An Underfrequency Load Shedding Scheme for Hybrid and Multiarea Power Systems

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***Abstract*—The purpose of underfrequency load shedding (UFLS) is to maintain the frequency of an interconnected or island power system within permissible limits in case of severe power deficits. Thus, the proper performance of UFLS scheme is of great importance. In hybrid power systems, disconnecting and connecting the power generation sources and loads result in variations in the system parameters. Moreover, the output power of some distributed energy resources, such as photovoltaic (PV) or wind turbine generator (WTG), might change during the load shedding process. These factors may affect the performance of the load shedding scheme and decrease the reliability of power system. Hence, in this paper, a UFLS scheme is proposed that has two advantages: 1) it is independent of power system parameters; and 2) it considers power generation variations during the load shedding process. To verify the effectiveness of the proposed load shedding method, simulation studies are carried out on a hybrid power system including PV, WTG, fuel cell, diesel generator, and battery energy storage system. Finally, the performance of the proposed method on a multiarea power system is evaluated.**

***Index Terms*—Hybrid power system, power deficit, renewable energy sources, underfrequency load shedding (UFLS).**

Nomenclature

P_d	Power deficit.
f_N	Nominal frequency of system in Hz.
$f^{/}_{Hz}$	Frequency first derivative in Hz/s.
t_0	Time at which power deficit occurs.
S_i	Apparent rated power of ith DER.
H_i	Inertia constant of ith DER.
H_{a-i}	Inertia constant of ith area of power system.
H_{eq}	Equivalent inertia constant of the hybrid power system.
n	Number of the DERs.
H_{eq_i}	Updated inertia constant used for the ith load shedding step.
$P_{sh_{i-1}}$	Value of shed load in $(i-1)$th load shedding step.
$f^{/}_{b_{i-1}}$	Value of frequency derivative immediately before the $(i-1)$th load shedding step.
$f^{/}_{a_{i-1}}$	Value of frequency derivative immediately after $(i-1)$th load shedding step.
f_i	Frequency of the ith area.
f_{COI}	Frequency of the center of inertia.

Manuscript received January 2, 2014; revised May 3, 2014 and July 5, 2014; accepted August 9, 2014. Paper no. TSG-00007-2014.

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Digital Object Identifier 10.1109/TSG.2014.2349999

I. Introduction

In SEVERE frequency decline situations, underfrequency load shedding (UFLS) is the only appropriate way to prevent a power system from collapsing. Underfrequency operation could be a huge threat to the secure and stable operation of a power system [1]–[4]. Therefore, the suitable amount of load should be shed as soon as possible to retain the power balance and prevent the frequency from falling below the specified value. The most common protection scheme used in power systems for this purpose is UFLS [5]. UFLS schemes use the frequency of system or its derivatives to determine the amount of power deficit and compensate it by several steps of load shedding [6]–[10].

Conventional method is the first generation of UFLS scheme introduced in [11] and used by some other authors in [12]–[14] for relay setting. The first stage in this method is determination of the worst probable generation loss event which results in the highest initial rate of frequency decay. Then, the amount of load shedding which ensures that the frequency will not deviate below the minimum permissible value in this case should be specified. After that, the number and size of load shedding steps are determined based on trial and error to achieve an acceptable operation in case of the worst probable contingency. However, determining the worst probable contingency and the size and number of load shedding steps are not trivial tasks. In this method, a specified amount of load is shed without considering the amount of power deficit. As a result, in most cases the amount of load which is shed will be more or less than necessary. This, in turn results in undesired damage and serious costs [10].

To overcome the above mentioned problems, an adaptive UFLS method is implemented in [6]. In this method, the amount of power deficit is calculated based on the frequency derivative at the moment when the disturbance occurs. Therefore, there is no need to determine the worst probable contingency and a proper amount of load based on the calculated power deficit is shed in the specified steps. It is worth mentioning that in cases where power deficit is caused by generating units outage or islanding a part of power system, a reactive power deficit also exists which results in an instantaneous voltage sag. This voltage sag changes the amount of power consumed by loads. Therefore, based on the fact that there is a delay in the measurement of the frequency and frequency derivative, the power deficit calculated using frequency derivative may be misleading, i.e., due to the decrease in power consumption the calculated power deficit will be less than the actual value. Another defect which this UFLS method suffers from is that the amount of shed load does not have a linear relation with power deficit. As a result, using this UFLS scheme the amount of shed load in consequence of two nearly equal power deficits may be significantly different.

In [7] and [8], some modifications are applied to improve the performance of adaptive UFLS scheme including an additional term, which represents the voltage dependence of loads, in determining amount of power deficit. Moreover, a term for considering the activated spinning reserve is added to minimize the amount of shed load in any steps. Also, it is claimed that using this method the shedding amount will be nearly a linear function of power deficit. However, as authors have declared, determining the coefficients which represent the voltage dependence of loads and the other parameters which are needed for determining the actual power deficit is difficult.

In [9], a new UFLS scheme based on the estimated minimum value which frequency reaches as a result of a power deficit is proposed. In this UFLS scheme no knowledge of power system parameters is needed. In this method the frequency second derivative is estimated based on a Newton method; then, the minimum frequency is forecasted using numerical integration. After that, the amount of load which is to be shed is determined based on the minimum frequency. Using this UFLS method the shed load is nearly a linear function of power deficit. However, measuring the frequency second derivative is a challenging problem.

As mentioned in [15], determination of the exact value of parameters used in load shedding scheme for the hybrid power systems in which power sources are distributed all over the system is more cumbersome. Also, the system parameters may change at any time as a result of connecting or disconnecting power generation sources. Furthermore, sudden changes in power generated by renewable energy sources such as solar cells or wind turbine may change the amount of power deficit during the load shedding process [16]. Moreover, islanded power systems are much weaker than integrated power systems; so, even a small disturbance can affect their stability [17]. Considering all of these, a fast and reliable UFLS scheme which is independent of power system parameters and considers the changes in the power during load shedding process is a vital need for hybrid power systems.

In this paper, an UFLS method is proposed which uses the frequency first derivative for estimating the amount of power deficit. Hence, inertia constant is the only parameter of power system that might affect the estimated power deficit. In the proposed UFLS method, the inertia constant is estimated after the first load shedding step. The next load shedding steps are carried out based on the updated power deficit which is calculated using the updated value of inertia constant. So, the proposed UFLS scheme will be independent of the power system parameters. In addition, this method considers the changes in generated power during the load shedding process. Therefore, the proposed UFLS method has a robust performance in case of power system parameters variation and additional power deficits which may occur during the load shedding process.

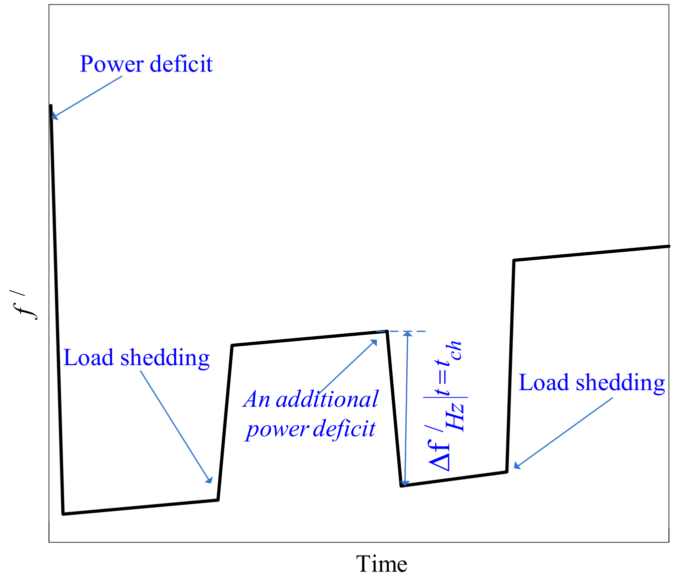

Fig. 1. Frequency derivative changes in case of change in power deficit.

II. Proposed Load Shedding Scheme

In load shedding schemes, at the first stage, the amount of power deficit should be determined. Here, using swing equation, the power deficit is estimated [6]–[8], [14]

$$P_d = \frac{2H_{eq}}{f_N} . f^{/}_{Hz} \left| t = t_0 \right. \tag{1}$$

where $f^{/}_{Hz} \left| t = t_0 \right.$ is the value of frequency derivative immediately after the disturbance and the equivalent inertia constant of the power system is calculated as follows:

$$H_{eq} = \frac{\sum_{i=1}^{n} H_i . S_i}{\sum_{i=1}^{n} S_i}. \tag{2}$$

In cases where the inertia constant of generating units are not available, after occurrence of a power imbalance the equivalent inertia constant of the hybrid power system can be estimated by [17]

$$H_{eq} = \Delta P \frac{f_N}{2 . f^{/}_{Hz} \left| t = t_{im} \right.} \tag{3}$$

where t_{im} is the moment when a change in generated or demanded power occurs and ΔP is the amount of this change.

Due to the fact that in hybrid power systems the output power of some generating units such as wind turbines or solar cells may change suddenly during the load shedding process, it is necessary to continuously update the value of P_d during the load shedding process. Any sudden change in power balance of system appears as a step change in frequency first derivative, as shown in Fig. 1. A sudden decrease in P_d, which is caused by load shedding or increase in output power of generating units, results in an incremental step change in the frequency derivative. On the contrary, a sudden increase in P_d, caused by a sudden decrease in the output power of generating units, results in a step decrease in the frequency derivative. As a result, when an additional power deficit occurs during the load shedding process, P_d can be updated for the next steps of load shedding according to (4)

$$P_{d-\text{new}} = P_{d-\text{old}} + \frac{2H_{eq}}{f_N}.\Delta f^{/}_{Hz}\,|t = t_{ch} \tag{4}$$

where $P_{d-\text{old}}$ is the previously calculated power deficit, t_{ch} is the time at which additional power deficit occurs and $\Delta f^{/}_{Hz}$ is the change in frequency derivative.

In this load shedding scheme, power deficit is compensated in four steps of load shedding. Namely, if the frequency reaches 49, 48.8, 48.6, and 48.4 Hz, then 35%, 30%, 20%, and 15% of the estimated power deficit will be compensated by load shedding, respectively. These steps are deliberately chosen to prevent the frequency from falling below 48.4 Hz. Finally, if, for any reason, the frequency falls below 48.4 Hz, an amount of load equal to the difference between the initial power deficit and the load shed in the previous steps will be shed. It is worth mentioning that these frequency thresholds and distribution of load shedding in different steps are chosen to minimize the total shed load for the higher amounts of power deficit and make maximum use of the primary frequency response for compensating the power deficit [7].

Actually, each step of load shedding reduces the rate of frequency drop and consequently enables the primary frequency control of generators to provide more power before the next step of load shedding. This characteristic can be implemented to optimize the load shedding scheme. A measure is required to estimate the power provided by primary frequency control. Namely, before triggering each load shedding step, it can be checked whether the increase in power generated by DERs is higher than the amount of load which is to be shed until that step. If the answer is positive, that load shedding step will be canceled. Namely, if the following criteria are satisfied, the kth step of load shedding will be canceled [8]:

$$f^{/}_k < 0 \quad \text{and} \quad \frac{f^{/}_0 - f^{/}_k}{f^{/}_0} \times 100 \geq \text{TLS}_k \tag{5}$$

where $f^{/}_0$ and $f^{/}_k$ are frequency derivatives at the time power deficit occurs and immediately before kth load shedding step, respectively, and TLS_k is total load, which is to be shed until the kth load shedding step.

It is worth noting that the power deficit is updated continuously using (4). If the percentage of shed load in the previous steps is different from the predetermined values (according to updated value of power deficit), it will be compensated in the next step. This reduces the possibility of under/overshedding which in turn enhances the reliability of the proposed UFLS scheme.

Due to the fact that the power generating units are distributed throughout the hybrid power systems and their composition might change with time, the equivalent inertia constant of system is not actually fixed. Hence, in the proposed load shedding scheme, a predefined value of inertia constant is used for the first step of load shedding. But, using the swing equation, the exact value of inertia constant is calculated as follows

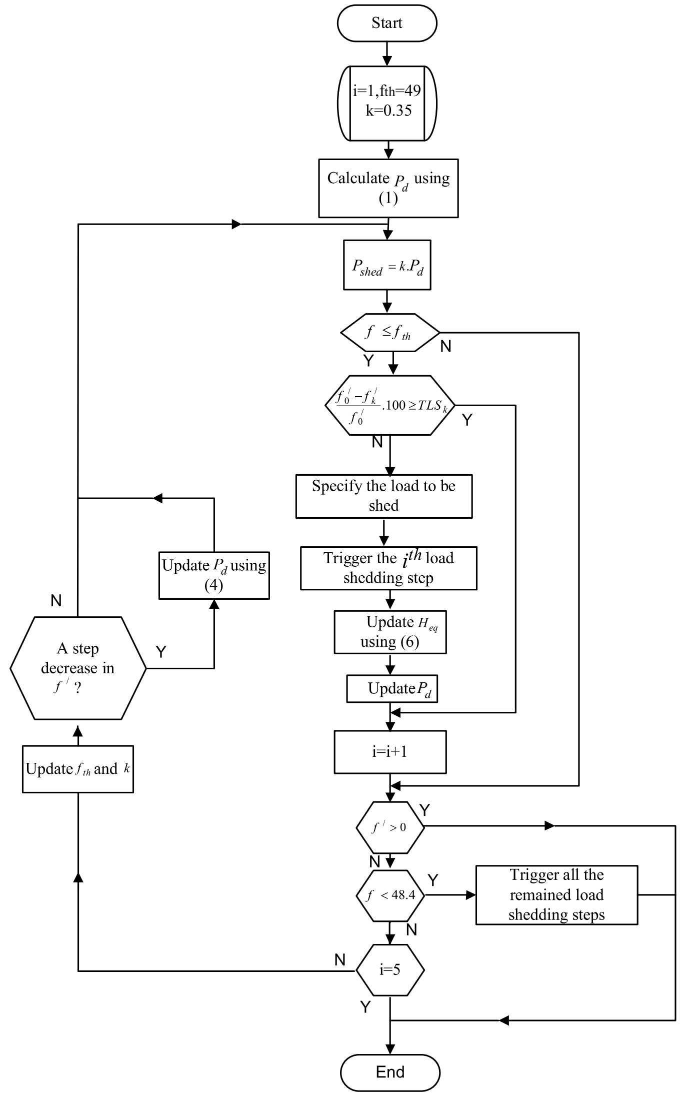

Fig. 2. Flowchart of the proposed UFLS method.

and used for the next load shedding steps:

$$H_{eq_i} = \frac{f_N \times P_{sh_{i-1}}}{2\left(f^{/}_{a_{i-1}} - f^{/}_{b_{i-1}}\right)}. \tag{6}$$

Having determined the exact value of power deficit, loads to be shed in each load shedding step should be specified. Based on the regulations and policies of the specific power system which implements the UFLS scheme, a wide variety of methods can be used to prioritize the loads to be shed. In most power systems, sheddable loads are prioritized based on their importance and most important loads are shed last [18]. On the other hand, the buses on which UFLS relays are installed, can be adaptively prioritized based on their voltage and then the relays with lower voltage trip first [19]. Alternatively, the sensitivity-based method proposed in [20] can be implemented to determine the amount of load should be shed from each bus. In fact, this method proposes that the loads supplied by the tripped generation should be shed. In this paper, the method proposed in [20] is used to determine the amount of load should be shed from each bus.

The flowchart of proposed UFLS scheme is given in Fig. 2.

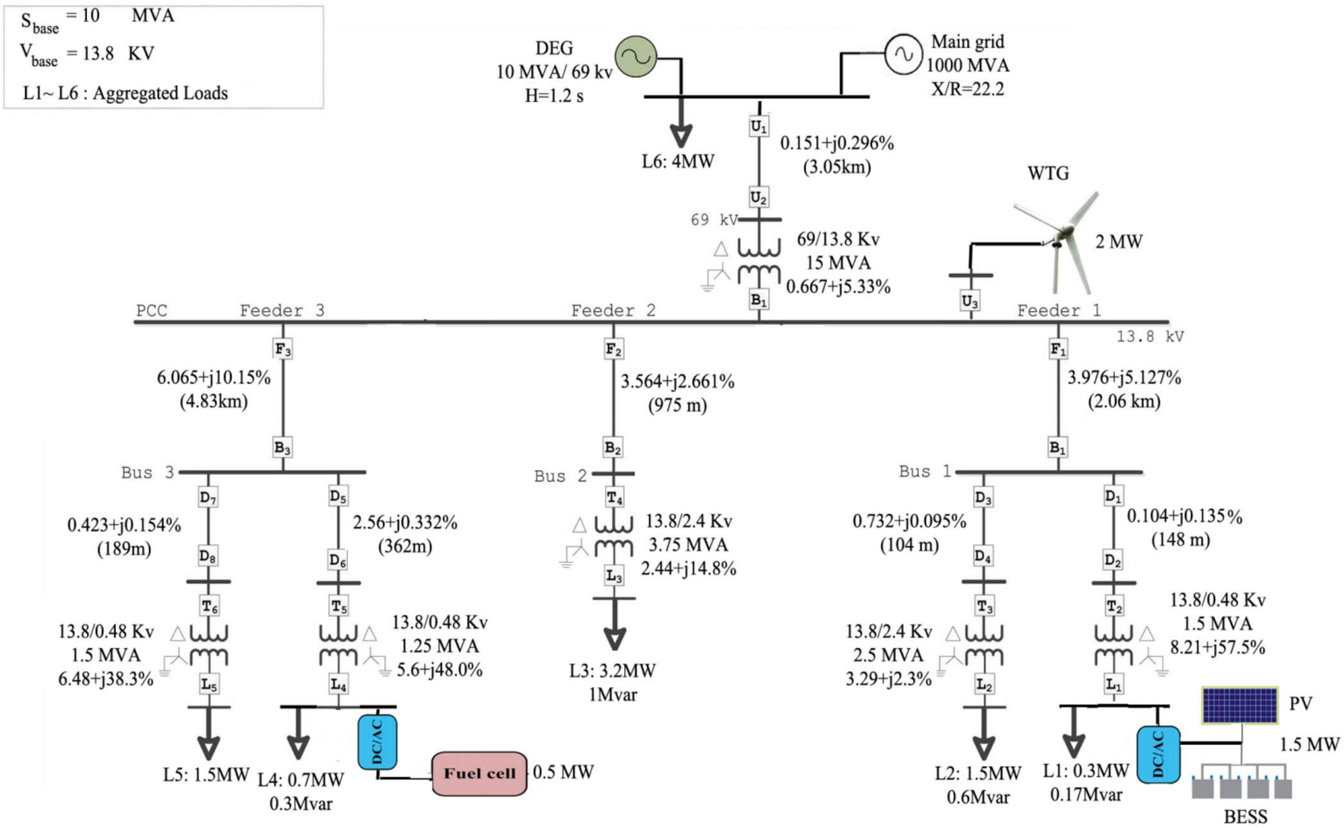

Fig. 3. Schematic diagram of the understudy hybrid power system.

III. Simulation Studies

This section has two parts. In the first part, the proposed UFLS scheme is compared with the adaptive UFLS scheme presented in [8] with the aid of several simulation studies which may affect the effectiveness of UFLS schemes. Here, the proposed UFLS scheme and the scheme presented in [8] are called novel and adaptive load shedding schemes, respectively. For the purpose of comparison between the UFLS schemes a hybrid power system configuration, explained in Section III-A is used.

In the second part, the performance of the proposed load shedding scheme in a multiarea power system is investigated. For this paper a three area power system is selected.

It should be mentioned that the aim of the proposed UFLS scheme is to prevent the frequency from deviating below 48.4 Hz in the both test systems.

A. Hybrid Power System

The understudy hybrid power system which is shown in Fig. 3 is a modified IEEE standard distribution system [21]–[23]. The loads in his distribution system are supplied by main grid, a 10 MVA diesel generator (DEG), a 2 MW wind turbine generator (WTG), a set of 1.5 MW photovoltaic (PV) and battery energy storage system (BESS), and a 0.5 MW fuel cell (FC).

To verify the effectiveness of the presented UFLS method several comparative case studies are carried out. Table I shows the amount of aggregate loads shed in each scenario.

TABLE I
Load Shed From Each Bus in Different Scenarios (MW)

Load	Step	Scenario I	Scenario II	Scenario III	Scenario IV
L2	1	0	0	0	0
	2	0	0.43	0	0
	3	0	0.13	0	0
	4	0	0.1	0	0
L3	1	0	0	0	0
	2	0	0	0	0.85
	3	0	0	0	0.26
	4	0	0	0	0.2
L4	1	0	0	0	0
	2	0	0	0	0.05
	3	0	0	0	0.01
	4	0	0	0	0.01
L5	1	0	0	0	0
	2	0	0	0	0.4
	3	0	0	0	0.13
	4	0	0	0	0.09
L6	1	0.60	0.60	0.52	0.60
	2	0.72	0.72	0.81	0.72
	3	0.41	0.41	0.41	0.41
	4	0.31	0.31	0.3	0.31

It should be mentioned that load 1 (L1) is a critical load never shed. It has been assumed that distributed energy resources are generating maximum power when the power deficit occurs.

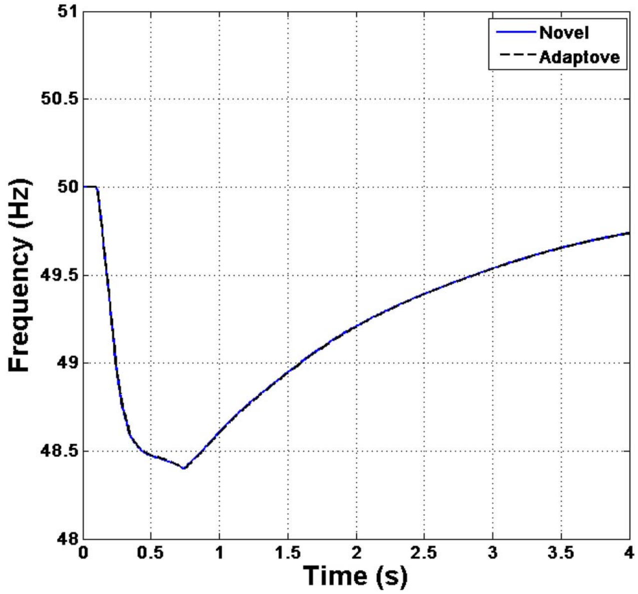

Fig. 4. Frequency after islanding the hybrid system.

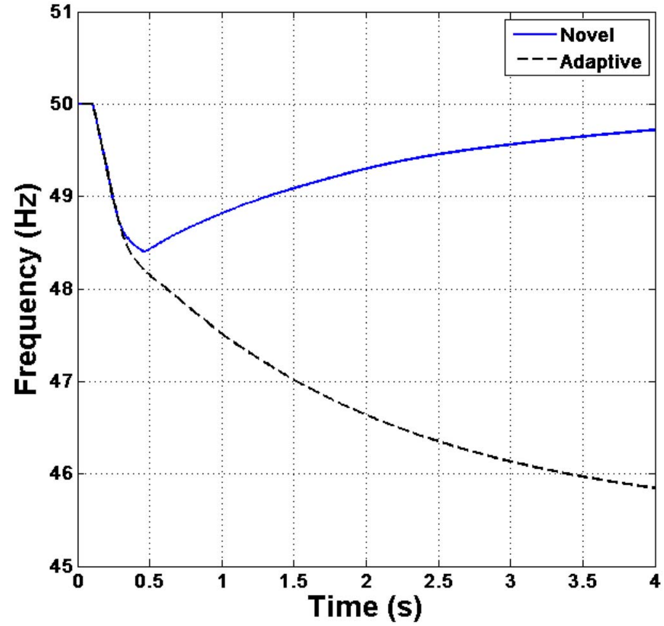

Fig. 5. 0.75 MW additional power deficit during the load shedding process.

1) Scenario I: Islanding Hybrid Power System: Usually hybrid power systems are connected to the main grid. But, in special situations, such as occurrence of faults in neighborhood of hybrid power system, it may be necessary to disconnect it from the main grid. So, if the hybrid power system receives power from the main grid before disconnection, a portion of its load should be shed to retain the power balance and maintain the frequency within permissible limits.

Here, the hybrid power system is islanded at $t = 0.1$ s when it receives 2.04 MW from the main grid. As Fig. 4 shows, both UFLS methods are successful in recognizing the amount of power deficit and have shed the proper amount of load to maintain the frequency within the allowed limits.

2) Scenario II: Decrease in Sun Irradiance During Load Shedding Process: The power generated by PV cells is a function of weather condition and cell temperature [24]. So, a sudden change in the weather condition or temperature affects the power generated by PV cells. In this case study, the performance of the novel and adaptive load shedding schemes in case of a 0.75 MW decrease in PV output power, due to a decrease in irradiance, at 0.26 s after beginning the load shedding process is investigated. The load shedding process has been started at $t = 0.1$ s in consequence of a 2.04 MW power deficit. From Fig. 5 it is clear that the decrease in the total power generation of the hybrid power system is recognized by the novel load shedding scheme and accordingly the amount of load which is to be shed is updated to prevent the frequency from falling below the permissible limits. But, the adaptive load shedding scheme is not able to recognize the decrease in power generation during the load shedding process and consequently it could not maintain the frequency within the permissible limits.

3) Scenario III: Inertia Constant Variations: Due to the fact that obtaining the exact value of inertia constant of hybrid power systems is not a trivial task and also it may change by connecting/disconnecting DERs, it is necessary for the load shedding schemes in hybrid power systems to be independent of the inertia constant. As explained in Section III, a predefined value of inertia constant is used to calculate the power deficit for the first step of load shedding in the novel scheme. However, to calculate the power deficit for the next steps of the load shedding, the exact value of H_{eq} will be determined from (6).

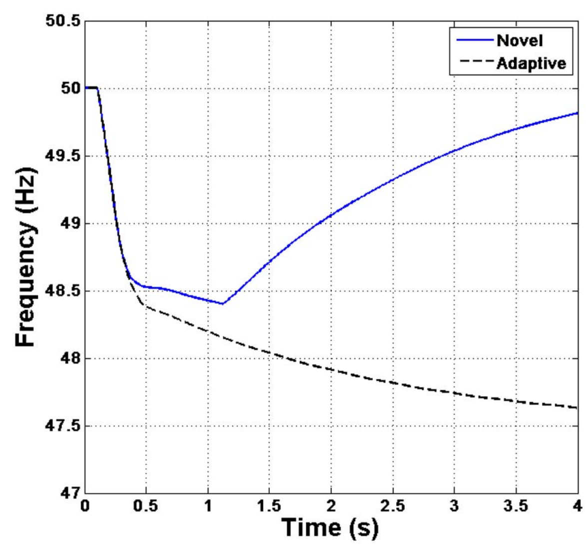

Fig. 6. Performance of novel and adaptive UFLS schemes in case of a 2.04 MW when the inertia constant (H_{eq}) is different from predefined value (H_0).

Here, the performance of the proposed load shedding scheme where the real inertia constant of the hybrid system (H_{eq}) is different from the predefined value (H_0), used in UFLS scheme, is evaluated. Fig. 6 demonstrates the performance of novel and adaptive load shedding schemes in case of a 2.04 MW power deficit when H_{eq} is 1.38, but H_0 is 1.2.

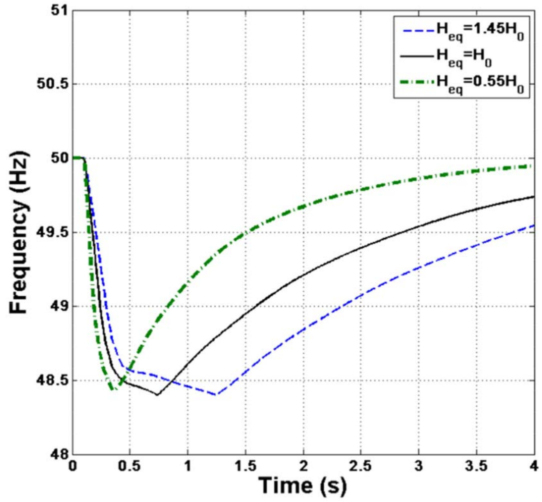

Fig. 7. Performance of the UFLS scheme in case of a 2.04 MW power deficit when inertia constant (H_{eq}) is different from the predefined value (H_0).

TABLE II
ESTIMATED INERTIA CONSTANT

H_{eq} (s)	Estimated P_d(MW)	Error (%)
0.66	2.04	0
0.84	2.06	1
1.02	2.08	2
1.2	2.04	0
1.38	2.08	2
1.56	2.08	2
1.74	2.08	2

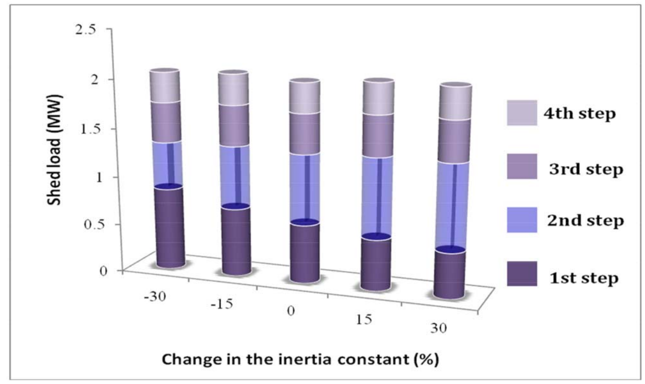

Fig. 8. Amount of shed load in every load shedding step.

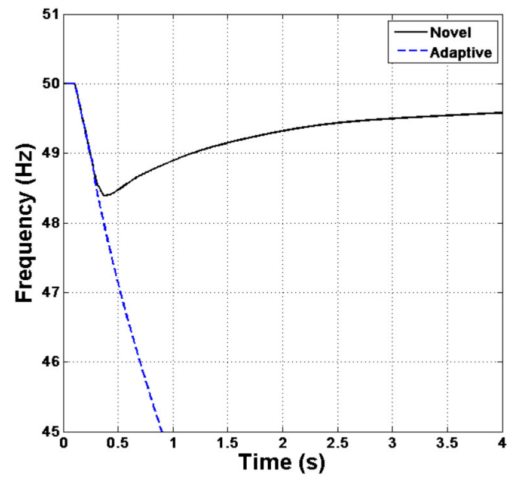

Fig. 9. Performance of novel and adaptive load shedding scheme in case of an additional power deficit resulted by WTG outage; the load shedding process is initially activated at $t = 0.1$ s due to a 2.04 MW power deficit.

It is clear that the novel UFLS scheme is successful in estimating H_{eq} after the first load shedding step and preventing the frequency from falling below the permissible limit. But, the adaptive UFLS method cannot estimate H_{eq}; therefore, it is not successful in maintaining the frequency in the desired interval.

Here, the performance of the novel UFLS scheme in case of H_{eq} variation is further investigated. Load shedding is triggered by a 2.04 power deficit in cases which H_{eq} ranges from 0.66 to 1.74 while H_0 is 1.2. It is clear from Fig. 7 that in all cases the novel load shedding scheme has a good performance. Table II shows that in all cases power deficit is estimated by a high precision, using the estimated H_{eq}. The load shed in every load shedding step when the inertia constant is different from the predefined value is shown in Fig. 8. From this diagram, it can be found that not knowing the exact value of H_{eq} leads to a difference between the amount of load shed and the amount of power deficit which was planned to be compensated in the first step of the load shedding (35% of total power deficit). Namely, if H_{eq} is lower/higher than H_0, the load shed in the first step will be more/less than the amount assumed to be shed in the first step. After the first step of load shedding, the exact value of H_{eq} is calculated using (6) and considering the error in the amount of shed load in the first step, an amount load is shed in the second step to make the total shed load in the first two steps equal to 65% of power deficit. Then, the shed load in the third and fourth steps of load shedding is 20% and 15% of power deficit, respectively.

Therefore, the total amount of shed load is not dependent on the error in predefined inertia constant and consequently this UFLS method is independent of the power system inertia constant.

4) Scenario IV: WTG Outage During Load Shedding Process: The output power of WTGs depends on wind speed. An increase/decrease in wind speed results in an increase/decrease in power generated by WTG. However, when the wind speed goes above/below cut-off/cut-in speed, WTGs output power will be zero [25]. WTG generates the maximum power when the wind speed is a little below cut-off speed; so, a small increase in wind speed will dramatically decrease the power generated by WTG to zero.

In this case study, the performance of novel and adaptive UFLS schemes when the wind speed goes beyond cut-off speed during the load shedding process and results in an additional power deficit is evaluated. The UFLS process is triggered at $t = 0.1$ s in consequence of a 2.04 MW power deficit and an additional 2 MW power deficit occurred at $t = 0.26$ s due to WTG outage.

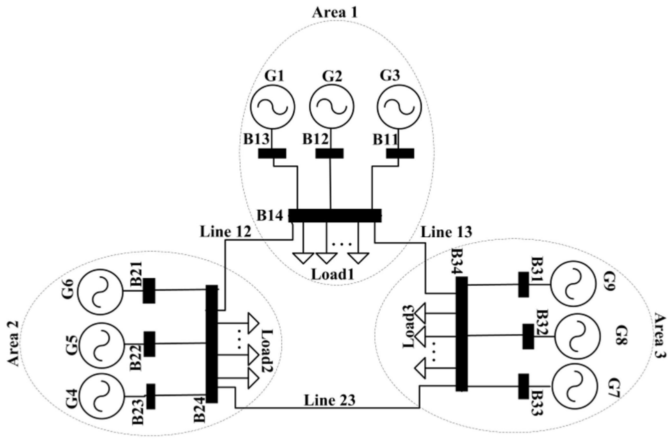

Fig. 10. Single line diagram of the three-area power system.

Fig. 9 shows that the novel UFLS has recognized the additional power deficit and has shed the proper amount of load to maintain frequency in permissible limits. But, the adaptive UFLS scheme doesn't have a proper performance in stopping the frequency fall and the power deficit results in the hybrid power system's collapse.

B. Multiarea Power System

In the previous section, the effectiveness of the proposed UFLS scheme in a single area hybrid power system has been verified. It has been shown that this load shedding scheme is robust in case of power system parameters changes and variation of power generated by renewable energy sources.

In this section, the performance of the proposed scheme on a three area power system is investigated. The single line diagram of the understudy power system is shown in Fig. 10.

The parameters values of this three-area power system are given in [26].

The frequency response of power system after a 0.02 P.U. power deficit in area 1 is shown in Fig. 11. In this figure, f_1, f_2, f_3, and f_{COI} represent the frequencies of areas 1, 2, 3, and center of inertia, respectively. The frequency of center of inertia is defined as follows:

$$f_{COI} = \frac{\sum_{i=1}^{3} H_{a-i} f_i}{\sum_{i=1}^{3} H_{a-i}} \tag{7}$$

where H_{a-i} is the inertia constant of the ith area.

It can be found from Fig. 11 that after occurrence of a power deficit in area 1, the frequency of all areas will drop and fluctuate. However, f_{COI} drops smoothly without fluctuations. Fig. 12 shows that due to the occurrence of a power deficit in area 1, there is a step change in f_{COI} and f_1. Hence, both of these frequencies can be implemented to estimate the value of power deficit. But, the frequency of area 1 fluctuates (it has semi-periodical variations). Usually, the load shedding schemes should have a fast operation to preserve the power system stability. The derivatives of f_{COI} and f_1 within 1 s after the power deficit is shown in Fig. 13. From this figure, it is clear that within this time period derivative of f_1 does not fluctuate, but increases rapidly and this increase is caused by the increase in power transmitted to the area 1 from the other areas via tie lines, not by the primary frequency response. So, if we want to make use of (5) as a measure representing the primary frequency response, f_{COI} is the best choice. Although the amount of power deficit is estimated using f_{COI},

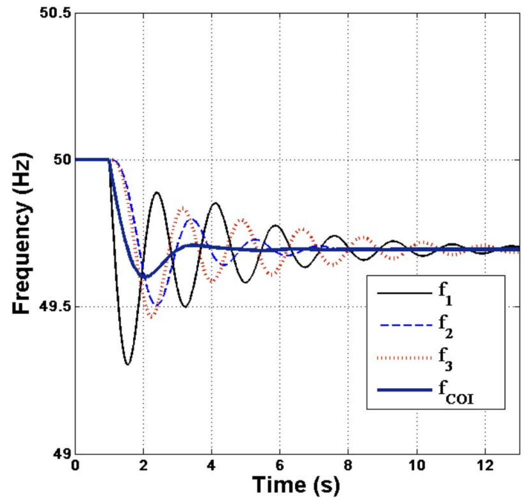

Fig. 11. Frequencies variation after a 0.02 P.U. power deficit in area 1.

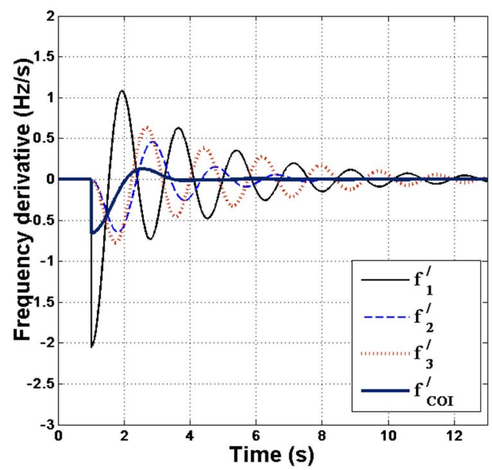

Fig. 12. Frequencies derivative after a 0.02 P.U. power deficit in area 1.

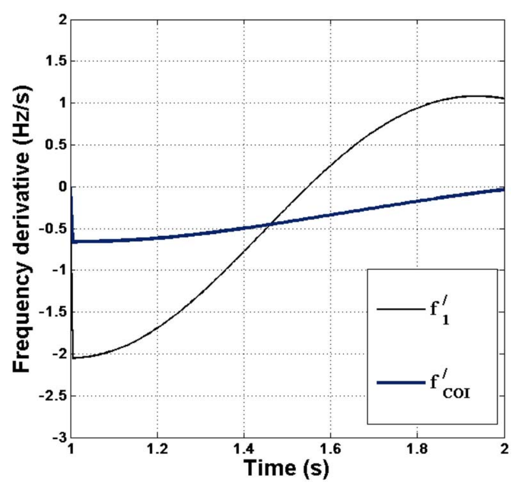

Fig. 13. Derivatives of f_1 and f_{COI}.

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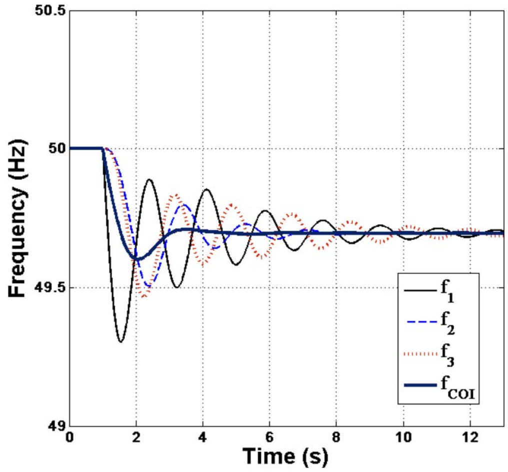

Fig. 14. Frequencies after load shedding due to a 0.05 P.U. power deficit.

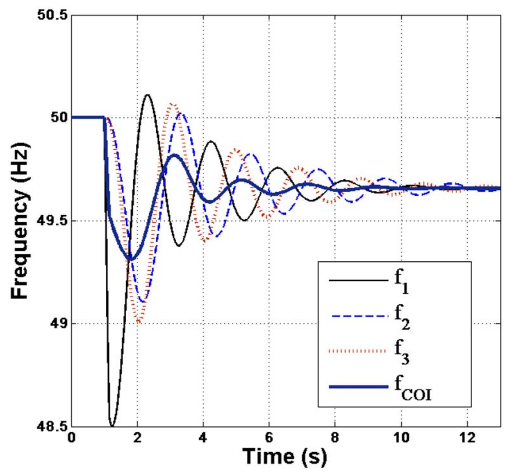

Fig. 15. Effect of change in H on performance of UFLS scheme.

the UFLS relays of each area trip based on the frequency of that area.

Having determined the value of power deficit, the load shedding process can be started. Actually, the load to be shed can be selected solely from the area in which power deficit has occurred or from all three areas. If the load shedding is carried out in all areas, the tie lines power may change from the scheduled values and this might make some of the tie lines overloaded. In this situation, the protection relays of the overloaded line may trip and result in more power deficit [27]. Hence, if load shedding is to be done in all areas the limits of tie lines power should be taken in to account. However, in this paper, load is shed only in the area with power deficit.

In Sections III-C–III-E, the performance of the proposed UFLS scheme on a three-area power is evaluated.

1) Power Deficit in Area 1: In this case study the performance of the proposed load shedding scheme in case of a 0.05 P.U. power deficit in area 1 is evaluated. The frequency response of system is shown in Fig. 14. It is clear that the load shedding scheme is successful in preserving the power system stability.

2) Effect of Change in H on UFLS Scheme: Here, the inertia constant of area 1 is increased by 50% from the value

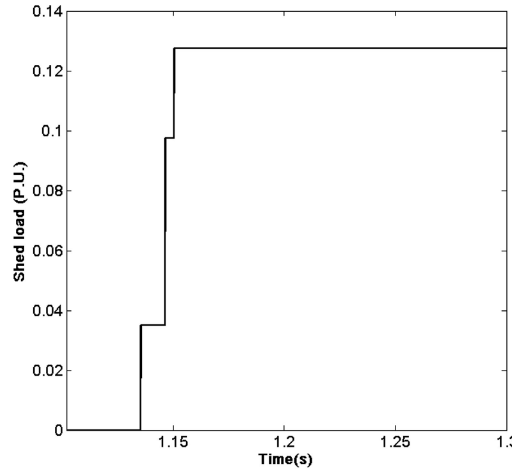

Fig. 16. Load shed in every load shedding step.

predetermined for the load shedding scheme. In this situation, a 0.15 P.U. power deficit is occurred in area 1 and the performance of the UFLS is studied. As shown in Fig. 15, the UFLS scheme is able to maintain the frequencies of all areas within the permissible limits. However, as explained in detail for the hybrid power system, because of this increase in inertia constant the load shed in the first step is less than predefined value (35%). But, as shown in Fig. 16, after the first step of load shedding inertia constant is estimated and in the second step an amount of load is shed to make the load shed in the first two steps equal to the predefined value (65%). In this case, the load shed in the first three steps, which equals 85% of power deficit, is enough for maintaining the frequency within permissible limits. Hence, the fourth step is skipped.

3) Effect of Change in Power System Parameters Except H on UFLS Scheme: In this case study, the effect of other power system parameters on the proposed UFLS scheme is investigated. Different parameters may affect the frequency response of power system in case of a sever power deficit. Inertia constant (H) affects the initial slope and rate of frequency decay. Load damping factor (D), governor time constant (T_g), turbine time constant (T_t), and governor's droop characteristic (R) influence the minimum frequency of system without load shedding. However, steady state frequency is mainly affected by D and R.

Fig. 17 shows the frequency of area 1 after a 0.1 P.U. in this area while the parameters of the area except the inertia constant (R, D, T_g, and T_t) are in increased/decreased by 50% from the normal values. It can be found from this figure that, although the change in these parameters may influence the frequency response, it does not deteriorate the effectiveness of the UFLS scheme. Because, as mentioned before, H is the only parameter that affects the initial rate of frequency decay and consequently the power deficit estimated using (1) and (4). The results given in Table III shows the proposed UFLS scheme is able to maintain the frequency of power system within the permissible limits. Moreover, it is obvious that the change in these parameters has not affected the estimated power deficits.

Fig. 17 shows the frequency of area 1 after a 0.1 P.U. in this area while the parameters of the area except the inertia h the exception of pagination.

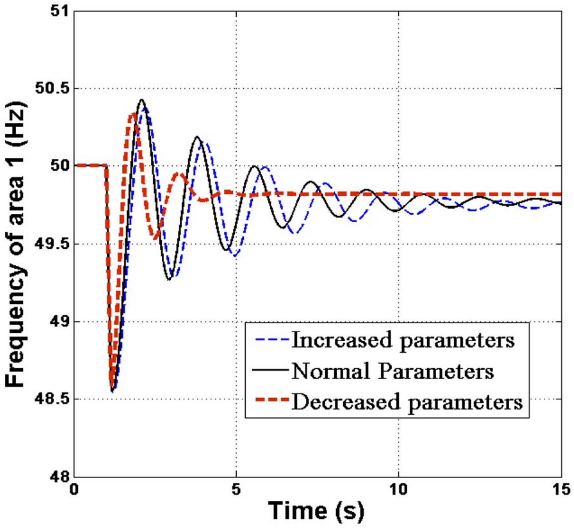

Fig. 17. Effect change in parameters of area 1 except H on the UFLS scheme.

TABLE III
PERFORMANCE OF THE UFLS SCHEME IN CASE OF PARAMETERS VARIATION

	Increased	Normal	Decreased
P_d(P.U.)	0.1	0.1	0.1
f_{min}(Hz)	48.54	48.55	48.59
f_{ss}(Hz)	49.75	49.77	49.82

constant (R, D, T_g, and T_t) are in increased/decreased by 50% from the normal values. It can be found from this figure that, although the change in these parameters may affect the frequency response, it does not deteriorate the effectiveness of the UFLS scheme. The results given in Table III shows the proposed UFLS scheme is able to maintain the frequency of power system within the permissible limits. Moreover, it is obvious that the change in these parameters has not affected the estimated power deficits.

IV. CONCLUSION

In this paper, an UFLS scheme for a hybrid distribution system including PV, FC, DEG, and BESS was proposed. This load shedding method estimates the power deficit based on the frequency first derivative. It was proved that this load shedding scheme is independent of power system parameters, particularly inertia constant. Moreover, considering the substantial variations in power generated by PVs and WTGs, the effectiveness of the proposed UFLS scheme in response to additional power deficit during the load shedding process was proved. It was confirmed that in case of an additional power deficit during the load shedding process, the proposed UFLS scheme is able to estimate the value of power deficit correctly. Consequently the proper amount of load is shed to prevent the frequency from falling below the minimum permissible value.

Then, the performance of the proposed UFLS scheme on a multiarea power system is discussed. It was shown that this load shedding scheme can maintain the frequency of all areas within the allowed limits.

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