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Review of Defence Plans in Europe: Current Status, Strengths and Opportunities

De Boeck, Steven; Van Hertem, Dirk; Das, Kaushik; Sørensen, Poul Ejnar; Trovato, Vincenzo ; Turunen, Jukka ; Halat, Milenko

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21 rue d'Artois - 75008 Paris – France

Tel : 33 (0)1 53 89 12 90

<http://www.cigre.org>

Review of defence plans in Europe: current status, strengths and opportunities

Steven De Boeck*, Dirk Van Hertem (KU Leuven, Belgium)
Kaushik Das, Poul Sørensen (DTU, Denmark)
Vincenzo Trovato (Imperial College, United Kingdom)
Jukka Turunen (Statnett, Norway)
Milenko Halat (AIA, Spain)

Abstract

In recent years the European power system has changed significantly, causing the system to be operated closer to the limits. The transition to more renewable generation is causing power injections at different locations from conventional generation. Secondly the integration of the internal electricity market is causing an increase in flows on interconnections between different areas of the European power system. Furthermore the time needed to construct new infrastructure pushes Transmission System Operators (TSOs) to better utilize the installed infrastructure. As the power system is strongly interconnected, a contingency in one area can affect the whole power system and possibly lead to a wide area black out. Therefore adequate defence plans need to be designed and in place to handle these situations. This paper starts with an overview of the terminology used in defence plans. Subsequently the current status of defence plans in Europe and the preferred sequence of actions to mitigate contingencies, is given based on a survey conducted among several European TSOs. Furthermore his paper gives an overview of how the ongoing changes with renewables, phasor measurement units (PMUs), power flow controlling devices and demand side response can affect the adequacy of defence plans.

1. Introduction

In recent years, the European energy system has experienced significant changes, the most outstanding

ones being the increased integration of renewable energy sources (RES), utility unbundling and the development of an internal electricity market (IEM) [1]. By 2020 the EU is targeting RES to provide up to 34% of electricity production and is aiming to extend the low carbon strategy to reduce greenhouse gas emissions by 80-95% by 2050 [2][3]. Both the large penetration of RES, which are often not located near load centres (e.g. Offshore wind farms), and the integration to an IEM have increased transnational power exchanges. As the general public is not in favour of installing more transmission assets, system operators are forced to operate the systems closer to their limits. Furthermore, due to the stronger linking of the national power systems a disturbance in one area, if not handled adequately, is more likely to affect other parts of the system. Additionally the shift towards more controllable devices and RES is causing the system dynamics to change. This is because these generation units are generally connected through power electronics, which do not deliver the same response to system disturbances. The power system is thus also being operated closer to its dynamic stability limits. As similar transitions are taking place in other parts of the world, operating the power system closer to its operational limits is becoming a global trend, which has translated in an increased risk on wide area blackouts. A worldwide overview of registered blackouts is depicted in Table 1 Frequency of outages [4-7]. A here considered wide area blackout affects at least 1000 people, last at least 1 hour and 1million person-hours of disruption.

*steven.deboeck@esat.kuleven.be

KEYWORDS

Blackout, Defence Plans, Distributed Generation, HVDC, Phasor Measurement Unit, Special Protection Schemes

Decade	Europe	Rest of the world	Total
1960-1969	-	1	1
1970-1979	-	4	4
1980-1989	2	4	6
1990-1999	1	10	11
2000-2009	13	30	43
2010-2013	3	6	9

Table 1 Frequency of outages [4-7]

Traditionally these issues were addressed by a defence plan which was designed at a nation or state level. Because current power systems cover more than one nation or state and because of the changes described above, these plans no longer guarantee the same adequacy. Therefore TSOs have made changes to these plans, but a wide variety of defence plans remains and also the coordination and harmonisation remain limited. On the other hand, the increasing use of technologies like power electronics connected renewables, phasor measurement units (PMU), high voltage direct current (HVDC) connections and the increased availability of data provide new opportunities to improve the existing defence plans.

Several technical organisations (CIGRE, IEEE,..) have realised the need for more detailed standards on defence plans and system protection schemes and have formed dedicated working groups [4] [7]. Similar initiatives related to special protection schemes have been taken by the North American Reliability Council (NERC) [8] [9]. In Europe, ENTSO-E has published recommendations for the implementation of defence plans and SPS and their research and development road map describes further actions needed [10]. Also within the FP7 project iTesla, new rules and harmonisation guidelines for defence plan design are being investigated [11]. This paper summarizes the results of a survey which was conducted among the iTesla partners and combines the results of other surveys [12] [13]. It gives a review of the current status of defence plans, defence plan terminologies, future challenges and opportunities.

The organisation of this paper is as follows. The second section of this paper elaborates on the terminologies used in defence plans. The third section gives a description of the current status of operational procedures and defence plans in Europe. Section four continues with the upcoming challenges and potential improvements. Finally the conclusions are presented in section five.

2. Defence Plans & Special Protection Systems

2.1. Stability phenomena leading to system deterioration

The power system is designed and operated to be able to cope with a number of predefined credible contingencies (e.g. N-1 events such as a line or generator outage). If such a contingency takes place, the power system is able to return to a stable operation point. It is also possible that the system is subjected to a contingency which is not conceived as credible and which is more severe (e.g. a multiple line or generation outage). When extreme contingencies disrupt the interconnected power system, the post disturbance effects can lead to a number of distinct types of power system breakdown. In the majority of cases the breakdown is related to instability (rotor angle, frequency or voltage) or cascading line tripping [4]. Breakdown can only be avoided by the timely control of these post disturbance phenomena. In order to protect the system, it is of primary importance to understand each of the phenomena involved in system collapse. Therefore it is key to keep the time horizon for the propagation of these issues in mind as this will determine the time available to mitigate the issue [14].

- Rotor Angle Stability: The ability of synchronous generators of an interconnected power system to remain synchronous after a disturbance. It can be divided into small-disturbance angle stability and transient stability (following a large disturbance such as a short circuit).
- Frequency Stability: The ability of the power system to reach and maintain a stable operating point following a severe disturbance resulting in a significant unbalance between production and consumption [14][15]. In large interconnected power systems this type of stability is mostly associated with the loss of multiple generation units (multiple contingencies) or the splitting of the system into unbalanced areas.
- Voltage Stability: The ability of the power system to maintain acceptable voltages at all buses in the system after a disturbance. Voltage stability depends on the ability of the power system to supply the active and reactive load.
- Static and Transient (Thermal) Overloads: The

ability of the power system to supply all load without damaging or triggering the thermal overload protection of any of the power system elements.

2.2. Description of a defence plan

To protect the power system from collapsing, it is equipped with a multi-layer protection scheme. The first protection layer is in the design. Sufficient redundancy is built in to manage the effects of an outage of a single element. Secondly, system elements are equipped with protection systems to assure no permanent damage is inflicted after contingencies. For example a flashover between a line and a tree will result in the temporary disconnection of this line by the distance protection. Thirdly a set of operational rules has been designed as a framework to ensure that credible contingencies can be contained by the system operators (e.g. manual actions). When extreme contingencies disrupt the power system, there is a last line of defence which is called the defence plan.

Cigré describes a defence plan as 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. The defence plan is used to minimize and reduce the severity and consequences of low probability and unexpected events and to prevent system collapse (prevent the progression to blackout state). Individual SPS, such as automatic generation run back schemes, load or generation rejection, load shedding, reactive switching, bus or system splitting, etc. are then regarded as coordinated elements used within a defence plan. ENTSO-E uses the same definition as proposed by Cigré [4]. ENTSO-E also uses a system state representation to identify when the defence plan is activated. In this approach, during system collapse the system evolves from normal state to alert, emergency and eventually blackout. The defence plan is activated on the transition from emergency state to blackout state [15].

Special and System Protections Schemes (SPS)

The defence plan is composed of several schemes intended to prevent instability. Several terms to describe these schemes are in circulation. One method to categorise them is to make the distinction based on

the trigger that activates the scheme. The scheme can be activated by a specific event, which is then called event based. An example can be a power plant connected via two lines to the rest of the system. In case of an outage of one of the lines, the generation unit is immediately curtailed or disconnected to avoid the remaining line being overloaded. Other schemes are activated based on a system response to a contingency: changes in voltage, frequency, etc. Here an example is the under voltage load shedding action. NERC uses the term Special Protection System or Remedial Action Scheme (RAS), which is an automatic protection system designed to detect abnormal or predetermined system conditions, and to take corrective actions in addition to the isolation of the faulted components.

ENTSO-E makes the distinction based on the issue the scheme is targeting. In that sense, system protection schemes focus on the stability problems described in section two of this paper, while special protection schemes are intended to operate for rare, but foreseeable events that could undermine the integrity of the grid. These are also called System Integrity Protection Schemes (SIPS). Subsequently, a system protection scheme is triggered by a system response, while a special protection scheme can be event or response based [11][12][13]. Many different schemes have been implemented by TSO's and often different names are used for similar schemes.

Finally one should also make the distinction between a defence plan and a shortage plan. While the defence plan protects the power system against sudden unforeseen phenomena, the shortage plan describes how to handle foreseeable adequacy problems (a foreseeable lack of generation or transmission capacity to supply all the load in an area).

3. Current status of defence plans in Europe

As a starting point for the ongoing research on defence plans within the iTesla project, a survey has been conducted among the participating TSOs. After each TSO completed the survey, an in depth discussions on the given answers took place. This enabled knowledge to be obtained about the current practices of SPS integrated in the defence plans of the participating TSOs (mainly

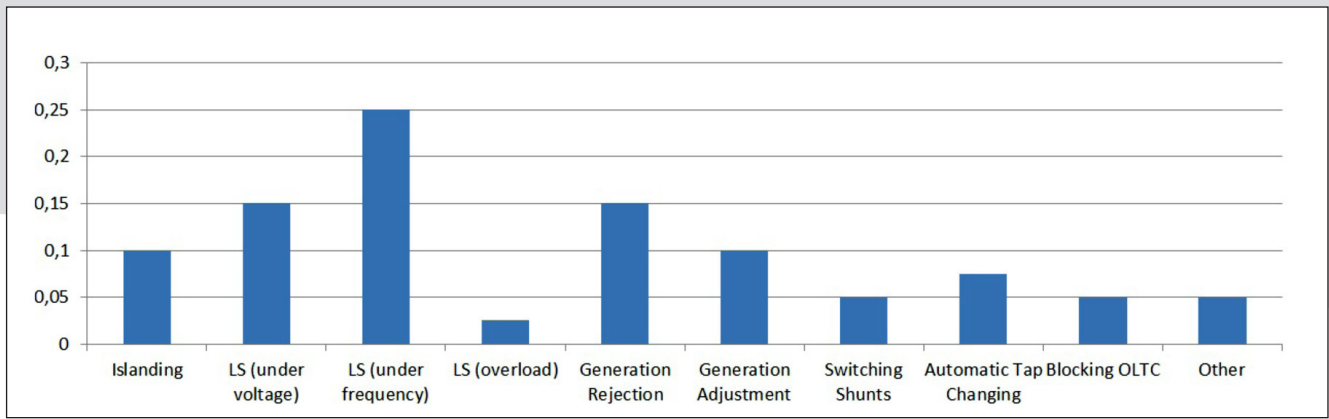


Figure 2: Types of SPS installed by the participating TSOs

from Western-Europe). The results are outlined and statistically categorised in this section.

In Figure 1 Types of Instability and distribution between event and response based schemes it is shown that for each of the instability issues, several protection schemes have been put in place. Each of the bars represents the relative number of schemes that are implemented for a specific stability issue. The colour of each column gives the distribution between response (blue-lower) and event based (red-upper) schemes. The majority of schemes are dedicated to resolving voltage issues, as voltage problems are more local and a larger set of measurements are available. The second largest number of SPS installed, target frequency instability. The number of schemes dedicated to rotor angle stability and overload mitigation are clearly lower. This figure also shows that the majority of triggers are response based (triggered when a power system parameter reaches a predetermined threshold).

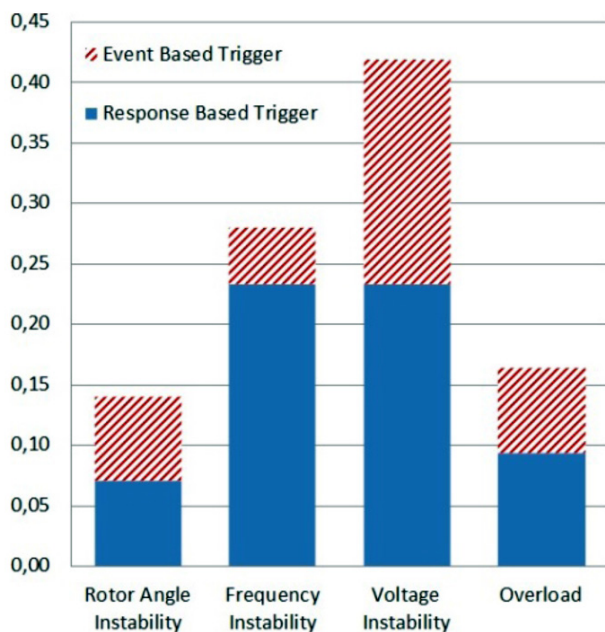


Figure 1: Types of Instability and distribution between event and response based schemes

Figure 2 Types of SPS installed by the participating TSOs gives an overview of the types of SPS, that the

participating TSOs have installed. The majority of schemes installed focus on load shedding (LS). In the majority of cases these schemes intend to restore the frequency, though there are also several LS schemes to maintain voltage. The second most commonly installed schemes are generation rejection schemes (disconnection of a generation unit from the grid) and generation adjustment schemes (automatic re-dispatch). Most of the islanding schemes are installed to mitigate rotor angle instabilities. Blocking of on load tap changers (OLTC) is used to avoid the situation where a fault on MV or LV also pulls down the voltage of the transmission system.

3.1. Handling Frequency Stability

As described earlier a sudden change in frequency occurs when one or multiple elements trip, leading to a significant imbalance between load and generation. In a large interconnected power system, this type of situation is most commonly associated with a multiple generation outage or a situation following system separation, as was the case in Europe on the 4th November 2006 [5]. In the case of system separation, some of the areas will have a surplus of generation (over frequency), while others will have a deficit (under frequency). In the over frequency area, generation will need to be reduced. In the under frequency area new generation needs to be started up or load will need to be disconnected. As the frequency is a system parameter, not limited to a certain area, coordination on over and under frequency schemes is considered to a certain extent and general guidelines have been formulated. Generally the activation of specific actions is determined based on a frequency threshold (Sometimes the rate of change is also used). The order of actions is mainly determined by the economic and social impact of the action.

3.1.1. Under frequency scheme

The first protection against a frequency below the nominal frequency is delivered by the primary response of the generation units. The primary response in Continental Europe is able to cope with an event that causes a maximum deviation of 200mHz (or a power unbalance of 3000 MW). This protection is part of normal operation. If the frequency deviation is bigger,

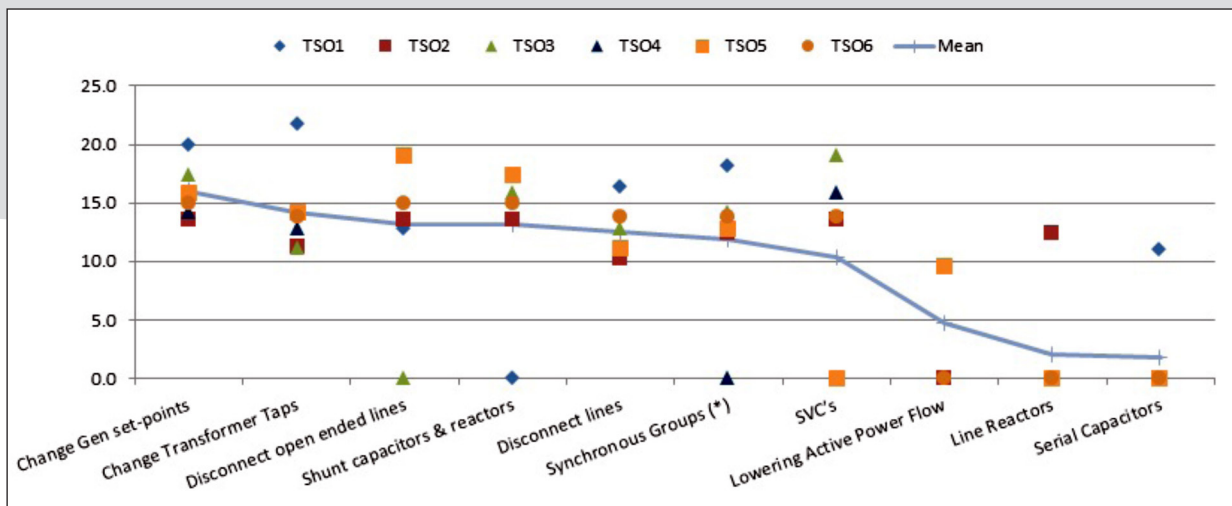


Figure 3: Preferred sequence of actions to mitigate over voltages (relative weight between actions).

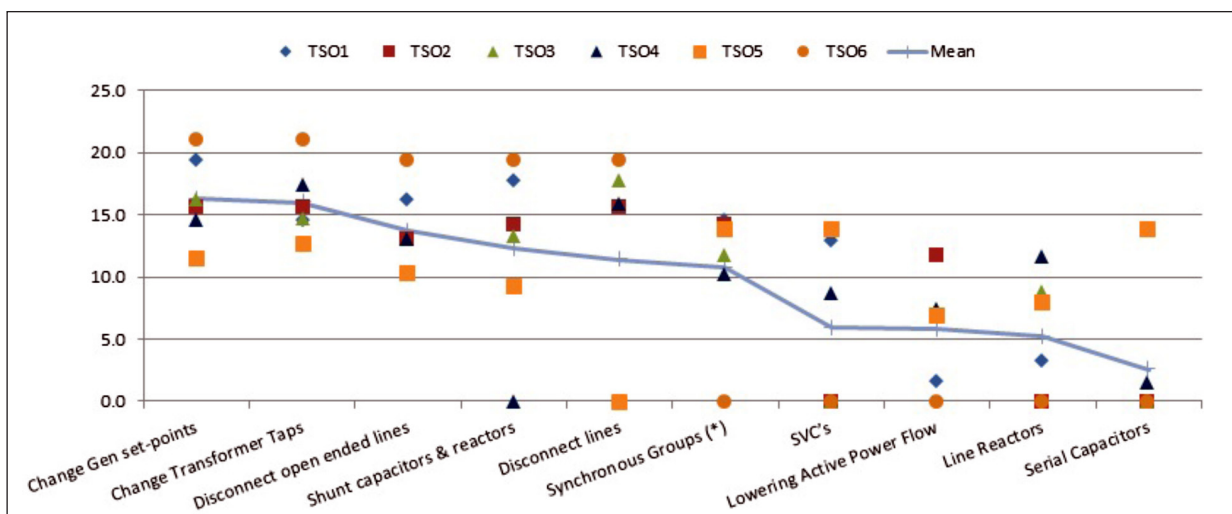


Figure 4: Preferred sequence of actions to mitigate under voltages (relative weight between actions).

the system operator can disconnect customers according to contractual arrangements, reduce the export on a HVDC line with another area, stop pumping storage units, start up new generation, or do soft load shedding. Contractual load shedding is carried out by reducing demand of clients who have made an agreement with the TSO which states that the TSO can reduce their consumption a number of times a year against a specified price. Reducing the export on a HVDC line has the same effect as disconnecting load, though this will shift part of the problem to the other area. Therefore, when using this action, coordination with the TSO of the other area is always needed. Operations of these lines are often predefined. Soft load shedding is done by reducing the voltage at the distribution side with 5 to 10%, which is assumed to be equivalent to a reduction of 2% of active load. With the increasing penetration of electronically connected devices, the efficiency of this action will decrease. Depending on the value of the frequency, each of these actions is activated manually or automatically. When the frequency drops below 49Hz the automatic load shedding plan will be activated. Each TSO is responsible for the design of these schemes (frequency thresholds and amounts disconnected) within its own area, though ENTSO-E policies describe that at 49Hz at

least 5% of the load should be disconnected. Below 49 Hz a linear load shedding scheme is advised [16]. Often the design of these schemes is done in close cooperation with the DSO, to be able to determine the high priority feeders (hospitals, communication facilities, military, etc.).

3.1.2. Over frequency scheme

A frequency between 50 and 50,2Hz is covered by normal operation as stated before. When the frequency rises above 50,2Hz manual and automatic power generation reduction will take place. This can either be done by generation adjustment schemes or by rejection (tripping) of generation. A generation adjustment scheme ramps down the generation output at a specific rate (%/Hz) if the frequency goes above a specified threshold (Ex. 50,3Hz). With the increased penetration of renewables and HVDC connections, parts of the design of these schemes can be improved. In section IV this will be further elaborated.

3.2. Typical under/over voltage scheme

Most of the reactive power needed to maintain the voltage is usually generated close to the load centres. This to reduce the reactive power flows and hence losses

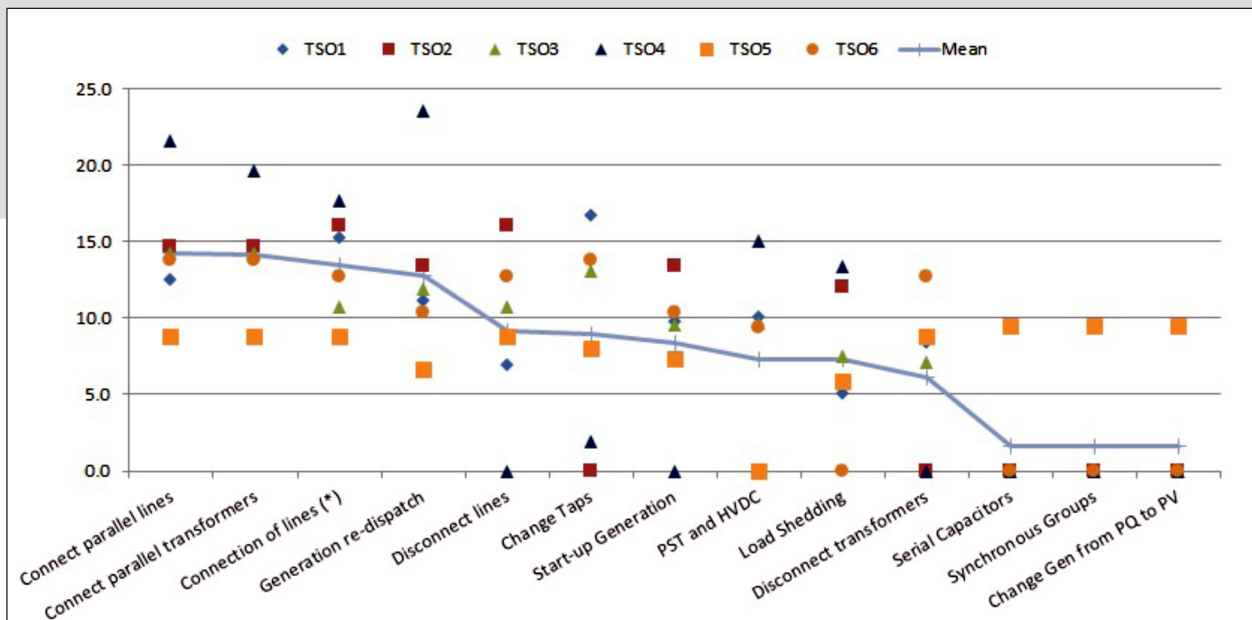


Figure 5: Preferred sequence of actions to mitigate overloads (relative weight)
 (*)Connect lines to increase system meshing.

on the system. Therefore, generally a local solution for the voltage problem is preferred. Several actions are at the disposal of the TSO such as: a change in reactive power set points for generation units, or the switching of shunt elements (capacitor banks, reactors, SVCs, STATCOMs, etc.). If these actions cannot resolve the voltage problem, the next step is to isolate the problem in a specific area of the system. One method to do this is by blocking the on load tap changers. The voltage of the medium voltage system will remain low, but the voltage in the high voltage system will be restored to normal. Some TSOs cannot implement this action, as they have a lot of shunt capacitors installed at medium voltage. Blocking of OLTC would then increase the risk for overvoltage at medium voltages. An ultimate measure to maintain the voltage is to reduce the demand for reactive power by disconnecting part of the load. Of the above described actions usually the transition to a defence plan is made starting from the blocking of OLTC, although some schemes exist where a loss of a line triggers a change of set point for shunt elements. In Figure 3 Preferred sequence of actions to mitigate over voltages (relative weight between actions). and Figure 4 Preferred sequence of actions to mitigate under voltages (relative weight between actions). an overview is given of the preferred sequence of actions for each of the TSO's for an over and under voltage problem respectively. In this figure, each TSO gave a relative ranking of all possible actions according to their importance. Some TSO's try to first solve the voltage problem with the shunt elements, as changing the generation set points can come at an extra cost.

3.3. Typical Rotor angle stability scheme

To avoid the loss of synchronism of a single generator or a group of generation units, sometimes fast valving

is implemented. If this action does not resolve the issue, a disconnection of the largest unit in the group of units that loses synchronism is often used. A final measure to prevent uncontrolled tripping is controlled islanding, where the system is separated into several non-synchronous zones. Some TSOs have implemented Out-of-Step relays at predefined location to execute this action, whilst others rely on the distance protection relays to separate the system at its natural points. As described before, most of the SPS covering rotor angle stability are islanding schemes.

3.4. Typical overload mitigation scheme

To resolve overloads on the system, most TSOs try to switch in extra system elements such as lines, transformers and cables. One TSO prefers the change of generation set points before changing the system topology, but with the unbundling this usually comes at a cost. Some TSOs also change the location of reactive power generation or adjust transformer taps to reduce reactive power flows on highly loaded lines. If the overload is located on a tie line, a solution is sought through direct communication with the TSO of the other area. An overview of the preferred actions is given in Figure 5 Preferred sequence of actions to mitigate overloads (relative weight) (*)Connect lines to increase system meshing.. The special protection schemes used to mitigate overloads are automatic generation rejection or adjustment schemes or line switching.

3.5. Coordination of defence plans

To execute a defence plan adequately at times when the system is under stress, it is important that there is good coordination between all stakeholders of the power system. Therefore system operators are trained in exercises on wide area incidents which include

cooperation with other parties such as other TSOs in the same synchronous area, DSOs and generation companies. For most TSOs, this training takes place every two years. For events which have an influence outside of the TSO's own region, agreements should be in place for adequate and appropriate actions to be carried out. These events can be the outage of an element or the activation of an SPS that causes a violation of system parameters in a neighbouring system, such as overloads, voltage or frequency problems, etc. An example could be the automatic change of an HVDC set point, causing a frequency change in another synchronous area. To mitigate overloads, all TSOs have bilateral contracts with generation companies. In the case of serious congestions, agreements are in place with neighbouring TSOs on congestion security management (CSM). Also with the increased penetration of distributed generation, there is a need for an increased coordination with the DSOs. In regions with large amounts of distributed generation it has been ascertained that automatic load shedding actions can disconnect more generation than load, thus resulting in the opposite to desired effect. To facilitate coordination, direct communication via phone, mail and fax takes place.

4. Further harmonization of defence plans: issues and solutions

The current harmonisation of defence plans has mainly been targeting under frequency load shedding plans, as they affect all areas of an interconnected synchronous grid. As stated before, ENTSO-E advises a linear load shedding scheme in Europe and obliges the TSOs to shed at least 5% of load, if the frequency drops below 49Hz (Figure 6 Load shedding scheme advised by ENTSO-E). But there is still a lot of variation in UFLS schemes after the initial step [17]. This paper gives an overview of a number of the installed under frequency load shedding schemes in Europe and the interaction between them. It is clear that if the schemes are not identical, the areas with the largest load shedding step at a specific threshold, will carry the largest burden. Also the transfers to or from this area can change significantly. Furthermore, because of increased penetration of RES, in some areas it has become more difficult to estimate the amount of load

behind each feeder and it has been shown that in several cases less than 5% was shed in the first stage of the UFLS scheme. Therefore several TSOs, have adapted their schemes to compensate for the loss of embedded generation, by shedding more load in the first step of the scheme. But this further prevents the equal spreading of load shedding between different areas and causes a larger impact than needed to mitigate the contingency. Therefore a more intelligent UFLS scheme needs to be developed.

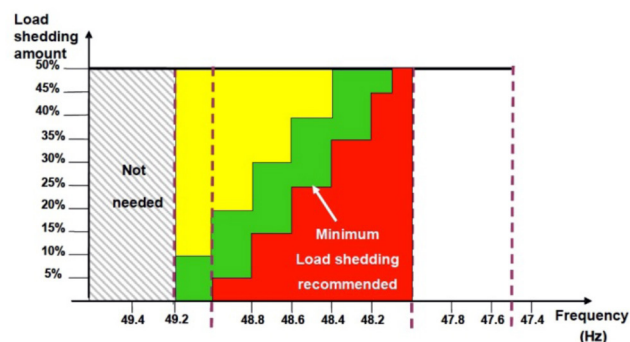


Figure 6: Load shedding scheme advised by ENTSO-E

4.1. Power Flow Controlling devices (PFC)

One of the changes in the power system is the increased installation of PFCs, such as phase shifting transformers and HVDC lines. HVDC lines can provide a fast response to changing active and reactive flows in the system and therefore can be used to respond quickly to overloads, power swings and voltage problems. Nevertheless, their use in defence plans has until now been rather limited. The reasons for this are that a limited number of PFCs are installed and cross border operation can benefit one area, but have an adverse influence on the neighbouring area. Therefore, focussing on HVDC interconnectors, the control actions are generally done manually and often after consulting the neighbouring TSO. For Example, an HVDC interconnector is operated with a bilateral agreement in place for emergency situations, specifying that the import can be ramped down to zero or up to maximum without changing the direction of the flow, when there is an over or under frequency problem respectively. To change the direction of the flow, a phone call has to be made to the neighbouring dispatching centre. This causes part of the technological benefit to

be lost (fast response). Although automatic reduction or ramp up scheme also exists. Some DC lines are installed with pole tripping schemes to avoid AC overloads. Also, as the number of DC lines is increasing, a more harmonised approach is needed as bilateral agreements will no longer suffice. In paper [18] it is shown, that for embedded HVDC lines (within a synchronous area) a more centralised approach can for example lead to higher flow transfers between areas in the power system, and as such deliver an extra safety margin to the power system and protection against cascading outages. But the full benefit is only achieved through automation of the control actions. To be able to use these controllable devices in automatic system protection schemes, new control methodologies and guidelines need to be developed. To be able to implement these methodologies, it is crucial to have a wide area view on the system in real time.

4.2. Phasor Measurement Units(PMU)

PMUs provide high accuracy time-synchronized information of the power grid variables (e.g. voltage, current, frequency, rate-of-change of frequency) [19] in different areas of the system, and can thus be used to observe oscillations, voltage levels and frequencies in different areas. Therefore, after further processing, PMU information could be used in response-based system protection schemes of various stability types. PMU information can also be used in detecting islanding situations. However, as became clear from the survey, some of the European TSOs stated that PMU information is not yet utilized in defence plans against different instability phenomena that can occur in the power system. The PMU information could possibly be utilized in the defence plans to provide a triggering signal in SPS when the measurements are processed appropriately. In paper [20] a defence plan methodology against voltage instability was developed, a test system implemented in simulation software, and the methodology tested in the test system. The methodology is based on calculation of sensitivities with linear regression, and it is capable of determining an impending long-term system collapse. Benefits of the method are that the network topology and dynamic models are not required, difficulties related to filtering techniques are avoided, and intrinsic time delays from using filtering methods are eliminated. In utilizing PMU information in defence plans in the future, it is

necessary to ensure that the algorithms used to initiate protection actions are reliable and robust. Also the PMU data transfer from different areas must be reliable enough and the quality of the data good enough. As PMUs are dependent on satellite synchronization it should also be noted that this causes an inherent vulnerability in the measurements.

4.3. Impact of Renewables

The goals set by the EU have resulted in a significant increase in renewable generation units connected to the power system. A large penetration of wind generation (WG) might have considerable impacts on defence plans for frequency and voltage stability. Paper [21] gives an overview of these problems. For frequency stability it makes clear that the partial replacement of conventional generation with WG will result in erosion of system inertia, which results in increased rates of change of frequency (RoCoF) during events and possibly unwanted trips of RoCoF relays. Therefore research is looking at supplementary control strategies to provide inertial response with WG and to make WG emulate primary or droop control to contain low frequency. If the drop in frequency is large, under frequency load shedding might be required to prevent frequency instability. However, traditional load shedding schemes may not be efficient with high penetration of distributed renewable generations. Therefore, advanced load shedding schemes considering distributed generation need to be developed. Similarly for over frequency situations, the fast active power control capability of modern wind turbines (WTs) is a relevant option, as converter connected WTs can be down regulated much faster than other types of generators. WG can deliver and absorb reactive power for short period to alleviate voltage stability issues. Although variable speed wind turbines can support voltage stability by regulating reactive power, the limited capacity of the partial scale converter in DFIG turbines results in a voltage control capability which cannot emulate a synchronous generator. Furthermore, it is also very important to look at the reserve requirements with high penetration of renewables. Dynamic reserve deployment instead of static reserve may be a better option to handle imbalances caused due to forecast errors. The forecast error decreases as the time horizon moves closer to real time, but can still be as high as 100%. This is mainly due to the inaccuracy of the

meteorological forecast [22]. Therefore, if reserves are defined statically instead of dynamically, it will require a much higher capacity of automatic reserves to be committed and deployed, which will remain unutilized for most of the time.

4.4. Demand Side Response (DSR)

Demand Side Response represents a promising contribution to smarter power system operation and at the same time improve network security under future scenarios characterised by large amounts of renewable energy sources. In fact, during normal operation, one can manage the devices' power consumption, shifting demand from peak to off-peak hours in order to re-shape system demand profile. DSR is also becoming a solution to the problem of lack of system inertial response introduced by wind turbines. The ability to disconnect distributed loads already within the inertial response time window testifies the possibility for demand response to provide effective inertia. Specifically, we have considered the smart control of thermostatic loads (TCL). In this application, each "smart" load identifies the frequency deviation and, according to the particular algorithm implemented, adjusts its power consumption. In case of a generation shortage resulting in a frequency drop, the devices will tend to switch off in order to quickly reduce the power imbalance. Current research [23] quantifies the impact on system security of the inertial support provided by controlling thermostatic loads, even though the conventional definition of an inertial constant does not apply to these appliances. Moreover it is shown that the increased "effective system inertia" resulting from the demand response allows the system operator to integrate a large share of RES which would otherwise be curtailed. The recovery pattern of TCLs has to be controlled to not cause a negative impact the network operation. A basic but effective control strategy in [24] avoids the need to synchronize individual devices and drastically reduces and postpones additional energy costs. More robust control strategies will be required to increase demand side reliability.

5. Conclusion

This paper provides an overview of the different terminologies used in defence plans in order to clarify the multiplicity of terms for these schemes in use around

the world. Thereafter an overview is presented of the phenomena which play a key role in the stability of a power system in emergency. Subsequently an overview has been given on the current practice of defence plans and SPS in Western Europe to form a starting point for further harmonization and coordination of defence plans. From the analysis, it has become clear that defence plan designs originated from a national approach. Most schemes are response based and focus on voltage related issues. Until now the most harmonized scheme is the under and over frequency scheme, which uses load and generation rejection schemes respectively. As part of the analysis an overview of the preferred sequence of actions for each of the participating TSOs has been given. The differences between TSOs generally depend on the installed system elements and contracts made with generator companies. It has also become clear that the use of PMUs is still limited to post mortem analysis. In the last decade, the adequacy of the current schemes has become more and more under pressure due to several changes taking place in the power system. The final section points out how these changes impact the adequacy of the current defence plans and where more research is needed. Here the main focus has been on the impact of distributed energy sources on UFLS schemes, the potential of using PFCs and PMUs, the impact and possibilities of improved control of renewables and demand side response. Currently TSOs are making adjustments to their UFLS schemes to take distributed generation into account (larger initial LS steps), though this method cannot be applied if the penetration further increases. For HVDC lines the number of installed control schemes remains limited and activation is mostly manual. Therefore new automatic control methodologies need to be developed to use the full potential of this technology. In order to assure the use of PMU devices in defence plans, the algorithms which are used to initiate protection actions need to be reliable and robust. To assure the further integration of WG in the system without jeopardising system security, it is necessary to define reserves dynamically and to design supplementary control strategies to provide inertial response. Also with regard to distributed energy sources, the impact on UVLS- and UFLS-relays should be reviewed. Another approach to deliver inertial support is by applying demand response, such as the smart control

of thermostatic loads. The increased “effective system inertia” resulting from demand response allows the system operator to integrate larger amounts of RES which would otherwise be curtailed. Finally it is important to notice that experienced and well trained dispatchers are a complementary necessity to operate the power system in a secure way. Therefore sufficient training on wide area system disturbances, involving several TSOs and DSOs, should take place on a regular basis.

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8. Biography

Steven De Boeck was born in 1988 in Diest, Belgium. He received the M.Sc. degree in electrical energy engineering from the University of Leuven (KU Leuven), Leuven, Belgium, in 2011. Currently, he is working towards a Ph.D. degree at KU Leuven in the research group Electa, dept. of Electrical Engineering. His special fields of interest are new methodologies to maintain power system security and the use of PFCs, such as PST and HVDC, in emergency plans.

Dirk Van Hertem graduated as a M.Eng. in 2001 from the KHK, Geel, Belgium and as a M.Sc. in Electrical Engineering from the KU Leuven, Belgium in 2003. In 2009, he has obtained his PhD, also from the KU Leuven. In 2010, Dirk Van Hertem was a member of EPS group at the Royal Institute of Technology (KTH), in Stockholm. Since spring 2011 he is assistant professor in the ELECTA group at the University of Leuven. His special fields of interest are power system operation and control in systems with FACTS and HVDC and building the transmission system of the future, including offshore grids and the supergrid concept. He is an active member of both IEEE (PES and IAS) and Cigré. Dr. Van Hertem was the general chair of the IEEE EnergyCon 2016 conference, held in Leuven.

Kaushik Das is currently working as a Post doc researcher at department of Wind Energy, Technical University of Denmark (DTU). His PhD research was on “Integration of Renewable Generations on Power System Defence Plans” at DTU. Previously he worked in IBM Research on different smart grid projects. His research interest includes weather dependency of power systems, power system defence plans, integration of renewable energy resources to grid, smart grid.

Poul Sørensen is professor in the area of Wind Power Integration and Control in the Department of Wind

Energy. He has worked with wind energy research since 1987 and managed several research projects in cooperation with other research institutes, wind energy industry and grid operators. He is involved in standardisation as a member of IEC 61400-21 on Electrical characteristics (power quality) since it started in 1997, and as convener of IEC 61400-27 on Electrical simulation models for wind power plants since it started in 2009.

Vincenzo Trovato was born in Bitonto, Italy. He received M.S. degree in Electrical Engineering from Politecnico di Torino, Italy, in 2010 and the Ph.D. degree in Electrical Engineering at Imperial College London, U.K. He is currently Research Associate within the Control and Power Group at Imperial College London. His research interests include demand side response and its impact on the power system control and economics.

Jukka Turunen (S’07–M’11) received the D.Sc. (Tech.) degree from Aalto University, Espoo, Finland, in 2011. He is currently working as a Specialist for Statnett SF, the Norwegian transmission system operator, in the R&D group. His main research interests are power system dynamics and power system wide-area monitoring. Recently, he has also been a post-doctoral researcher at Aalto University School of Electrical Engineering, Finland, and continues close co-operation with the university.

Milenko Halat is a Chilean theoretical physicist currently residing in Barcelona, Spain, who has a strong background in power systems due to 5 years of Electrical Engineering coursed at Santa María Technical University (Chile). The topic of his PhD Thesis is Renormalization in Quantum Field Theories (Pisa University, Italy 2004). Nowadays Milenko works as Research and Innovation consultant, in management and technical tasks, focusing in heterogeneous areas like optimization, machine learning, modelling, power systems, etc.