RoCoF-based Improvement of Conventional Under-Frequency Load Shedding

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Abstract

Conventional under-frequency load shedding exhibits an important deficiency: it is not capable of adjusting its intervention to seriousness of the root disturbance. This is mainly due to the number of stages that can be implemented in practice, having for consequence high probability of equally undesired frequency overshoots. For the protection of such importance, the robustness of wide-area solutions is questionable due to required communications. Therefore, improvements in local methods are expected for increasing situational awareness of under-frequency relays. In this paper, locally measured rate of change of frequency is innovatively yet transparently applied in order introduce an additional shedding criterion in each relay. The results indicate a significantly increased efficiency of under-frequency protection in many ways. Among most important are more favorable frequency response and decreased amount of disconnections. The simplicity of the suggested improvement makes it suitable for practical implementations with minor interventions into existing settings.

Index Terms

Power system dynamics, power system protection, smart grids, power system measurements, power system stability.

I. Introduction

Under-Frequency Load Shedding (UFLS) protection plays an important role in preventing power-system collapse after major active-power imbalance occurs in the Electric Power System (EPS). Up to a certain level of imbalance (e.g. so-called *reference incident* of 3000 MW imbalance in ENTSO-E [1], [2]), EPS primary frequency control mechanism should be capable of maintaining frequency stability without curtailing any load. However, since larger imbalances are much less probable in large interconnections, this is not the case after unexpected island formation. Not only that power imbalances are difficult to predict, the total inertia in the island is much lower than that during interconnected operation. Existing conventional UFLS setting may not be tuned to such conditions. Consequently, it would require improved situational awareness for assuring proper system response after its activation.

Major number of researchers share the vision of Rate of Change of Frequency (RoCoF) being the clue factor for achieving this goal ([3], [4], [5]). However, up to this point scarce number of transparent solutions can be found of its implementation in the existing literature. ENTSO-E Policy 5 document [6] even prohibits use of RoCoF below 49.0 Hz. According to our viewpoint, this is either due to the lack of intuitive use of RoCoF or considering wide-area solutions in contrast to local ones. It was shown in [7] that time delays introduced by harvesting Wide-Area Monitoring System (WAMS) capabilities for the protection of such importance, can cause malfunction of UFLS under high-RoCoF conditions. This is why it was concluded in [7] that WAMS-based UFLS should represent a smart supplement to local UFLS, functioning upon locally (within substation) measured electrical quantities.

This paper presents a RoCoF-based improvement of conventional UFLS, where an intuitive use of locally measured RoCoF is applied. In section II, conventional UFLS setting is critically evaluated, whereas in section III suggested improvement is presented. In section IV, simulation results are presented obtained from implementing both conventional as well as suggested UFLS to a part of a Slovenian EPS 110 kV network. Finally, conclusions are drawn in section V.

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II. Current Situation - Conventional UFLS

A. Settings

Currently, most of UFLS schemes used in practice are of conventional type, encompassing several stages. The setting of each stage involves *i)* amount of disconnected load per stage and *ii)* frequency threshold at which it is being activated. However, load feeders, assigned to individual stage, are a subject to different power flows, depending on different factors such as the season within a year, day in a week, time of day, etc. In addition, EPSs with high penetration of distributed energy sources, power flow can be even more diverse due to volatile character of such generation units. Therefore, a certain load feeder does not always represent the same share of the entire EPS loading, whereas the large group of feeders relatively well inter-balances those divergences introduced by individual feeders. UFLS schemes of this type vary from one EPS to another, depending on operator's experience and requirements. Mostly they differ in:

- number of shedding stages (denoted by n),
- frequency thresholds ($f_{\mathrm{thr,i}}$ where $i = 1,\ldots, n$),
- shedding amount associated with each stage ($P_{\mathrm{thr,i}}$),
- maximum sum of all disconnections ($P_{\mathrm{tot}} = \sum P_{\mathrm{thr,i}}$).

The electrical-voltage frequency is being measured at the substation level (i.e. on the relay location), from this being referred to as *local UFLS*. Such UFLS schemes harvesting from local measurements are much more favorable in practical applications compared to other solutions, as the absence of the need for wide-area communication networks increases the scheme's efficiency significantly.

B. Pros & Cons

The importance of UFLS protection dictates its high level of efficiency. Often this is mistaken by assuring *enough* load disconnections to stop the frequency drop. Conventional UFLS is without a doubt capable of achieving that, which was proved many times in the past. However, one should keep in mind that too much disconnected load can easily transform initial under-frequency situation into an over-frequency one, which is also not desired. It is clear that not only UFLS should disconnect enough load, but also it should not disconnect *too much* load. This is exactly where conventional UFLS has its most evident weakness. To summarize, an *appropriate amount* of load should be tripped and by this a smooth and secure frequency response obtained. Unfortunately, conventional UFLS does not match the latter criterion, which is also confirmed by research presented in the continuation. Sometimes, this issue is referred to as the un-adaptive operation of UFLS (un-adaptive to variety of possible situations it might encounter).

C. Characteristics

By increasing the number of stages n and therefore decreasing the associated shedding amounts per stage $P_{\mathrm{thr,i}}$, traditional UFLS gains more and more adaptive capabilities. Let us consider using a validated real power-system model [8] for performing dynamic simulations of frequency stabilization after the model is stressed by a wide palette of active-power imbalance amounts. In each of the situation, different settings of traditional UFLS is applied in terms of the number of shedding stages n. The total sum of individual-stage amounts is kept constant (P_{tot} = 50 % of the power-system loading) and the corresponding frequency thresholds are linearly distributed between 49.0 Hz and 48.0 Hz in all cases (see Fig. 1).

The analysis results are presented in Fig. 2. In Fig. 2 the realized disconnection amounts are presented with respect to different simulation cases, each of them providing different active-power stress imposed to the model (sorted in an ascending manner). With the thick gray curve, results corresponding to four-stage setting are depicted (n = 4), whereas with the thick black curve results of the ten-stage (n = 10) settings are given. The rest of the curves (thinner and all of the same gray color) represent the remaining schemes encompassing settings having between five and nine stages (n = 5, 6, 7, 8 and 9, respectively). It can be clearly seen that by increasing the number of stages n, the resulting curve is getting closer and closer to linear dependence on the disturbance seriousness. In theory, increasing the number of stages towards infinity would yield a perfect adaptability of such scheme to any situation. In practice however, the number larger than approximately ten stages (give or take a few) can rarely be seen, whereas some average number of stages is around six.

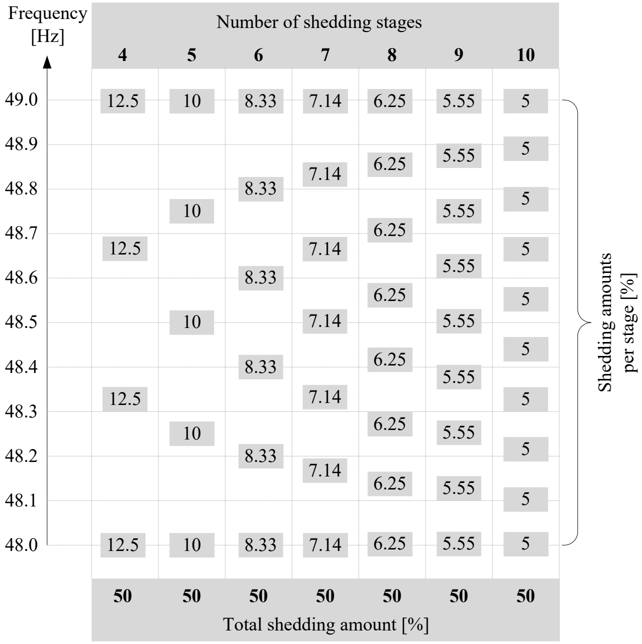

Fig. 1: The schematic representation of tested conventional UFLS

As long as conventional UFLS is in question, pre-defined blocks of load feeders are disconnected within a single stage. Lesser the number of stages, larger the blocks and consequently larger discrete steps can be noted in Fig. 2a. These discontinuous changes coincide with situations when frequency just slightly violates one of the frequency thresholds (low-RoCoF situation when tripping). For improved frequency response, only a small portion of a corresponding block would have to be disconnected. Instead, the entire block is disconnected which results in over-shedding and (in terms of frequency) leads to frequency overshoot. This is confirmed by additionally analyzing Fig. 2b, which includes two sets of information: minimum (MIN) and maximum (MAX) frequency value, recorded during the transient. Curve color and thickness properties are the same as in Fig. 2a.

It can be noticed that increasing the number of stages does not affect the scheme's ability to prevent frequency drops in any way. This is expected, as conventional UFLS successfully plays a role of an under-frequency protection for decades. On the other hand, it affects recorded overshoots significantly; in case of the four-stage setting, the largest recorded overshoots reach as high as 52.5 Hz, whereas in case of ten-stage setting they are kept below 51.0 Hz. So actually, in many situations, instead of providing appropriate solution to an under-frequency problem, merely a transformation into an over-frequency problem is achieved. Without a doubt, this is undesirable.

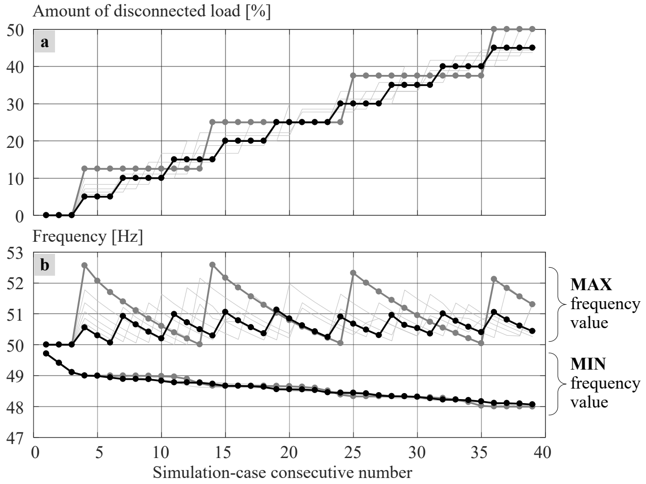

Fig. 2: Conventional UFLS testing results

However, conventional UFLS re-setting in terms of changing the number of stages n requires a complex and long-lasting procedure to be performed by the system operator in a close cooperation with distribution companies. This is why in continuation, much simpler and easy-to-implement alternative for achieving similar effects on EPS frequency response is presented.

III. RoCoF-Based Improvement Introducing Situational Awareness

A. Calculating frequency-stability margin

Conventional UFLS lacks a capability of recognizing conditions when certain stage can be omitted/delayed without jeopardizing the EPS frequency stability. This can be introduced by adding a second shedding condition (apart from the frequency itself) in each stage that would prevent over-shedding when there is still some maneuver space left before the frequency violates the minimum allowable limit (considered as f_{LIM} = 47.5 Hz but it can be assigned an arbitrary value).

To this end, RoCoF is applied with the aim of predicting/estimating the *frequency-stability margin* $M(t)$, which can be expressed by the remaining time before f_{LIM} is violated. RoCoF(t) is a standard variable, calculated internally in all processor-based under-frequency relays requiring approximately 100 ms time window. The calculation of $M(t)$ can easily be performed in real time within the relay itself, as it follows a very simple equation, whose structure is represented graphically by Fig. 3:

$$M(t) = \frac{f_{\mathrm{LIM}} - f(t)}{RoCoF(t)} \qquad (1)$$

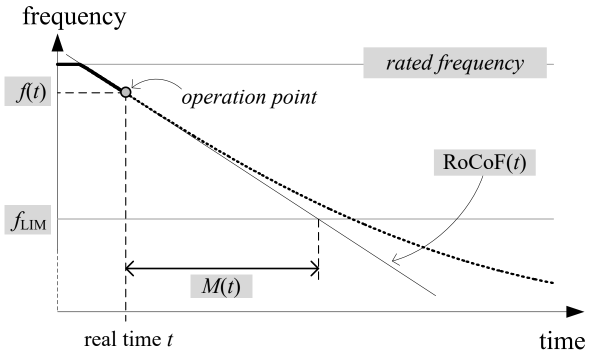

Fig. 3: Calculation of a frequency-stability margin $M(t)$

B. Modified representation of the situation

A newly-obtained variable $M(t)$ requires representing the frequency situation in a different, more appropriate manner. It turns out that the use of a frequency $f(t)$ versus $M(t)$ diagram appears as most suitable – see Fig. 4. Fig. 4a shows operation-point trajectories for several active-power deficit conditions when no load shedding takes place. In the steady-state conditions (pre-fault), operating point is outside the diagram in the upper-right-hand-side corner of Fig. 4a ($f(0)$ = 50 Hz, $M(t) = \infty$ because RoCoF(0) = 0 Hz/s). Operating-point snapshots corresponding to three other arbitrary-selected moments in time are denoted by dots (at moments t = 3.85 sec, t = 5.85 sec and t = 7.85 sec). In Fig. 4b, the corresponding frequency-versus-time curves are represented by means of time-domain simulations. The appropriateness of such graphical representation is revealed as soon as we realize that trajectories corresponding to cases when f_{LIM} is violated converge towards the diagram origin. In contrast, in the rest of the cases when frequency stability is maintained the trajectory is sooner or later re-directed towards the right-hand side of the diagram, corresponding to large values of $M(t)$ as an indication of small RoCoF(t). In the latter case, shedding is unnecessary as the frequency stays above f_{LIM}. In the former case on the other hand, shedding is a necessity.

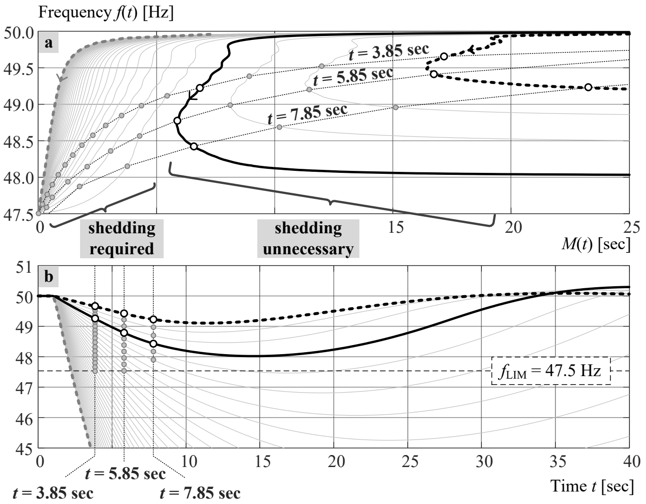

Fig. 4: EPS frequency response: frequency $f(t)$ versus $M(t)$ diagram (a), frequency $f(t)$ versus time t (b)

C. *Introducing additional criterion*

In a frequency $f(t)$ versus $M(t)$ diagram, shedding criteria of conventional UFLS can be represented by means of horizontal lines, each of them corresponding to individual shedding stage f_{thr} (see an example of an individual UFLS stage in Fig. 5). One of these characteristics is actually employed in every under-frequency relay, depending on the load-block into which individual load feeder is assigned. It is clear from Fig. 5 that when conventional settings are applied in all cases but one the first shedding stage is activated at frequency $f(t) = f_{\text{thr}}$ regardless of circumstances. This seems unnecessary, as examination of Fig. 4 reveals that even if the first stage is blocked, the frequency-control alone is fully capable of stabilizing the frequency in three more cases. Not only this would keep several loads supplied (with substantial financial impact [9]), but it would also avoid unnecessary frequency overshoot.

According to findings presented in Section III.B, an improvement of conventional UFLS setting by introducing additional shedding condition M_{thr} in each shedding stage is suggested (see thick grey curve in Fig. 5). Conceptually, for large values of $M(t)$ the violation of f_{LIM} is expected to occur far in the future. This is why under such conditions, activation of individual stages is temporary unnecessary despite the corresponding frequency threshold is perhaps already violated. It should be stressed that this does not mean the activation of stage under question is unconditionally canceled. Quite the opposite, it can still be activated later on (at frequency below f_{thr}) when on top of f_{thr} a newly-introduced criterion M_{thr} is violated as well – see an example presented in Fig. 6. So according to the suggestion, each load-shedding stage should be modified from setting frequency thresholds f_{thr} alone towards setting a pair of values f_{thr} and M_{thr} for each individual stage.

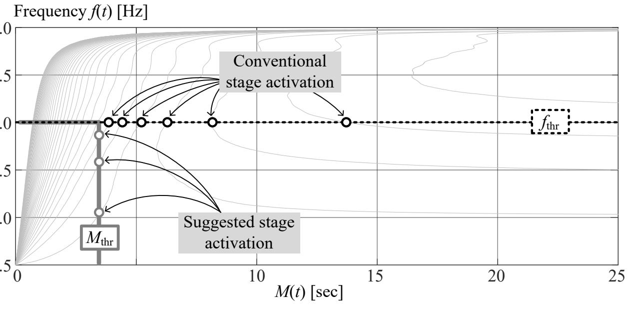

Fig. 5: Suggested modification of existing UFLS by introducing additional shedding condition M_{thr}

D. *Changed relay characteristics*

Suggested improvement can be evaluated through examination of a relay operating time (for each stage individually) versus power-imbalance scenario – see Fig. 7. Results confirm that stage activation during high-RoCoF conditions does not change (dashed and full curves overlap). On the other hand, in low-RoCoF conditions for achieving the same operating times, significantly larger active-power imbalances are required. This is a result of postponing or even avoiding the activation of certain shedding steps, when the conditions allow such action. In addition, selectivity among different steps is maintained despite the improvement, so there is no possibility for leaving out any of steps. If shedding is required, steps are activated in the same order as conventional UFLS dictates.

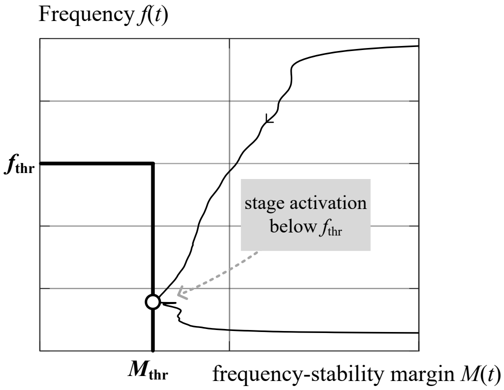

Fig. 6: Postponed activation of the first shedding stage

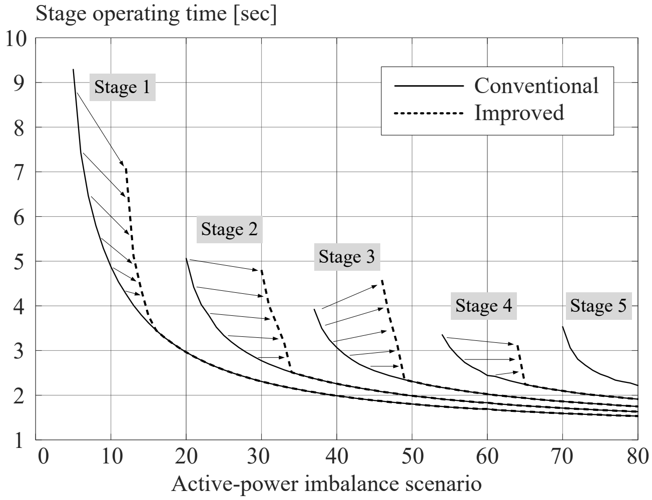

Fig. 7: Operating time of individual load-shedding stages (conventional versus modified approach)

IV. Simulation Results

In this paper, some initial test results are presented, conducted on a dynamic EPS model, representing a part of a Slovenian EPS 110 kV network [7]. As a reference, existing six-stage conventional UFLS setting from the Slovenian EPS was considered which will be put into operation at the end of year 2018 – see TABLE I. The setting of newly-suggested $M_{thr,i}$ parameter for each stage i in also provided in TABLE I, whereas the procedure behind it was omitted due to space limitation. Nevertheless, it should be stated at this point that preliminary tests revealed that $M_{thr,i}$ settings in the order of a few seconds (as in TABLE I) provide a comparable level of improvement in large variety of system inertia.

A large amount of dynamic simulations was performed to illustrate how significant a presented improvement is. Results are presented for a case study, in which the average value of the EPS inertia constant equals 6 seconds. Fig. 8a depicts the percentage of disconnected EPS loading with respect to eighty scenarios, arranged in an ascending order with respect to simulated active-power imbalance. With the empty circles (o) results corresponding to unmodified conventional UFLS from TABLE I are given, whereas with the stars (*) results obtained by adding M_{thr} as an additional shedding condition are depicted. Fig. 8b provides relevant information about the EPS's frequency response. The upper set of circles and stars refers to maximum-recorded frequency during the transient f_{MAX}, whereas the lower set of circles and stars refers to minimum-recorded frequency f_{MIN} (often referred to in the literature as the frequency nadir). The gray-shaded areas mark the improvement obtained by the introduction of M_{thr}.

TABLE I. Considered conventional and improved UFLS settings

Stage consecutive number *i*	**Frequency threshold $f_{\text{thr},i}$ [Hz]**	**Stage size [% of EPS loading]**	**additional shedding condition $M_{\text{thr},i}$ [sec]**
1.	49.0	10	4.0
2.	48.8	10	2.5
3.	48.6	10	2.0
4.	48.4	10	1.5
5.	48.2	10	1.0
6.	48.1	5	0.5

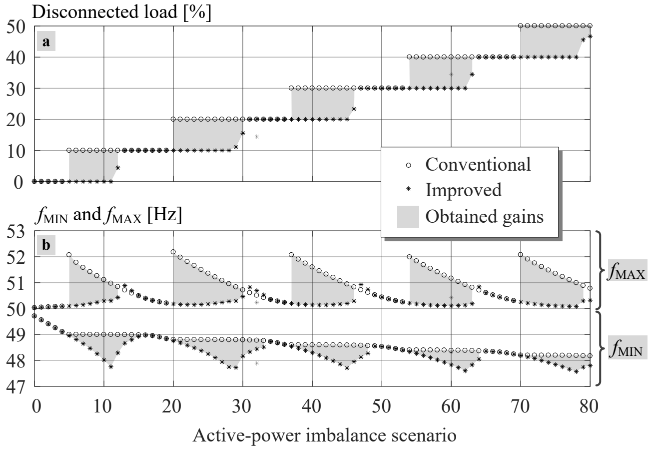

Fig. 8: Study-case results

The following conclusions can be drawn from the presented results:

- by applying unmodified conventional scheme, frequency overshoots reach over 52.0 Hz despite a six-stage setting. Such overshoots are unacceptable and would initiate over-frequency protection triggering of generation units, which is considered as unfavorable result of UFLS activation,
- extreme frequency-overshoot values can be avoided by implementing additional criteria M_{thr}. Results indicate a significant decrease in overshoot values, which do not exceed 51.0 Hz regardless of the simulation case.
- decreased frequency overshoots are achieved on the account of letting the frequency drop closer to f_{LIM}, which was cautiously set to the frequency-stability limit. This happens when its violation is not expected to happen soon, which in other words means that RoCoF is moderate.
- the amount of disconnected load is decreased for an entire shedding stage in 63 % of the simulated cases. An important financial gain is obtained in this way by keeping many consumers supplied.

V. Conclusion

As wide-area UFLS solutions raise practical concerns among engineering community, improvements in *local* UFLS are expected in terms of increasing situational awareness of under-frequency relays. In this paper, RoCoF-based improvement of conventional UFLS is presented, following the concept of introducing additional shedding criterion. The so-called frequency-stability margin is calculated from locally measured RoCoF and innovatively applied for giving each relay the capability for distinguishing between more and less serious EPS conditions. In this way, frequency overshoots of conventional UFLS are significantly decreased and more favorable frequency response obtained after UFLS activation. Lesser the number of conventional UFLS stages, larger the improvements. Moreover, required interventions into existing UFLS concept are minor. Further research activities are already under process, mostly encompassing *i)* different concepts of M_{thr} settings and *ii)* defining f_{LIM} individually per stage. A comprehensive research paper is also expected, where the suggested improvement will be thoroughly tested in different inertia conditions and by applying real relay equipment along with Real-Time Digital Simulator.

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