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Minimize the load reduction considering the activities control of the generators and phase distance

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ABSTRACT

This study shows how to calculate the minimum load that needs to be reduced to restore the frequency to the specified threshold. To implement this problem, the actual operation of the electricity system in the event of a generator outage is considered. The main idea of this method is to use the power balance equation between the generation and the load with different frequency levels. In all cases of operating the electrical system before and after the generator outage, the reserve capacity of other generators is considered in each generator outage situation. The reduced load capacity is calculated based on the reciprocal phase angle sensitivity or phase distance. This makes the voltage phase angle and voltage value quality of recovery nodes better. The standard IEEE 9-generator 37-bus test scheme was simulated to show the result of the proposed technique.

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1. INTRODUCTION

Generator outage is reason for the inequality of real power and frequency reduction in the electrical system. In some cases, this may blackout the system. In [1] presented a summary of the load shedding solutions implemented over the years. In [2-4] presented intelligent solutions to maintain electricity system stability. Besides the implementation of all control solutions, including the solutions using FACT equipment [5, 6] to maintain electrical system constraints, the load shedding is an undesirable action of electricity suppliers and also for electricity consumers because it has impacts on socio-economic impacts. However, this is an unavoidable case when other possible solutions are used to restore the frequency. What is needed here is to cut the load to reduce the consequences for electricity consumers and socio-economic. The design and calculation the amount of load shedding is a complex process, requiring large amounts of input data on incident situations that cause serious frequency attenuation. Conventional load-shedding methods typically use load shedding relays [7-11] with step-by-step load shedding that correspond to levels of frequency attenuation or df/dt [12]. Most of these methods, the power of load that need to be cut in the form of load shedding tables is built by the electrical system specialist. This may cause inadequate or excessive load shedding compared to the value required. Some of the current load shedding methods used the swing rotor equation and voltage electrical distance application [13-15] to estimate the load to be cut. They combined with knowledge technology algorithms to calculate the minimum economic losses. However, these methods have not considered the technical and operational factors of electricity system after power inequality.

In this article, a technique of calculating the load curtailment that takes into account generator control problems is appropriate for the actual operation of the electrical system such as: primary control issues, secondary control issues of generators. Furthermore, load reduction based on phase distance ensures that phase angle and frequency recover faster than traditional load shedding methods.

2. METHODOLOGY FOR RESEARCH

2.1. The frequency responds

The ability to vary power according to frequency or the frequency stability ability of a turbine is determined by the drop of the speed control characteristic [16, 17]. Characteristics present the ability to adjust the turbine's power when the rotation speed changes are presented in Figure 1. The correlation is determined by equation:

$$R = \frac{\Delta f_p}{\Delta P_G} \tag{1}$$

where R is the speed or droop adjustment factor; Δf_p is the frequency change; ΔP_G is the change in generator power. Variation of both power and frequency is determined by equation:

$$\Delta P_G = \frac{-P_{G_n}}{R_i} \cdot \frac{\Delta f_p}{f_n} \tag{2}$$

where: P_{G_n} is the rated power of the generators.

The load in the electricity system is a diverse collection of different electrical equipment. The power can be either relied on the frequency (for instance the case of a motor load like fan or pump, the change in power and frequency leading to the change of motor speed) or not relied on the frequency (for instance resistive loads like lighting or heating). The power of the combined load can be expressed by the (3) [18, 19]:

$$P_L = P_{ID} + P_D \tag{3}$$

where P_L is the combined load component, P_{ID} is the frequency-independent load component, e.g. heat load, lighting… P_D is the frequency-relied load component. The change correlation between the load power characteristics and frequency is shown in Figure 2.

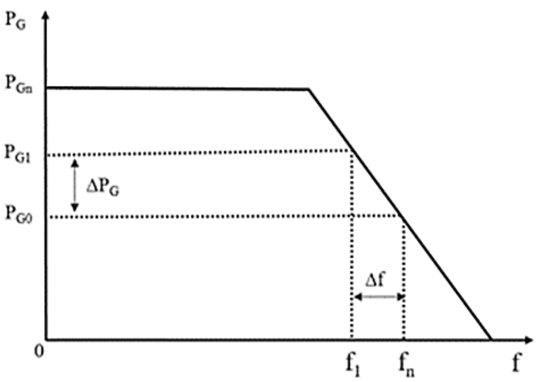

Figure 1. Correlation between generator power change and frequency change

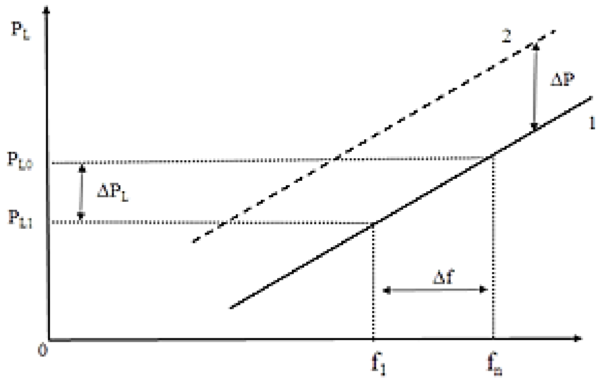

Figure 2. The change correlation between the load power characteristics and frequency

The variation of load according to the frequency variation is shown in the following equation [18]:

$$\Delta P_L = \Delta P_{ID} + \Delta P_D \tag{4}$$

When the frequency is equal to the rated frequency f_n, the required power of the load is the same as the actual consumed power P_{L0}, when the frequency decreases from f_n to f_1, the actual power used decreases from P_{L0} to P_{L1}. The correlation between the load variations and frequency variation is determined by equation:

$$\Delta P_D = -\frac{\Delta f}{f_n}.P_{\text{combined load}}.D \tag{5}$$

where ΔP_D is the variation of load power according to frequency variation; D is the percentage variation of load according to the percentage frequency variation [16]; D value ranges from 1% to 2% and is determined by experimental methods on electricity systems.

2.2. Regulator activities the generators in accordance with the actual operation

When the generator is failed, the frequency adjustment will start and include the following operations: primary regulating effects and secondary regulating effects. In case, at the end of this impact activity and the frequency is still below the permissible constrains, the next step will implement the load reduction. The objective is to restore the frequency to the required threshold value. These impact activities are indicated in Figure 3.

In this figure, line (A) is the normal operating characteristic of the system; line (B) and (D) are the feature of generators without the governor; line (C) is the feature at the time the generator is disconnected; line (E) is the operating characteristic after the secondary regulating effects of the generator; line (F) and (G) are the load characteristics before and after implement the load reduction; the fpermit value is the frequency parameter achieved after the load reduction.

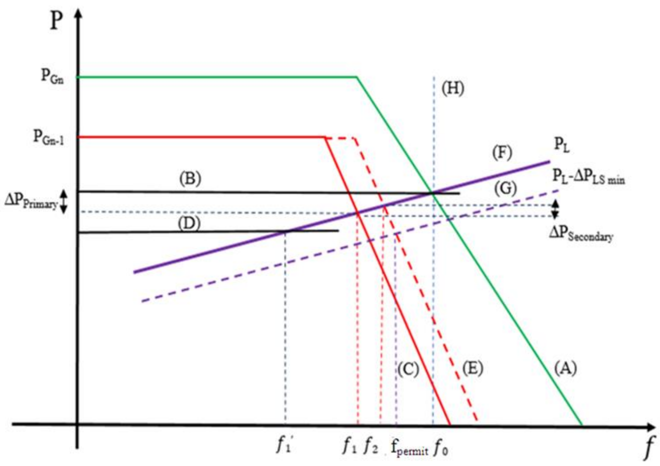

Figure 3. Regulator activities the generators and load reduction

2.3. The minimum load reduction capacity

Calculating minimum load reduction $P_{LS\ min}$ ensures restoration of electricity system frequency to the allowable value, minimizing damage to electricity consumers. The calculation includes the activity control of the generators in accordance with the actual operation. In a power system with n generators, when a generator outage, the primary regulating effects of the others (n-1) generators is made with the adjustment of the power with the below equation:

$$\sum_{i=1}^{n-1} \Delta P_{\text{Pr}\,i} = -\sum_{i=1}^{n-1} \frac{P_{G_{n,i}}}{R_i}.\frac{\Delta f_p}{f_n} \tag{6}$$

The amount of power of the frequency-dependent load reduces the amount of ΔP_D is shown in (5). Power balance status is presented in the following equation:

$$P_L - \Delta P_D = \sum_{i=1}^{n-1} P_{G_i} + \sum_{i=1}^{n-1} \Delta P_{\text{Primary control}} \tag{7}$$

$$P_L - \sum_{i=1}^{n-1} P_{G_i} = \Delta P_D - \sum_{i=1}^{n-1} \frac{P_{G_{n,i}}}{R_i} \cdot \frac{\Delta f_p}{f_n} \tag{8}$$

$$P_L - \sum_{i=1}^{n-1} P_{G_i} = -\frac{\Delta f_p}{f_n} P_L . D - \sum_{i=1}^{n-1} \frac{P_{G_{n,i}}}{R_i} \cdot \frac{\Delta f_p}{f_n} \tag{9}$$

$$P_L - \sum_{i=1}^{n-1} P_{G_i} = -(\frac{\Delta f}{f_n})(P_L . D + \sum_{i=1}^{n-1} \frac{P_{G_{n,i}}}{R_i}) \tag{10}$$

Set $\Delta P_L = P_L - \sum_{i=1}^{n-1} P_{G_i}$ and $\beta = P_L . D + \sum_{i=1}^{n-1} \frac{P_{G_{n,i}}}{R_i}$

From (10) infer:

$$\Delta P_L = \frac{-\Delta f}{f_n} . \beta \tag{11}$$

In the case of the considering secondary control power, the new power balance equation with the new frequency value f_2, the (7) becomes:

$$P_L - \Delta P_D = \sum_{i=1}^{n-1} P_{G_i} + \sum_{i=1}^{n-1} \Delta P_{\text{Primary control}} + \Delta P_{\text{Secondary control max}} \tag{12}$$

$$\Delta P_{\text{Secondary control max}} = \sum_{j=1}^{k} (P_{Gm,j} - \Delta P_{\text{Primary control, j}}) \tag{13}$$

If frequency value after implement the secondary regulating effects is lower than tolerable rate, load reduction is required to restore frequency. The minimum load reduction P_{LSmin} is considered by:

$$P_L - \Delta P_D = \sum_{i=1}^{n-1} P_{G_i} + \sum_{i=1}^{n-1} \Delta P_{\text{Primary control}} + \Delta P_{\text{Secondary control max}} + P_{LS\,\min} \tag{14}$$

$$\Delta P_{LS\,\min} = P_L - \Delta P_D - \sum_{i=1}^{n-1} P_{G_i} - \sum_{i=1}^{n-1} \Delta P_{\text{Primary control}} - \Delta P_{\text{Secondary control max}} \tag{15}$$

$$\Delta P_{LS\,\min} = P_L - \sum_{i=1}^{n-1} P_{G_i} + \frac{\Delta f_{permit}}{f_n} . \mathrm{P}_L . D + \sum_{i=1}^{n-1} \frac{P_{G_{n,i}}}{R_i} . \frac{\Delta f_{permit}}{f_n} \Delta P_{\text{secondary control max}} \tag{16}$$

Equation (15) is abbreviated according to the following equation:

$$\Delta P_{LS\,\min} = \Delta P_L + \frac{\Delta f_{permit}}{f_n} . \beta - \Delta P_{\text{secondary max}} \tag{17}$$

2.4. The phase angle sensitivity or phase distance (PD)

The reciprocal phase angle sensitivity or phase distance (PD) from the load reduction to disconnected generator is considered using the methods in [20-24], that is applied as procedure:

- Calculate the Jacobian matrix from the power flow distribution according to Newton Raphson, and from there obtain the sub matrix J_1 with $J_1 = J_{P\delta} = \left[\frac{\partial P}{\partial \delta}\right]$.
- Inverse matrix, $J_{P\delta}^{-1}$
- Calculate the PD between two bus i and j according to the formula [20, 21]:

$$D_{PD}(i,j)=\frac{\partial\delta_i}{\partial P_i}+\frac{\partial\delta_j}{\partial P_j}-\frac{\partial\delta_i}{\partial P_j}-\frac{\partial\delta_j}{\partial P_i} \tag{18}$$

The purpose of the delivery the load reduction at each buses is to restore the rotor angle deviation faster. The load near the generator outage will have a much reduced load. The formula for this delivery is given in the following:

$$P_{LSi}=\frac{D_{PD,eq}}{D_{PD,m_i}}.P_{LS\min} \tag{19}$$

$$D_{PD,eq}=\frac{1}{\sum_{i\neq m}\frac{1}{D_{PD,m_i}}} \tag{20}$$

where D_{PD,m_i} is the phase space or distance from load reduction to m_i disconnected generator; $D_{PD,eq}$ is the equivalent phase distance

3. SIMULATION AND RESULTS

The PowerWorld simulator version 19 is used to set up the simulation background. The standard IEEE 9-generator 37-bus test system [25] is used to support simulation and calculation. This diagram is shown in Figure 4. The accepted frequency values are between 59.7 Hz and 60 Hz.

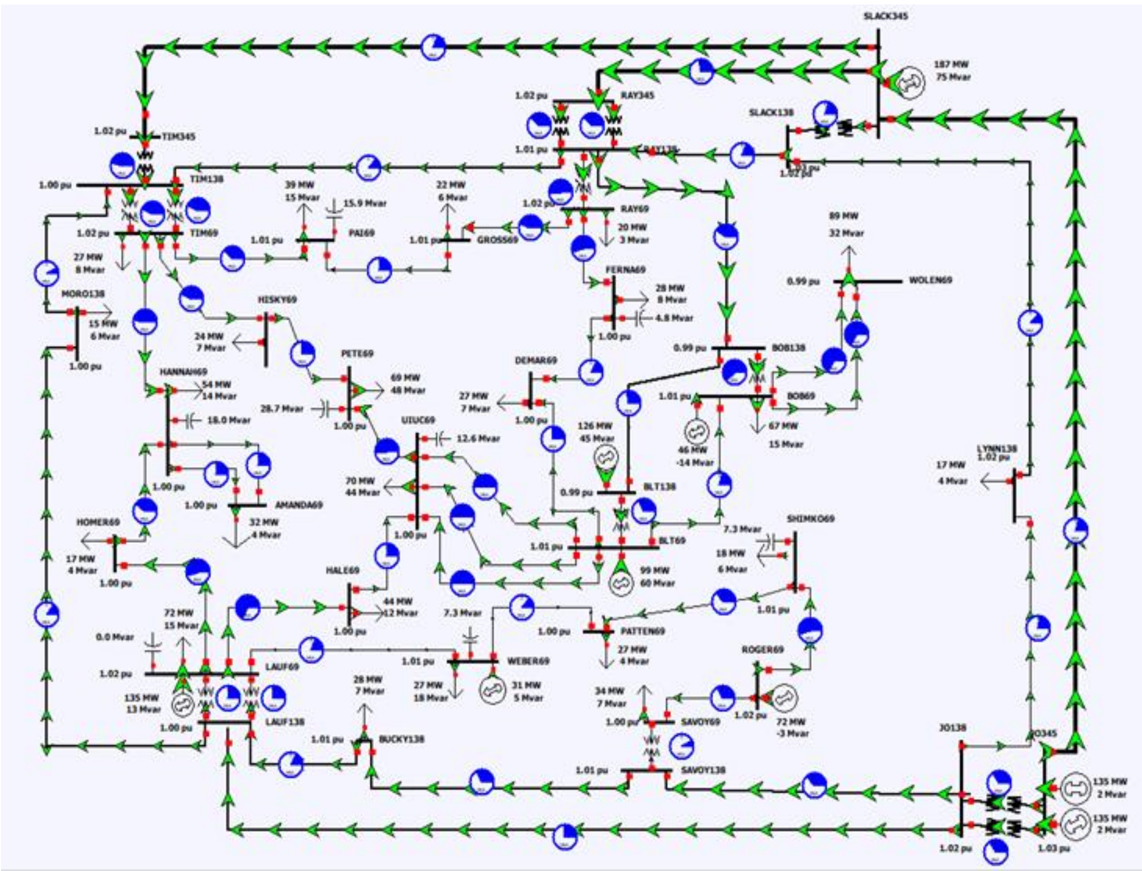

Figure 4. The standard 9-generator 37-bus test system

In this study, the generator JO345#1 is disconnected from the grid. From (11), the frequency obtains 59.6 Hz. Therefore, it is necessary to implement the frequency adjustment action to restore frequency. This adjustment activity is done automatically. The reaction of the turbine governor is performed immediately after the generator JO345#1 is disconnected. The spinning standby power values of the others generators are presented in Table 1.

Table 1. Parameter values and standby power of generators

No	Gen	$P_{G\,(MW)}$	$P_{G\,(pu)}$	R	ΔP_{Pri}	$\frac{P_{G,n}}{R}$
1	WEBER69	31.5	0.315	0.05	0.035	7
2	JO345#1	0	0	0.05	0	0
3	JO345#2	135	1.35	0.05	0.15	30
4	SLACK345	187.28	1.8728	0.05	0.22	44
5	LAUF69	135	1.35	0.05	0.15	30
6	BOB69	46	0.46	0.05	0.052	10.4
7	ROGER69	72	0.72	0.05	0.08	16
8	BLT138	126	1.26	0.05	0.14	28
9	BLT69	99	0.99	0.05	0.11	22
	Total	831.78	8.3178		0.937	187.4

The standard IEEE 9-generator 37-bus test system, the SLACK 345 (SLACK Bus) is selected as the secondary frequency control generator. In this case, application (13) calculates the ability of secondary regulating effects of 10.72 MW. This frequency response following the others generators implement frequency adjustment is displayed at Figure 5.

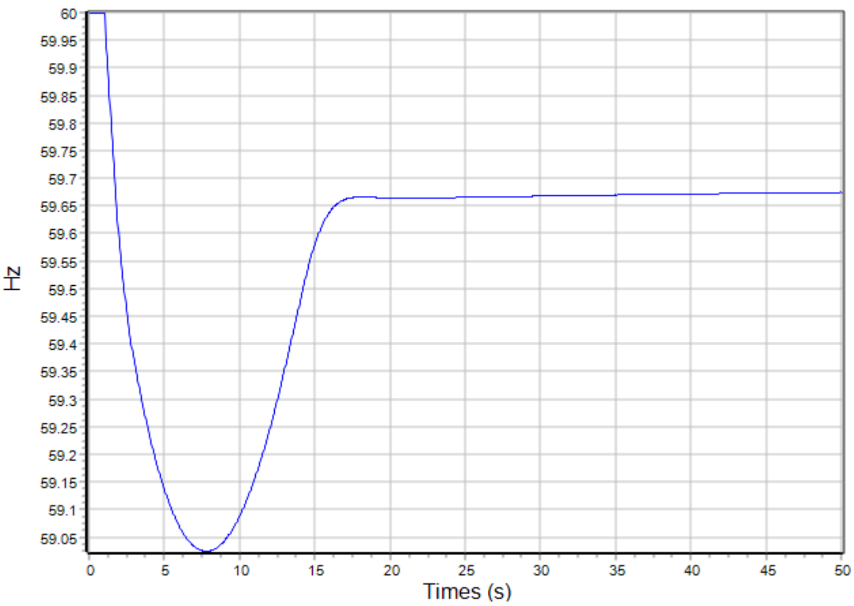

Figure 5. The frequency response after remaining generators implements frequency adjustment

The frequency reaction displays that frequency value has not been reestablished to the permissible operating series. Applying (17) calculates the load to be cut or reduced to reestablish the frequency value to the required operating range.

$$\Delta P_{LS\,\min} = \Delta P_L + \frac{\Delta f_{cp}}{f_0}.\beta - \Delta P_{\text{Secondary control max}}$$

$$\Delta P_L = P_L - \sum_{i=1}^{n-1} P_{G_i} = 9{,}5394 - 8{,}31780 = 1{,}2216$$

$$\beta = P_L.D + \sum_{i=1}^{n-1} \frac{P_{Gi}}{R_i} = 9,5394.0,02 + 187,4 = 187,59$$

$$\Delta P_{LS\min} = 1,2216 + \frac{(-0.3)}{60}.187,59 - 0,1072 = 0,1764\,pu$$

So, the minimum load shedding capacity of P $_{\text{Load shedding min}}$ is 17.64 MW. This value is distributed for each load according to the (19). The comparison of frequency response and rotor angle is shown in Figure 6 and Figure.

It is marked that the suggested method is produced a lesser load reduction than the traditional load reduction method [4], in particular the load shedding number is reduced from 82.93 MW to 17.64 MW. The frequency response of the traditional load reduction method is better than the proposed method. Due to the traditional method, the load is reduced more than the proposed method of reducing the load. However, this value is acceptable because it is inside the suitable range of 59.7 Hz. The rotor deviation angle of both solutions is approximately equivalent. This has many positive implications in maintaining system stability.

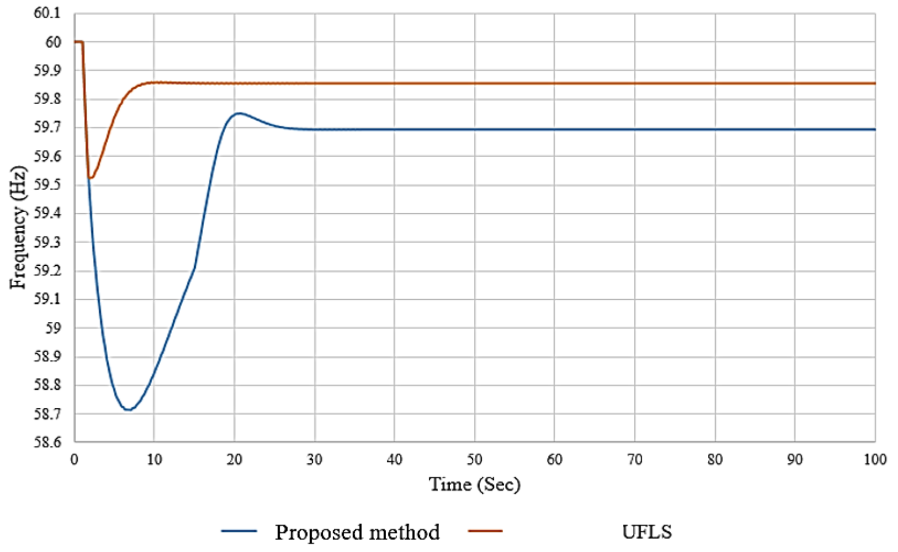

Figure 6. Frequency response of the offered load reduction and old load reduction method

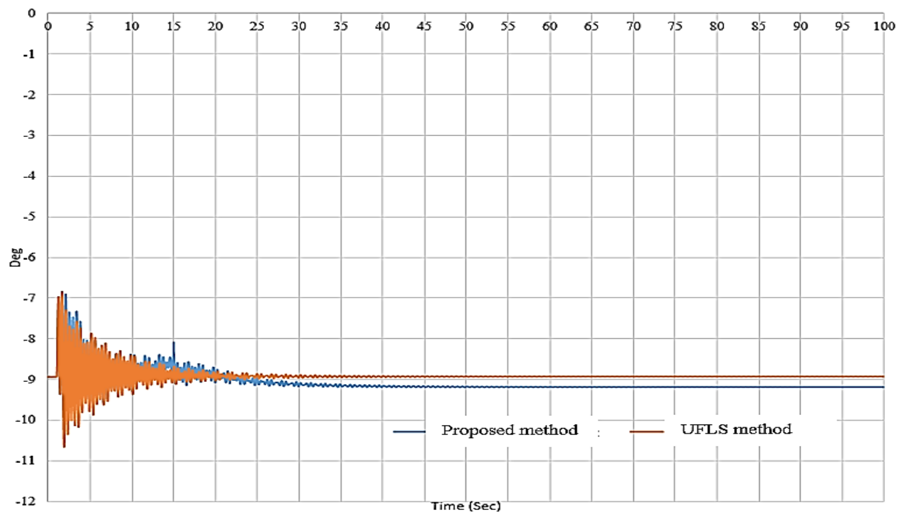

Figure 7. Rotor angle when applying the traditional and the proposed load reduction method

4. CONCLUSION

The consideration of the standby power of the generators has supported to calculate the load to be reduced in accordance with reality. This calculation makes the recovery frequency to an acceptable value. The calculation method takes into account the standby ability the generators, and the process of adjusting frequency of generator in the event of a power outage. Calculating the amount of load to disconnect causes damage to the lowest level for customers, important services when cutting load. The distribution of load shedding capacity based on Phase Electrical Distance makes the rotor deviation angle equivalent to UFLS method. This increases the stability of the system when a power outage occurs.

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