Generator name	System frequency at the initial condition in Hz	The frequency reached after stage 3 in Hz	Time is taken to reach the system frequency in seconds
G02	60	58.932	8.577
G03	60	58.933	8.517
G04	60	58.935	8.337
G05	60	58.938	9.057
G07	60	58.930	8.257
G10	60	58.956	8.827

Table 10. The summary of the results obtained at stage 4 load shedding

Generator name	System frequency at the initial condition in Hz	The frequency reached after stage 4 in Hz	Time is taken to reach the system frequency in seconds
G02	60	59.999	12.886
G03	60	59.999	13.116
G04	60	59.999	12.946
G05	60	59.999	13.216
G07	60	59.999	13.056
G10	60	59.999	13.046

Table 11. Summary results for all 4 stages of UFLS scheme

Stages	Frequency limits in Hz	Recovered frequency in Hz	Time is taken to reach to recover in seconds	Load shed in %
Stage 1	59.78	56.588	12.196	10.06
Stage 1, 2	59.47	57.962	9.1241	10.06+16.64=26.46
Stage 1,2,3	58.99	58.937	8.595	10.06+16.64+12.87=39.33
Stage 1, 2, 3, 4	58.57	59.99	13.044	10.06+16.64+12.87+10.17=49.5

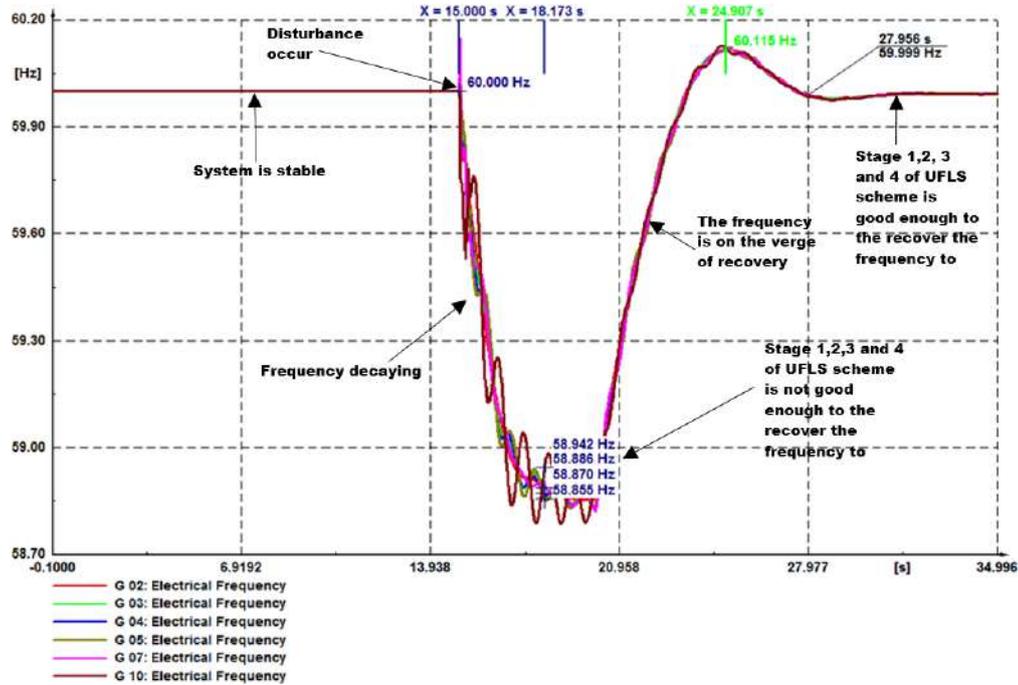


Figure 29. Six generators frequency dynamic behavior combined during stages 1, 2, 3 and 4 for the case of 4 generators lost and the governors and stabilizers in action

#### 4. DISCUSSIONS

A modified IEEE 39 bus power system was developed in the software environment of the DIgSILENT Power Factory. To receive accurate results, the IEEE 39 bus system was divided into four interconnected areas. A load flow simulation of the power system was performed to establish the initial steady-state conditions of the network. The paper first focused on analysing all the possibilities that influence system instability of the power system and especially when contingencies such as sudden loss of generation and sudden increase of loads. Various scenarios were implemented to analyse the response of the system frequency. Simulations based on RMS/EMT methods were implemented in DIgSILENT power factory platform. This method successfully calculated the initial condition of the system as well as the execution time when then the loss of generator and load event was implemented.

When all the credible-contingency cases were achieved, the IEDs with UFS were then introduced to the system. They were then configured to operate when the system frequency drop below the calculated frequency stability margins. The complete scheme was programmed to shed the required number of loads to maintain the stability of the power system under study. The shedding of loads was based on multi-stages. This algorithm aimed to make sure that the scheme does not cover shed or under the shed.

The operation and performance of the developed scheme and the power system were investigated by the application of various case studies. A procedure in a DIgSILENT environment was developed and implemented to compare the available in the soft relays, two algorithms for under frequency decision-taking for load shedding: UF and ROCOF. The second part of this paper based on a sudden loss of generator G8 which ends up overloading the system by 8.89%. Therefore, it was required to shed 8.89% of loads to maintain stability. The solution for this case was based on taking advantage of a three-stage based UFLS. The first stage was configured to shed 5.3% of the 8.89% load that required to be shed. Therefore 3.59% still need to be shed. The second stage was configured to shed 2.6% of the 3.59% load that is required. Therefore 0.99% still need to be shed. The third stage was configured to shed 0.99% of the 0.99% load is required. After this stage, no-load needs to be shed, and the system frequency was recovered.

The third part of the paper was a sudden loss of the following generators: G 01 situated at Area B that injects 16.47% of power, G 06 situated at Area D that injects 10.71% of power, G 08 situated at Area A that injects 8.89% of power, and G 09 situated at Area C that injects 13.67% of the power into the system. This loss of power adds to a total of 49.74%. The loss requires 49.74% of the load to be shed. In this case, 4 stage UFLS scheme was proposed. The first stage was configured to shed 10.06% of the 49.74% load that is required. Therefore 39.68% still need to be shed. The second stage was configured to shed 16.64% of the 39.68% load as required. Therefore 23.04% still need to be shed. The third stage was configured to shed 12.87% of the 23.04% load as required. Therefore 10.17% still need to be shed. Lastly, stage 4 was configured to shed 10.17% of the 10.17% load is required.

The performance of the algorithms was monitored for the case of a sudden loss of four generators in the system, which presents a severe contingency. Every algorithm had multi-stages of decision making. The time taken for bringing the power system back to stability was compared. Based on this the conclusion was that the ROCOF algorithm is faster. Based on the results obtained in case studies 2 and 3 the developed scheme was successful.

## 5. CONCLUSION

To overcome the drawbacks of existing load shedding methods, a multi-stage UFLS scheme for a power system network using DIgSILENT power factory software was developed and verified in this paper. Three case studies were implemented in this paper. The first case study determined the IEEE 39 bus power system stability margin. In this case, the disturbance type was based on the adaptive step size algorithm. This algorithm was developed to increase the load demand using the RMS/EMT Simulation toolbox. The action that was performed was based on gradually applying an increment of 1% at every second until the maximum load margin was reached and passed to a point where the generators became out of step (pole slip). The second case study was to compare two algorithms of UFS that are used in IEDs in the DIgSILENT power factory simulation. One method used an under-frequency IEDs with F81 UFS as the load shedding solution and the second used the F81R ROCOF as the load shedding solution. The third case study was to validate the proposed multistage UFLS when the whole IEEE 39 bus network when a severe contingency occurs in the system. At this point, the system frequency successfully returned to its nominal value. Also, the multi-stage UFLS effectively contributes to maintaining stability in the whole IEEE 39 bus network. The simulation outcomes have proved that the proposed UFLS scheme effectively improved the frequency stability of the system when subjected to a large disturbance. All three case studies were implemented successfully. Additionally, for practical merit in the case of large-scale systems, the network can be divided into several areas and the proposed UFLS scheme can be implemented in each area independently. It must be noted the above studies will perfect when designing an adaptive protection scheme that can be integrated with the traditional scheme used for power system stability.

## APPENDIX

Table 1. Case studies performed

Case study name	Aim	Type of disturbance used	Action performed	Measured variables
<b>Case study 1</b> Investigating at what point the generators of the system under the load increase loose synchronism and to identify the variables of the system influenced by this process	To determine the IEEE 39 bus power system stability margin. At what point the 10 generators become out of step (pole slip).	Increasing the load demand using the RMS/EMT Simulation toolbox	Gradually applying an increment of 1% at every second until maximum load margin was reached and passed to a point where the generators became out of step (pole slip)	<b>In Figure 5.</b> The magnitude of the generators Excitation voltages, Speed in pu, the Terminal voltages in pu and the active power, in MW for all 10 generators <b>In Figure 6 :</b> The Speed (s:xspeed) variable behavior for all generators <b>In Figure 7:</b> Frequency (n:fehz:bus1) variable behavior for all generators

Case study name	Aim	Type of disturbance used	Action performed	Measured variables	
<p><b>Case study 2</b> To compare the UF and the ROCOF algorithms of the UFLS elements of a DIgSILENT protective relay and select one with better performance.</p>	<p>1) To compare two algorithms of UFS that are used by the relay in the DIgSILENT power factory simulation. One method used an under-frequency IEDs with F81 UFS as the load shedding solution and the second uses the F81R Rate of the frequency change element (ROCOF) as the load shedding solution</p> <p>2) To implement the UFLS when the system loses a generator and experience overloading of 8.89%</p>	<p>A sudden loss of generator G8 = to 8.89% of system overloading. Therefore, required to shed 8.89% of loads. How the sudden loss is done in the software</p>	<p><b>Stage 1</b> The UFLS scheme was configured to shed 5.3% of the 8.89% load that required to be shed. Therefore 3.59% still need to be shed</p> <p><b>Stage 2</b> The UFLS scheme was configured to shed 2.6% of the 3.59% load that is required. Therefore 0.99% still need to be shed</p> <p><b>Stage 3</b> The UFLS scheme was configured to shed 0.99% of the 0.99% load is required. After this stage, no-load need to be shed and the system frequency was recovered</p>	<p>1) Measure the system frequency 2) When the load frequency &lt; f min Activate the Under frequency relays 3) Calculate the required number of loads to be shed 4) Shed 5.3% of the total (6070.9MW) load 5) Measure whether the frequency has recovered to 60Hz if not trigger stage 2</p> <p>6) Measure the system frequency 7) When the load frequency &lt; f min Activate the Under frequency relays 8) Calculate the required number of loads to be shed 9) Shed 2.6% of the total (6070.9MW) load 10) Measure whether the frequency has recovered to 60Hz if not trigger stage 3</p> <p>11) Measure the system frequency 12) When the load frequency &lt; f min Activate the Under frequency relays 13) Calculate the required number of loads to be shed 14) Shed 2.6% of the total (6070.9MW) load 15) Measure whether the frequency has recovered to 60Hz if yes end the UFLS scheme</p>	<p><b>In Table 4:</b> Summary of the system frequency when the load shedding is using UFS algorithm</p> <p><b>In Table 5:</b> Summary of the system frequency when the load shedding is using ROCOF algorithm</p>
<p><b>Case study 3</b> To investigate and analyze the performance of the UFLS scheme and the behavior of the whole network under the severe contingence of loss of 4 generators</p> <p>Implementation of 4 stages the UFLS schemes in DIgSILENT power factory platform for a worst-case scenario</p>	<p>To analyze the behavior of the whole network when a severe contingency occurs in the system. The worst-case in this study is defined to be when roughly 50% of the supply is disconnected from the system</p> <p>In this case, at least 49.74% of power is lost and therefore it is considered as the worst-case</p>	<p>Sudden loss of the following generators: G 01 situated at Area B that injects 16.47% of power, G 06 situated at Area D that injects 10.71% of power, G 08 situated at Area A that injects 8.89% of power, and G 09 situated at Area C that injects</p>	<p><b>Stage 1</b> The under-frequency load-shedding scheme was configured to shed 10.06% of the 49.74% load that is required. Therefore 39.68% still need to be shed</p> <p><b>Stage 2</b> The under-frequency load-shedding scheme was configured to shed 16.64% of</p>	<p>1) Measure the system frequency 2) When the load frequency &lt; f min Activate the Under frequency relays 3) Calculate the required number of loads to be shed 4) Shed 10.06% load 5) Measure whether the frequency has recovered to 60Hz if not trigger stage 2</p> <p>6) Measure the system frequency 7) When the load frequency &lt; f min Activate the Under frequency relays</p>	<p><b>In Table 7:</b> The summary of the system frequency and time obtained at stage 1 load shedding</p> <p><b>In Table 8:</b> The summary of the system frequency and time obtained at stage 2 load shedding</p>

Case study name	Aim	Type of disturbance used	Action performed	Measured variables	
	scenario	13.67% of the power into the system. This loss of power adds to a total of 49.74%. The loss requires 49.74% of the load to be shed. How the loss of a generator is performed in the software.	<p>the 39.68% load as required. Therefore 23.04% still need to be shed</p> <p><b>Stage 3</b> The UFLS scheme was configured to shed 12.87% of the 23.04% load as required. Therefore 10.17% still need to be shed</p> <p><b>Stage 4</b> The UFLS scheme was configured to shed 10.17% of the 10.17% load is required. Therefore no-load need to be shed and the frequency is recovered</p>	<p><b>8)</b> Calculate the required number of loads to be shed <b>9)</b> Shed 16.64% of the load <b>10)</b> Measure whether the frequency has recovered to 60Hz if not trigger stage 3</p> <p><b>11)</b> Measure the system frequency <b>12)</b> When the load frequency &lt; f min Activate the Under frequency relays <b>13)</b> Calculate the required number of loads to be shed <b>14)</b> Shed 2.6% of the load <b>15)</b> Measure whether the frequency has recovered to 60Hz if not trigger stage 4</p> <p><b>16)</b> Measure the system frequency <b>17)</b> When the load frequency &lt; f min Activate the Under frequency relays <b>18)</b> Calculate the required number of loads to be shed <b>19)</b> Shed 10.17% load <b>20)</b> Measure whether the frequency has recovered to 60Hz if yes end the UFLS scheme</p>	<p><b>In Table 9:</b> The summary of the system frequency and time obtained at stage 3 load shedding</p> <p><b>In Table 10:</b> The summary of the system frequency and time obtained at stage 4 load shedding</p>

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