Future Defence Plan Requirements with High Penetration of Renewable Generations

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***Abstract*—Increasing levels of penetration of renewables may pose challenges to power system security. When security is compromised due to some disturbances, defence plans must be in place to prevent system blackout. Traditional defence plans have been developed without considering large penetration of renewable generations. Therefore, opportunities and threats of renewable generations towards defence plans need to be studied in order to properly revise the defence plans for future. This paper discusses the traditional defence plans with some exemplary case studies. The aim of this paper is to show how renewable generations like wind power can be relevant to the power system defence plans. Recommendations for protection and control strategies as well design for power systems with high penetration of renewable generations are discussed in this paper.**

I. Introduction

More and more renewable energy sources (RES) are being integrated to electrical power systems in the face of growing concerns for environment, increasing fuel price, energy conservation, decreasing cost of renewable generations and sustainable development. The growth of renewable power generation has been steadily increasing and expected to grow further in future. In European power systems, among other renewables hydro power plants net generation capacity is expected to remain stable until 2025, the installed wind power and solar net generation capacity can increase by 80% and 60%, respectively. Biomass and other renewable generation technologies will have a marginal role [1]. Wind power generations are connected both at high voltage transmission networks and medium/low voltage distribution networks. Whereas, during the last years, 80 % of the installed generation capacity of solar Photovoltaics (PV) panels is connected to low voltage grids [2]. India has set a very ambitious target of 175 GW renewable power installed capacity by the end of 2022. This includes 60 GW from wind power, 100 GW from solar power, 10 GW from biomass and 5 GW from small hydro power. Major proportion of RES are converter based generations. These generations do not add any inertia to the system. Therefore, power systems with high penetration of these generations face new challenges. On the other hand, these converters have very high switching frequency and therefore, have high controllability.

Integration of high volumes of RES in power systems provide many opportunities and threats to the stability and security of the power system. Power systems are planned to operate in secured manner where loads and generations are balanced in real-time. However, an unforeseen and unavoidable disturbance can move the system to alert or emergency operational state. Defence plans are required in such situations to prevent blackouts. Traditional defence plans have been developed without consideration of high penetration of RES. This paper aims to review the traditional defence plans and tries to identify impacts of RES on these defence plans.

This paper is structured as following. Section II discusses different traditional defence plans around the world. Section III gives two practical examples of situations where defence plans was imperatively required. Section IV analyses relevance of RES for future defence plans. Section V concludes the paper.

II. Defence Plans

Several definitions of defence plans have been framed by different utilities and organisations over the years. European Network Transmission System Operators for Electricity (ENTSO-E) classifies the system operating conditions into states for the purpose of analyzing power system security [3]. Fig. 1 illustrates different possible states of the power system. The system is operated at normal state based on security analysis. Generally, security analysis is performed based on N-1 criterion where the operation of the system is ascertained through off-line studies of some pre-identified contingencies like generation disconnection or line trippings. These normal contingencies can move the system to stressed condition called alert state. However, there can be multiple contingencies such as cascading line trippings which are categorized as out-of-range (out-of-range of normal security analysis) contingencies. Following such out-of-range contingencies, system can move to an emergency state. When the system is either in alert or emergency state, defence plans are essentially required to bring back the system to normal/alert state and more essentially to prevent blackout.

These defence plans are categorised as “Special Protection Schemes (SpPS)” and “System Protection Schemes (SyPS)” by ENTSO-E as shown in Fig. 1. SpPS are generally designed for alert state and prevent the system from entering emergency state. SpPS are often designed for a particular combination of events triggered by limited number of pre-identified (through off-line studies) critical contingencies, and are therefore called “event based”. SyPS are developed and implemented mainly in

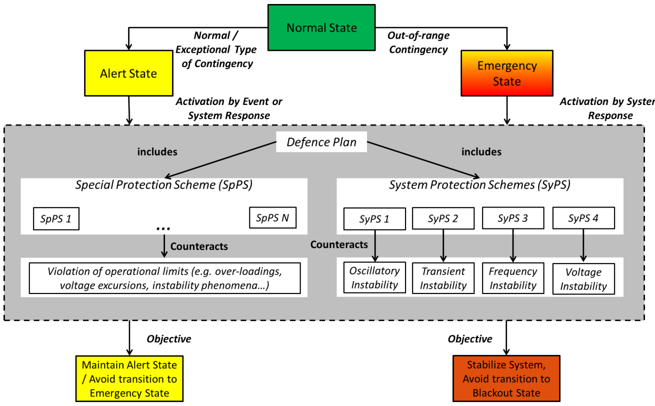

Fig. 1. ENTSO-E Definition of Defence Plan, System Protection Scheme, Special Protection Scheme [3]

emergency state by the utilities to minimize impact of extreme contingencies to prevent system blackout. SyPS mostly include a set of coordinated and automatic measures initiated as a final attempt when a wide spread collapse is imminent. Since system collapse is caused by loss of stability, SyPS are generally designed as response based corrective actions to avoid a specific instability, and are therefore called "response based".

Although the definition of states can generally be agreed upon, for any power systems, nevertheless the definition of defence plans may vary for different power systems based on their individual requirements. According to CIGRE's Technical Brochure "Defense Plans Against Extreme Contingencies" [4] - Defence plans are a set of coordinated *automatic* measures intended to ensure that the overall power system is protected against major disturbances involving multiple contingency events, generally not caused by natural calamity. Defence plans are used to minimize and reduce the severity and consequence of low probability and unexpected events and to prevent system collapse. These actions such as load shedding, generator rejection etc. are defined as System Integrated Protection Schemes (SIPS).

North American Electric Reliability Corporation (NERC) defines SpPs as an *automatic* protection system designed to detect abnormal or predetermined system conditions, and take corrective actions other than and/or in addition to the isolation of faulted components to maintain system reliability. NERC definition of Special Protection System does not include (a) underfrequency or undervoltage load shedding or (b) fault conditions that must be isolated or (c) out-of-step relaying (not designed as an integral part of an Special Protection System) [5].

From these definitions, it is clear that CIGRE and NERC make defence actions as automatic but it is not clear whether these actions should be initiated in alert state or emergency state. ENTSO-E has relaxed the definition of defence actions to not being necessarily automatic, and to be initiated either in the emergency state (SyPS) or the alert state (SpPS). Further, NERC defines the schemes as corrective actions and therefore preventive schemes like underfrequency load shedding (UFLS) are not considered as a defence action as contrary to ENTSO-E.

There have been many definitions of defence actions in literature too. Anderson [6] defines System Protection Schemes in his book as "a protection scheme that is designed to detect a particular system condition that is known to cause unusual stress to the power system and to take some type of predetermined action to counteract the observed condition in a controlled manner. In some cases, system protection schemes are designed to detect a system condition that is known to cause instability, overload, or voltage collapse. The action prescribed may require the opening of one or more lines, tripping of generators, ramping of HVDC power transfers, intentional shedding of load, or other measures that will alleviate the problem of concern. Common types of line or apparatus protection are not in the scope of interest here". Knight [7] defines Special Protection Schemes in the book titled "Power systems in emergencies" as " These will be designed to detect and alleviate conditions which would otherwise cause unusual stress on the power system, and (to distinguish these from normal protection schemes) which perform a function other than or beyond the tripping of elements directly required to clear a fault."

Power System Operation Corporation Limited - National Load Dispatch Centre (POSOCO-NLDC) has defined System Protection Schemes as "a system protection scheme in addition to the normal protection system to take care of some special contingencies like tripping of important corridor/flow gates etc. to avoid the voltage collapse, cascade tripping, load generation mismatch and finally blackouts in the system" [8]. The System protection schemes are generally event based and can be divided in to three categories of major events[8]:

1) SPS related to tripping of critical line / corridor
2) SPS related to safe evacuation of Generation
3) SPS related to overloading of Transformers

Any of these events can induce generation-load imbalance causing frequency fluctuations thereby invoking defence actions such as[8]:

- SPS related to Generation rejection
- SPS related to Load rejection
- SPS related to Generation/Load rejection
- SPS related to HVDC controls
- SPS related to others

Based on [8], load rejection or load shedding is generally performed at 66kV/132kV/220kV level at different steps based on the severity of the event. Load sheddings are expected to be performed within 500 ms following the disturbance.

This paper is mainly focused in frequency stability and associated defence plans. Some of the traditional defence actions with respect to frequency stability are as follows [4]:

A. *Defence actions against overfrequency instability*

- Generator Rejection [9]: This scheme involves fast ramping down of generators and/or tripping of generating units especially hydro-generator units. Hydro-generator units are quite rugged as compared to thermal units and the risk of damage to hydro-generator unit from a sudden trip is low.

- HVDC fast power change [4]: Since HVDC transmission links are highly controllable devices, they can be used for fast power flow change through the connecting systems. Power flow on HVDC links can be modulated by controlling the converters. The DC power can be either ramped down or ramped up (taking advantage of short-term overload capability) to assist power system frequency stability. The beneficial effect of DC modulation on the AC system is similar to the effect of generation rejection or load shedding. An issue with this scheme is that imbalance from one AC system can be transmitted to neighbouring system. Therefore, proper care should be taken while designing such schemes.

B. *Defence actions against underfrequency instability*

- Fast start-up [4]: Power support by fast unit (e.g. gas turbine) or pump storage start-up could be used when frequency is going down. These units are also used as peaking power plant. Consequently, their availability can differ based on operational condition of the system. The gas turbine start-up process takes several minutes or tens of minutes whereas pump storage start-up can be even faster.
- Underfrequency load shedding (UFLS) [4]: UFLS scheme is the last resort to prevent frequency instability. UFLS is initiated by underfrequency relays designed to trip blocks of load in distribution networks when frequency drops below discrete frequency thresholds and/or the rate of change of frequency (RoCoF) exceeds pre-set RoCoF values. UFLS is generally done in several steps to prevent excessive load disconnection and to allow the frequency to recover before the next step.
- Controlled opening of interconnection [4]: Controlled system separation or system islanding is generally a last resort for saving the power system following a major disturbance involving loss of generation or imminent instability between areas. Controlled system separation is applied when specific load and generating areas can be defined within a large interconnected system. Instability between areas is usually characterized by sudden change in tie-line power. However, it can be very difficult task to define system separation points for a large interconnected system since power flows through tie-lines change all the times. Therefore, this scheme is not widely applied.
- HVDC fast power change: as discussed before.

III. Practical examples of frequency instabilities

There has been history of system collapse due to frequency instabilities. In most of the cases, either defense plans were not available or not sufficient to prevent the blackout such as [10]:

- In Italian Blackout of September 28, 2003 [11] frequency decay was not controlled adequately to stop generation from tripping due to underfrequency. Thus, over the course of several minutes, the entire Italian system collapsed causing a nationwide blackout.
- In the blackout in Southern Sweden and Eastern Denmark at September 23, 2003 [12], voltage collapse followed by frequency collapse caused blackout
- 2012 Indian Blackout (described in details)

There are also incidents where blackouts could be prevented by adequate defence plans.

- Proper activation of out-of-step relays inhibited spread of loss of synchronism and frequency instability during 1999 storm in the South- West of France.
- Disturbance on November 4th, 2006 at UCTE (described in details)

One of such events from each category are discussed in details below.

A. *2012 Indian Blackout*

2012 Indian Blackout is discussed here based on the enquiry committee report [14]. These were world's largest blackout (in terms of people affected) on the 30th and the 31st July 2012 which have affected large parts of the Indian power system. During this period, Northern system was highly loaded while Western region had low load and high generation. Consequently, large volume of power was flowing from the Western Grid to the Northern Grid directly as well as through the Eastern Grid.

Grid Disturbance on 30th July 2012: A disturbance occurred in the Northern Region at 02:33 hours of 30th July 2012 leading to a blackout affecting almost the entire Northern region covering 8 States. The frequency just before the incident was 49.68 Hz. The Northern Regional System was fully restored by 1600 Hrs. The frequency recordings of the event is shown in Fig. 2

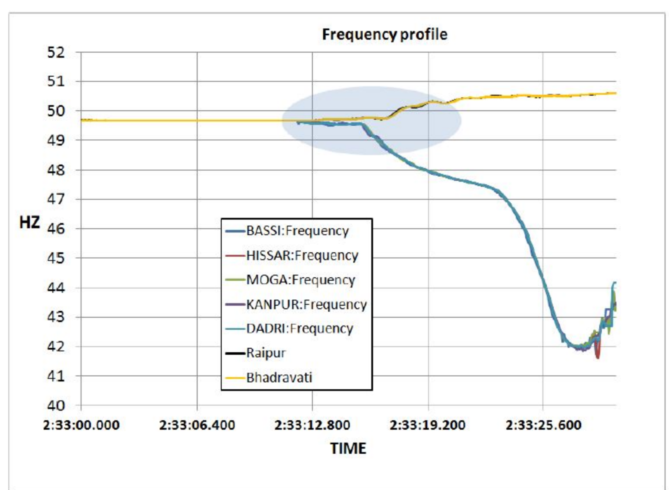

Fig. 2. Frequency recordings on 30^{th} July, 2012 [14]

Grid Disturbance on 31st July 2012: Another disturbance that occurred at 13:00 hours of 31st July 2012 affected the Northern, Eastern and North-Eastern electricity grids. The frequency before the incident was 49.84 Hz. Approximately 48000MW of consumer load across 21 States and 1 Union Territory was affected by the grid disturbance. The system was restored fully by about 21:30 hrs of 31st July 2012. The frequency recordings of the event is shown in Fig. 3

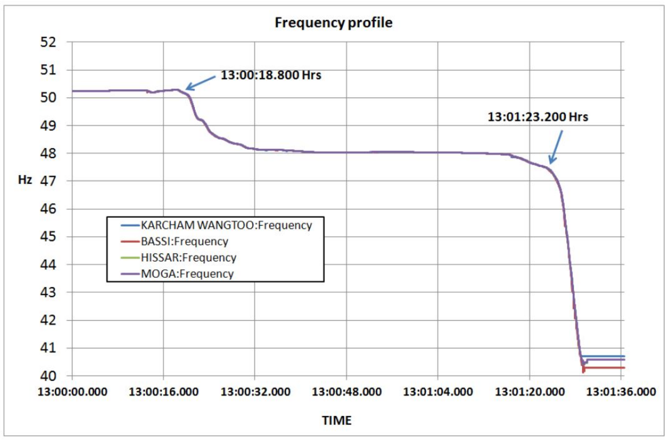

Fig. 3. Frequency recordings on 31^{st} July, 2012 [14]

Northern Region had approximately 10 GW of load-shedding capability planned for UFLS out of which 4 GW was only frequency based and 6 GW was through RoCoF based relays. The rapid frequency decline illustrated that actual load-shedding was not realised as per the planning which demonstrates the failure of defence plans.

B. *UCTE disturbance on November 4th, 2006*

The disturbance on November 4^{th}, 2006 [13] at the "Union for the Co-ordination of Transmission of Electricity" (UCTE) network is one of the most important phenomenon seen related to cascading overload phenomena leading to splitting of the UCTE network and large frequency deviations. Tripping of a 380 kV line due to overload and other cascading trippings led to the final separation of the entire UCTE network in three islands [13] as shown in Fig. 4. Frequency excursions in these three islands after the split are shown in Fig. 5. Countries in the Western part were in power deficiency situation of about 9 GW. That led to a frequency drop down to about 49 Hz. Further frequency drop was stopped by automatic load-shedding and by tripping of pumping storage units. The tripping of small and/or distributed generation units due to underfrequency increased power/consumption unbalance. The countries in the South-Eastern area encountered a slighter deficiency of power which led to a frequency drop to about 49.7 Hz and were not seriously affected by the disturbance. Countries in the North-Eastern area encountered a surplus of generation. The value of frequency was over 50.5 Hz in most of the cases and it peaked at 51.4 Hz. It was observed that a more efficient and coordinated UFLS scheme among Transmission System Operator (TSO)s in Europe is required. It is evident that DGs need to be monitored and controlled appropriately in a coordinated way between TSOs during emergency situations. North-Eastern area of the UCTE network experienced overfrequency situation. This area had high proportion of wind power generation which were being disconnected and reconnected arbitrarily. This demonstrates the requirement for proper control and protections settings of wind power generations.

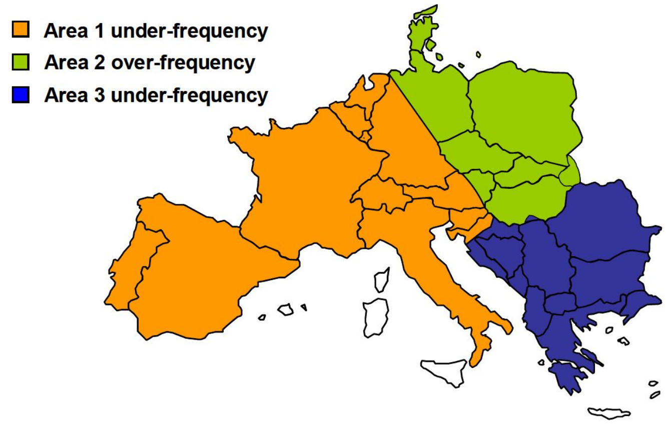

Fig. 4. Schematic map of UCTE area split into three areas [13]

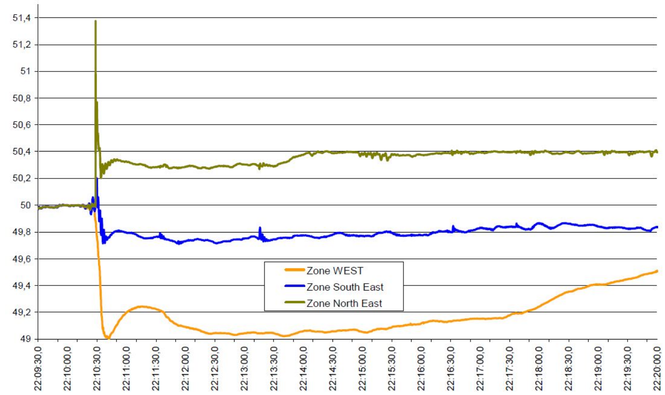

Fig. 5. Frequency recordings after the split [13]

IV. Relevance of renewable generations for defence plans

Discussions above showe the importance of properly designed defence plans for secured operation of any power system. Traditional defence plans face more and more challenges with increased penetration of renewable generations and hence, need to be revised. However, modern controllable renewable generations not only pose challenges to the system but also provide opportunities for improved operation through faster control of these converter based generations. For example, future defence actions pertaining to transmission networks should consider impacts of large variable speed wind turbines (VSWTs) based wind power plants (WPPs) whereas, defence actions involving distribution networks should consider dispersed fixed speed wind turbines (FSWTs) and solar photovoltaic (PV) generations.

With reference to defence plan regarding frequency stability, first consideration should be made on planning adequate volume of reserves for power systems. Different types of operating reserves - both manual and automatic are used to handle different power system uncertainties arising from loads, generations, weather, contingencies etc.

Among the renewables, large WPPs are major contributor towards uncertainties. While small wind tubines (WTs) and PV generations connected to distributions networks are too dispersed to have large impacts on uncertainties in a large interconnected power system like Continental European (CE) or Indian power system. Imbalance in wind power due to the variability of wind speed is mainly caused by wind forecast error. This imbalance could be quite high with high penetration of wind power generation. Therefore, it is required to estimate the amount of reserves required for future power systems with high penetration of wind power generation. This can be considered as precursory to design of defence plans against frequency instability, since frequency instability may occur in the absence of enough operating reserve in the system.

Authors of this paper have developed a probabilistic methodology to estimate the adequacy of frequency reserves in future power systems with high penetration of wind power [15]. The methodology was applied to expected wind installation scenarios in CE for 2020 and 2030. Sensitivity studies were performed for different volume and activation time of secondary reserves (reserve for Load frequency Control). The results are shown in Fig. 6 and Fig. 7. Note that primary automatic reserve based on N-1 criterion in CE is 3000 MW.

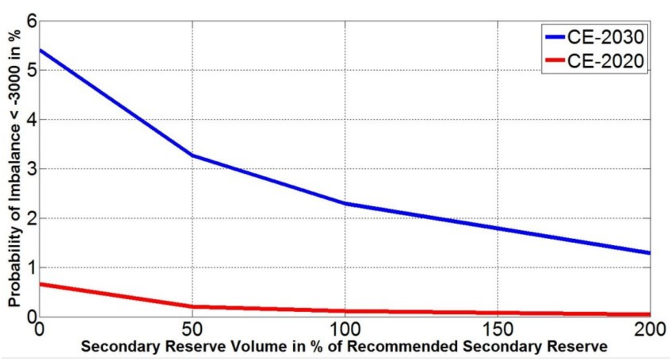

Fig. 6. Probability of power imbalance exceeding 3000 MW for CE for for different volume of secondary reserve

It was observed that the probability of imbalance due to wind forecast error in 2030 can be high enough to utilize the primary reserve dedicated for handling contingencies thereby, reducing security of the system. However, as evident from the results shown in Fig. 6 that impact of the imbalance can be reduced by increasing the volume of secondary reserve of the system. Fig. 7 illustrates that faster activation of secondary reserves does not have large impact in reducing the imbalance caused by wind forecast error. These studies are pertinent for

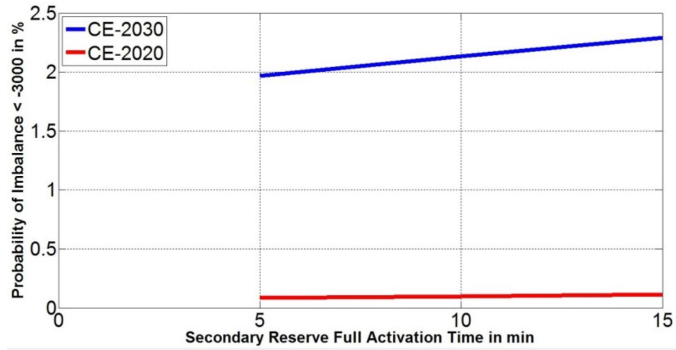

Fig. 7. Probability of power imbalance exceeding 3000 MW for CE for different activation time of secondary reserve

other power systems like Indian Grid where high penetration of renewables are envisaged in future.

Although proper designing of reserves are essential to reduce the probability of frequency emergency, nevertheless, emergency situations can never be avoided with 100% certainty. Therefore, proper defence plans should be designed for frequency emergencies. SPS requirements during an underfrequency event is different from than that of an overfrequency event. Therefore, relevance of renewable generations for overfrequency and underfrequency situations are discussed separately below:

1) Overfrequency: Frequency in high wind power generation area can increase very fast if power system inertia is not high. The automatic overfrequency protection system prevents frequency rise above or equal to 51.5 Hz (typical value for European power systems) that can cause conventional generating units to trip causing frequency instability [16]. The fast active power control capability of modern WPPs is a relevant option in the future defence plans as WTs can be down-regulated quite fast pertaining to fast control capabilities of power electronic converters. Although an important point to be considered is that if RoCoF is very high when system inertia is reduced, there is a high possibility of tripping of instantaneous df/dt (RoCoF) based relays in the system causing unintentional disconnections of generations. This aspect brings up the challenge of redesigning the protection settings meant for defence against extreme contingencies with high penetration of wind power generation. This issue has more pronounced effects in island systems like Ireland power system [17]. Ramping requirements for the renewable generations are dictated by grid codes and vary largely from one network to another.

In order to study the impact of emergency support from WTs, studies are performed for different settings for WTs during overfrequency emergency. A representative model of European Transmission Network called PEGASE EHV network [18] has been used. This model is representative of the CE system. The system has 16578 buses, 3240 generators, 14044 lines, 9654 transformers, and total load of 400 GW [18]. These simulations are performed in Eurostag. In order to simulate overfrequency event in the PEGASE network, system split is simulated. Fig. 8 indicates the split of Denmark + Germany network from the rest of the CE network. Area 1 consisting of Danish and German networks experience overfrequency while Area 2 consisting of rest of the network experiences underfrequency. 40% wind penetration is simulated in the Area 1 (overfrequency region) where WTs are modelled as IEC 61400-27-1 Type 4B fully rated converter based VSWT [19], [20].

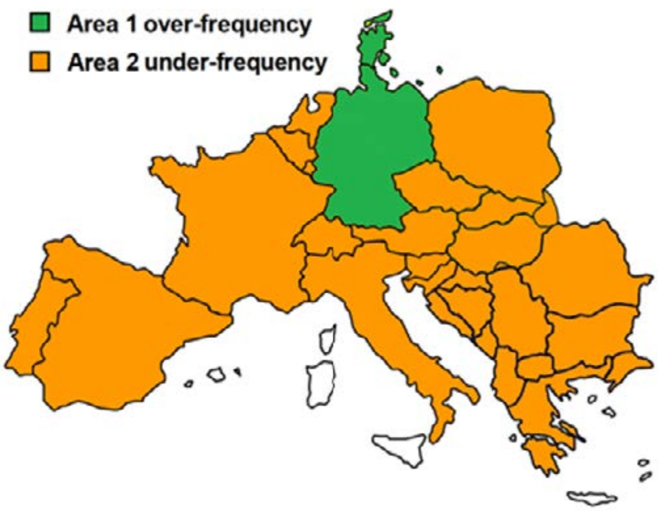

Fig. 8. Simulated Scenario in PEGASE network

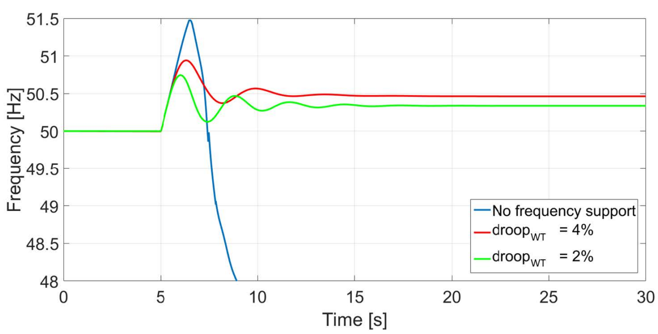

Fig. 9. Frequency with 40% Wind Power Penetration in Area 1 in PEGASE network

Fig. 9 depicts the frequency response when wind power penetration is 40% in Area 1 of the PEGASE network. It can be seen that without any frequency support from WTs system becomes unstable. However, system becomes stable with frequency support from WT generators. Droop setting of 2% can even restrict the peak frequency to less than 50.75 Hz.

These results clearly indicate the importance of considering renewable generations for power system defence plans.

2) Underfrequency: Quite a high proportion of DGs (including converter connected renewable generations) are connected to distribution networks. These DGs can be high volume of small PV panels in a country like India with high availability of solar irradiance. These DGs are connected at low voltage or medium voltage levels in close proximity to loads. DGs can impose major challenge to defence plans like UFLS. UFLS is considered as last resort to prevent frequency instability and thereby need to have high reliability. ENTSO-E recommendation for UFLS for European networks is shown in Fig. 10 [21]. Minimum load shedding is recommended to start at 49 Hz and multiple stages of load shedding are continued until 48.1 Hz as represented by the red region. However, load shedding from 49.2 until 48.6 (as represented by the green region) is desirable. UFLS is generally performed by automatically disconnecting the medium voltage feeders connected to distribution substations. Disconnecting feeders with large penetration of DG may disconnect substantial amount of DG. Consequently, the required amount of load disconnection as per design requirements cannot be achieved. Traditional load shedding relays do not consider this effect. "IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration" [22] has clearly mentioned that tripping feeders that have active DG certainly diminishes the beneficial effects of load shedding, and can even have negative impact by eliminating sources of generation that supports system inertia. Thus high penetration of DG advocates for advanced UFLS approach which would take DG into account [22].

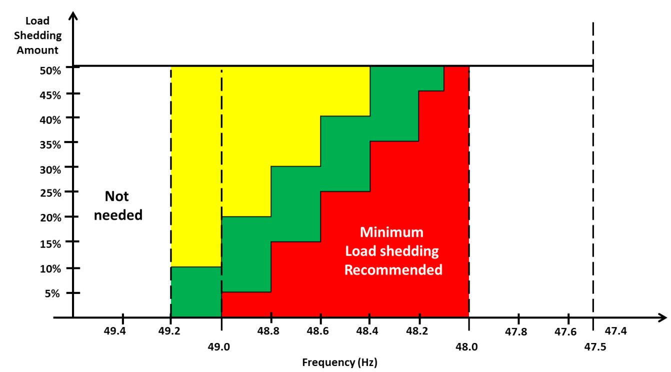

Fig. 10. ENTSO-E Recommendation for UFLS [21]

Authors have developed an intelligent scheme for UFLS considering DGs [23]. Four different load shedding schemes were developed and compared. Frequency response following an underfrequency event for all the four load shedding schemes are shown in Fig. 11. Static load shedding scheme (LSA-Static) uses traditional flat frequency based relays. LSA-Directional scheme has an additional directional element to the LSA-Static relay to prevent disconnection of a feeder with reverse power flow, i.e., a feeder with more generation than load. LSA-PF is an intelligent relay which uses the power flow measurements from all the available feeders to identify the required amount of load to be disconnected based on real-time measurements. This scheme tends to disconnect more DG, however ascertaining that the designed amount of load is disconnected to prevent frequency instability. LSA-

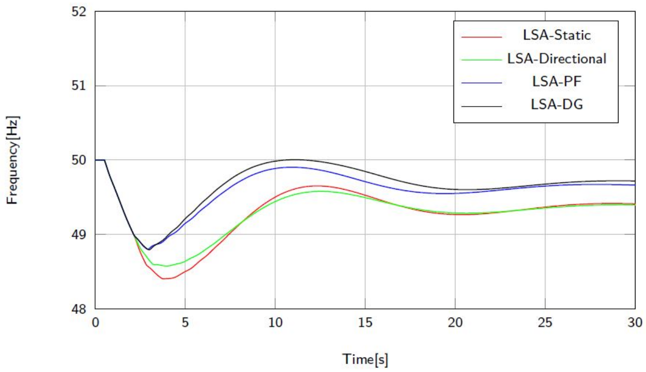

Fig. 11. Frequency responses for different load shedding schemes

DG uses available data about DG along with power flow measurements to estimate ad optimize the required amount of load disconnection while disconnecting minimum amount of DG. LSA-PF and LSA-DG are the optimal schemes in terms of frequency response as evidenced by the frequency response shown in Fig. 11. However, LSA-DG disconnects less amount of DG as compared to LSA-PF.

V. Conclusion

The studies shown in this paper clearly indicates that revision of traditional defence plans are essentially required when operating the system with high penetration of renewables. Results have shown requirements for additional reserves in order to prevent frequency emergencies. Additionally, improved control and protection algorithms (such as UFLS) should be developed as future defence actions.

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