

Power System Load Shedding: Key Issues and New Perspectives

H. Bevrani, A. G. Tikdari, and T. Hiyama

Abstract—Optimal load shedding (LS) design as an emergency plan is one of the main control challenges posed by emerging new uncertainties and numerous distributed generators including renewable energy sources in a modern power system. This paper presents an overview of the key issues and new challenges on optimal LS synthesis concerning the integration of wind turbine units into the power systems. Following a brief survey on the existing LS methods, the impact of power fluctuation produced by wind powers on system frequency and voltage performance is presented.

The most LS schemas proposed so far used voltage or frequency parameter via under-frequency or under-voltage LS schemes. Here, the necessity of considering both voltage and frequency indices to achieve a more effective and comprehensive LS strategy is emphasized. Then it is clarified that this problem will be more dominated in the presence of wind turbines.

Keywords— Load shedding, emergency control, voltage, frequency, wind turbine.

I. INTRODUCTION

AS the use of renewable energy sources (RESs) increases worldwide, there is a rising interest on their impacts on power system operation and control. The important impacts of a large penetration of variable generations in area of operation and control can be summarized in the directions of regional overloading of transmission lines in normal operation as well as in emergency conditions, reduction of available tie-line capacities due to large load flows, frequency performance, grid congestions, increasing need for balance power and reserve capacity, increasing power system losses, increasing reactive power compensation, and impact on system security and economic issues [1].

The distributed power fluctuation (due to using of variable generations) negatively contributes to the power imbalance, frequency and voltage deviations. Significant disturbance can cause under/over frequency/voltage relaying and disconnect some lines, loads and generations. Under unfavorable conditions, this may result in a cascading failure and system collapse.

There are few reports on the role of distributed RESs in emergency conditions. The impact of distributed utilities on transmission stability is addressed in [2], and an optimal load shedding (LS) strategy for power systems with

distributed sources is introduced in [3]. The need for re-tuning of automatic under frequency load shedding (UFLS) df/dt relays is emphasized in [4, 5]. The system performance and frequency stability during a severe short-circuit and after a sudden loss of generation is discussed in [6].

The most existing LS schemas use only voltage or frequency via UVLS or UFLS methodologies. The under-frequency and under-voltage relays are working in the power system without any coordination. In this paper, a survey on the past achievements on the LS design is presented. Then, the necessity of considering both voltage and frequency indices to achieve a more effective and comprehensive LS strategy in a power system with a high penetration of wind turbines is illustrated.

II. LS CONCEPT

Load shedding is an emergency control action to ensure system stability, by curtailing system load. The emergency LS would only be used if the frequency/voltage falls below a specified frequency/voltage threshold. Typically, the LS protects against excessive frequency or voltage decline by attempting to balance real and reactive power supply and demand in the system. Most common LS schemes are the UFLS schemes, which involve shedding predetermined amounts of load if the frequency drops below specified frequency thresholds. The UVLS schemes, in a similar manner, are used to protect against excessive voltage decline.

The LS curtails amount of load in the power system until the available generation could supply the remind loads. If the power system is unable to supply its active and reactive load demands, the under-frequency and under-voltage conditions will be intense.

To prevent the post-load shedding problems and over loading, the location bus for the LS will be determined based on the load importance, cost, and distance to the contingency location. Coordination between amount of spinning reserve allocation and LS can reduce total costs that generation companies should pay in the emergency conditions [7].

The number of LS steps, amount of load that should be shed in each step, the delay between the stages, and the location of shed load are the important objects that should be determined in an LS algorithm.

An LS scheme is usually composed of several stages. Each stage is characterized by frequency/voltage threshold, amount of load, and delay before tripping. The objective of

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an effective LS scheme is to curtail a minimum amount of load, and provide a quick, smooth, and safe transition of the system from an emergency situation to a normal equilibrium state [8].

There are various types of UFLS/UVLS schemes discussed in literature and applied by the electric utilities around the world. A classification divides the existing schemes into *static* and *dynamic* (or *fixed* and *adaptive*) LS types. Static LS curtails the constant block of load at each stage, while dynamic LS curtails a dynamic amount of load by taking into account the magnitude of disturbance and dynamic characteristics of the system at each stage. Although the dynamic LS schemes are more flexible and have several advantages, most real-world LS plans are of static type [4].

There are two basic paradigms for LS: a *shared* LS paradigm, and a *targeted* LS paradigm. The first paradigm appears in the well-known UFLS schemes, and the second paradigm in some recently proposed wide-area LS approaches. Using simulations for a multi-area power system, it is easy to illustrate the difference between these two paradigms, following generation loss in one area [10].

Sharing load shedding responsibilities (such as induced by UFLS) is not necessarily an undesirable feature and can be justified on a number of grounds. For example, shared load shedding schemes tend to improve the security of the interconnected regions by allowing generation reserve to be shared. Further, LS approaches can be indirectly used to preferentially shed the least important load in the system. However, sharing load shedding can have a significant impact on inter region power flows and, in certain situations, might increase the risk of cascade failure.

Although both shared and targeted LS schemes may be able to stabilize overall system frequency/voltage, the shared load shedding response leads to a situation requiring more power transmission requirements. In some situations, this increased power flow might cause line overloading and increase the risk of cascade failure.

III. A SURVEY

Many algorithms for UFLS and UVLS have been proposed over many years [4, 8-15]. A brief literature review on UFLS schemes can be found in Ref. [4]. In some references, LS schemes are classified into wide-area (centralized) or decentralized approaches [4].

Several dynamic or adaptive UFLS are proposed [10, 16-24]. Recently, the rate of frequency change has been used as an additional control variable to improve UFLS by many researchers [10, 17, 18, 21-30]. Some of these methodologies are given for setting the under frequency relays, based on the initial rate of frequency change at the relays. Various modified LS schemes have been promoted in support of improved protection, including: adaptive LS schemes, dynamic LS schemes that dynamically adjust the

size of load shed stages, and optimized LS schemes, amongst others.

The load characteristics and demand side management (e.g., distributed interruptible loads control) have been considered to provide an effective LS design [13, 31]. Recently, some improvements have been added to the conventional optimal load flow to minimize the load curtailments necessary to restore the equilibrium of operating point during load shedding [32].

A renewed investigation of the LS for frequency protection is necessary because decentralized LS can actually induce temporarily overloaded power lines and/or increase voltage support requirements [30, 33, 34]. Wide-area, or centralized, LS approaches appear to be one obvious candidate framework for developing LS schemes that offer better co-ordination with other cascade failure considerations [34, 36-38]. Numerous wide-area LS studies have demonstrated the role of disturbance size and location, LS size and location, and shed delay time in the effectiveness of load shed actions [23, 33-36].

Unfortunately, from a cascade failure perspective, standard UFLS/UVLS schemes tend to share LS responsibilities throughout the system. This sharing behavior arises as a natural consequence of a power system's tendency to distribute power adjustments throughout the system according to the machine inertias (although the initial impact of any disturbance tends to be distributed according to synchronizing power coefficients) [24]. This LS behavior is undesirable from the perspective that overloaded lines have been identified as an important source of the observed cascade failure behavior [39]. In comparison, recently proposed wide-area LS schemes have demonstrated that the optimal action often rapidly sheds load near the source of power imbalance, and hence minimizes the impact on inter area power flows [33, 34, 36].

The initial rate of frequency change is in use as an additional control variable in the recent introduced emergency control algorithms [5]. The initial frequency gradient is proportional to the amount of power imbalance [4]. Therefore, it can be used to determine the amount of load to be shed at the first step of LS algorithms.

The LS schemes are studied completely in the literatures but, there are few reports on the role of distributed wind turbines in emergency conditions. Frequency and voltage are more frequent decision tools in the emergency control strategies. Interconnection of wind turbines into power system significantly affects the frequency and voltage behavior following the contingencies [40]. Therefore, emergency control schemes may be needed a revision in the presence of a high penetration wind turbines.

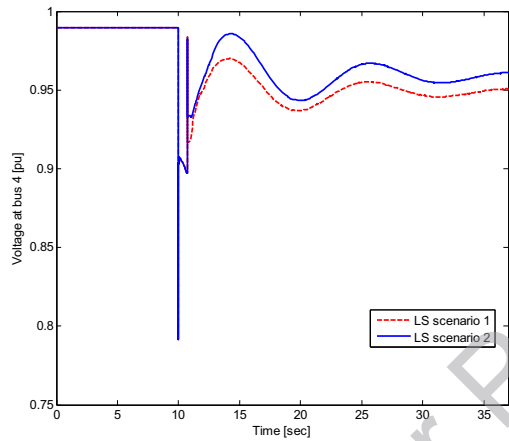
IV. WIND POWER IMPACTS ON FREQUENCY AND VOLTAGE

Increasing the penetration of wind turbine generators (WTGs) in the power system may affect the security/stability limits, frequency, voltage and dynamic

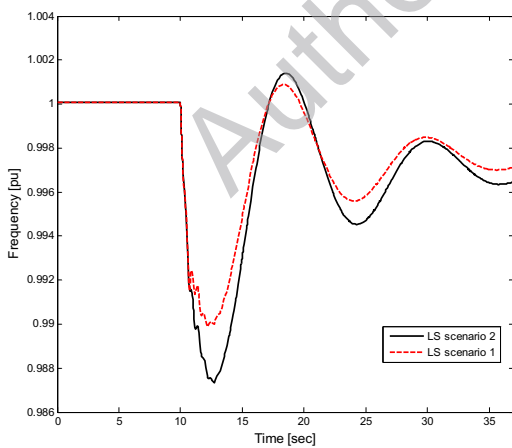
A majority of published research on the under frequency load shedding, consider only the active part of load. While, by considering the reactive power part, frequency decline to be affected as shown in Fig. 2. Furthermore, in the actual power system, the loads contain both active and reactive parts. It is noteworthy that P-Q coupling (coupling between active and reactive part of load) can significantly affect the LS schemes.

Figs. 2a and 2b do not show which case is more effective. Fig. 2a illustrates a better performance for scenario 2; while, Fig. 2b shows an inverse result. This simulations show that by individual monitoring/using of frequency and voltage there is no guaranty to achieve an effective LS strategy. Case 1 is a sample of UFLS schemes that does not consider the voltage variation impacts.

For the sake of studying on the UVLS schemes, when their efficiency may be affected by frequency behavior, case 2 is designed.



(a)



(b)

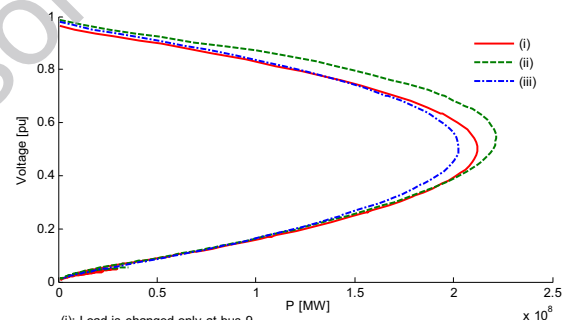
Fig. 2 System response in two different LS scenarios; a) voltage deviation, b) frequency deviation

Case 2

In the voltage based LS schemes like one proposed in [43], an indicator is often defined to make decision about LS algorithm. The indicator proposed for this purpose is zero for no-load condition and in the collapse points reaches into one. In the LS problems, the buses with higher indicators are firstly selected for curtailing purposes. The UVLS schemes usually bias LS decisions toward the weakest buses that are closer to collapse.

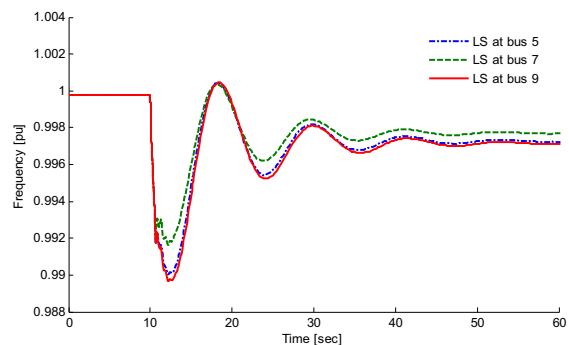
Fig. 3.a shows the P-V curves of the nine-bus test system. Each bus P-V curve is produced by load variation at the same bus. Considering Fig. 3a it may be expected that load shedding at bus 5 and bus 9 is more effective than load shedding at bus 7 because the distance of bus 7 to collapse is larger than bus 5 and bus 9. Hence, the voltage instability indicator of bus 7 is smaller than bus 5 and bus 9.

But, as shown in Fig. 3b, the power system frequency behavior is completely in the opposite direction of the voltage behavior. Fig. 3b illustrates the frequency behavior following loss of G1 and one step load shedding at different buses. All of load shedding scenarios in the present example shed the same value of active part of loads. Frequency nadir and steady-state frequency value when load is shed at bus 5 or bus 9 is settled below the case of load shedding at bus 7.



(i): Load is changed only at bus 9
(ii): Load is changed only at bus 7
(iii): Load is changed only at bus 5

(a)



(b)

Fig. 3 Case 2; a) 9-bus P-V curves b) frequency deviation following G1 loss and load shedding scenarios

The described dynamic behaviour can be analytically explained using the following fundamental equations:

$$\frac{2H}{\omega} \frac{d\omega}{dt} = P_m - P_e \quad (1)$$

$$P_e \cong \frac{V_s V_r}{x} \sin \delta \quad (2)$$

Based on the swing equation (1) the gradient of frequency decline depends on the amount of mechanical and electrical power mismatch. The frequency drop events are triggered by mechanical power reduction (generation loss) or electrical power increasing (load increasing).

On the other hand, following a generation loss disturbance, the voltage reduction will be experienced. Thus the implemented UVLS schemes throughout the power system attempt to restore the power system voltages. Assuming the Eq. (2), it can be seen that the voltage improvement leads to the increasing of load active power injection (P_e). This behavior causes that the value of mismatch will be not as less as value predicted by UFLS scheme. Therefore, the frequency decline is going to be larger than its expected value.

The under-frequency and under-voltage relays are working in the power system without any coordination. To arrest the frequency decline, a UFLS scheme may be used. A UFLS scheme sheds a portion of load demand when the frequency decline reaches the predetermined thresholds. The impact of voltage behavior on the frequency variation is neglected here.

This study shows that to design an optimal LS plan, it is necessary to consider both voltage and frequency indices, specifically in the presence of high penetration of wind turbines.

VI. CONCLUSION

This paper presents an overview of the key issues on load shedding concerning the integration of wind turbines into the power system. The most important issues with the recent achievements in this literature are briefly reviewed. The impact of wind power on power system frequency and voltage is described. It is realized that considering just one of frequency or voltage indices cannot lead to an effective and optimal LS plan, especially when the reactive power is incorporated into studies.

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