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MINIMIZING THE AMOUNT OF LOAD SHEDDING CONSIDERING THE PRIMARY CONTROL OF GENERATOR

TỐI THIỂU LƯỢNG CÔNG SUẤT SA THẢI PHỤ TẢI CÓ XÉT ĐẾN YẾU TỐ ĐIỀU KHIỂN SƠ CẤP MÁY PHÁT ĐIỆN

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ABSTRACT

The imbalance of power between generation power and load consumption causes a decline in the frequency of the power system. The frequency deviation depends on the power of generator outage and the operating status of the system. The monitoring and control system of the power system will immediately implement the control solutions to restore the frequency back to the allowed value. Among these solutions, it is necessary to mobilize the reserve power of the remaining generator turbines to restore the system frequency. This article proposed a method for calculating the amount of load shedding considering the primary control of generator in a power system. The proposed method calculates the amount of load shedding to recover frequency to allowed value when the lack of generation source due to outage generator leads to overload in an electric power system. The effect of the proposed solution which was tested on a diagram of the electric power system standard IEEE 37 bus 9 generators proved the effectiveness of the proposed method.

Keywords: *load shedding; minimal load shedding; generator outage; primary control; frequency stability.*

TÓM TẮT

Việc mất cân bằng công suất tác dụng giữa máy phát và phụ tải tiêu thụ gây ra sự suy giảm về tần số trong hệ thống điện. Giá trị tần số suy giảm phụ thuộc vào công suất máy phát sự cố và tình trạng vận hành của hệ thống điện. Hệ thống giám sát và điều khiển hệ thống điện sẽ thực hiện ngay các biện pháp điều khiển để phục hồi tần số về giá trị định mức cho phép. Trong đó phải kể đến là việc huy động lượng công suất dự phòng của các turbine máy phát còn lại nhằm khôi phục tần số hệ thống. Bài báo này đề xuất phương pháp tính toán lượng công suất sa thải phụ tải cần thiết có xét đến yếu tố điều khiển sơ cấp của tổ máy phát điện trong hệ thống điện. Phương pháp đề xuất tính toán lượng công suất sa thải phụ tải đảm bảo khôi phục tần số về phạm vi cho phép khi có sự thiếu hụt công suất nguồn phát do sự cố máy phát hoặc tăng tải dẫn đến quá tải trong hệ thống điện. Hiệu quả của phương pháp đề xuất được thử nghiệm trên sơ đồ hệ thống điện chuẩn IEEE 37 bus 9 máy phát đã chứng minh hiệu quả của phương pháp đề xuất.

Từ khóa: *Sa thải phụ tải; tối ưu hóa sa thải phụ tải; sự cố máy phát; điều khiển sơ cấp; ổn định tần số.*

1. INTRODUCTION

Incidents in an electric power system are usually momentary incidents. However; there are big incidents like outage a generator, or suddenly increased load in a power system will cause seriously decreasing frequency. Finding the amount of optimizing load shedding is more concern than the others load shedding methods. The old load shedding models have not mentioned spinning reserve capacity in each generator. Most of traditional load shedding solutions based on decreasing frequency. The load shedding method by Under Frequency Load Shedding (UFLS) relay, or Under Voltage Load Shedding relay is the solution which is used for recovery frequency control, voltage stability of the grid. When frequency and voltage are under of working threshold which is installed, Under Frequency or Under Voltage Load Shedding relays will transmit the signal cut each fixed load in predefined steps, so it helps to prevent decreased frequency/voltage and their effects. Under Frequency Load Shedding is applied by operating electric power system company: Florida Reliability Coordinating Council (FRCC) [1], Electric Reliability Council of Texas [2], Electric Power System Vietnam [3]. In Viet Nam, most load shedding methods by frequency are used relay 81. When the frequency decreases to the receive points, it is definitely determined by the percentage of total load shedding power. In addition, adaptive load shedding methods use swing rotor equation to estimate the power required to shed. The power imbalance in the system is determined by the equation (1) [4]:

$$\Delta P = \frac{2H}{f}.\frac{\partial f}{\partial t} = P_m - P_e \qquad (1)$$

Where, ΔP is the amount of power imbalance; H is the inertia constant, f: rated frequency (Hz), df/dt: the change of frequency (Hz/s).

When the system disturbs causing changes in frequency as well as the speed of frequency's change (Rate Of Change Of Frequency). By applying the values in equation (1), the power imbalance can be estimated. After estimating the amount of power imbalance, the amount of power required to shed is made to stabilize the electrical system.

Recently, Intelligent Load Shedding Methods-ILS was proposed by the researchers. The main components of this technique are: knowledge base, incident list and intelligent load shedding calculation tools. These techniques include artificial neural networks (ANNs) [5-6], adaptive neural-fuzzy systems (ANFIS) [7], fuzzy logic control (FLC) [8], genetic algorithms (GA) [9] and particle swarm optimization algorithm (PSO) [10]. These techniques can easily solve nonlinear, multi-objective problems in electrical systems that normally cannot be solved by conventional methods with the desired speed and accuracy.

A reasonable load shedding solution is shed a minimum load capacity as soon as possible and at the same time satisfy all the constraints required to maintain the system frequency stability. This paper presents the method of calculating the minimum load shedding to maintain the electrical system frequency within the allowable value.

2. MATERIAL AND METHODOLOGY

Primary frequency control is the instantaneous adjustment process which performed by a large number of a governor units that adjusts the active power according to frequency variation [11].

In case the generator unit is not equipped with governor, the power generation characteristic is shown in Figure 1.

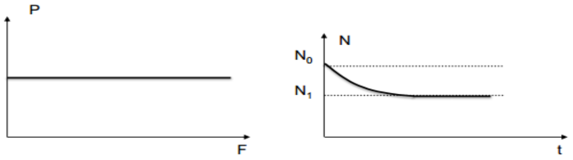

Figure 1. *The power generation characteristics of generator units do not have governors [12].*

In case the generator unit is equipped with governor, the power generation characteristic is shown in Figure 2.

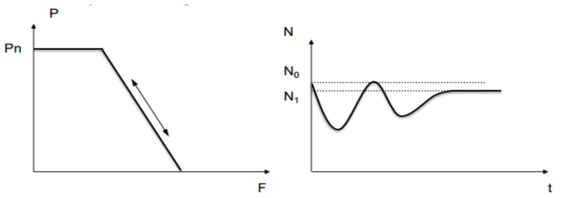

Figure 2. *The power generation characteristics of generator units have governors [12].*

The change characteristic of turbine power according to the change of frequency is shown in Figure 3. In steady state, balanced operation, the intersection of the power generation characteristic (1) with the frequency characteristic of the load P_t determines the frequency f_0. Assume that it is a standard frequency, 50 Hz or 60 Hz.

In case of the load increased ΔP, respectively, the new load characteristic line is P_t + ΔP. The new frequency f_1 is the intersection of the power generation characteristic (1) with the new characteristic of the load. In this case f1 <f0, the governor cannot prevent the frequency reduction. However, because the generators have the governor, the limited the large deviation of the frequency. Compared to the case where the generator does not have a governor (characteristic (2)), the intersection with the new characteristic of load P_t+ΔP will determine the frequency f1 ', then $f_1' < f_1$.

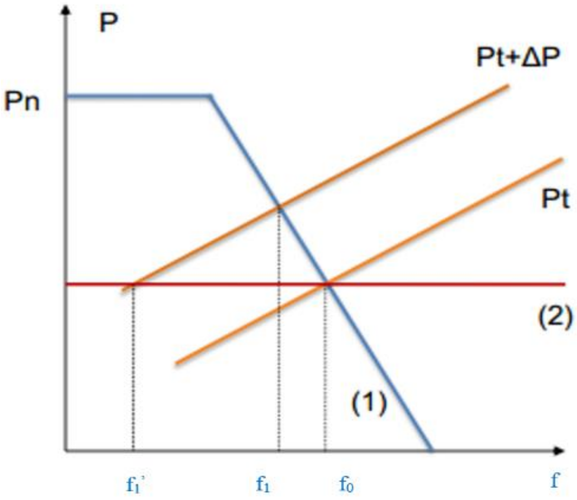

Figure 3. *The comparison of turbine power change characteristics according to the change of frequency of the generator unit with the governor (1) and without the governor (2) [12].*

Thus, the governor of the generator unit has the effect of adjusting the frequency and is called the primary frequency regulator. This process is called the primary control of generator. The efficiency of the primary frequency adjustment depends on the slope characteristic of the unit generator.

3. THE PROPOSED LOAD SHEDDING METHOD

In steady-state mode, the relationship between frequency and the output mechanical power of the generator's turbine are determined by the equation [13]:

$$\Delta p_m = \Delta p_{ref} - \frac{1}{R} \times \Delta f \tag{2}$$

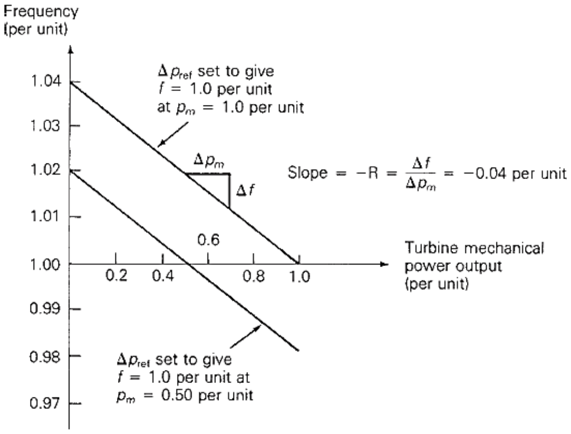

Figure 4. *Steady-state frequency–power relation for a turbine-governor [13]*

Where Δf is the change in frequency (Hz); Δp_m is the total change in turbine output mechanical power (MW); Δp_{ref} is the change in installed reference power

In Figure 4, the adjusting constant R (Hz/MW) in Equation (2) is negative with respect to the slope of the curve Δf and Δp_m , all parameters are in terms of per unit.

Frequency-to-power relation in steady-state mode in each region of the interconnected power system can be determined by estimation via equation (5) [13].

$$\begin{aligned}\Delta p_m &= \Delta p_{m1} + \Delta p_{m2} + \Delta p_{m3} + \Delta p_{mn} \\ &= \left(\Delta p_{ref1} + \Delta p_{ref2} + \dots + \Delta p_{refn}\right) - \left(\frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}\right)\Delta f \\ &= \Delta p_{ref} - \left(\frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}\right)\Delta f \end{aligned} \tag{3}$$

From there, put: $\beta = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \dots \frac{1}{R_n}\right)$ (4)

Where: β is frequency response characteristic

Replace equation (3) by equation (4):

$$\Delta p_m = \Delta p_{ref} - \beta \Delta f \qquad (5)$$

Equation (5) [13] is the frequency-to-power relationship in steady-state mode of multiple generators.

Ignore the power losses and the dependence of load on frequency in steady-state mode when the total output mechanical power of the turbine is equal to the increase of the load capacity, apply equation (5) with $\Delta p_{ref} = 0$.

$$\Delta f = -(\frac{1}{\beta})\, \Delta p_m \qquad (6)$$

Equation (6) [13] calculates the frequency reduction in steady state mode when a generator outage, which results in generation-load demand imbalance. When any generator in the electrical system opens, the Governor controller will automatically "increase" the mechanical power to compensate for the power shortage. This increase power process is called the primary control power of each generator. This increasing power value of each generator depends on the R factor. In Equation (6), the change in capacity has taken into account the capacity of the remaining generators increased due to the response of the governor.

In the 60 Hz power system, the permitted frequency reduction is 0.3Hz ($\Delta f_{cp} = -0.3\ Hz$). Therefore, in the per unit system (pu), the $\Delta f_{cp}\ is \frac{-0.3}{60}\ (pu)$.

Thus, from formula (6), the relationship between the allowed frequency reduction and the minimum amount of load shedding P_{LS}^{OPT} is calculated as follows:

$$\Delta f_{cp} = (-\frac{1}{\beta})\, (\Delta p_m - P_{LS}^{OPT}) \qquad (7)$$

From the formula, the minimum amount of load shedding inferred:

$$P_{LS}^{OPT} = \Delta p_m - \left(\Delta f_{cp} \times \beta\right) \qquad (8)$$

Where: Δf_{cp} is the allowed frequency reduction (pu); P_{LS}^{OPT} is the amount of load required to shedding (pu); Δp_m is the change mechanical power of the turbine (pu).

The proposed algorithm calculates the required load shedding capacity

Step 1: Determine the generator outage via the SCADA system.

Step 2: Calculate the frequency reduction of the system when there is an imbalance of generation-load demand, applying the equation (6).

Step 3: Compare the frequency reduction calculated in step 2 with the permitted frequency reduction.

If $|\,\Delta f\,| < \Delta f_{cp}$, no load shedding.

If $|\,\Delta f\,| > \Delta f_{cp}$, go to step 4.

Step 4: Calculate the amount of load shedding, apply equation (8):

$$P_{LS}^{OPT} = \Delta p_m - \left(\Delta f_{cp} \times \beta\right) \qquad (8)$$

Step 5: Distribute the amount of load shedding at the load nodes using the equation:

$$\Delta P_{LS_i} = \frac{\frac{df_i}{dt}.P_{LS}^{OPT}}{\sum \frac{df_i}{dt}} \qquad (9)$$

Where: $\frac{df_i}{dt}$ is the change in frequency at load nodes as soon as the transmitter fails during the transition period.

4. PROPOSED METHOD TESTED ON A STANDARD ELECTRICAL SYSTEM MODEL

The proposed load shedding algorithm is tested on the IEEE 37 bus 9 generators. The electrical diagram is presented in Figure 6 and the PowerWorld software is used. Calculation and simulation are performed according to the flowchart shown in Figure 5.

In the simulation process, the frequency of the system is tested and evaluated in the case of a generator outage. Moreover, the frequency after the load shedding by applying the proposed equation in section 3 is also considered.

Before the simulation, the standard parameters of the IEEE 37 bus 9 generators system are installed. The voltage adjustment system, the exciter adjustment system, the frequency adjustment system, the optimal power flow is enabled. The value of the adjustment factor R = 0.05 pu. The generator model uses the GENCLS model. The exciter uses the IEEET1 model. The governor uses the TGVO1 model [13].

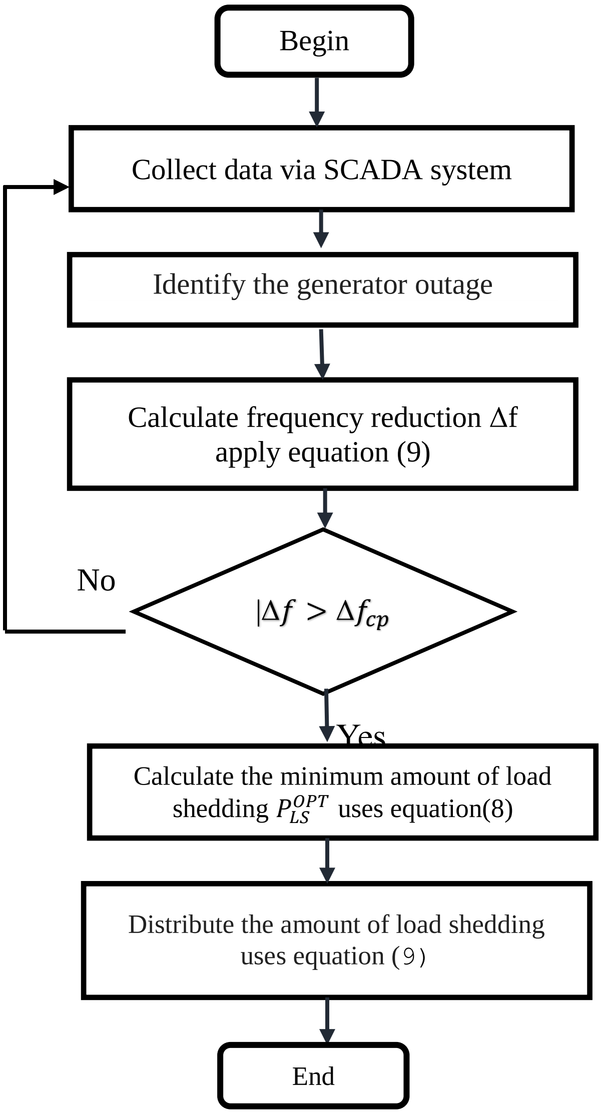

Figure 5. *Flowchart of the proposed algorithm for calculating load shedding*

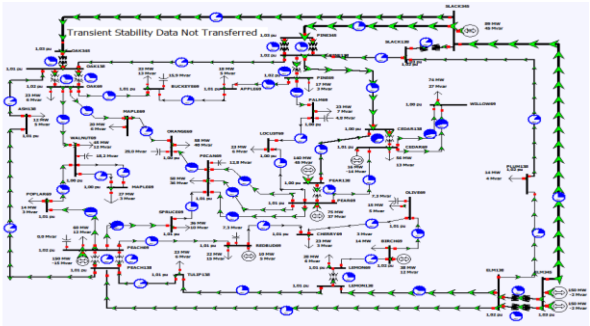

Figure 6. *The IEEE 37 bus 9 generators diagram.*

Case study, when the system suddenly opens a generator (e.g. PEAR138 = 140MW). Immediately, the governors of the other generators will increase their mechanical power based on the principle of adjusting the generator's primary frequency.

Apply the expression (4) to calculate the frequency response characteristic β:

$$\beta = \frac{1}{R_{1p.u.new}} + \frac{1}{R_{2p.u.new}} + \frac{1}{R_{3p.u.new}} + \frac{1}{R_{4p.u.new}} + \frac{1}{R_{5p.u.new}} + \frac{1}{R_{6p.u.new}} + \frac{1}{R_{7p.u.new}} + \frac{1}{R_{9p.u.new}} = 213.4\, p.u$$

Table 1. *Generators and governors' parameters*

Bus	**Generator**	**Apparent power (MVA)**	**Type of governor**	**Active power of generator (MW)**	$\mathbf{R_{i\_old}}$	$R_{i\_pu.new} = R_{i\_old}\frac{S_{base\ (new)}}{S_{i\_old}}$
14	REDBUD69	40	TGOV1	10.01	0.05	0.125
28	ELM345	180	TGOV1	150	0.05	0.0278
28	ELM345	180	TGOV1	150	0.05	0.0278
31	SLACK345	250	TGOV1	88.9	0.05	0.02

44	PEACH69	160	TGOV1	150.55	0.05	0.03125
48	CEDAR69	57	TGOV1	16.01	0.05	0.088
50	BIRCH69	85	TGOV1	38.06	0.05	0.059
53	PEAR138	150	TGOV1	140.19	0.05	0.033
54	PEAR69	115	TGOV1	75.29	0.05	0.043

Where: S_{base} =100 MVA

Apply the formula (6) to calculate the frequency when the PEAR138 generator is disconnected:

$$f=-\left(\frac{1}{\beta}\right)\Delta p_m=-\left(\frac{1}{213.4}\right)1.4$$
$$=-6.56\times10^{-3}\,p.u$$
$$=-6.56\times10^{-3}\times60$$
$$=-0.39\,Hz$$

When the stabilization mode is reached, the frequency decreases by 0.39 Hz and the frequency value is:

f_{new} = 60-0.39=59.61 Hz

The result of the frequency simulation of the system in the case of PERAR generator 138 outage is shown in Figure 7.

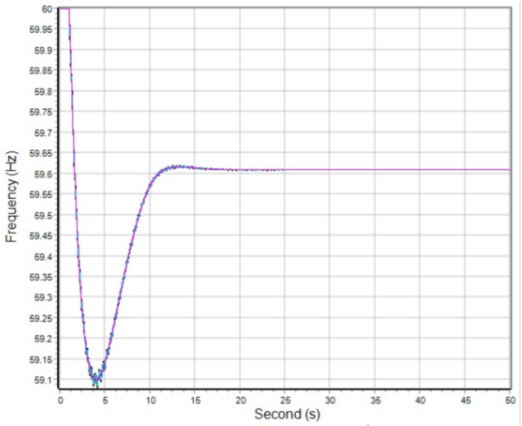

Figure 7. *Frequency of system when PEAR 138 generator outages*

Observing the frequency in Figure 7 shows that after the loss of the PEAR 138 generator, the remaining generators increase their mechanical power according to the generator's primary control principle. After the generators have automatically increased their power up, the stable frequency is 59.61 Hz. Thus, this value is less than the allowable frequency. Therefore, it is required to load shedding to recover the frequency of allowed value.

The amount of load shedding needed to restore the frequency to the permitted value is given by the formula (8):

$$P_{LS}^{OPT}=\Delta P_{mech}-\left(\Delta f_{cp}\times\beta\right)$$
$$=1.4-\left(\frac{0.3}{60}*213.4\right)$$
$$=0.0333\,p.u=33.3\,MW$$

Apply the formula (9) distributes amount of load shedding at load nodes according to the proposed formula:

$$\Delta P_{LS_i}=\frac{\frac{df_i}{dt}.P_{LS}^{OPT}}{\sum\frac{df_i}{dt}} \tag{9}$$

The results of the calculation of the load shedding at the load bus are presented in Table 2.

After calculating the amount of power distributed at the load nodes, it is simulating the load on the PowerWorld software to perform the load shedding in the proposed method. The frequency plot after performing the load shedding according to the proposed method is shown in Figure 8.

Table 2. *Distribution load shedding at load bus*

Bus's name	Bus ASH138	Bus POPLAR69	Bus PINE69	Bus OAK69	Bus PALM69	Bus REDBUD69	Bus PECAN69	Bus ORANGE69
Load shedding (MW)	1.14	1.16	1.26	1.24	1.41	0.92	1.71	1.60

Bus's name	Bus BUCKEYE69	Bus WALNUT69	Bus APPLE69	Bus OLIVE69	Bus WILLOW69	Bus SPRUCE69	Bus MAPLE69	Bus TULIP138
Load shedding (MW)	1.24	1.21	1.26	0.82	1.76	1.54	1.54	0.97
Bus's name	Bus LEMON69	Bus CHERRY69	Bus MAPLE69	Bus PEACH69	Bus CEDAR69	Bus BIRCH69	Bus PEAR138	Bus PEAR69
Load shedding (MW)	0.87	0.87	1.21	1.11	1.76	0.76	1.68	1.78
Bus's name	Bus LOCUST69	Bus PLUM138						
Load shedding (MW)	1.51	0.94						

Figure 8 shows the recovery frequency at steady state of 59.7 Hz, which is within the allowable range and fits the calculated result.

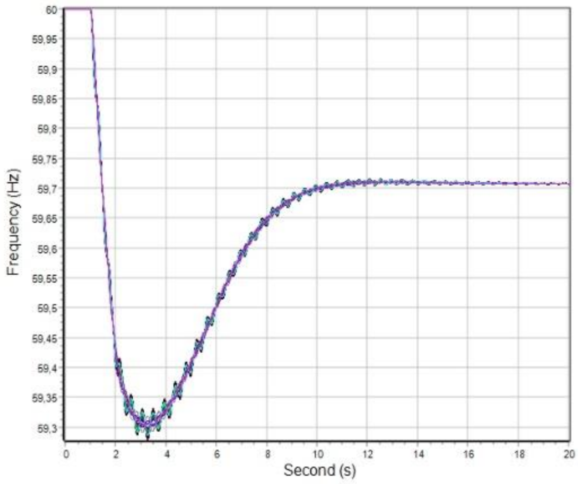

Figure 8. *Frequency of the system after applying the proposed load shedding algorithm*

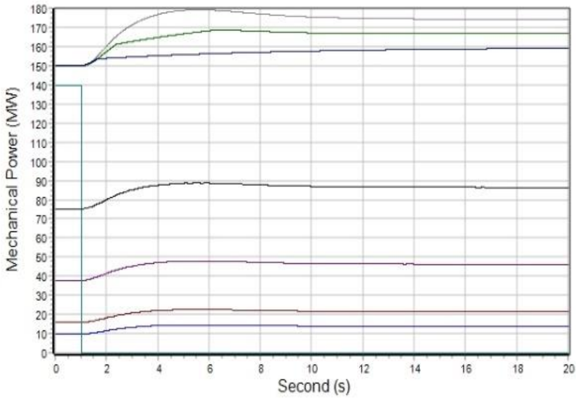

Figure 9. *Mechanical power of generators after applying the proposed method*

To demonstrate the effectiveness of the proposed method, we simulate to compare with conventional load shedding using under frequency relay [1]. When the frequency decreases below the allowable threshold, the UFLS relay will be cut at a percentage of pre-defined load. The value of cut loads is shown in Table 3.

Table 3. *Load shedding based on UFLS relay of FRCC step by step [1]*

UFLS Steps	Threshold load shedding (Hz)	Time delay (s)	Amount of load (percent of total load) (%)	Cumulative Amount of Load (%)
1	59.7	0.28	9	9
2	59.4	0.28	7	16
3	59.1	0.28	7	23
4	58.8	0.28	6	29
5	58.5	0.28	5	34
6	58.2	0.28	7	41
7	59.4	10	5	46
8	59.7	12	5	51
9	59.1	8	5	56

The results in ccomparison of the proposed method with the traditional method using under the frequency load shedding relay is showed in Table 4.

Table 4. *The comparison of the load shedding methods*

Values / **Methods**	**A mount of load shedding (MW)**	**Recovery time (s)**	**Frequency (Hz)**
Load shedding method based on UFLS relay	77,87	4,933	59,836
Proposed load shedding method	33,3	10,608	59,7

At Table 4, the proposed shedding method has less amount of load shedding than UFLS relay. Specifically, in case of testing is the outage PEAR138 generator, the amount of load shedding was reduced by 57.2% compared to the load shedding based on UFLS relay. It can be seen that traditional method has a fixed amount of load shedding, which causes over load shedding. Because of the lower load shedding capacity and the process of mobilizing reserve capacity of the generators, the recovery frequency of the proposed method is lower and the recovery time is longer than the traditional method. However, although the proposed method has a lower recovery frequency, longer recovery time after load shedding, the amount of load shedding is less than traditional method. After load shedding, the frequency restored to the allowable value and the power system remains the stability, therefore it helps minimizing the amount of load that is cut very much. This helps to reduce the economic damage caused by load shedding.

5. CONCLUSION

The paper proposed a method for determining minimum load shedding in the case of disturbance of the generator causing power imbalance in the electrical system in order to recover the allowable frequency. The results of the performance testing of the proposed load shedding method for the IEEE 37 bus 9 generators system showed that the load shedding was less than the traditional method.

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