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Predictive underfrequency load shedding scheme for islanded power systems with renewable generation

Urban Rudez*, Rafael Mihalic[1]

University of Ljubljana, Faculty of Electrical Engineering, Trzaska 25, 1000, Ljubljana, Slovenia

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ABSTRACT

Underfrequency load shedding is one of the most important protection mechanisms in a power system. However, in the majority of power systems it has remained unchanged for decades, despite the advances in computer and communication technologies. Wide Area Monitoring System proved to be very useful and reliable in the last few years and this is why much effort is given into development of Wide Area Monitoring, Protection and Control concepts. Adaptive underfrequency load shedding is certainly a very suitable candidate for the task. In order to accelerate changes in this area, a proposal for an adaptive scheme has been developed, which is a good option from both the technical and economic points of view. In contrast to majority of adaptive schemes, it handles problems of active-power deficit estimation and its variations during the transient due to voltage dependent loads differently, i.e., by on-line forecasting the operating point trajectory in a phase space. The scheme has been tested on previously proven (by comparison to WAMS measurements) dynamic model of a part of a Slovenian power system and the results indicate a large improvement compared to the traditional scheme.

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1. Introduction

Electric power system (EPS) protection is playing a vital role in ensuring the safe operation of vast and complex EPSs. It is of vital importance to provide all the EPS's consumers with reliable and high-quality electrical energy, despite the disturbances that constantly occur in the EPS. Hence, a power-system blackout should be avoided at all costs, both from economic and technical points of view.

The EPS's frequency is often considered as a parameter that never deviates much from its nominal value (e.g., first-swing stability analysis). However, one has to keep in mind that the frequency of the sinusoidal voltage, produced on the generators' terminals, determines the term that is known as EPS's frequency.

Consequently, after/during larger disturbances in the EPS, these generators might oscillate between one another, and this is reflected in greater deviations of the local frequencies from the global one [1]. The only indicator of the global frequency in such cases is the frequency of the Centre of Inertia (COI). This was acknowledged and confirmed in many cases [1–4]. However, a system-wide frequency (referred to in the paper as COI frequency, even though a certain deviation exists) is with satisfactory accuracy estimated by simply averaging several (those available) available PMU frequencies. This can be explained by imagining the high-voltage network busses somewhere near the electrical centre between generating units, each of them connected to a high-voltage network by a step-up transformer whose impedance far exceeds transmission line impedances.

A sudden unexpected islanding of some part of an EPS is undoubtedly considered as a major disturbance. There is a high possibility that the formation of a power-system island is accompanied by a generation/consumption power imbalance (generally an imbalance of the active as well as the reactive power). The island condition might appear with different power-imbalances, system might become a subject to either deficit or surplus of power. If the active-power deficit is in question, the COI frequency in the island starts to decrease. Due to the limitations introduced by synchronous generators, which in ENTSO-E interconnection should not operate at frequencies below 47.5 Hz [5], underfrequency load-shedding (UFLS) protection might be required to regain the power balance by disconnecting certain amounts of the power-system load. An overview of many different types of UFLS protection approaches is systematically provided in [6].

In the majority of EPSs around the globe, UFLS has remained unchanged for decades, despite the advances in computer and communication technologies in recent years. Even so, many proposals can be found in the literature for constructing an adaptive,

* Corresponding author. Tel.: +386 1 4768 418.
E-mail addresses: urban.rudez@fe.uni-lj.si (U. Rudez), rafael.mihalic@fe.uni-lj.si (R. Mihalic).
[1] Tel.: +386 1 4768 438.

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efficient, secure and simple UFLS scheme that uses the advantage of the state-of-the-art technology. The Wide Area Monitoring System (WAMS) proved to be very useful, especially in off-line analysis, and this is why much effort is given into the development of Wide Area Monitoring, Protection and Control (WAMPAC) concepts [7]. Adaptive UFLS is one of the most suitable candidates for the task. The majority of adaptive UFLS schemes are based on the system frequency-response model [8], which enables a calculation of the active-power deficit in the system by measuring the initial value of the frequency's first time derivative (FTD) [3,9–13]. However, the power-system load is, in general, affected by the voltage deviations and, consequently, the calculation of a correct value for the active-power deficit is rather difficult to obtain [14]. The importance of considering voltage changes in the formation of UFLS scheme was also noted in [15] where a suggestion was made how to combine both the voltage and frequency stability issues, rather than treat them separately. Similarly, but on the local level, a combinational approach to UFLS is tested in [16]. Nevertheless, in [17] a mechanism is presented that is able to successfully identify the parameters of the system frequency-response model on-line. This gives a basis for a good estimation of the active-power deficit. However, an unanswered question remains as to what is the best way to distribute the calculated deficit into several shedding steps [11,18].

A completely different approach to UFLS is given in [4], which laid the basis for the so-called predictive UFLS schemes. The frequency's second time derivative (STD) is used for forecasting the response of all the regulatory mechanisms that influence the EPS frequency. By doing so, the frequency trajectory can be on-line foreseen in advance which enables the decision-making according to the severity of the situation. Two issues arise from this approach, and these are the use of an iterative approximation procedure and the use of the frequency STD, which might run into difficulties during the actual implementation of the scheme. Consequently, a more implementation-friendly idea of using a frequency versus frequency FTD locus diagram from [19] and [20] is used (referred to in [19] as a phase plane) in this paper. The iterative procedure is replaced by a simple analytical calculation, while the results remain at a very high level.

Instead of using the swing equation and measurement of initial value of frequency FTD (as it is usually the case in research papers on this topic), a stochastic analysis is made off-line, prior to applying the UFLS scheme in the system. By doing so, the probability density curves of system load (consumption) as well as generation can be considered. This means that the whole range of different operating conditions are taken into account and most importantly renewable generation (such as wind and solar power plants) can easily be implemented in the model. As a result, one obtains the probability function of active power deficit in the system. However, for the proposed mechanism, only the maximum deficit value among all possible conditions is required. Details of how this is accomplished are given in the paper.

In Section 2 the background of the presented methodology is described. First, an important, but not vital procedure of an off-line stochastic analysis of active-power imbalance is presented. Next, the phase-plane trajectory of a frequency versus frequency FTD is studied under condition of the active-power deficit. In the same section the procedure for future frequency situation forecasting is presented. In the last subsection, the way of selecting the amount of disconnected load per step is also presented. In Section 3, the study case and the overview of the testing results are given, and finally, the conclusions are drawn.

2. Methods

In order to understand the presented UFLS methodology, first some characteristics of the islanded EPS suffering an active-power deficit have to be presented and explained. Firstly, the presented approach takes the advantage of an off-line stochastic analysis of active-power imbalance in the observed EPS (actual data from realistic Slovenian test-case is used, forming a ground-base for results presented in Section 3.2). Such analysis is expected to be periodically performed on a monthly to yearly basis, as according to its results the parameterization of UFLS scheme is performed. Second, it is important to understand the typical shape of the curve that corresponds to the COI in the frequency versus frequency FTD phase plane during underfrequency conditions. Purely theoretical IEEE 9-bus test system was used for the purpose of clear and unambiguous explanation of the method's core philosophy. Tests on the other hand (shown in Fig. 10) were performed on a (as much as possible) realistic model of 110 kV part of a Slovenian power system (results are). The model was constructed during a two year research project for the Slovenian TSO that required a validation of model simulation results by comparing it to WAMS measurements for numerous events taking place in the last few years.

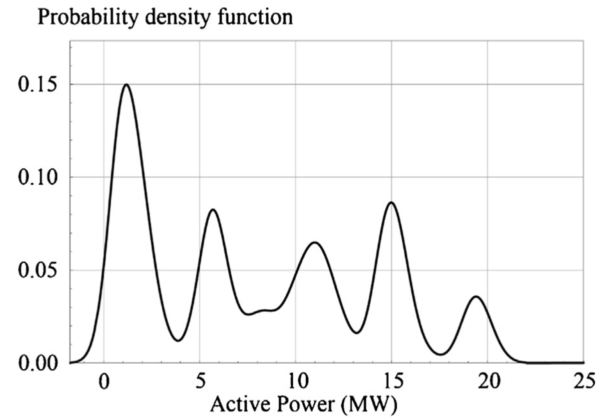

Fig. 1. The probability density function of load active-power at substation Anhovo.

2.1. Off-line stochastic analysis of active-power imbalance

The major issue of adaptive UFLS schemes with active power deficit calculation is the uncertainty of the calculated amount. Namely, research in the past [9] has shown that this calculation does not take into account the load voltage dependency, which might have a substantial influence on the result and might be a root cause of the system collapse due to inadequate amount of shedding. This is why it is reasonable to establish a different approach. As the amount of installed renewable generation is getting larger in the last years, an approach is needed that takes the stochastic nature of generation sources into account. In order to make the procedure as general as possible, the stochastic nature of the consumption is considered as well.

For the purpose of this paper past measurements of active-power consumption on several 110 kV substations in the north-western part of the Slovenian EPS were obtained (total number of nine consumption busses). One among of the most diverse (substation Anhovo) is shown in Fig. 1. The obtained probability density function (PDF) has several local maxima, the most probable being around 2 MW.

On the other hand, the past measurement data for the generation capacities were not available. The analysed part of the Slovenian EPS, which is relatively often required to operate in the islanded mode due to poor connections, includes ten hydro generation units. However, in the future plans several wind turbines are included as well. This is why it was decided that testing should be done with the assumption of two different PDF distributions for the generating capacities in order to show that the selection of the

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