Experimental and HIL investigation of under-frequency and rate of change of frequency load shedding schemes in interconnected networks with high penetration of renewable generation

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Abstract

Under-frequency Load Shedding Schemes (UFLS) are a well-established part of any under-frequency defence plan. Their future effectiveness in systems with increased penetration of renewable energy sources without rotating mass should however be questioned: lower inertia implies higher frequency gradients; more power electronics implies higher harmonics. Both factors will concur to make frequency measurements and short relay operation times more challenging: In this contribution, the impact of the penetration of renewable sources on the rate of change of frequency (RoCoF) in continental Europe has been simulated with the dynamic ENTSO-E model for different penetration levels, confirming the higher RoCoF and lower frequency nadir to be expected in case of large disturbances. The operation of the current UFLS scheme is included in the model and has been compared with a scheme incorporating a RoCoF criterion. The authors have also performed laboratory tests in order to assess the use of RoCoF-based load shedding as an improvement to frequency-only based load shedding schemes. Central European transmission and distribution system operators have established joint bodies for agreeing on the best evolution of underfrequency defence plans: challenges include frequency measurement and correct coordination of several control schemes and approaches within the CE transmission system community.

1 Introduction

With higher shares of renewable energy sources (RES) in the power system, its physical inertia will decrease, and the dominant characteristics of the plant controllers will also evolve. Limiting the rate of change of the frequency (RoCoF) is increasingly difficult in small systems [1] but also in interconnected systems, especially in the event of system splits [2]: presently, 0.5 Hz/s is considered as a realistic rate, whereas in the future, rates in excess of 1 Hz/s can be expected more frequently. Similarly, the measurement of the frequency itself is challenging during transients [3, 4]. The impact of the penetration of RES on the RoCoF in the Continental European power system has been simulated with the dynamic ENTSO-E model for different penetration levels. A suggested improvement to UFLS schemes is the addition of a RoCoF criterion to the load shedding scheme. This could potentially allow to anticipate low frequency situations and maintain the action time of the load shedding despite the increasing RoCoF. Such schemes however introduce their own challenges [5].

It is acknowledged that testing UFLS and RoCoF-based protection is not straightforward [6]. The authors have

chosen to reproduce events close to the real-world behaviour by using a reduced-scale physical network model and real protection relays to investigate some of these anticipated evolutions. This contribution will review the current challenges and investigate the addition of rate of change of frequency (RoCoF) relays as a possible improvement.

2 Frequency response of the ENTSO-E CE system with high levels of RE penetration

Using the ENTSO-E initial dynamic model of Continental Europe [7], different shares of converter-interfaced generation (CIG) were simulated to analyse their impact on system frequency response. For merely illustrative purposes, the sudden outage of several generators in countries such as France, Turkey, Netherlands, Bulgaria, Belgium and Spain were assumed to simulate the loss of a significant amount of generation (around 17 GW). Figure 1 illustrates the dynamic response of the system under this disturbance for incremental amounts of CIG share (the frequency at a representative bus in Switzerland is shown).

Figure 1: Frequency dynamics for different CIG shares.

It is important to highlight that, for the study described here, the shares of CIG indicated in Figure 1 refer to the percentage of synchronous generation displaced by CIG in each country considered for this purpose (only those countries represented with at least 10 synchronous generators in the original dynamic model were considered for the integration of CIG). Besides, non-synchronous generation was modelled through aggregated PV generating plants, according to [8].

As noticed from Figure 1, it is evident that as the penetration levels of CIG increase and the system inertia is decreased, the impact on RoCoF, frequency nadir (f_{nadir}), and steady-state deviation (Δf_{ss}) is expected to be more and more significant after an important loss of generation. Performance indicators in this regard for the results in Figure 1 are given in Table 1, where RoCoF values correspond to the frequency first derivative at 500 ms after the disturbance.

Table 1. Performance indicators

% CIG	RoCoF [Hz/s]	f_{nadir} [Hz]	Δf_{ss} [Hz]
0	-0.094	49.21	-0.48
10	-0.104	49.15	-0.52
20	-0.117	49.08	-0.56
30	-0.128	48.99	-0.61
40	-0.149	48.88	-0.68

According to the ENTSO-E RG CE general UFLS scheme [9, 10], an amount of demand corresponding to at least 5% of the total load must be disconnected as part of a defence plan when the system frequency drops to 49.0 Hz. In this sense, the 40% CIG case in Figure 1 will be considered for further analysis here due to the nadir of frequency reached.

By implementing UFLS relays in the study system to disconnect around 5% of the total load supplied with a total disconnection delay of 150 ms, the system frequency response for the 40% CIG scenario is now illustrated in Figure 2, where no specific mechanisms against over-

frequency conditions have been taken into account in this study, i.e. the conformity of the CIG units is assumed.

Figure 2: Frequency dynamics with UFLS at 49.0 Hz (load shed = 22033.67 MW).

As seen in Figure 2, the operation of UFLS relays makes the system frequency recover quickly and reach a final value marginally higher than the maximum permissible steady-state deviation (within ± 200 mHz of the nominal value) [10, 11], as a consequence of the important load disconnection in the grid, but lower than the over-frequency limit of 51.5 Hz [11].

Now, since the results in Table 1 show an increasing RoCoF with growing CIG penetration levels, this situation may be leveraged to properly incorporate the RoCoF into load shedding schemes in order to anticipate their action and potentially enhance frequency performance. In this regard and for illustrative purposes, a df/dt criterion at 49.5 Hz is added to the UFLS relays considered in the operating scenario of Figure 2, and a total load disconnection of only 3.4% is selected. Corresponding results for this test case are given in Figure 3.

Figure 3: Frequency dynamics with UFLS and RoCoF function (load shed = 15815.37 MW).

As compared to the case of UFLS without RoCoF function, the load shedding strategy applied in Figure 3 leads to a frequency overshoot of only 50.04 Hz and a steady-state frequency of 49.93 Hz, and the amount of shed load is relatively smaller. Since the RoCoF can be used to somehow foresee significant critical situations, load shedding schemes can benefit from it for proper anticipated reactions.

3 Challenges for system operation and underfrequency protection

The current trend to significantly increase the share of renewables through converter-interfaced generation is leading to detrimental effects on system frequency dynamics due to reduction in overall system inertia and primary frequency control capabilities as synchronous generators equipped with active governor control are gradually displaced. The sudden loss of a relatively significant amount of generation under these scenarios may give place to unacceptable rates of change of frequency and important frequency deviations that result in uncontrolled cascading failures and eventually the system collapse.

Although UFLS schemes are designed to arrest critical frequency declines and support system frequency stability after severe generation contingencies, their operation and effectiveness may be jeopardized by higher values of rate of change of frequency in the system. Since increased RoCoF values will be experienced with further system inertia reductions, system protection schemes such as UFLS will have consequently a relatively shorter time margin to react [12].

4 Experimental investigation of UFLS and RoCoF-based load-shedding

Experimental testing of UFLS and RoCoF is the most suitable way to consider the effects of the frequency measurement and tripping of the UFLS or RoCoF criteria as well as of time delays associated with real equipment. The limitation is indeed that such testing cannot be performed in the real system. In this work, an existing reduced scale island system shown in Figure 4 was used.

Figure 4: Reduced-scale model for testing real-world UFLS schemes.

In a first step, typical operation conditions for real UFLS relays, using the reduced-scale network including real UFLS relays and an adjustable load have been established. Different underfrequency events have been obtained by varying the parameters and characteristics of the test set-up:

- several RoCoFs are obtained by varying the quantity of load and the rate at which it is added. The added load creates an imbalance of load and generation causing the frequency to drop. This can further be influenced by adjusting the droop of the drives used for emulating turbines.
- the relays were placed either at the same location or they were separated by lines (i.e. the load was shed at different locations).

The test results suggest that the trip time slightly increases with the RoCoF and with the complexity of the topology used. The increase can be more marked if the relay is at the end of a line, where the time is anyway higher. The lower frequency stages are apparently less sensitive to RoCoF.

The set-up was then used in different configurations including a "UFLS only" scheme that was subsequently compared with two possible extensions using RoCoF-related criteria for either additional or extended load shedding stages. The following additions were considered:

- Adding a RoCoF load shedding stage at 49.5 Hz. In this study, the load additionally shed was dependent on the measured RoCoF at a frequency of 49.5 Hz. For a RoCoF exceeding 2 Hz/s, all load shedding stages (8) of the current UFLS implementation were shed, whereas for a RoCoF of 0.1 Hz/s only the last load stage of the current UFLS was shed. There were four additional intermediate RoCoF stages between these extreme cases.
- by making the 49 Hz (first) UFLS stage's size dependent on the RoCoF, in a manner like the above case.

Measurements performed within the reduced scale model are shown in the following Figures for low (Figure 5), moderate (Figure 6) and high (Figure 7) RoCoF. These measurements indicate that for a high RoCoF, the load shedding is not necessarily much faster with a RoCoF criterion, but the frequency nadir is significantly reduced. Also, in the scenarios considered, the application of the RoCoF-based load shedding at a lower frequency implies a larger share of the load to be shed and hence a slightly reduced nadir. When considering these Figures, it is most helpful to focus on the initial 1-3 seconds of the phenomenon considered, since for longer run, the effect of reserves not modelled in the reduced-scale system will dominate. The behavior of the frequency at the end of the recorded time however reveals that in the cases with RoCoF-based load shedding, more load was shed in the short term, which is a desired effect.

Figure 5 also shows a possible drawback of the RoCoF-based approach: if the RoCoF changes during a perturbation and the RoCoF-based tripping occurs "too early", too much load might be shed, this phenomenon is called over-shedding.

Figure 5: Frequency curves for low RoCoF.

Figure 6: Frequency curves for moderate RoCoF.

Figure 7: Frequency curves for high RoCoF.

5 TSO/DSO action plan for the improvement of underfrequency defence plans

Based on the current grid codes [9, 10, 13, 14] requirements the system operators of the transmission and distribution systems are requested to permanently update and check their system defence plans in such a way that for the case of severe events followed by significant power imbalances with frequency drops below 49.0 Hz the transmission power system backbone shall remain in stable operation due to activation of Low Frequency Demand Disconnection schemes (LFDD) or UFLS. A related intensive and close cooperation is required as on the one hand side the demand disconnection relays are in the distribution systems and the TSOs must coordinate their schemes with all the other TSOs of the same synchronous area. One of the most critical scenarios consists in a system islanding with areas of overproduction and areas of load deficit. The main challenge for all players is to have available a robust common system defence plan which is able to react with a certain selectivity in such a way that system balance can be established after severe events when the available normal system control reserves are already exhausted. In the same time the relay settings and capabilities shall ensure no load shedding in normal system operation conditions.

6 Concluding remarks

Maintaining the equilibrium between consumption and generation will obviously remain a key function of the power system and similarly, last resort systems to avoid a frequency collapse might be needed more than ever. The authors have shown that UFLS and related schemes require the coordinated attention of all players in the system and that action needs to start now in order to ensure the stable operation of tomorrow's RES-based power system.

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