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Introducing a New Optimized Emergency Demand Side Management Method to Restore the Power System Frequency

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ABSTRACT

Emergency demand response (EDR) and under frequency load shedding (UFLS) are used as two separate methods for frequency restoration of power systems after the common methods of frequency control fail to maintain the frequency stability of the system. This paper proposes an optimized emergency demand side management (OEDSM) method that improves the performance of previous methods by integrating UFLS and EDR methods along with introducing new critical status detection and optimization modules. The proposed method is characterized by simultaneous operation of EDR and UFLS processes, the high speed of critical condition detection using the proposed emergency index, higher speed of the algorithm with parallel operation of modules, and optimal load shedding by providing a separate optimization module. To validate and evaluate the performance of the proposed method, a power system was tested under different scenarios using DIgSILENT software. The results indicate the better performance of the proposed method in frequency restoration, as well as the higher utilization and power quality of the system compared to previous methods.

Article Info

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Adaptive Control, Emergency demand response, Frequency restoration, Optimal load shedding, Under frequency load shedding.

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I. Introduction

In stable conditions of a power system, the total power generation is equal to the total power consumption (i.e., demand and losses), so that the system frequency operates within its allowable range. Any disturbance or incident in the network can reduce the network generation capacity and cause a frequency drop in the power system [1]. Once the critical situation of the system frequency drop happens, frequency control systems such as automatic generation control (AGC) start operating to return the system frequency to its allowable range [2]. However, when these systems are unable to restore the frequency and the frequency is less than a certain limit, their set point relays are adjusted to disconnect generators and sensitive devices from the grid to prevent damage to power system elements such as generators. Consequently, hierarchical and sequential generators and power transmission lines tripping will further reduce the frequency and increase the probability of cascading blackouts in the power system [3]. Various methods have been proposed to prevent the collapse of a power system and then ensure the return of its frequency to its nominal value. These methods are all based on creating a balance between the total power generation and the power consumption of the power system. Now, depending on whether the power system is conventional or modern and intelligent, the methods of creating power balance and recovery will be different. In older power systems, under frequency load shedding (UFLS) methods are used, but modern and intelligent systems use, in addition to UFLS, the emergency demand response (EDR) method, which is a type of contracted interruption demands (CIRs) with spinning reserves (SRs).

The UFLS methods are generally divided into three

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categories of conventional methods, computational intelligent algorithms, and adaptive methods [4], among which adaptive methods are more appropriate than the other two due to efficiency, up-to-datedness and the practicality. Recent researches have improved the performance of adaptive UFLS algorithms by making some modifications in the main algorithm and optimizing interruptible loads selection. Accordingly, new methods are introduced in [5] and [6] for adaptive UFLS that use state estimators. In [7] and [8] adaptive UFLS methods are presented in the presence of sources using wide-area measurements. Based on voltage and frequency data and the use of phasor measurement units (PMUs), an adaptive algorithm considering UFLS and UVLS has been proposed in [9], which improves frequency and voltage stability. In [10], a semi-adaptive method is used for multi-stage UFLS using the rate of change in frequency value to recover the frequency. In [11], a continuous UFLS method is used to control the adaptive frequency of the power system. The loads to shed are calculated based on the event signal. In [12], different loads are prioritized to optimize the adaptive algorithm, and in selecting the priorities, a combination of loads is selected that the amount of load shedding is closer to the calculated values.

Demand response (DR) programs include methods of demand side management (DSM) that refer to any changes in customer consumption due to changes in electricity prices in the market. It is worth mentioning that some of such programs are used in the traditional power systems in the form of multi-tariff meters, but in the restructured power systems, these programs have taken on a new form and are reviewed and revised according to the economic and competitive approach of the market [13-14].

Accordingly, to improve the operation of the power grid when an imbalance occurs between power generation and consumption, the power system can delay UFLS and forced interruption by the power system operator as much as possible. In the DR program, due to the importance of decision speed to create a balance between production and consumption, an operational subdivision at the moments and seconds time range, namely physical-DR and SRs is used. This part of the DR is called EDR. The process of frequency control by the EDR method is such that after the AGC system is unable to control the frequency and prevent its reduction, in the first stage, the emergency EDR system is activated [15]. Physical-DR programs are applied to control and prevent excessive frequency reduction. Then, at the moment when the frequency is less than a certain level, to prevent the operation of the under frequency relays, fast-spinning reserves are entered in the second stage to increase the frequency by a certain amount. In the last step, to return the frequency to its nominal value, the lower speed SRs or fast non-spinning reserves such as hydropower plants enter. Most EDR devices can start quickly as soon as they receive signals of an event. Participants in EDR programs contract to commit to a certain amount of capacity. They will be charged for their presence and may face a fine if they do not attend. In another type of contract, load shedding is optional and will not be penalized if the customer does not interrupt the loads. Also in another contract, the telecommunications company interrupts the demand by a controlled switch and pays a fee in return [16].

In [17], a comprehensive central demand-based response algorithm is presented for frequency regulation by minimizing the amount of load manipulation in a smart microgrid. Simulation studies in a standard 13-bus distribution system have been performed considering the effect of producing a variable wind unit. The results, show that the proposed control strategy is effective in regulating the frequency and consequently the voltage. In [18], a responsive end-user is used that can change power such as solar cells and electric vehicles connected to the grid by an inverter to support the power system in the transmission system. The paper shows how the power sources that are connected to these buses are controlled.

This paper presents a new method for optimal frequency restoration of the power system and prioritization of interrupts in the process of the proposed method. Accordingly, in Section 2, the emergency demand side management (EDSM) method is proposed as an alternative method for frequency restoration of the power system, which is the result of a combination of UFLS and EDR methods. The tasks of its sections and modules is described in the following. One of the advantages and innovations of this method is the simultaneous performance of UFLS and EDR methods, which has improved the speed of frequency restoration performance. Modulation of the proposed method and separate and parallel operation of the modules are also effective in improving the speed of frequency restoration. Also, by creating an emergency index module (EIM), it has contributed to timely detection of the critical situation, the frequency decline, and the minimization of the possibility of power system collapse. Then in Section 3, presents the optimized emergency demand side management (OEDSM) method by optimizing the EDSM method and presenting a module called the optimization module (OM). This optimal algorithm can improve the frequency restoration process and power quality indices by using the dynamic programming method. The OM optimally controls the process of disconnecting or connecting resources by forming sub-sections for each of the UFLS and EDR sections. Section 4 performs simulations on the New England 39-bus standard grid to validate and evaluate the performance of the proposed method. Section 5 also reviews the results and presents the achievements of the proposed method.

II. EMERGENCY DEMAND SIDE MANAGEMENT (EDSM)

A. EDSM algorithm

To improve the performance and efficiency of the EDR and UFLS frequency restoration algorithms, which operate separately in the power system, by integrating them and applying changes and adding modules, the emergency demand side management (EDSM) method is proposed. Accordingly, the modules available in the EDSM frequency restoration method are suggested as follows:

1) Center Of Inertia Frequency Module (COIFM): calculates the instantaneous frequency of the system at the center of inertia of the power system [12]:

$$f_{COI} = \frac{\sum_{i=1}^{N} H_i f_i}{\sum_{i=1}^{N} H_i} \tag{1}$$

where:

f_{COI} frequency of center of inertia (in Hz);
H_i inertia constant of i-th generator (in seconds);
f_i frequency of i-th generator (in Hz);
N number of generators;

2) Power Deficit Estimation Module (PDEM):

The power deficit estimated at each stage based on the equation in [12] is considered as follows:

$$P_{deficit} = \left(\left(2 \times \sum_{i=1}^{N} \frac{H_i}{f_n}\right) \times \frac{d}{dt} f_{COI}\right) \tag{2}$$

where:

$P_{deficit}$ power deficit (in MW);
$\frac{d}{dt} f_{COI}$ rate of change of center of inertia (in Hz/s);
f_n rated frequency (in Hz);

3) Emergency Index Module (EIM):

A new diagnostic index called Emergency Index (EI) has been unveiled. By defining frequency first-order derivative (FFD) and frequency second-order derivative (FSD) and determining the sign of each of the two characteristics, we have the following:

$$FFD = \frac{d}{dt} f_{COI} \tag{3}$$

$$FSD = \frac{d^2}{dt^2} f_{COI} \tag{4}$$

$$EI = FFD \times FSD \tag{5}$$

where:

FFD Frequency First-order Derivative (FFD);
FSD Frequency Second-order Derivative (FSD);
EI Emergency Index (EI);

Table I shows an example of different values of the indicators in the form of stable and unstable frequency response waveforms.

TABLE I
AN EXAMPLE OF DIFFERENT VALUES OF THE INDICATORS IN THE FORM OF STABLE AND UNSTABLE FREQUENCY RESPONSE WAVEFORMS.

Index / Stability	Stable	Unstable
FFD	-0.0937	-0.19880
FSD	+0.0181	- 0.05016
EI	-0.00169	+0.00997

4) Frequency Emergency Condition Identity Module (FECIM):

It is a module to identify the critical frequency state of the frequency and start the proposed frequency restoration algorithm. The operation of the algorithm is such that the three indexes EI, f, and FFD are constantly monitoring and receiving data from their respective modules. Therefore, as soon as the frequency drops and the FFD index becomes negative, assuming that the EI is positive, which is an indication of the acute state and the movement of the frequency curve towards divergence and instability (Table II), the command is immediately sent to the frequency restoration module (FRM) and announce the acute condition. Now, if the frequency decreases and the FFD index are negative, assuming the negative EI, it indicates that the frequency converges to a certain value (Table II). In this case, only if the frequency is less than a certain limit ($f_{threshold}$), by announcing the non-acute status, the command is sent to activate the FRM module.

TABLE II
DIFFERENT SITUATIONS OF EI INDEX.

Stability / Indexes	f	*FFD*	*EI*
Stable	Decreasing	-	-
Unstable	Decreasing	-	+
Stable	Increasing	+	-
Unstable	Increasing	+	+

5) Frequency Restoration Module (FRM):

When a severe disturbance occurs in the power system, as soon as the critical situation is detected, the command will be sent to the FRM module and the module will perform the frequency restoration process as shown in Fig. 1.

The operation of each module is separate and in each step, the data and outputs of each section are sent to the next section and are related to each other. The COIFM, PDEM, and EIM modules, which are responsible for calculating the frequency of center of inertia, the estimated power deficit, and the emergency index, respectively, constantly calculate and record the values. In a critical situation, the most important point at the first stage is to know the extent of the crisis so that the system can react appropriately. The frequency response behavior of the system can be detected by analyzing the EI index and determining the acute or non-acute critical state that will occur in the stability (convergence) or instability (divergence) of the curve, respectively.

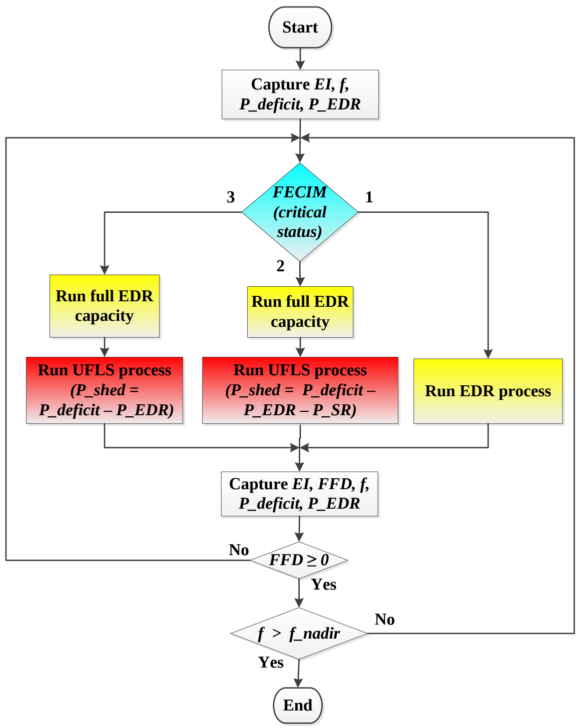

Fig. 1. Frequency Restoration Module (FRM).

In general, for non-acute cases, we will have:

$$P_{shed} = P_{deficit} - P_{EDR} - P_{FSR} \quad (6)$$

where:

P_{shed} UFLS's share of total power deficit (in MW);

$P_{deficit}$ Power deficit (in MW);

P_{EDR} EDR's share of total power deficit (in MW);

P_{FSR} Fast SR's share of total power deficit (in MW);

Also, this equation for the acute situation will be as follows:

$$P_{shed} = P_{deficit} - P_{EDR} \quad (7)$$

B. *Performance of UFLS and EDR algorithms in EDSM compensation algorithm*

As was mentioned in the previous section, after the amount of power deficit ($P_{deficit}$) is calculated by the PDEM module, this value is compensated by the UFLS and EDR algorithms in the corresponding module (FRM). Therefore, to improve the quality of customer service, the load related to each of the UFLS and EDR sections can be classified into different categories. Accordingly, in the UFLS section, loads will be divided into two parts of without priority and with priority, and they eill be divided by the type of contract and their nature in the EDR section. Therefore, the UFLS share of power deficit will be equal to:

$$P_{shed} = P_{NO} + P_{WO} \quad (8)$$

where P_{NO} represents the no order-interruption priority of loads and P_{WO} represents the with-order interruption priority of loads that will participate in the UFS.

Also, EDR's share of power deficit will be equal to:

$$P_{EDR} = P_{CD} + P_{CG} \quad (9)$$

where P_{CD} represents the sum of contracted demands and P_{CG} represents the sum of contracted generations with the ability to inject power that will participate in the EDR process.

Therefore, the different states that occur in each step of the algorithm will include the following:

1) Type 1 critical situation:

In this case, the existing P_{EDR} capacity is estimated to be greater than the power deficit and the EI is less than zero, so the frequency drop is in the non-acute state, where only the EDR process will operate in the algorithm and no UFLS will need to be performed, so we will have:

$$P_{shed} = 0 \quad (10)$$

$$P_{EDR} = P_{deficit} - P_{FSR} \quad (11)$$

2) Type 2 critical situation:

In this case, the EI is less than zero, so the frequency drop trend is non-acute, but the P_{EDR} -capacity that is ready to participate is less than the estimated power deficit. In this case, the EDR process alone will not be responsible and the UFLS process needs to start. In this case, because the network is not in an unstable condition and the existing SRs may be activated with a slight delay to restore the frequency, the amount of load to be shed is equal to:

$$P_{EDR}: in\ \ full\ \ capacity \quad (12)$$

$$P_{shed} = P_{deficit} - P_{EDR} - \ P_{FSR} \quad (13)$$

3) Type 3 critical situation:

Under this condition, the EI coefficient is greater than zero and the frequency response curve is in an unstable condition. Therefore, the frequency drop is in an acute state, in which the EDR process algorithm is activated with all its capacity and at the same time, the UFLS process will be executed regardless of the SRs, so we will have:

$$P_{EDR}: in\ \ full\ \ capacity \quad (14)$$

$$P_{shed} = P_{deficit} - P_{EDR} \quad (15)$$

After the first stage of EDR or UFLS is performed, additional monitoring and analysis are needed to determine the frequency restoration process and make the appropriate decision to achieve the desired result. Therefore, the required indexes and variables are received from the relevant modules again. The index that will help the proposed restoration algorithm at this stage is the FFD index. Thus, if the rate of frequency change with respect to time is positive (ascending frequency curve) and the acceptable frequency value (f_{nadir}) is reached, the operation of the FRM module ends. However, if it has not yet reached the desired frequency if the EI index is negative (convergent frequency curve), the EDR or UFLS residue will be used for the second time, otherwise, the FRM module will stop. However, if at the end of the first stage the FFD index is positive (descending frequency curve), in terms of positive or negative EI index, the first stage will be repeated according to the mentioned situation and will be implemented depending on the EDR and UFLS algorithm. This process continues until the system frequency is within the acceptable range.

III. Optimization Module Design and Presentation of OEDSM Algorithm

As was mentioned in the previous section, the UFLS and EDR processes involve divisions in terms of power deficit supply. Hence, different combinations of different parts can be formed. Extendable combinations can be considered in terms of operating priority, cost of operation, fines, and so on. Therefore, by defining different objective functions, the most appropriate combination can be found according to the respective objects.

The sum of the various UFLS combinations are divided as follows:

$$\begin{cases} Comb(P_{NO}) = \sum_{j=1}^{J} s_j \cdot p_{NO_j} \\ s.t. \\ j = 1, 2, 3, \dots, J \\ s_j = 0 \ \ or \ \ 1 \end{cases} \tag{16}$$

where

j number of no-order loads;

s_j coefficient of the j-th no-order load;

p_{NO_j} no-order load's share of total UFLS (in MW);

$Comb(P_{NO})$ sum of the combinations of no-order loads;

$$\begin{cases} Comb(P_{WO}) = \sum_{k=1}^{K} s_k \cdot p_{WO_k} \\ s.t. \\ k = 1, 2, 3, \dots, K \\ s_k = 0 \ \ or \ \ 1 \end{cases} \tag{17}$$

where

k number of with-order loads;

s_k coefficient of the k-th with order load;

p_{WO_k} with-order load's share of total UFLS (in MW);

$Comb(P_{WO})$ sum of the combinations of with-order loads;

Also, the sum of different EDR combinations can be distinguished as follows:

$$\begin{cases} Comb(P_{CD}) = \sum_{l=1}^{L} s_l \cdot p_{CD_l} \\ s.t. \\ l = 1, 2, 3, \dots, L \\ s_l = 0 \ \ or \ \ 1 \end{cases} \tag{18}$$

where

l number of contracted demands;

s_l coefficient of l-th contracted demand;

p_{CD_l} contracted demand's share of total EDR (in MW);

$Comb(P_{CD})$ sum of the combinations of contracted demands;

$$\begin{cases} Comb(P_{CG}) = \sum_{m=1}^{M} s_m \cdot p_{CG_m} \\ s.t. \\ m = 1, 2, 3, \dots, M \\ s_m = 0 \ \ or \ \ 1 \end{cases} \tag{19}$$

where

m number of contracted generations;

s_m coefficient of the m-th contracted generation;

p_{CG_m} contracted generation's share of total EDR (in MW);

$Comb(P_{CG})$ sum of the combinations of contracted generations;

The process of selecting the right combination to participate in power deficit compensation follows the pattern that the load shedding process starts from no-order loads in the UFLS algorithm. If the amount of no-order loads is not enough to shed, with-order loads will also participate. Also, in the EDR algorithm, at first, the process of participation from contracted generations starts, and then, if it is necessary, contracted demands will also participate. The process is summarized as follows:

- If $P_{Shed} \leq \sum_{j=1}^{J} p_{NO_j}$ then:
  $$Comb(P_{NO}) = P_{Shed} \tag{20}$$
- If $P_{Shed} > \sum_{j=1}^{J} p_{NO_j}$ then:
  $$\sum_{j=1}^{J} p_{NO_j} + Comb(P_{WO}) = P_{Shed} \tag{21}$$
- If $P_{EDR} \leq \sum_{m=1}^{M} p_{CG_m}$ then:
  $$Comb(P_{CG}) = P_{EDR} \tag{22}$$
- If $P_{EDR} > \sum_{m=1}^{M} p_{CG_m}$ then:
  $$\sum_{m=1}^{M} p_{CG_m} + Comb(P_{CD}) = P_{EDR} \tag{23}$$

Now according to the previous equations, after selecting the different combinations, the error values will be defined as follows:

$$error_{P_{Shed}} = |P_{Shed} - (Comb(P_{NO}) + Comb(P_{WO}))| \tag{24}$$

$$error_{P_{EDR}} = |P_{EDR} - (Comb(P_{CD}) + Comb(P_{CG}))| \tag{25}$$

Now a combination must be selected for each equation to create a minimum error. So, to achieve this purpose, the optimal values must be found. There are various methods derived from optimization algorithms and mathematical methods, among which the dynamic programming method, which is a practical mathematical method, has been used to find optimal values due to the specificity of the problem variables and the need for an accurate (not approximate) response and the proper response speed [19].

To achieve the purpose of minimizing UFLS and EDR errors, an OM has been designed which finds the answers in interaction with the FRM module based on the dynamic programming method and sends the data to execute the EDSM algorithm. Fig. 2 shows an overview of the optimal EDSM algorithm and related modules and the location of the OM. The objectives of the proposed OM are:

$$\begin{cases} \min(error_{P_{Shed}}) \\ \quad and \\ \min(error_{P_{EDR}}) \end{cases} \tag{26}$$

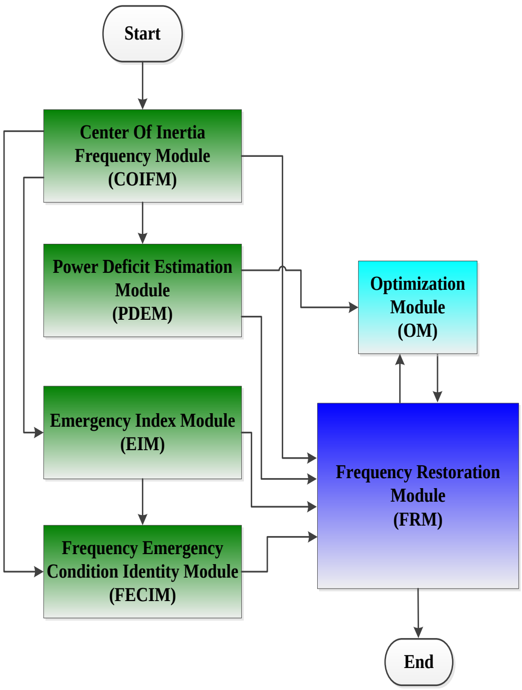

Fig. 2. The block diagram of the OEDSM algorithm and its related modules.

IV. TEST OF THE OEDSM ALGORITHM

The frequency restoration process of the OEDSM method was tested to confirm the performance. One of the purposes of frequency restoration with this method is to reduce UFLS participation and increase EDR participation in the frequency restoration process. Another purpose is the participation of each of the sections mentioned in the previous section optimally and with the least error. Accordingly, the standard New England 39 bus grid was selected to validate the proposed frequency restoration method. The network has a nominal frequency of 60 Hz and is composed of 10 main power plants, 19 feeders, and 34 lines at the transmission level, which has a generation capacity at a nominal load of about 6140 MW. The total load in the current operation of the network is about 6098 MW, of which 30% is of no-order interruption priority type and 70% is with-order interruption priority type. The total EDR capacity is about 305 MW composed of about 260 MW EDR with contracted demand and 45 MW EDR with contracted generation. Also, fast SRs and slower SRs have been considered with a capacity of about 50 and 100 MW, respectively. This power system is simulated in DIgSILENT software under the following scenarios. Based on this, the simulations were performed once using the conventional frequency restoration method and then using the OEDSM method.

A. *Turbulence with a power deficit of 250 MW*

In this part, the system is faced with a power deficit of 250 MW, which is a small disturbance for the studied system. Now the performance of the conventional and proposed frequency restoration methods is examined in the face of this turbulence. When the conventional method [12,15] is used for restoration, with the occurrence of turbulence and the beginning of the frequency reduction process when its value reaches 59.7 Hz, the EDR algorithm starts working and after a delay of a few seconds, the system frequency returns to the nominal value.

Since the EDR capacity of this method is 305 MW and the power deficit is 250 MW, the EDR algorithm will be able to fully return the frequency to its nominal value, which is well demonstrated in Fig. 3. In the other case, the system is evaluated under the proposed method. In this method, as soon as the frequency reduction process is identified by the FECIM diagnostic module, the FRM, and then the OM modules start working. Therefore, after detecting the critical state of type 1, only the EDR algorithm starts working and returns the frequency to its nominal value well. One of the advantages of the proposed method compared to the conventional method is faster performance and consequently less frequency drop, which is well shown in Fig. 3.

Table III is compares the results of the two methods. As can be seen, in both methods the value of UFLS is zero, a lower EDR value is applied in the proposed method than in the conventional method. Based on the comparison of the minimum frequency and the duration of the frequency convergence, it is clear that the proposed method is in a more favorable situation. But both methods could bring the final frequency to the nominal value of 60 Hz. Another advantage of the proposed method is optimal load shedding. The details of the operation of the OM in the optimal classification of load shedding are presented in Table IV. As it is known, out of the total 207.27 MW EDR, the amount of 162.27 MW is the share of the contracted demands, and 45 MW EDR is the share of the contracted generations. Also, the share of each UFLS segment in load interruption is zero. This means that there is no need to share load shedding with no-order and with-order loads.

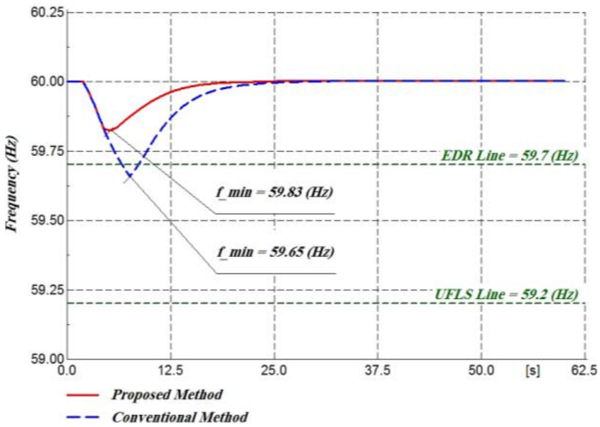

Fig. 3. The frequency response of the network with a power deficit of 250 MW.

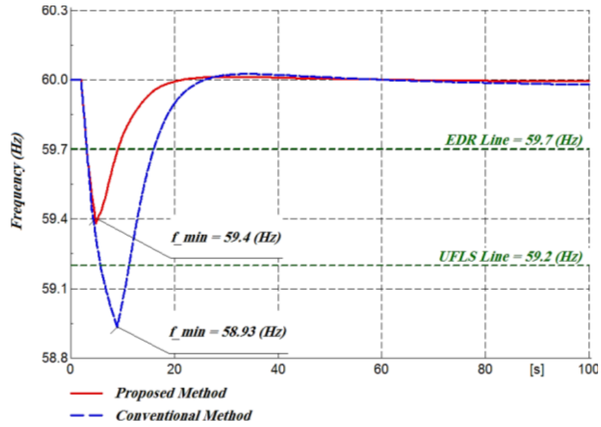

Fig. 4. The Frequency response of the network with a power deficit of 830 MW.

TABLE III

A COMPARISON OF THE RESULTS OF THE VARIABLES BETWEEN THE CONVENTIONAL AND PROPOSED METHODS IN SCENARIO 1.

Variable	Conventional Method [12,15]	Proposed method
Total Load Shedding (MW)	0	0
Total EDR (MW)	253.23	207.27
Minimum Frequency (Hz)	59.65	59.83
Convergence Time (s)	23	17
Steady-State Frequency (Hz)	60	60

TABLE IV

A COMPARISON OF SHED COMBINATIONS IN THE PROPOSED METHOD IN SCENARIO 1.

Variable	UFLS [12]	EDR [15]
Total P_{NO} (MW)	0	-
Total P_{WO} (MW)	0	-
Total P_{CD} (MW)	-	162.27
Total P_{CG} (MW)	-	45

B. *Turbulence with a power deficit of 830 MW*

In the next scenario, we evaluate the system under 830 MW turbulence. Accordingly, after this turbulence, the conventional algorithm [12,15] is implemented first. As shown in the system frequency response in Fig. 4, after the system frequency becomes less than 59.7 Hz, the EDR algorithm starts to return the system frequency to its nominal value. Since the generated power deficit is 830 MW and the maximum EDR capacity is 305 MW, EDR will not be able to restore the system frequency and the frequency will continue to decrease until it reaches the UFLS limit of 59.2 Hz. As soon as the frequency reaches 59.2 Hz, the UFLS algorithm starts working and compensates for the remaining power deficit, and after a while, brings the system frequency closer to the nominal value. The results are shown in Table V.

In the next case, the system is evaluated under the proposed algorithm scheme. In this case, as soon as the disturbance occurs and after the system frequency starts to decrease and the emergency status and its type are announced by the FECIM, the frequency restoration process starts operating. In this case, the FECIM module detects type 2 critical situation, in which both EDR and UFLS algorithms are started. As can be seen in Fig. 4, the algorithm performed the restoration process faster and the system frequency decreased less, which minimized the possibility of tripping the under-frequency relays of generators.

As shown in Table V, the comparison of the frequency restoration process related to the two methods clearly reveals the superiority of the proposed method in terms of fewer loads shedding amount, less frequency reduction, less convergence time, and the steady-state frequency closer to the nominal value.

TABLE V

A COMPARISON OF THE RESULTS OF THE VARIABLES BETWEEN THE CONVENTIONAL AND PROPOSED METHODS IN SCENARIO 2.

Variable	Conventional Method [12,15]	Proposed method
Total Load Shedding (MW)	500.47	467.25
Total EDR (MW)	305	305
Minimum Frequency (Hz)	58.93	59.40
Convergence Time (s)	77	46
Steady-State Frequency (Hz)	59.98	59.99

Table VI also shows the results of the OM performance in the optimal share segmentation of each of the EDR and UFLS segments. As it is known, out of the total 305 MW from the share of the EDR algorithm, 260 MW is the share of contracted demands and 45 MW EDR is the share of the contracted generations. Also, 467.25 MW, which is the total share of the UFLS, is provided by no-order loads, and there is no need to be shared by with-order loads.

TABLE VI
A COMPARISON OF SHED COMBINATIONS IN THE PROPOSED METHOD IN SCENARIO 2.

Variable	UFLS [12]	EDR [15]
Total P_{NO} (MW)	467.25	-
Total P_{WO} (MW)	0	-
Total P_{CD} (MW)	-	260
Total P_{CG} (MW)	-	45

C. Turbulence with a power deficit of 2490 MW

In the third scenario, the system is severely disturbed by 2490 MW. For frequency restoration, the system has been evaluated once under the conventional algorithm [12,15] and then under the proposed algorithm.

Under the conventional algorithm, when the power deficit is 2490 MW, its frequency decreases sharply. Therefore, as soon as the system frequency exceeds 59.7 Hz, the EDR algorithm starts working, which will not be effective in practice due to the large difference in the capacity of this algorithm owing to the lack of power. When the system frequency reaches 59.2 Hz, the UFLS algorithm starts working and tries to return the system frequency to its acceptable level. The implementation process of the mentioned algorithm is due to the high speed of system frequency drop to such an extent that the system frequency is reduced to 56.97 Hz.

Since the system frequency was set at frequencies below 57 Hz for about 1.3 seconds, which is close to the critical level, and in case of further delay in the operation of UFLS relays in real systems, the under-frequency turbine relays allow tripping. Generators will not be allowed to stay at this frequency for more than 2.4 seconds [20]. (IEEE Std C37.117 will be allowed for frequencies below 57 Hz for a maximum of 2.4 seconds.) Therefore, the generators may be disconnected from the power grid and prevent their turbines from twisting and breaking down.

The system is then evaluated under the proposed frequency restoration method. Accordingly, as soon as the system frequency began to decrease and the emergency status and type were announced by the FECIM module, the frequency restoration process began. In this case, the module detected critical state 3, and both EDR and UFLS algorithms started working. As can be seen in Fig. 5, the proposed algorithm copes well with the frequency restoration and could bring the system frequency to an acceptable level close to the nominal value by dropping a frequency much lower than the conventional method. As it turned out, the network frequency is always kept above 58 Hz, which is a safe area in terms of the performance of under-frequency relays of turbines.

Table VII also provides a comparison of conventional [12,15] and proposed methods. As it turns out, the proposed method is in a better position both in terms of the amount of load shedding in the UFLS algorithm and the larger frequency and the shorter convergence time.

Table VIII also shows the share of each of the EDR and UFLS segments in the proposed algorithm. As it is known, out of the total 305 MW from the share of the EDR algorithm, an amount of 260 MW is the share of contracted demands and 45 MW EDR is contracted generations. Also, out of the total 2101.43 MW which is the total share of UFLS, 1829.4 MW is supplied by no-order loads and 272.03 MW by with-order loads.

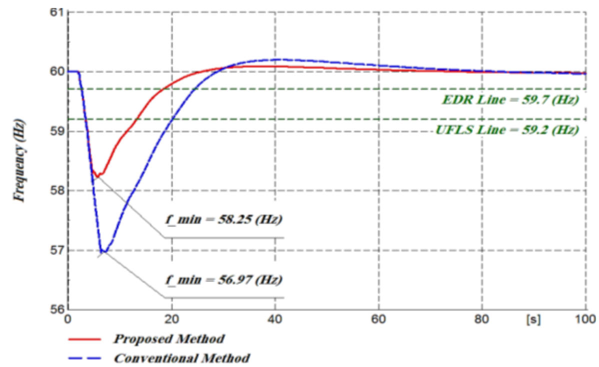

Fig. 5. The Frequency response of the network with a power deficit of 2490 MW.

TABLE VII
A COMPARISON OF THE RESULTS OF THE VARIABLES BETWEEN THE CONVENTIONAL AND PROPOSED METHODS IN SCENARIO 3.

Variable	Conventional Method [12,15]	Proposed method
Total Load Shedding (MW)	2129.10	2101.43
Total EDR (MW)	305	305
Minimum Frequency (Hz)	56.97	58.25
Convergence Time (s)	81	60
Steady-State Frequency (Hz)	59.98	59.98

TABLE VIII
A COMPARISON OF SHED COMBINATIONS IN THE PROPOSED METHOD IN SCENARIO 3.

Variable	UFLS [12]	EDR [15]
Total P_{NO} (MW)	1829.40	-
Total P_{WO} (MW)	272.03	-
Total P_{CD} (MW)	-	260
Total P_{CG} (MW)	-	45

V. CONCLUSIONS

When a power system encounters a serious disturbance that results in an imbalance between power generation and consumption and a drastic change in system frequency, it needs a comprehensive and flexible system for frequency restoration to the nominal value in the minimum time and with the least frequency drop. This paper presents the OEDSM method, which consists of various modules with specific tasks.

This method improves the reliability of previous methods. The method is formed by integrating EDR and UFLS algorithms and then adding diagnostic, control, and OMs. The results of the simulations under different scenarios with different turbulence sizes well show the high capability of the proposed algorithm in the system frequency restoration process. As the results show, this method leads to the simultaneous operation of EDR and UFLS algorithms, which in itself increases the speed of critical state detection in the process of frequency restoration. Other desirable results of the proposed method include lower network frequency drop, lower load shedding amount, higher convergence speed, optimal load shedding, and load classification based on interruption priority that increases consumer satisfaction, improves the power quality of the system, and minimizes the possibility of network blackouts.

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