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Enhancement of Power System Voltage Stability Using New Centralized Adaptive Load Shedding Method

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Abstract

This paper presents a new centralized adaptive method under frequency load shedding. Sometimes, after initial frequency drop following severe disturbances, although the system frequency returns to its permissible value, however, the system might become unstable due to voltage problems. In this regard, the paper proposes a new centralized adaptive load shedding method to enhance the voltage stability margin during under frequency conditions. Selection of loads to be shed in the proposed method depends on the loads' power factor, generators reactive power output as well as the location of the disturbance. The proposed method is implemented on the dynamic simulated model of the modified IEEE 30-Bus test system and is compared with the conventional approach to confirm the applicability and effectiveness.

Keywords: Centralized adaptive load shedding; Under-frequency load shedding; Voltage stability margin

1. Introduction

In power system operation, deviation of the frequency from its rated value is an indication of an imbalance between real power generation and load. If generation is smaller than load, system frequency will drop. In the case of small difference between power system consumption and generation, governors can return the system back to the normal state by controlling output power. Spinning reserves are the extra generation capacity of the connected generators to the network. Spinning reserves can also adjust the imbalance by producing power [1]. Under frequency load shedding (UFLS) considering spinning reserves is completely described in [2]. However, when generation deficiency is too large, system frequency will decrease significantly, which can lead to system blackout. Power system blackouts have become a serious problem for electric utilities especially in recent years. For instance, the blackouts in Greece, Italy, North America, Sweden and Denmark, Iran and many other countries have been mentioned in the literature [3-5]. Hence, proper actions should be taken to retrieve the balance and return back system frequency within its permissible range to prevent a major power system blackout. In the case of abrupt reduction in the frequency, governor and spinning reserve responses are not fast enough to restore system to the normal operation. In order to solve this frequency issue and return the system back to the normal state, UFLS schemes would be put into the action. Under frequency load shedding schemes implement relays to disconnect appropriate amount of load and maintain system stability. The available UFLS algorithms can be divided into the following categories [6]:

(1) Conventional UFLS.

(2) Semi adaptive UFLS.

(3) Adaptive UFLS.

The conventional UFLS method is designed to return back the system frequency within its acceptable range through shedding the fix amounts of load using a predetermined fix number of step sizes. In other words, in the conventional UFLS scheme the same load feeders would be dropped from the system, regardless of the location of disturbance. In this scheme, loads are categorized into three groups of vital, semivital and nonvital [7]. Therefore, nonvital loads have the highest priority to be shed. However, in the case of severe disturbances, semivital loads could also be shed. It is obvious that conventional UFLS system could not be the most efficient scheme and might cause some problems in the system. For the new power systems which are operated closer to their stability limits, it is favorable to use adaptive load shedding schemes and disconnect the minimum required system load at different circumstances and maintain system stability. After incident of the system disturbance, frequency initially decreases, and then it might return to its near-normal value, however, the system might become unstable due to voltage problems. In the power system, loss of major generation unit could cause transfer of a high amount of power in long distances. As a consequence, voltage stability margin of the system would be reduced.

Application of centralized load shedding algorithms has been presented in some research works [8-10]. In [11], an implementation of a real-time centralized adaptive UFLS scheme has been presented. In order to improve the voltage stability margins, prioritizing the loads to be shed is considered with new centralized adaptive load shedding methods in [12]. The first algorithm in [12] is response-based and the second one is a combination of response-based and event-based methods. In centralized adaptive algorithms, measured amounts of required signals are transferred to the control center and the suitable decision to shed loads is made in this center. Hence, a reliable and fast communication link is vital in centralized adaptive methods. Communication systems provide a lot of helpful information for the load shedding process.

The current paper aims at the proposing a new centralized adaptive UFLS method. In the proposed algorithm, selection of loads to be shed depends on the location of the disturbance, the generators reactive power output and the load's power factor. The paper accomplishes more accurate model of the problem by modeling the dependency of load upon voltage and frequency. The efficiency of the proposed algorithm is evaluated by using IEEE 30-bus test system. According to simulation results, applicability and efficiency of the proposed method is inferred.

The rest of this paper is organized as follows. Section II presents the voltage stability margin definition. Section III describes the conventional UFLS and proposed adaptive load shedding method. Simulation results are presented in Section IV. Finally, the findings of this work are summarized in Section V.

2. Voltage stability margin

Voltage Stability Margin (VSM) could be defined as the amount of additional load on a specified pattern of load increase that would cause power system instability [13]. Voltage instability is one of the most important concerns that recently received major attention of researchers. Reports show the voltage collapse for the recent incident in North American power system on August 14th, 2003 caused approximately 50 million customers spend more than 15 h without electricity [14]. After occurrence of the system disturbance, frequency initially decreases, and then it might return to its permissible range, however, the system might become unstable due to voltage problems. Hence voltage stability assessment is an essential issue for power system planners and operators.

PV curve diagram demonstrates the voltage variation versus active power demand. Fig. 1 illustrates a typical PV curve diagram for given status of power system. Referring to Fig. 1, distance between points A and B, corresponding to the current operating point and the voltage collapse point, respectively, is measured as the VSM. This margin can be achieved implementing different ways. In fact voltage stability is a dynamic phenomenon and can be studied using extended transient/midterm stability simulations [15]. Due to less computational burden of static methods, they have been used to a large extent in the literature. Modal analysis has been used in [15] to determine the VSM. In [16] a nonlinear programming method has been presented in order to evaluate the VSM. In addition, continuation power flow (CPF) is implemented in [17] for voltage stability evaluation. Interested readers can refer to the relevant available papers published in this area of research for more details and discussions. The current paper employs continuous power flow method in order to calculate the VSM.

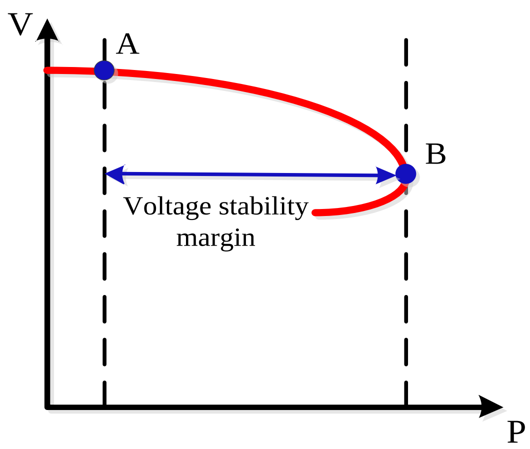

Fig. 1. A typical PV curve for a given condition.

3. load shedding schemes

A. Conventional UFLS Scheme

Under Frequency Load Shedding scheme is a common practice for electric utilities around the world for generation and load mismatch protection which may be the consequence of generator- or tie-line outages.

In the conventional UFLS scheme, whenever frequency of the system falls below predetermined thresholds, parts of the system load would be shed according to pre-selected amount and some predetermined steps. Design of conventional UFLS schemes involves four stages [18]:

- Determination of the anticipated overload
- Determination of the number of load shedding steps
- Determination of the amount of load to be shed
- Calculating relay settings

More information of the conventional UFLS scheme could be found in [12].

In the conventional UFLS scheme the setting might not adjust to the present power system condition and the power system would be subjected to under/over load shedding. In addition, conventional UFLS scheme may lead the power system to voltage instability. Therefore, the current paper proposes a new centralized adaptive load shedding method in order to improve performance of the conventional UFLS scheme.

B. Proposed adaptive load shedding method

In this method selection of the loads to be shed is according to the generators reactive power output, loads power factor and lines impedance. The objective of the proposed method is to enhance voltage stability margin of the system while returning the system frequency to its acceptable value following large disturbances. The method selects the loads that are in the vicinity of the generator which has further reactive power output after the disturbance. Therefore, the loads with lowest line impedance from the generator with the highest increase in the reactive power production are prior to be shed. The reactive power variation may be calculated as follows:

$$\Delta Q_i = \hat{Q}_i / Q_i \tag{1}$$

In which, ΔQ_i, Q_i and $\hat{Q}_i$ are the normalized reactive power variation, reactive power production in the normal state and post disturbance reactive power production of generator *i*, respectively.

In order to implement this method a distance matrix Z as shown in (2) would be provided. Elements of this matrix are minimum electrical distances or impedance between each generator and each load of the network.

$$\begin{array}{c} \quad L_1 \quad \cdots \quad L_m \\ Z = \begin{bmatrix} z_{11} & \cdots & \cdots \\ \vdots & z_{ij} & \vdots \\ \cdots & \cdots & z_{nm} \end{bmatrix} \begin{matrix} G_1 \\ \vdots \\ G_n \end{matrix} \end{array} \tag{2}$$

Where, element z_{ij} is the minimum per-unit transmission line impedance between i'th generator and j'th load. n and m are the number of generators and loads, respectively. The information pertaining to the system generation and load values and their locations are usually available for each power system.

When the generator G_k is tripped, the matrix Z would be updated with one row less than primary Z matrix.In the proposed algorithm, the load with minimum power factor has the highest priority to be tripped. The elements of updated matrix Z would be multiplied by $\frac{\cos\theta_j}{\Delta Q_i}$. Therefore, the LSH matrix is defined as follows:

$$LSH = \begin{bmatrix} \frac{z_{11} \times \cos\theta_1}{\Delta Q_1} & \cdots & \cdots \\ \vdots & \frac{z_{ij} \times \cos\theta_j}{\Delta Q_i} & \vdots \\ \cdots & \cdots & \frac{z_{(n-1)m} \times \cos\theta_m}{\Delta Q_{(n-1)}} \end{bmatrix} \tag{3}$$

$\cos\theta_j$ is the power factor of *j*'th load. $\Delta Q_{i,k}$ and z_{ij} will be calculated according to (1) and (2), respectively.

In this method the load with the lowest power factor and less distance from the generator with the largest increase in the reactive power production are in priority to be shed. It affords a greater voltage stability margin for the power system after the disturbance. Therefore, selecting the loads to be shed will be performed considering the following equation:

$$\min_{i=1:m} \sum_{\substack{j=1 \\ j\neq h}}^{n} \frac{z_{ij} \times \cos\theta_j}{\Delta Q_i} \tag{4}$$

When the tripped generator is recognized, a signal would be sent to the control center, instantaneously. Information about governors of the system, dynamics of prime movers, as well as the acceptable system frequency drop are also available. Using the available information, the required amount of load to be shed for different outage scenarios could be determined off-line using appropriate computations. Since the total amount of load to be tripped is known, various loads which had to be shed could be selected and shed simultaneously. In this regard, after choosing the first load according to the (4) the second load would be selected similarly until the required amount of the load to be shed is reached. If tripping the high priority load was not possible due to the significance of the load and social aspects the next load which has the next maximum priority could be considered as the load that had to be shed. Shedding the loads simultaneously prevents probable system instability due to postponements associated with conventional load shedding schemes.

Power system configuration, load amount at different bus bar, generator's produced power could be monitored and updated periodically, e.g. for a duration of every fifteen minutes. After every change of system topology, the system status and reactive power output of generators at the control center should be updated, which needs a fast communication link. In the paper, single contingency is studied for every case of generator tripping using the proposed method. Flowchart of the proposed method is presented in Fig. 2.

4. Results of Simulation Studies

This section presents the results of comprehensive simulation studies. The proposed method is applied to the modified IEEE 30-bus test system. The system data are available in [19]. In the modified form of the IEEE 30-bus standard test system, the total load of the system is increased about 1.45 times with respected to its base case and proportionally distributed among the load buses based on their shares in the total demand. Set points of generators locating on busses 8 and 13 have been changed to 60 and 70 MW, respectively. It should be mention that locations of the loads to be shed in the conventional UFLS scheme are distributed in the network. The simulation studies are performed using DIGSILENT Power Factory 14.1 software and PSAT, MATLAB-based power system analysis toolbox.

The standard IEEE model for automatic voltage regulator (AVR) and hydraulic governor model are implemented [20].

Combination of static and dynamic load models is implemented to appropriately represent the load behavior. Two events have been simulated in this section.

Event 1: Outage of the generator located on bus 2 with 40 MW generations

The first event is the outage of the generator located on bus 2. The network imbalance after the generator trip is 10 MW.PV margin of the system is calculated for the conventional algorithm and adaptive UFLS scheme proposed in this paper. Fig. 3 presents the PV curve of sample bus 7 after applying the adaptive load shedding. As obvious from Fig. 4, the value of PV margin after applying the proposed load shedding method would be about 1.342. From the results of Table I, it is concluded that adaptive method will result in enhancement of PV margin for the event 1. Table 1 includes the load shedding calculation results based on the proposed method. According to Table 1, load feeders of bus 8 are selected to be shed. Referring to the simulation results, about 24% of load in bus 8 will be shed in order to enhance voltage stability margin of the system.

Event 2: Outage of the generator located on bus 8 with 60 MW generations

The second event is the outage of the generator located on bus 8. Fig. 4 shows the system frequency during outage of the generator at bus 8 without load shedding.

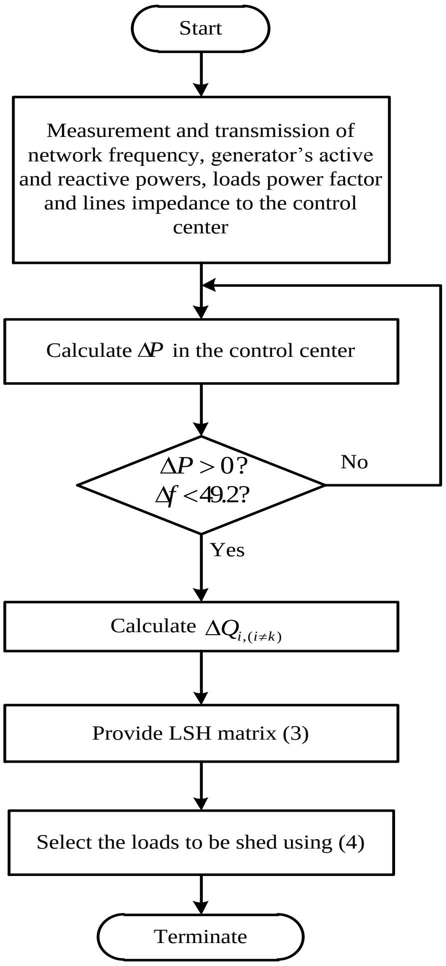

Fig. 2. Flowchart of the proposed method

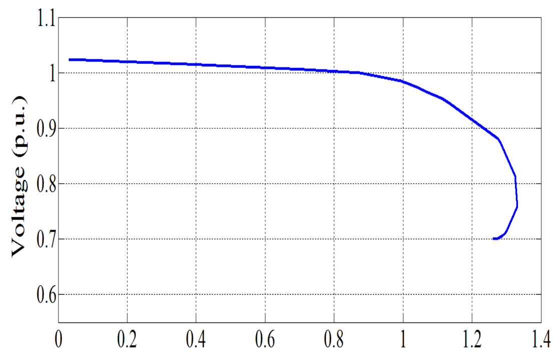

Fig. 3. Resulted PV curve of Bus 7 after G2 trip and adaptive load shedding.

Table 1.
Simulation Results of modified IEEE 30-bus system

Event	Selected loads for the proposed method	PV margin for the Conventional UFLS	PV margin for the proposed method
1	Load 8	1.337	1.342
2	Load 8	1.317	1.331

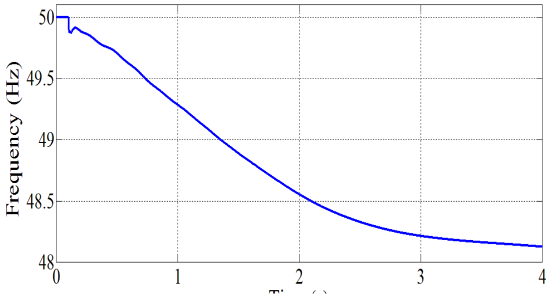

Fig. 4. System frequency for outage of the generator at bus 8 without UFLS.

Generation unit is tripped at time t = 0.1 s. It is obvious that system frequency stability is jeopardized without applying load shedding schemes. The outage of generation unit located on bus 8 will impose 30 MW imbalances to the network. Table 1 provides the load shedding calculation results for the conventional UFLS as well as proposed method. The value of PV margin would be about 1.317 and 1.331 for the conventional and adapted UFLS schemes, respectively. The comparison between the conventional and proposed methods illustrates the effectiveness of proposed method in enhancing the voltage stability margin. In addition, according to simulation results, 0.69% of load in bus 8 will be shed in the proposed method.

5. Conclusion

In this paper, a new adaptive UFLS scheme has been proposed. The main objective of the proposed scheme is to improve the voltage stability margin of the system during under frequency conditions. The method selects the loads to be shed based on the loads power factor, deviation of reactive power production of generators and loads distance to the generators. The performance of the scheme is analyzed by applying to IEEE 30-bus test system. Single contingency has been considered for every case of generator tripping. The proposed method provides promising results and considerably enhanced the power system voltage stability margin in comparison with the conventional UFLS scheme. The proposed method could be easily applied to the power system since the communication link requirements are currently available in most power systems.

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