Necessary Contribution of Electric Vehicles to Limited Frequency Sensitive Mode

Impact on frequency stability in the ENTSO-E Continental Europe Synchronous Area

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***Abstract*— This paper analyses the contribution of electric vehicles (EV) to Limited Frequency Sensitive Mode (LFSM) and its impact on frequency stability in the ENTSO-E Continental Europe Synchronous Area. In case of a system split the system can be affected by high active power imbalances together with high rates of change of frequency, due to increasing transmission capacities and increasing share of non-synchronous (inverter based) renewable generation. The contribution of EV to frequency stability by LFSM has a big impact in case of high penetration of EV connected to the grid. Due to the fact that EV and non-synchronous generation are connected to the distribution grids, the implementation of LFSM has also an impact on distribution grids, even if not directly responsible for frequency stability issues. The paper shows that both transmission system and distribution grid implications have to be considered for a stable system behavior.**

Keywords- Frequency stability; inertia; non-synchronous generation; system split, rate of change of frequency, limited frequency sensitive mode; under-frequency load shedding

I. Introduction

Power systems all over the world are affected by decreasing power system inertia caused by increasing infeed of non-Synchronous (inverter based) renewable and decentralized generation (DG), in particular wind and photovoltaics. In small synchronous areas, temporary low system inertia already affects system operation during normal operation. In contrast, this is not the case in big synchronous areas like the ENTSO-E Continental Europe Synchronous Area. Low inertia in parts of the synchronous area is not an issue during normal interconnected system operation where imbalances typically do not exceed the reference incident of 3 GW.

However, in case of an unintentional system split, dividing the system into two or more asynchronous islands, low inertia combined with high imbalances (much bigger than the reference incident) can have a significant impact on frequency stability due to the resulting high rate of change of frequency (RoCoF).

The analysis of potential system split scenarios identifies the risk of very high RoCoFs in case of a system split with a high impact on frequency stability. Different emergency control schemes are designed to prevent the power system from blackout. In case of generation deficit (under-frequency island), the under-frequency load-shedding (UFLS) and the limited frequency sensitive mode under-frequency (LFSM-U) and in case of generation surplus (over-frequency island) the limited frequency sensitive mode over-frequency (LFSM-O) come into operation.

The implementation of the UFLS is within the responsibility of the Distribution System Operator (DSO) and historically it is implemented within the protection of the high voltage (HV)/medium voltage (MV), for example 110/20 kV, transformer protection or – in newer systems – within the MV-feeders. The UFLS scheme were set up based on the annual peak-loads of the feeders or transformer loads.

Nowadays, at least in rural regions of Germany, the Distribution Grid is also used to transfer the distributed generation up to the Transmission System. Therefore, former UFLS schemes also shed generation instead of load in the distribution system in case of generation surplus. Caused by this issue the UFLS scheme had to be updated with a load-flow sensitive UFLS lock [1]. In fact, this prevents unintended generation shedding but the load-shedding within the distribution system is also impaired.

The only sustainable solution for this problem is to move the UFLS function directly to the load or – even more efficient – to implement LFSM-U in every non-vital and continuous controllable consumer load. Suitable loads are in particular inverter based loading applications for battery storages (e.g. in households or in electric vehicles) of all sizes.

Therefore, the present paper focuses on the contribution of electric vehicles (EV) to Limited Frequency Sensitive Mode (LFSM) and its impact on frequency stability in the ENTSO-E Continental Europe Synchronous Area.

In chapter II the general approach of load-frequency control within the ENTSO-E Continental Europe Synchronous Area is defined and the Limited Frequency Sensitive Mode is described in chapter III. The impact on the Distribution Systems is shown in chapter IV. In chapter V the impact on the Transmission System is analysed. Conclusions and an outlook are given in chapter VI.

II. Load-Frequency Control

Control schemes related to load-frequency control (LFC) can be divided into control schemes related to operating conditions “Normal State” and “Emergency State”.

A. *Operating condition “Normal State”*

According to [2] the Synchronous Area comprises of one or, in case of large Synchronous Area, more LFC Blocks. The ENTSO-E Continental Europe Synchronous Area (Synchronous Area CE) covers several LFC Block. Each LFC Block consists of one or more LFC Areas.

For operating condition “Normal State” LFC and reserves are designed to keep frequency within defined limits and to restore the Area Control Error (ACE) of every LCF area. LFC is divided into three main controls, the Frequency Containment Reserve (FCR), Frequency Restoration Reserves (FRR) and the Replacement Reserves (RR).

This proportional load-frequency control, typically provided by generating units via Frequency Sensitive Mode (FSM) [3], is designed to keep frequency within defined limits for normal operating conditions. Basis for dimensioning of FCR is the reference incident of 3 GW in the Synchronous Area CE. Full activation of FCR has to be realized after 30 seconds. At a frequency deviation of ± 200 mHz, the full activation of FCR is required. For an imbalance equal or less than the reference incident, a maximum instantaneous frequency deviation of 800 mHz is allowed.

According to [2] Frequency Restoration Reserves (FRR) means the Active Power Reserves activated to restore system frequency to the nominal frequency. For synchronous areas consisting of more than one LFC, FRR has to restore the power balance to the scheduled value.

Replacement Reserves (RR) refer to the reserves used to restore the required level of FRR to be prepared for additional system imbalances [2].

B. *Operating condition “Emergency State”*

Disturbances exceeding the reference incident for normal operating conditions (leading to frequencies outside of 50 ± 0.2 Hz) have to be coped with further automatic control schemes to prevent the power system from blackout. These emergency control schemes, designed for emergency operating conditions are decentralized mechanisms mandatory for generating units and loads, defined in the ENTSO-E network codes [3], and the respective national implementations [4][5]

Emergency control can be divided into over-frequency and under-frequency. In case of over-frequency, the Limited Frequency Sensitive Mode – Over-frequency (LFSM–O) and in case of under-frequency, the Limited Frequency Sensitive Mode – Under-frequency (LFSM–U) and the Under-Frequency Load Shedding (UFLS) are designed to prevent the power system from blackout.

Due to the fact that this paper focuses on the contribution of electric vehicles and storages to LFSM, LFSM is described more in detail in chapter III.

According to [6] UFLS has to cover between 40 % and 50 % of the reference load. Load has to be shed in six up to ten steps at defined frequency threshold, starting at 49.0 Hz. The last step has to be shed at 48.0 Hz.

III. Limited Frequency Sensitive Mode

Network operators (TSO and DSO) are authorized by law to operate every generation or load to stabilize the system [7] without regard to the energy market. When the frequency deviation is bigger than the defined frequency deviation for normal operating conditions of ±200 mHz, LFSM has to come into effect. The latest implementation of LFSM can be found in the draft of the VDE V AR N 4110 [5]. A suggested adaption of this LFSM behavior is shown in Figure 1. The implementation should be harmonized over all voltage levels from low voltage (LV) up to the extra-high voltage (EHV). Implementation differences only exist based on different technical limits of the generation units.

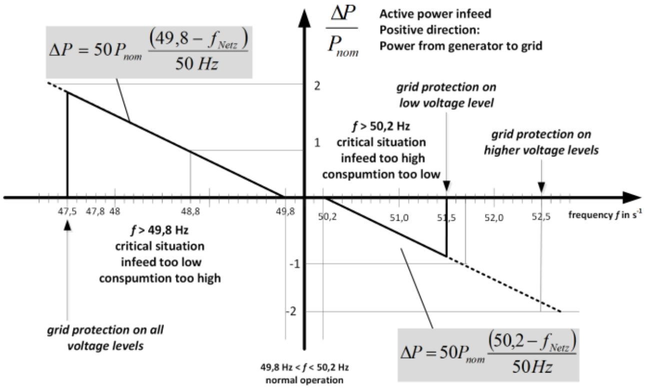

Figure 1. Suggested power-frequency behavior of energy storages and EV

A. *LFSM-O*

When exceeding of 50.2 Hz, LFSM-O has to come into operation. Therefore, every generation unit has to reduce its power output as fast as technically feasible with a specified droop. The droop is related either to the actual power output P_{act} or the nominal power P_{nom} of the generators.

The only further measure to cope with over-frequencies (caused by generation surplus) is to increase the load. For that reason the new standards also include continuous controllable loads (especially home storage systems and EV). They have to increase their load with a droop $s = 2$ % related to their nominal power P_{nom} unless there are safety issues within the appliance.

B. *LFSM-U*

In case of frequencies below 49.8 Hz, LFSM–U has to come into operation. In that case every generation unit capable of increasing its power has to increase it as fast as technically feasible. Unfortunately, increasing active power generation is usually much slower than decreasing it. Additionally, numerous generation facilities (e. g. the very fast controllable PV generation) are typically already operating at maximum power output.

Due to the fact that an assured contribution of UFLS becomes more and more challenging, the contribution of the loads itself becomes more important. Therefore, within the new standards the continuous controllable loads (especially home storage systems and EV) have to decrease their load with a droop $s = 2$ % related to their nominal power P_{nom} unless there are safety issues within the appliance.

If the frequency has been stabilized and brought back to 49.8-50.2 Hz the "Emergency mode" has to be maintained for another 10 minutes while slowly changing the power of the affected appliances back to normal operation.

IV. Impact on the distribution Systems

In the Distribution Grid most of the DG are connected on low voltage (< 1.0 kV) and medium voltage (< 35 kV) level (LV and MV level). In these grids, there is typically a mix of loads and infeed without a reliable communication to the Distribution System Operator (DSO). Therefore, the DG units and loads can only react based on the local information of the power system which is inherently transmitted via voltage and frequency. This leads to a dispersed behaviour of different autonomous control system implemented in every DG units. The feedback between the control systems is based on the grid voltage and frequency. The required behaviour of the DG connected to the distribution grid is defined in the specific grid codes. Since 2015 these grid codes are significantly affected by the entso-e RfG [3] which defines a basic behaviour of DG in case of frequency deviations for DG above 0.7 kW. Nevertheless, only new DG is affected.

Since the voltage is essentially a local issue within the distribution grid the control effects on the voltage regulation [8] are not in the focus of this paper.

The effect of a single DG unit in the distribution system on the system frequency is neglectable but their swarm behaviour can have a critical impact [13]. Therefore, the grid codes have been developed to require a stabilizing effect on frequency deviations, even for DG connected to the distribution grid.

In cases when parts of the distribution grid are disconnected from the transmission grid this behaviour is still effective. This can occur during switching operation causes by:

1. Grid protection
2. Service and maintenance

In the first case the disconnected grid is intended to be without voltage (dead). With the stabilizing effect of DG a simple "open switch" can also lead to an unintended islanding operation in the disconnected part of the grid [9][10]. There have been at least two documented incidents with an unintended islanding operation on the MV-level. The first was an interference during an automatic short-interruption cycle for 400 ms – until the automatic (asynchronous) reconnection. The second was an islanding operation of a whole MV substation with a power exchange of several Megawatts for 10 minutes. It ended after a manual shutdown of the main DG unit.

Although this operation is undisired it is not an immediate risk for the safety of the equipment or persons if this is kept in mind and the five safety rules according to EN 50110-1, clause 6.2 [11] are consistently applied.

Another problem with the self-stabilizing effects of DG occurs when the DSO wants to supply LV-grids with a mobile backup generator while maintenance (e.g. service of MV-switchgear). If the DG infeed exceeds the consumer-load there is a negative load on the backup generator which leads to a shutdown. Nowadays the backup generators of DSOs in Germany were upgraded for negative load resilience and to operate of frequencies between 50.5–52.0 Hz to force the automatic disconnection of the DG units at 51.5 Hz [4]. This is in compliance with the EN 50160 [12].

A further increase of the frequency-protection set point of DG higher than 51.5 Hz in the LV-network is a benefit for the system stability but would lead to problems with the daily usage of backup generator-supply for maintenance within the LV-grids all over Germany.

V. Impact on the Tranmmission System

According to [13] the Synchronous Area CE is facing very high imbalances in case of a system split within the synchronous area. With two examples, the impact of a high share of EV on frequency stability is illustrated, showing the necessity to contribute to Limited Frequency Sensitive Mode (LFSM).

First example is an over-frequency scenario according to [13]. This system split scenario leads to an imbalance $\Delta P_{Imbalance}$ of 30 % related to the system load P_{Load} with a remaining acceleration time constant of the system $T_N = 7.5$ seconds. Fig. 2 shows the frequency behavior of the over-frequency area after the system split. The green dotted line shows the base scenario without EV taking part in LFSM–O. The green line shows the frequency behavior of a 10 % EV-scenario assuming that 10 % of the load is covered by EV, taking part in LFSM–O. It is assumed that they are connected to the grid without loading, able to increase loading by nominal active power for LFSM–O. It gets clearly visible, that the overshoot of the frequency can be reduced significantly.

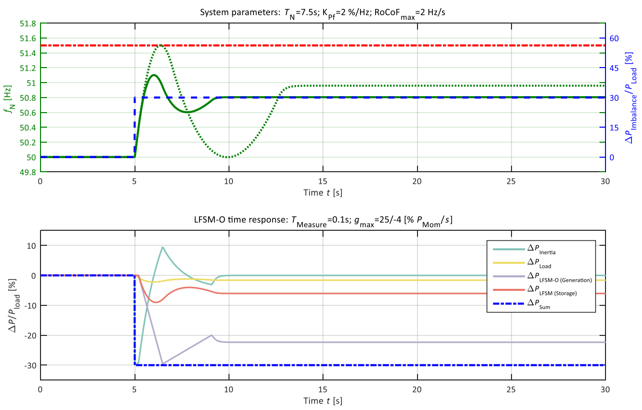

Figure 2. Frequency behavior for OF-scenario 2 with 10 % EV contributing to LFSM-O

The second example is an under-frequency scenario. Again a system split leads to an imbalance $\Delta P_{Imbalance}$ of 20 % related to the system load P_{Load} with a remaining acceleration time constant of the system $T_N = 5$ seconds. Fig. 3 shows the frequency behavior for this scenario. The green dotted line shows the base scenario without EV taking part in LFSM-U. The green line shows the frequency behavior for a 10 % EV-scenario assuming that 10 % of the load is covered by EV, taking part in LFSM-U. It is assumed that they are connected to the grid with full loading, able to reduce loading by nominal active power for LFSM-U. The dotted grey line in the second subplot shows the shedded load for the base scenario. The grey line shows the shedded load for the 10 %-EV-scenario. It gets clearly visible, that only 10 % (two load-shedding steps) instead of 20 % (four load-shedding steps) of the load have to be shed.

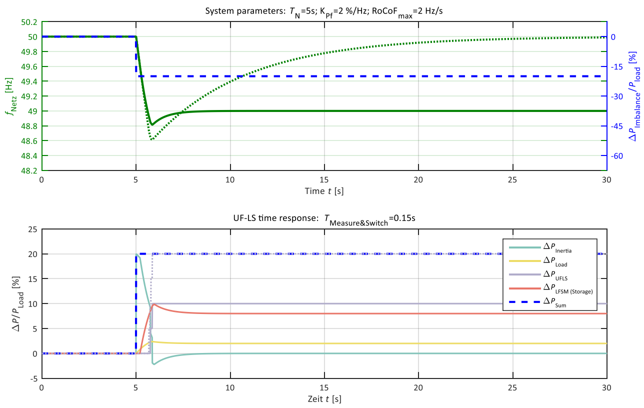

Figure 3. Frequency behavior for UF-scenario 3 with 10 % EV contributing to LFSM-U

The two examples show the positive impact of EV contributing to LFSM.

VI. Summary and Outlook

Caused by the distributed generation on all voltage levels the classic under-frequency load-shedding (UFLS) will become less effective in the future. LFSM-U (Limited Frequency Sensitive Mode Under-frequency) in every controllable (non-vital) load, especially in electric vehicles (EV) and electric storage systems, are an efficient and suitable contribution to solve this problem.

In addition, load has to assist generating units in LFSM-O (Limited Frequency Sensitive Mode Over-frequency) to solve over-frequency problems.

Concerning the impact of EV to the Transmission System, it was shown that their contribution to LFSM has a big value to frequency stability. For over-frequency scenarios it could be shown, that the contribution of EV clearly helps to stabilize system frequency and reduce frequency to overshoot. In case of under-frequency scenarios it could be shown, that the contribution of EV to LFSM-U help to avoid load shedding.

The implementation of LFSM at all voltage levels will also have an impact on the dynamic behavior and the operation of the distribution grid. The DSO has to adapt some operation strategies (regarding islanding risk). In return, TSOs have to accept a few limitations regarding possible frequency ranges on low voltage level.

Nevertheless, for the implementation of LFSM a good compromise has been suggested for all voltage levels.

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