POSSIBILITIES FOR UPDATING UNDERFREQUENCY LOAD SHEDDING PROTECTION IN THE SLOVENIAN POWER SYSTEM

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POVZETEK

Hiter razvoj komunikacijske in računalniške tehnologije se v zadnjih desetletjih koristno izrablja na večini tehničnih področij za posodabljanje raznih mehanizmov delovanja ter delovnih procesov. To velja tudi za vodenje elektroenergetskega sistema in njegovo zaščito. Kljub temu pa avtorji ugotavljajo, da je ponekod v tujini uvajanje moderne tehnologije hitrejše kot v Sloveniji. V primeru nenadnih izpadov večjih proizvodnih enot v elektroenergetskem sistemu ter posledično nastanka kritičnih podfrekvenčnih razmer je za dober vpogled v resnost razmer in ugotovitev ustreznih ukrepov nujno potreben centraliziran mehanizem, katerega implementacija v sistem je mogoča zgolj z uporabo globalnih meritev sistemskih spremenljivk (npr. uporaba WAMS in GPS tehnologije). Zaščita podfrekvenčnega razbremenjevanja je v takšnih primerih velikokrat zadnje sredstvo za preprečevanje popolnega razpada sistema. Zato je ustreznost njenega delovanja velikega pomena, tako iz tehničnega kot tudi ekonomskega stališča. Ker je v slovenskem elektroenergetskem sistemu shema podfrekvenčnega razbremenjevanja še vedno na tradicionalni ravni kljub že vgrajenim naprednejšim podfrekvenčnim relejem, avtorji v članku povzemamo znane metodologije iz tega področja, ki ponujajo precej uporabnih možnosti za posodobitev obstoječe sheme na tako imenovano adaptivno raven, ki je ponekod po svetu že v obratovanju.

ABSTRACT

In recent decades, the advantages of a fast development in the communication and computer technology have been successfully harvested in the majority of technological areas for updating various mechanisms and processes. Power system control and protection is no exception. However, in certain other countries actual implementation of modern technologies into power system control and protection mechanisms takes less time compared to Slovenia. In case of a sudden major generation unit outage severe underfrequency conditions appear in the power system and only a centralized gathering of measurements and global actions (e.g. use of WAMS and GPS technology) can represent an appropriate approach to a global problem. In such circumstances, underfrequency load shedding is in many times the last resort tool for avoiding a total power system blackout. Consequently, its appropriate actions are of great importance both from technological and economical point of view. As a current status of an underfrequency load shedding protection in the Slovenian power system is still on the traditional level, in this paper authors summarize some of known developed mechanisms, *among which some of them might be considered as an actual possibility for an upgrade of current underfrequency scheme in the Slovenian power system to an adaptive level.*

1. INTRODUCTION

Use of different protection mechanisms can ensure a safe operation of electric power system (EPS) by preventing operation in a so-called unwanted operating state. One of such circumstances is underfrequency operation. It is a commonly known fact that in Europe EPS operates synchronously at the nominal frequency value of 50 Hz. Every imbalance between generated and consumed active power reflects in the frequency deviation. When smaller amount of imbalance is in question, primary frequency control should be able to compensate this imbalance without any serious system consequences [1]. However, in case of higher amounts of imbalance, frequency control alone is not enough to cope with the disturbance within reasonable time scope. Consequently, frequency deviation reaches such values that an appropriate power system protection should be activated in order to prevent further problems. In case the frequency deviation is negative (i.e. frequency drop is caused by an excess of active power load compared to generation) corresponding power system protection is called underfrequency load shedding (UFLS). Such circumstances might be a consequence of two possible causes [2]:

- a sudden generation unit outage (a sudden occurrence of active power generation deficit),
- power system islanding (a formation of a power system island with an excess of active power load).

EPS operation at lowered frequency is especially problematic due to generation units. Namely, every commercial turbine can withstand only a finite number of disturbances, which cause operation at rotating speed below 47.5 Hz. Here we should keep in mind that the time duration of such underfrequency operation plays an important role at determining the number of allowed excursions below 47.5 Hz [3]. Therefore, in order to protect very expensive generating equipment, the operating limitations are said to be between 47.5 Hz and 52.5 Hz [1]. In case power system frequency drops below 47.5 Hz, an undefreuqency protection of generating units is activated that disconnects generating units from the grid. Consequently, frequency decays even faster and total power system blackout can no longer be avoided. This reflects in major technical and financial problems and can without any doubt be considered as a critical state in a certain country [4]. In addition, building up a normal power system operation takes a lot of time. Consequently, it is very reasonable to assure a high efficiency and reliability of UFLS protection.

A concept of UFLS itself is rather simple: disconnecting such amount of load that the frequency does not drop below lowest acceptable limit [5]. It is very useful to keep in mind the list of target performance features of an ideal UFLS scheme:

- scheme should be simple due to its importance,

- scheme should react fast. Consequently, as a human reaction time is not sufficiently small, automation is required,
- scheme should be highly reliable. This feature prefers applications without global communication. However, the use of a global communication channels is necessary, as underfrequency operation is a global rather than a local issue,
- scheme should be highly effective. Effectiveness is also closely related to automation whereas unnecessary measures have to be avoided,
- scheme should disconnect as less load as possible.

It is clear from the above list that it is impossible to fulfil all listed requirements. However, by applying some compromises it is possible to sufficiently approach the so-called target performance of UFLS protection. There are many different approaches available in the literature dealing with this matter. All of them have one thing in common: frequency is the only indicator of circumstances that require load shedding. A main reason for local frequency measurements not being a sole satisfactory input in UFLS methodology is the dynamic performance of the EPS at a sudden active power deficit occurrence [6]. Namely, frequency is a global system parameter only during the steady state.

2. CURRENT STATUS IN SLOVENIAN POWER SYSTEM

In Slovenian power system, currently used UFLS scheme can be considered as traditional, despite the fact that quite a few implemented underfrequency relays are already based on the microprocessor technique and consequently enable measuring derivative of the frequency (frequency time derivative – frequency gradient) and communication possibilities [7]. Traditional UFLS schemes are the simplest kind of UFLS schemes and do not require microprocessor based relays. This is the reason why the majority of transmission system operators (TSOs) implement this kind of protection.

Traditional UFLS schemes are based on disconnecting fixed amounts of load when the local frequency at the connected bus reaches predefined frequency threshold. Load shedding stages are being activated as long as the frequency continues to fall. The amount of load shed in individual load shedding stage and their number depend on each TSOs experience and specifics of their power system network. Taking into account these facts it is clear that by implementing traditional UFLS scheme in the power system, under-shedding as well as over-shedding might occur. In case of under-shedding a total system blackout might occur and in case of over-shedding a substantial over-frequency might take place which is also not very suitable for a corresponding TSO.

In Table I currently used traditional UFLS scheme in Slovenian power system is summarized [8]. However, with a special permission from Slovenian TSO ELES, the actual parameterization of relays might slightly deviate from the data in Table I. When the frequency at the point of relay connection reaches the threshold of 49.0 Hz, 10 % of load busses are disconnected. If the frequency continues to fall despite this action, at 48.8 Hz another 15 % of load busses are disconnected. Similar can be written also for thresholds 48.4 Hz and 48.0 Hz. One must be aware that no further load shedding takes place for frequencies below 48.0 Hz.

Therefore, if the amount of active power deficit is greater than 55 % (10 % + 15 % + 15 % + 15 % = 55 %), there is a possibility that blackout occurs despite a correct reaction from UFLS protection.

Table I: Currently used traditional UFLS scheme in the Slovenian power system [8]

Frequency threshold [Hz]	Amount of disconnected load [%]	Comment
49.0	10 %	Disconnection of 10 % of the total system load
48.8	15 %	Disconnection of additional 15 % of the total system load
48.4	15 %	Disconnection of additional 15 % of the total system load
48.0	15 %	Disconnection of additional 15 % of the total system load

Adaptive UFLS shedding schemes represent an upgrade possibility. Namely, the maximal amount of disconnected load depends on the seriousness of the disturbance. The majority of them acquire the information regarding the active power deficit by calculating it via measuring the initial system frequency first time derivative of centre of inertia. More information regarding adaptive UFLS schemes is given in the following section.

3. ADAPTIVE UFLS SCHEMES

It is reasonable to expect that in the (near) future traditional UFLS schemes will be replaced by technically more sophisticated kind of schemes, called adaptive UFLS schemes. This name has been used throughout the literature as it describes their most typical feature: being able to adapt its reaction to the seriousness of the occurred disturbance. Due to already written fact that frequency is a global rather than a local system parameter, a calculation of a Centre Of Inertia (COI) frequency is required.

3.1 Centre of Inertia - COI

COI frequency can be calculated according to the following expression [6]:

$$\omega_{\mathrm{el,COI,pu}} = \sum_{i=1}^{j} \omega_{\mathrm{el,i,pu}} \cdot H_{\mathrm{i,sys}} \Big/ \sum_{i=1}^{j} H_{\mathrm{i,sys}} \qquad (1)$$

where $\omega_{\mathrm{el,COI,pu}}$ represents the electrical COI frequency in per unit, j is the number of all synchronous generators in the system, $\omega_{\mathrm{el,i,pu}}$ the electrical frequency of the i-th synchronous generator and $H_{\mathrm{i,sys}}$ the inertia constant of the i-th synchronous generator based on a common system base. COI inertia constant can be calculated as follows:

$$H_{\mathrm{COI}} = \sum_{i=1}^{j} H_{\mathrm{i,sys}} \tag{2}$$

where it is important to be aware of the difference between the synchronous generator inertia constant H_{i} and $H_{\mathrm{i,sys}}$. The base for calculating H_{i} is the apparent nominal power of the i-th generation unit $S_{\mathrm{n,i}}$. This is very convenient, as the typical value of H_{i} is in the range of 1-5 seconds [9]. However, when observing the multi generator system, the base should be some other value, typical for the whole system in question and not just for one of the generators. If we define a new system base $S_{\mathrm{base,sys}}$, the inertia constants of all generators should be modified to the new base:

$$H_{\mathrm{i,sys}} = H_{\mathrm{i}} \cdot S_{\mathrm{n,i}} / S_{\mathrm{base,sys}} \tag{3}$$

The COI frequency calculation can therefore be calculated according to (1) – (3) in the system dispatch centre, which can be graphically presented in Fig. 1. The information regarding the calculated COI frequency has to be simultaneously communicated to underfrequency relays, scattered across the system.

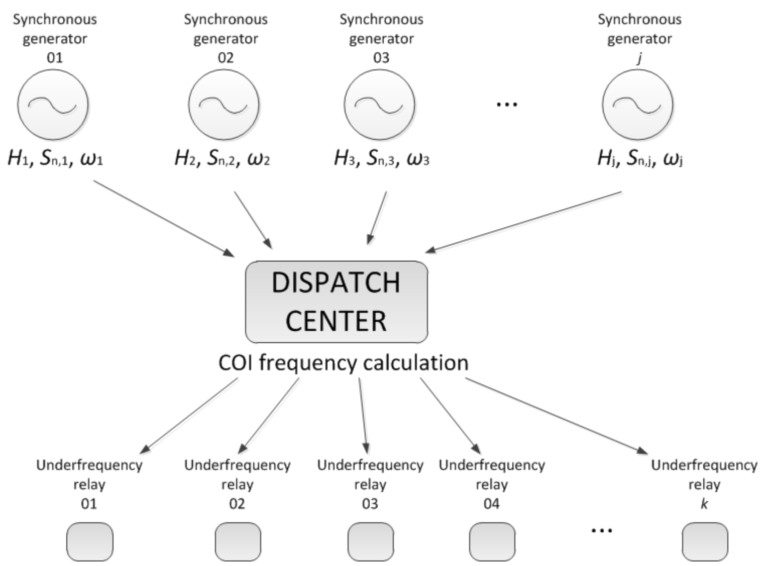

Fig. 1: Required communication for the implementation of adaptive UFLS schemes

3.2 3.2 UFLS schemes with calculation of active power deficit

The majority of adaptive UFLS schemes are based on calculation of an active power deficit P_{deficit} that actually disturbed the observed power system. According to the theory summarized in [6], this is possible by measuring the initial (at time t = 0) COI frequency first time derivative and by applying the multi-machine swing equation:

$$P_{\text{deficit}} = 2H_{\text{COI}} \cdot \left. \frac{\text{d}\omega_{\text{el,COI,pu}}}{\text{d}t} \right|_{t=0} \tag{4}$$

There are a few obstacles when using such a calculation [10]. First, it is impossible to expect that the frequency would be actually measured at theoretical moment of the disturbance occurrence (t = 0). Consequently, the measurement is delayed. Second point arises as the consequence of the first one; system load is in general voltage and frequency dependent. Frequency dependency does not present much difficulty as the frequency cannot change instantly. However, as active power deficit might be in general accompanied by a reactive power deficit also, this might cause drastically change in the voltage profile in the system. As a result, the total load demand in the system changes and the initial frequency steepness appears different than at t = 0. By using such measured gradient, a wrong active power deficit value is calculated which might result in the power system blackout. Therefore, load voltage dependency must be taken into consideration while performing such calculation. The problem is that in reality load characteristics varies from one moment to the next. Using such uncertain conditions as a base for an effective UFLS scheme does not seem to be the most rational decision to make.

Nevertheless, despite these problems many authors are still developing such schemes. A useful outcome of this doing is the growing level of implementation of newest microcontroller based relays in the actual power system. Even though above described calculation does not appear to be practically applicable, microcontroller based relays offer great possibilities for implementation of many other developed techniques, available in the literature. One must not forget: as the underfrequency protection deals with the global power system problem, in order to participate in the communication process between the locally distributed relays and a central dispatch centre, microcontroller based relays have to be implemented.

The mentioned measurements and communication processes can be handled by using WAMS (Wide Area Measuremens System) with the help of PMUs (Phasor Measurement Units), which enable simultaneous measurement of phasors across the power system and transfer of these signals within reasonable and acceptable time frame.

3.3 Predictive UFLS schemes

In the last year, authors have published and presented a few papers, in which they introduce a new sub-type of adaptive UFLS schemes, the so-called “predictive UFLS schemes”. Their operation is based on predicting the frequency situation in advance. Many different possibilities exist how to achieve that. However, in this paper two methodologies are presented that were already published by the authors of this paper.

First methodology is based on predicting the COI frequency second time derivative (FSTD). Namely, FSTD can be considered as an acceleration of the frequency and therefore reflects the level of frequency control activity, as this has the most crucial influence on the actual frequency trajectory. It has been proven in [11] that FSTD, after a sudden active power deficit appears in the system, maintains some typical shape with respect to time, regardless of the amount of active power deficit. This shape can suitably be mathematically represented with an exponential function, which can be seen from Fig. 2. The upper graph represents the system COI frequency in Hz and the lower graph the system COI FSTD in Hz/s^2.

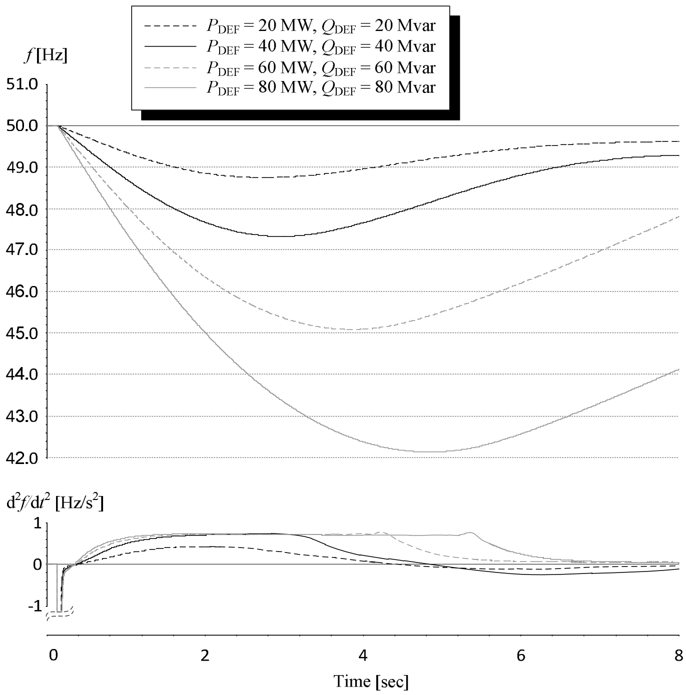

Fig. 2: Frequency and its second time derivative for various active power deficit amounts

Approximation of a FSTD curve is possible by applying an iteration procedure in every time step of the calculation, based on sliding window input information. For iteration procedure authors have used the Newton method approximation, whose iteration number is rather low as long as appropriate starting values are selected. When the parameters of approximation curve are calculated, two times numerical integration is required in order to obtain the frequency forecast. However, we are interested in the lowest value that the frequency would reach if no further actions (e.g. load shedding) takes place. By calculating this value in every calculation time step very valuable information regarding the future situation is obtained. In Fig. 3, the frequency with the black curve (*f*) and its lowest value forecast with the gray curve ($f_{\mathrm{MIN,forecast}}$) are depicted.

It can be concluded that first few forecasts are least exact, whereas after couple of 100 ms the forecast becomes reliable enough so that load shedding can be activated according to forecasted value. Such predictive methodology has few important advantages:

- the total load shedding amount varies with seriousness of the disturbance,
- the amount of load shed in each further load shedding stage is decreasing,

- the total amount of disconnected load is very close to the theoretically possible amount,
- over-shedding is avoided.

Second methodology is an upgrade of the first one, where the improvements are:

- frequency first time derivative (FFTD) is used instead of FSTD,
- prediction of future frequency trajectory is calculated with a single algebraic equation instead of using iterative procedure.

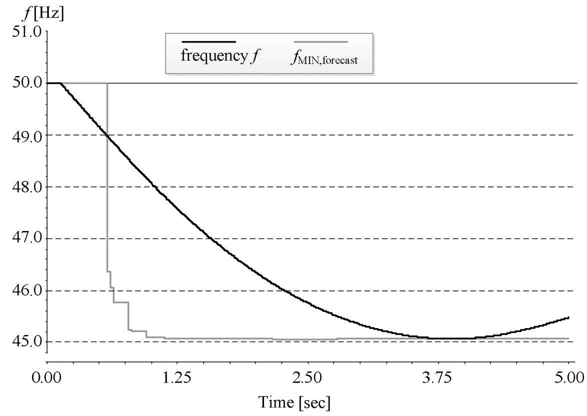

Fig. 3: Frequency and its lowest value forecast

The main idea of this approach can be explained by analyzing a locus diagram of a COI frequency versus FFTD after a sudden deficit of active power appears in the system. An example of such locus diagram is depicted in Fig. 4a. In the steady state frequency is equal to nominal value of 50 Hz and FFTD equals zero. After a sudden deficit appears, frequency cannot change instantly. However, FFTD can change instantly from 0 to the maximal value (minimal to be exact as the FFTD is negative when the active power deficit appears). When the frequency actually starts to decay, primary frequency control is regaining balance between the production and the consumption of active power and consequently, FFTD is again approaching to a value of 0. At this point, the frequency is at its lowest value. After post-fault steady state is obtained, the power system frequency is less than nominal value due to permanent droop of the turbine controllers in the system. If we take a look at the trajectory in this diagram it is clear that its shape can be described as a spiral.

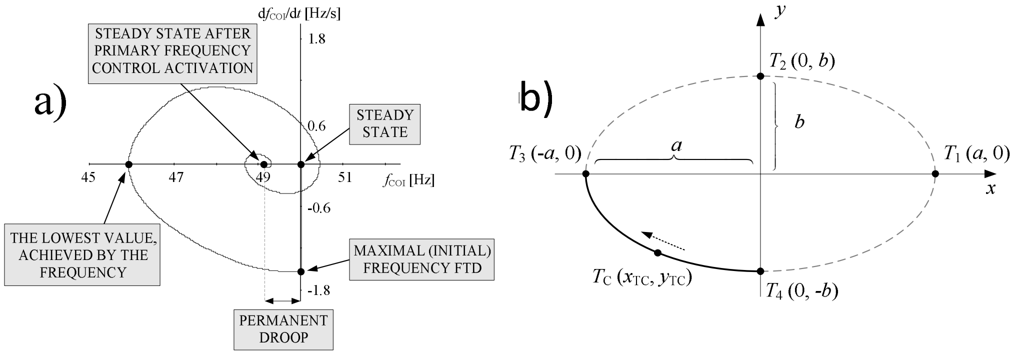

Fig. 4: a) Locus diagram of a COI frequency versus FFTD, b) general ellipse definition

However, in order to predict the behaviour of the system only a part of a spiral is relevant. For a purpose of approximation a part of an ellipse can be used, which is depicted in Fig. 4b with a thick black curve. Therefore, by measuring the frequency and FFTD it is possible to predict the lowest value achieved by the frequency ($f_{MIN,forecast}$) with a simple algebraic calculation.

Both presented methodologies achieve very good results in the dynamic simulations, both for small and large power system models. The amount of disconnected load is very close to the theoretically best possible results, which can be seen from Fig. 5. This figure has been obtained by using a dynamic model of an IEEE 9 bus test system, with different active power deficit scenarios: ranging from 20 to 90 MW. With the dashed gray curve results of the traditional UFLS scheme are depicted and with a solid grey curve the best possible results are shown. Both predictive methodologies (first one with dashed black curve and second one with solid black curve) show results which are much closer to theoretically optimal results than traditional UFLS scheme.

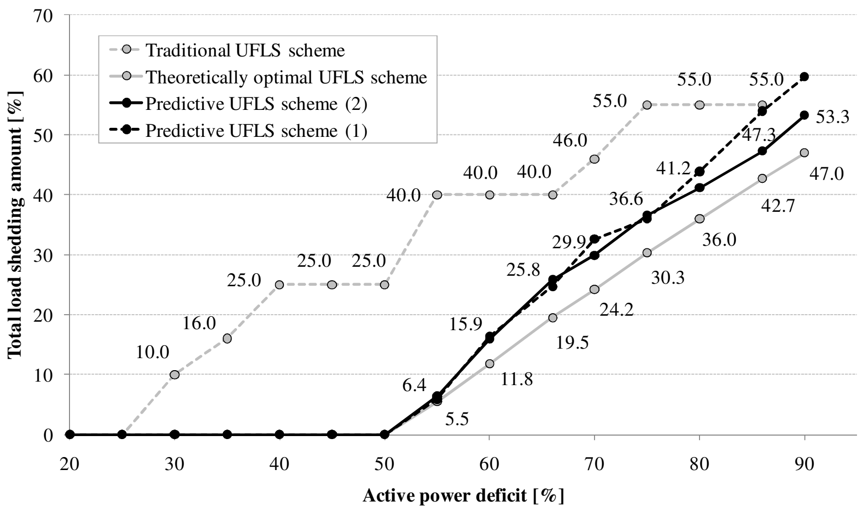

Fig. 5: A summary of simulation results, obtained by using a dynamic model of an IEEE 9 bus test system [9]

4. CONCLUSION

To summarize, traditional UFLS scheme, which is currently used in the Slovenian power system is the simplest and the most unsophisticated type of UFLS scheme. According to the low effectiveness of such scheme it would be reasonable to upgrade the current status of UFLS scheme in Slovenian power system, especially when considering an enormous advance in communication and computer technology during the last few decades. However, a special attention should be given to a process of choosing among many available UFLS methodologies. It has previously been proven that typical adaptive UFLS schemes (with calculating the actual active power deficit in the system) do not meet the practical requirements that are necessary for the actual implementation in the power system.

On the other hand, predictive sub-type of adaptive UFLS schemes is more appropriate for actual implementation. Of course, as system conditions in question are a global rather than a local issue, a certain level of communication is required in order to calculate the COI frequency in the dispatch centre and to forward the information regarding necessary action to geographically scattered underfrequency relays. One must be aware that this kind of communication is an unavoidable part of all adaptive UFLS schemes. Nevertheless, predictive schemes acquire enough information of system reaction to a disturbance simply by observing the FFTD or FSTD and disconnect load accordingly. In this way, very good results are obtained which far exceed the results of the traditional UFLS scheme. Therefore, authors suggest that Slovenian system operator would seriously consider upgrading the current status of implemented UFLS protection in the Slovenian power system.

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