A Topology-based Scheme for Adaptive Underfrequency Load Shedding

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Abstract—**This paper presents a topology-based scheme for adaptive underfrequency load shedding (UFLS). By tracking changes of power system topology and information about power flow, the proposed method is able to identify islanded conditions, the number of islands and their deficits of active power, which are fundamental parameters for the adaptive UFLS scheme. The algorithm is also applicable to interconnected power systems, where islanding of the power grid can go beyond country borders and create new asynchronous areas that can comprise several national transmission systems. In this case, the proposed method can properly estimate the power deficit of each area and coordinate the load shedding of several affected power systems in the underfrequency area. The main idea of the proposed method is demonstrated by simulations of the IEEE reliability test system in PSS/E and real time coordination of the adaptive UFLS schemes in Labview.**

Index Terms— **Adaptive load shedding, Islanding, Power deficit, System topology, Underfrequency.**

I. INTRODUCTION

Underfrequency load shedding (UFLS) has been used for many years to protect power grids against system collapse when they are experiencing underfrequency problem. However, the conventional load shedding scheme, in some cases, was not able to fulfil its important task. As a result, blackouts occurred and affected millions of people [1]-[3]. One of the reasons is the conventional scheme does not sufficiently consider the location and amount of the power deficit, which is the main driving force of the frequency drop. To improve the existing load shedding scheme, several methods for adaptive UFLS have been proposed in [4]-[6]. In [4], a low-order system frequency response model [7] is used to estimate the power deficit from the initial slope of the frequency. Based on this information, a certain amount of load is adaptively shed. Similarly, [5] proposes a new model for frequency response, taking into account the load dependency factor. Given a power deficit, the method in [5] can estimate the maximum frequency deviation and the steady state frequency, which are used for adaptive load shedding. Alternatively, [6] estimates magnitude of the disturbance based on the derivative of frequencies measured at all terminals of generators in the network. This magnitude is indeed the power deficit when a generator is tripped, which is then used to determine the amount of load shed.

From a different perspective, the method proposed in this paper detects islanded areas and their power deficit based on system topology and monitoring outages of lines and generators. The method can work properly under various islanding scenarios in power systems, provided that the necessary measurements and breaker statuses are available.

II. REVIEW OF RECENT UNDERFREQUENCY-RELATED BLACKOUTS AND DISTURBANCE

Although blackouts and large disturbances are unwanted events in power system operation, they contain valuable information about power system behaviors, which are highly complex and not fully predictable. The past incidents can help us improve our understanding of the power grid, paving the way for new solutions. In this section, the two recent blackouts (in Turkey in 2015 and in Italy in 2003) and a large system disturbance in the UCTE interconnected network in 2006 are presented. Lessons learned from these incidents form the basics of the proposed algorithm for the adaptive UFLS.

A. Blackout in Turkey in March 2015 [1]

The blackout in Turkey occurred on March 31, 2015. Details of this incident are described in [1]. Here, only the relevant events related to the UFLS are presented. Before the event, a large amount of power (around 4700 MW) was transferred from the eastern area to the western area as illustrated in Fig. 1. The initial event was a tripping of a tie line connecting the two areas. This disturbance triggered cascading tripping of all of the other tie lines; it took roughly 1.9 s. As a result, the Turkish power system was islanded into two areas. In the western area, there was a power deficit of 4700 MW. Therefore, the frequency declined and fell below 49 Hz. As expected, the UFLS operated and shed the load. This protection system was designed to shed the load step by step, i.e. 49 Hz, 48.8 Hz, 48.6 Hz and 48.4 Hz. In total, the underfrequency protection shed 4800 MW of load, which is equivalent to the power deficit caused by tripping of the tie lines. However, this could not stop the frequency drop. The reason is that several generators in the western subsystem were tripped when the frequency was still higher than 47.5 Hz. In addition, the three tie lines between the western subsystem and the Bulgarian and Greek systems were tripped due to the out-of-step function, causing further power deficit. These incidents made the frequency continue dropping and finally led to the blackout in the western area. It took about 10 s from the instant this area was islanded to the time the frequency reached 47.5 Hz.

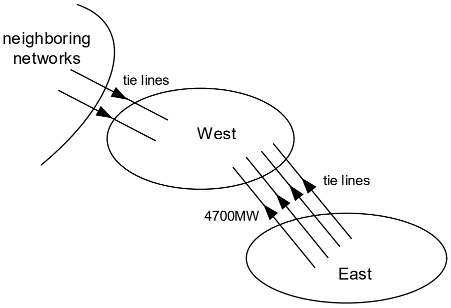

Figure 1. Sketch of the Turkish power system when the blackout occurred.

B. *Blackout in Italy in September 2003 [2]*

The blackout of the Italian transmission system occurred on September 28, 2003. This incident is a complicated one, involving several stability problems. This section just summarizes events relevant to the UFLS. Details of the blackout are presented in [2]. As seen in Fig. 2, before the blackout, the Italian power system was as normal connected to the Swiss, Austrian, French and Slovenian grids (the HVDC link to Greece is not mentioned since it is not relevant). The total power import of the Italian system from its neighboring countries was around 6651 MW. The blackout was initiated by a loss of the line Mettlen-Lavorgo at the corridor between Italy and Switzerland, which weakened the link between the two grids. This event led to a tripping of another interconnection line (Sils-Soazza), triggering cascading outages of all the tie lines between the Italian system and its neighboring systems (the Swiss, Austrian, French and Slovenian grids). This separated the Italian grid from the rest of the UCTE network, just 12 s after the tripping of the line Sils-Soazza. Since the Italian system lost a power import of 6651 MW, the frequency quickly dropped, and then was stabilized temporarily by the primary frequency control, UFLS scheme and automatic disconnection of pumped storage power plants. However, due to the underfrequency and low voltage condition, several power plants were tripped by different protective functions, which worsened the situation. During the frequency drop, 10900 MW of load was shed, but it could not solve the problem. Eventually, the frequency fell further and led to a total blackout.

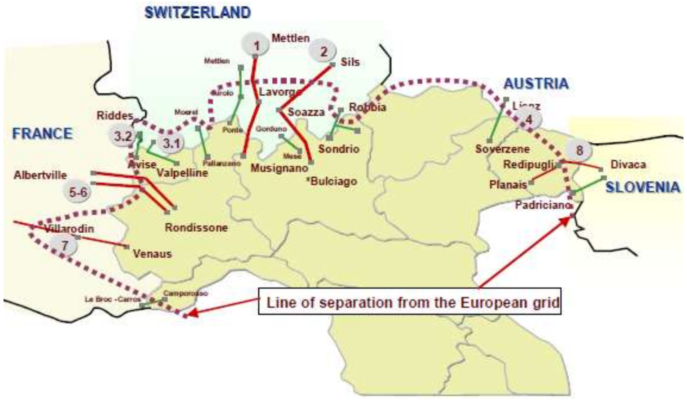

Figure 2. Tie lines between the Italian system and the UCTE network [2].

C. *System disturbance of the UCTE interconnected network in November 2006 [3]*

The separation of the UCTE network on November 4, 2006 was a large disturbance, which affected several countries in Europe. The incident is, in detail, described in [3]. The essence of the incident is a cascading tripping of several lines (not tie lines) in many countries, which divided the UCTE network into three asynchronous areas. As seen in Fig. 3, Area 1 was an undergeneration area with an initial power deficit of around 8940 MW. Therefore, after the separation, the frequency dropped down to 49 Hz, which triggered the UFLS schemes and disconnection of pump storage units. In total, 17 GW of load and 1600 MW pump storage units were shed. This helped the area stabilize the frequency around 49 Hz. It is noted that, under low frequency condition, around 11 GW of generation was also tripped, mainly wind generation and power plants connected to the distribution grid.

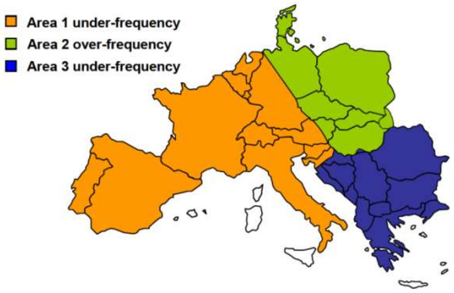

Figure 3. Splitting of the UCTE network [3].

D. *Discussion on the recent blackouts and disturbance*

Based on the above-mentioned incidents, some discussion points are raised:

- Islanding can happen to a part of a power system (like the Turkish case) or to a national transmission system (the blackout in Italy) or to a large area consisting of several power systems (the disturbance in the UCTE network). Additionally, the islanded areas are unknown until the incident occurs. This issue should be considered when building a centralized adaptive UFLS scheme, simply because only loads in the island with power deficit should be shed, not the opposite. In this context, identifying loads connected to the underfrequency islanded area comes into the picture.

- The conventional UFLS scheme has one major drawback. It does not sufficiently consider the location and amount of the power deficit, which is the main driver of the frequency drop. Moreover, when loads are shed, the frequency is already low. If the power imbalance still exists, the frequency will continue falling, posing a risk of tripping generators. This was a decisive factor in the blackouts of the Turkish and Italian power systems. In these incidents, the total amount of load, which was shed, was comparable or event more than the initial power deficit, but it could not arrest the frequency decline.

- In the conventional UFLS scheme, loads throughout a synchronous network are shed when the frequency is low, regardless of the actual power deficit in the area where the load is connected. For example, in the disturbance of the UCTE system in 2006, if the Portuguese power system would not have had power exchange with its neighbor, the load in this system should not have been affected and tripped. However, it is not possible to have this option in the conventional UFLS scheme since all the loads in the synchronous area share the same (or almost the same) frequency.

- The underfrequency condition is not caused by tripping of a single generator, which is commonly used to validate methods for adaptive UFLS based on frequency measurements. As observed, the underfrequency problem was caused by an islanding process. It comprised a series of disturbances. During this transient period, measurements of the frequency and its derivative might have large errors. This consequently would greatly affect accuracy of the power deficit estimation. Therefore, this issue should be taken into account when testing methods for adaptive UFLS based on only frequency measurements.

III. A TOPOLOGY-BASED SCHEME FOR ADAPTIVE UNDERFREQUENCY LOAD SHEDDING

A. Description

The adaptive UFLS scheme proposed in this paper is designed based on observation of the incidents mentioned in the previous section. The main idea is

- to continuously monitor and detect which areas are islanded and the boundary of each island,
- to continuously track and detect power deficit of each island at the instant the grid is separated. This information is then used to shed load in the area that has an active power shortfall,
- and to coordinate UFLS schemes between power systems in an interconnected network.

Consider an interconnected system as shown in Fig. 4, where five power systems are connected to each other by several tie lines. In this configuration, there are several possibilities to break the interconnected system into asynchronous islands. Here, a power system can be either a national transmission grid or just a part of the national transmission grid operated by a particular transmission system operator. Further, one can divide each power system into zones that have weak connections with the others. A line connecting two zones of a system is here denoted by an internal tie line; meanwhile, a line connecting two systems is defined as an external tie line. It is noted that the concept of tie line is not limited to a physical line connecting two buses of different zones/systems. It can include several lines as long as it is a single connection between two different zones/systems, e.g. the 400 kV line from Sils to Musignano, including Soazza, or the 400 kV line from Divaca to Planais, including Redipuglia, in Fig. 2 is considered as one external tie line.

After defining the zones in each power system, one can build a two-tier UFLS scheme that consists of the Zone Protection (ZP) and System Protection (SP); their functions are presented in the next paragraphs.

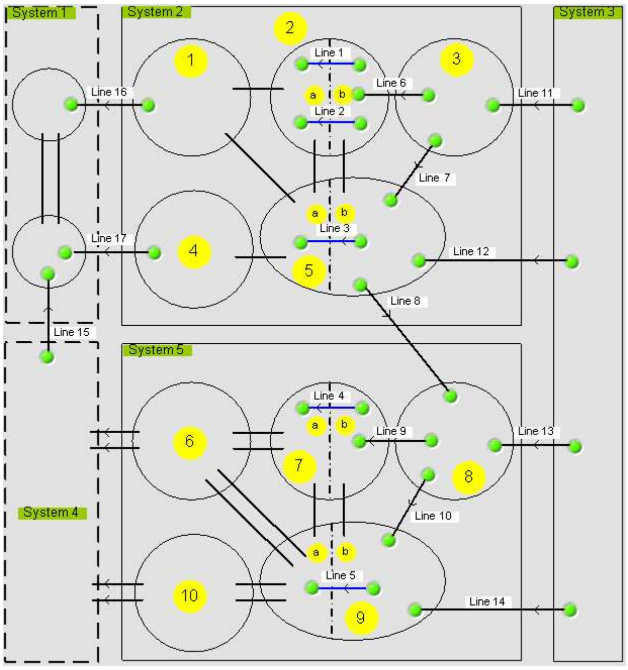

Figure 4. Example of an interconnected power system.

1) Zone protection

Each zone in the system has its own ZP, whose main task is to protect the zone against underfrequency when the zone is separated from the system. Moreover, the ZP also shed load in the zone when requested by the SP. The next paragraphs will describe operation principle of the ZP, which is illustrated in Fig. 5.

a) Block 1: tracking power deficit and other tasks

- **Tracking power deficit**: This block continuously tracks the tripping of generators and lines in the zone. This event should be detected as soon as possible. Whenever a generator or a tie line is tripped, its active power before the disturbance is added into the power deficit. Fig. 6 describes how the power deficit is computed. After the first disturbance, if another generator is tripped when Timer 1 is running, its active power before the first disturbance is taken into the accumulated power deficit. This technique is to estimate the power deficit accurately and avoid wrong measurements during the transient period, especially power swing. After Timer 1 has elapsed, if there is not further tripping and the frequency is still with the permissible band, the power deficit is reset, meaning that the recent disturbances do not lead to the underfrequency problem. Then the ZP will start a new cycle, continuously waiting for disturbances and updating the power deficit.

- **Checking islanded conditions**: there are basically two islanded conditions: internally and externally. The zone is defined as externally islanded when it does not have any connections to the rest of the system; meanwhile, the zone is deemed as internally islanded if it is split into two islands. The algorithm for checking the islanded conditions is presented in the next section.

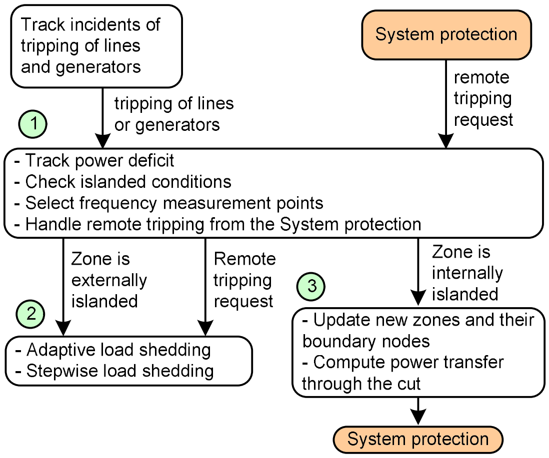

Figure 5. Operation of the ZP.

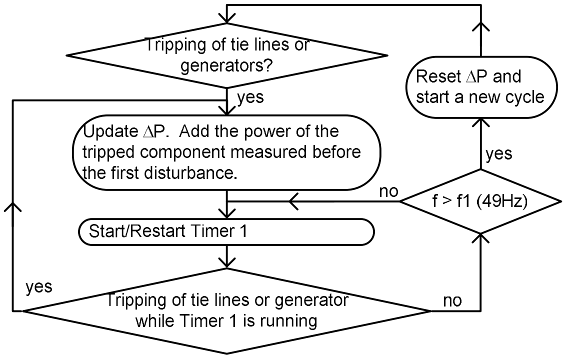

Figure 6. Flow chart of detecting power deficit.

- **Frequency measurement**: When the zone is internally islanded, the frequency measurement points should be updated to represent the actual frequency of each island.
- **Handling remote tripping request**: This function is to shed a certain amount of load requested by the SP.

b) Block 2: Load shedding

- **Adaptive load shedding**: In case the zone is externally islanded, Block 2 receives the power deficit from Block 1. If the frequency is lower than a threshold, e.g. 49 Hz, Block 2 will start shedding the load. The amount of load that needs to be shed is

$$P_{shed} = \Delta P - \sum_i \frac{\Delta f \bullet P_{Ni}}{k_i} \tag{1}$$

where ΔP is the power deficit, P_{Ni} and k_i are the rated active power and droop setting of the i^{th} machine in the zone, respectively, and Δf is the expected frequency deviation after the load shedding.

- **Stepwise load shedding**: If the zone is externally islanded and the frequency of the island is still within a permissible band for a period of time (longer than the time delay of Timer 1 in Fig. 6), the power deficit will be reset. After that, if the frequency decreases, e.g. due to load increase, the adaptive load shedding function does not work because the power deficit is zero. In this case, the stepwise load shedding functions as a conventional UFLS scheme. Based on the frequency, it will shed the load step by step in order to recover the frequency.

c) Block 3: power deficit when internally islanded

When a line (not a tie line) is tripped, information about the bus number of its two ends and the power transfer on the line is recorded. Block 1 uses this information to detect the internally islanded condition. If the zone is internally islanded, Block 3 will compute the power transfer through the cut and send it to the SP. Moreover, information of the new islands and their boundary nodes are also included. The SP needs this information to detect the internally islanded condition of the entire system.

2) System protection

The main task of the SP is to protect the system from underfrequency problem and to coordinate the UFLS with its neighbors. As shown in Fig. 7, the SP consists of three blocks; their functions are described in the next paragraphs.

a) Block 1: power deficit and islanding condition

- **Tracking power deficit**: whenever a generator or an external tie line between the considered system and its neighbors is tripped, this event will be registered. In this case, information about the bus number and active power of the tripped element is stored. The mechanism to update this event is similar to the flow chart shown in Fig. 6. In case the system is separated from the interconnected system and facing the underfrequency problem, the registered events are used to compute the power deficit of the system, which is, in turn, utilized in the adaptive load shedding scheme.

  In case the system is internally islanded, e.g. Line 1, 2, 3, 4 and 5 of System 2 in Fig. 4 are tripped, the ZP of Zone 2 and 5 will send the amount of power, which was transferred through the cut before the internally islanding event, to the SP. This power is added into the power deficit. In this case, active power of generators or tie lines that have been tripped is also accordingly added to the deficit of each island.
- **Checking islanded condition**: Information about islanded condition is vital to computing the power deficit and coordinating load shedding with neighboring SPs. The main task of this function is to detect two islanded conditions of the system: internally and externally. The system is internally islanded when it is split into two islands which do not have any connections with each other, regardless of whether the islands still have connections to external systems or not. On the other hand, when the system is separated from all neighboring systems, it is considered as externally islanded.
- **Frequency measurement**: when the system is internally islanded, the measurement points must be selected appropriately to accurately represent the frequencies in each island.
- **Handling remote tripping request**: As previously presented in Section II, a group of power systems can be islanded from the rest of an interconnected system. Therefore, coordination between these systems is needed

to tackle the problem on a wide-area scale. In this case, when a system is internally islanded, the power transfer through the cut is computed. This is a part of the power deficit of the entire underfrequency area seen by the system, which is internally islanded. This system then asks its neighbors to shed a certain amount of load equal to the power transfer between the two systems. For example, if Line 1, 2, 3, 4 and 5 in Fig. 4 are tripped, the power deficit detected by System 2 is the power transfer on the Line 1, 2 and 3. Based on this value, it will ask System 1 to shed its load which is equal to the power exchange between the two systems. System 2 also sheds its load, which is equal to the power deficit subtracted by the amount of load shed in System 1. Similarly, System 5 will send tripping command to System 4. By this way, each system is responsible for its own power balance in emergency condition; therefore, the risk for cascading tripping of tie lines can be avoided. Alternatively, the share of load shedding can be different, e.g. based on mutual agreements between neighboring system operators, as long as the total amount of the load shed is equal to the power deficit.

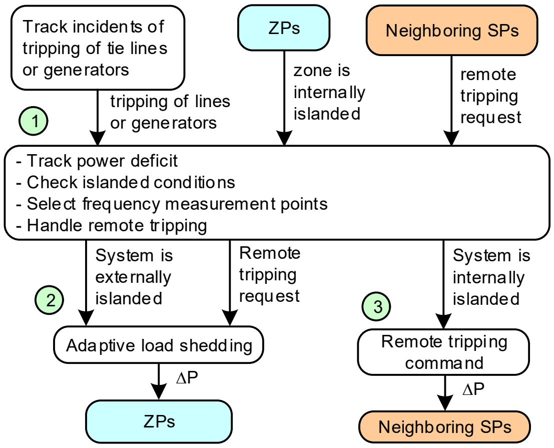

Figure 7. Operation of the SP.

b) Block 2: Adaptive load shedding

Based on the power deficit identified by Block 1, Block 2 will allocate the amount of load shed to relevant zones that are experiencing underfrequency problem. The principle is that each zone sheds an amount of load which is proportional to its share in the total load, mathematically expressed by

$$\Delta P_i = \frac{P_i}{P_\Sigma}\Delta P \tag{2}$$

where ΔP is the active power deficit, P_Σ is the total load, P_i and ΔP_i are the active power and the amount of load shed of the i^{th} zone, respectively.

c) Block 3: sending remote tripping command

In case the multi-system islanding in an interconnected network occurs, the system, which is internally islanded, will ask its neighbors to shed their load, according to the power exchange between the two systems. This task is handled by this block. After detecting that the system is split and the frequency is lower than a certain limit, the SP will immediately send the tripping command and the amount of load shed to its neighboring systems.

B. Detecting the internally islanded condition

Given a zone or a power system, one can build an incidence matrix [8], which contains information about connections of nodes in the zone/system. Based on this matrix, an algorithm to detect the internally islanded condition is described in Fig. 8.

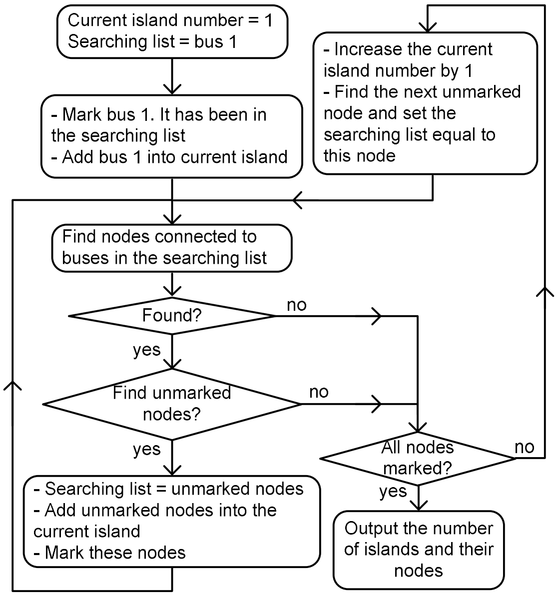

Figure 8. Flow chart for detecting internally islanded condition.

IV. SIMULATIONS

A. Simulation of the IEEE reliability test system

To validate the effectiveness of the proposed method, an islanding case has been created in the IEEE reliability test system [9]. At $t = 5$ s, the line 15-24 is tripped, marking the onset of the islanding process. This event triggers cascading tripping of the other tie lines, i.e. line 11-14 tripped at $t = 20$ s line 12-23 tripped at $t = 60$ s and line 13-23 tripped at $t = 110$s. As a result, the 138 kV area is islanded, and, due to the deficit of active power, the frequency in this area sharply drops, which is depicted by the red and dashed curve in Fig. 9. After line 13-23 is tripped, the frequency falls from 60 Hz to 57 Hz within 3.4 s. Fig. 10 shows the power deficit detected by the proposed method. As can been seen, the deficit increases each time the tie line is tripped and stays at 722.8 MW after the system is islanded. Using (1) with $\Delta f = 0.5$ Hz, an amount of 510.3 MW should be shed. Therefore, loads at bus 4, 8, 9 and 10 with the total power of 553.1 MW are disconnected. This action has prevented the frequency collapse, which is seen the blue curve in Fig. 9, showing that the frequency, after transient period, stabilizes at 59.63 Hz.

B. Coordination of UFLS schemes in interconnected systems

To emulate the system disturbance of the UCTE grid in 2006, the system in Fig. 4 is simulated in Labview. Here, there is no dynamic simulation of the grid, and, therefore, the power flow as showed in Table 1 is assumed unchanged.

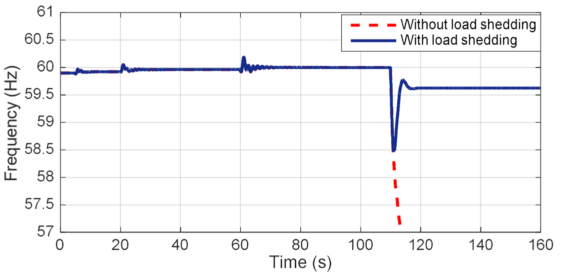

Figure 9. Frequency excursion.

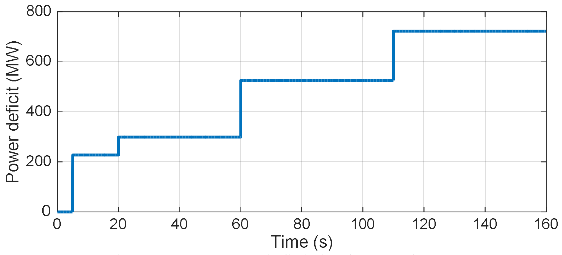

Figure 10. Power deficit in the 138 kV area.

TABLE I. POWER FLOW OF THE CONSIDERED LINES

	From zone	To zone	Power (MW)
Line 1	2	2	4000
Line 2	2	2	2000
Line 3	5	5	1000
Line 4	7	7	1500
Line 5	9	9	700

As can been seen in Fig. 11, the cascading tripping is simulated by a tripping of Line 1 at $t = 20$ s. This leads to the tripping of Line 2 and 3 at $t = 30$ s and $t = 40$ s respectively, and the simultaneous tripping of Line 4 and 5 at $t = 45$ s. It is noted that at $t = 40$ s the SP of System 2 detects that this system is internally islanded and the power deficit is 7000 MW as shown in Fig. 12. Similarly, System 5 is islanded at $t = 40$ s and its deficit is 2200 MW. Based on the estimated deficits and power exchange with neighboring systems, System 2 and 5 will accordingly shed their load and, at the same time, send tripping commands to their neighbors.

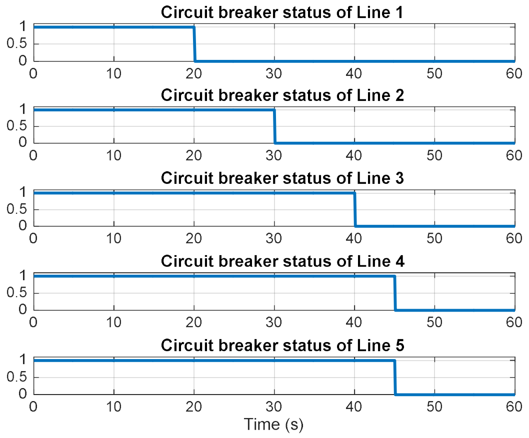

Figure 11. Status of circuit breakers.

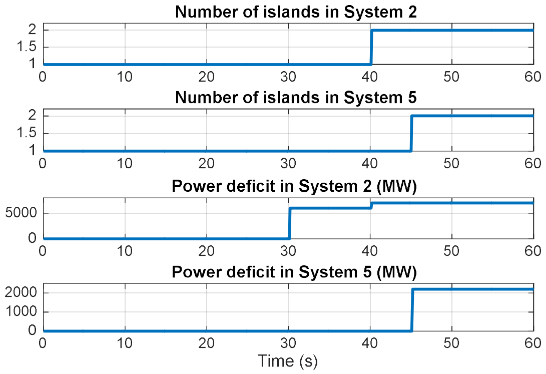

Figure 12. Detection of islanded condition and power deficit.

V. COMMENTS ON PRACTICAL IMPLEMENTATION/REQUIREMENTS

The proposed method requires information from the SCADA/EMS system and circuit breaker statuses, preferably data from wide area measurement system to monitor frequency and power flows.

Tripping of generators should be distinguished from scheduled switching in order to improve quality of the estimated power deficit.

VI. CONCLUSION

The paper has presented a scheme for the adaptive UFLS using information of system topology, wide area measurements and communication. The proposed method is suitable for both isolated power systems and interconnected networks, which has been demonstrated in the simulation section.

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