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Power System Load Shedding: Key Issues and New Perspectives

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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 though-out 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 affects the security/stability limits, frequency, voltage and dynamic behavior of a power system. WTGs commonly use the induction generators to convert the wind energy into electrical energy. The induction generators are reactive power consumer. Therefore, the voltage of system would be affected in the presence of wind turbines especially in the case of fixed-speed type of WTGs. The wind turbines impacts on the power system frequency and voltage have been studied in many research works [40].

Power system frequency response model in the presence of high WTG penetration, frequency control issue, a survey and some new perspectives are addressed in [4, 5]. In [41], the effects of the doubly-fed induction generator (DFIG) and induction generator (IG) type of WTGs on the voltage transient behavior are explained and the disadvantages of the IG type are shown. Frequency nadir in the presence of different type of the WTGs has been compared and it is shown in [5].

Some reports have also addressed the impacts of various WTGs technologies on the voltage deviation following a contingency event, and have analyzed their influences on the transient voltage stability [41]. In [40], it is illustrated that the P-V curve is significantly affected by changing the network topology.

Some parameters such as power system reserve and inertia constant are influenced by interconnecting the WTGs on the power system. Therefore, the frequency deviation will be also affected in the presence of the wind turbine [40]. Following a disturbance, the frequency decline and initial rate of frequency change in the presence of IGs is smaller than the DFIGs case. Because of their structure, IGs add more inertial response to the power system than DFIGs.

Recent works indicate that using frequency gradient for the power system emergency control in the presence of wind turbines needs to be revised. Since, in the presence of WTGs, the undesirable oscillations are added to the frequency deviation, the measuring of frequency gradient introduces another difficulty to achieve this variable in emergency control strategies. This issue encourages power design engineers to use $\Delta f / \Delta t$ instead of df / dt [5].

Furthermore, as it is discussed in next section, the voltage and frequency behavior does not address the same results about contingency conditions. This phenomenon encourages researchers to re-evaluate the emergency control schemes for the future of the power systems which are integrated with high wind power penetration

V. The Need for Considering Both Voltage and Frequency

Because of wide range of contingencies in the power system, only use of voltage and frequency indices is not sufficient to arrest all post contingency conditions. The most LS schemes proposed so far used voltage and frequency parameters, separately and also, the under-frequency and under-voltage relays are working in the power system without any coordination. The individual use of these indices may be also not reliable/effective, and may even lead to the over load shedding problems. The coordination between UFLS and UVLS schemes is very difficult and may be impossible in many situations.

Studying on the under-frequency load shedding is often done using the system frequency response models. The impact of voltage variation on the frequency deviation is not considered in these models. Furthermore, the UVLS methods that proposed so far for adjusting the under-voltage relays, does not consider the frequency behavior. While, as illustrated in the next section, these two parameters (voltage and frequency) are not independent. The dependency between voltage and frequency will affect LS performance. These impacts are considerable in the presence of wind turbines. Therefore, an algorithm that uses these parameters simultaneously for making load shedding decisions will be more reliable and effective than the conventional schemes.

Here, for the sake of dynamic simulations and to describe/examine the above explanations, the IEEE nine-bus power system is considered as a test system. A single line diagram for the test system is shown in Fig. 1. As shown, two wind farms are added in buses 5 and 9. Simulation data and system parameters are available in [42].

Some test scenarios are considered to demonstrate the necessity of considering both voltage and frequency data in an effective load shedding scheme.

Case 1

Fig. 2 shows the voltage and frequency deviations for two different LS scenarios following the same contingency. In these tests, G1 is tripped at 10s. In scenario 1, only 9% of total system active power is curtailed, while in scenario 2, in addition to 9% active power, 9% of total reactive power is also discarded. Both scenarios shed the load when the frequency falls below 59.7Hz as used in some existing LS standards. Considering the frequency and voltage behavior in the performed two scenarios, some important points are achieved.

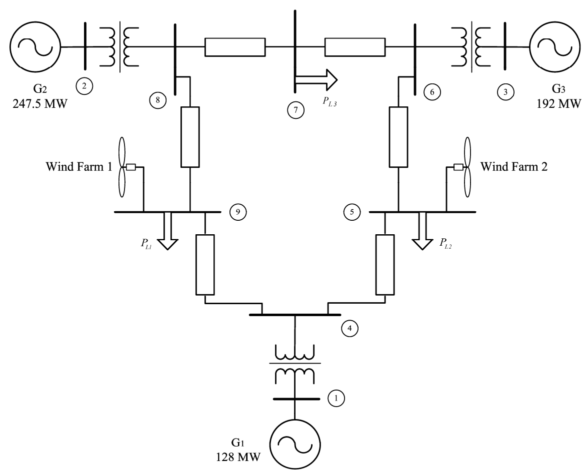
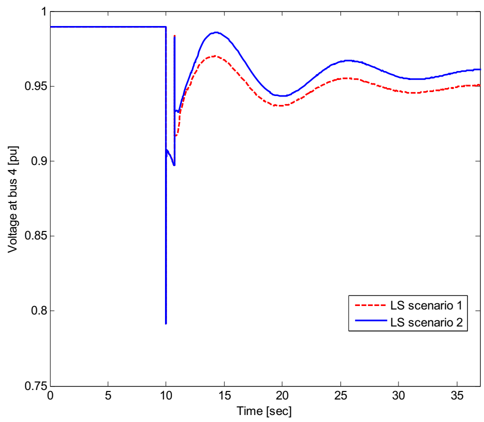


Fig. 1 Nine-bus test system including two wind farms

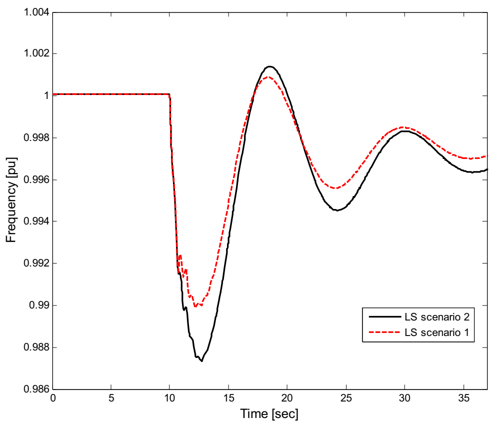
A majority of published research on the under frequency load shedding, consider only the active part of load. While, by considering the reactive power part, frequency decline to be affected as shown in Fig. 2. Furthermore, in the actual power system, the loads contain both active and reactive parts. 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)

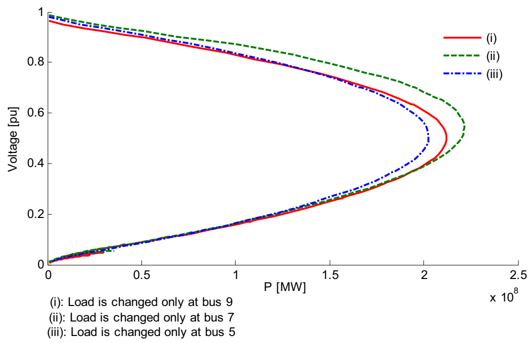
Fig. 2 System response in two different LS scenarios; a) voltage deviation, b) frequency deviation

Case 2

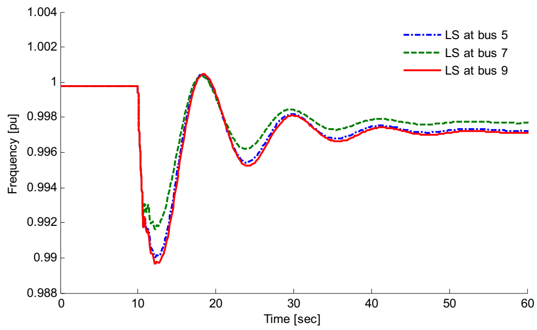
In the voltage based LS schemes like one proposed in [43], an indicator is often defined to make decision about LS algorithm. The indicator proposed for this purpose is zero for no-load condition and in the collapse points reaches into one. In the LS problems, the buses with higher indicators are firstly 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 bellow the case of load shedding at bus 7.



(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 analitically 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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