Proceedings of the Ninth IASTED European Conference
Power and Energy Systems (EuroPES 2009)
September 7 - 9, 2009 Palma de Mallorca, Spain

A SUGGESTION OF A FREQUENCY GRADIENT BASED UNDERFREQUENCY LOAD SHEDDING SCHEME

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ABSTRACT
The importance of a well established electric power system protection is a fact, underfrequency load shedding included. In order to upgrade and improve the traditional approach to underfrequency load shedding, suggestions of using the frequency gradient can be found in the literature. However, many system parameters must be known in order to obtain useful information from measuring the frequency gradient. If the assumption of knowing those parameters is made, it is possible to lower the amount of the total shedding volume, by gathering the information that the second frequency gradient carries. In the paper, one of such ideas is presented, that is showing considerable improvement compared to traditional scheme.

KEY WORDS
Frequency, shedding, gradient, scheme, protection.

1. Introduction

Secure operation of an electric power system (EPS) is of great importance, as the earth population is getting more and more dependent on electric power supply. In order to achieve the highest level of operational security as possible, different protection systems must be applied to the EPS. One of such protection systems is underfrequency load shedding (UFLS).

Otherwise interconnected EPS might in some situations experience such disturbances that cause the separation of certain parts of the system from the rest of the EPS (formation of so called islands). In such islands the imbalance between active and reactive power generation and consumption is very likely to occur. Namely, the liberalization of the electricity market has made situations with high level of electric power import from distant areas very common. Bigger consumption centers might, during normal operation, therefore be supplied by an imported electrical power and suffer the lack of electrical power in case of island formation.

The great majority of the generating capacities (power plants) are using the synchronous generators for the electrical power production. To depict the physical background that takes place in the island with an imbalance between active power generation and consumption, Fig. 1 can be helpful. The synchronous speed of the generator can be maintained only if the input power (mechanical power on the turbine) is equal to the output power (electrical power), withdrawn from the generator terminals to supply the EPS load. The excess of input power causes the rotor to accelerate and the excess of output active power causes rotor to decelerate, as the lacking power is drawn from the spinning masses of the generators.

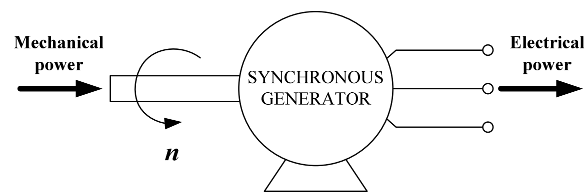

Fig. 1: Synchronous generator power balance

Such deviations from the synchronous speed are reflected on the EPS frequency. Frequency is therefore the most obvious and direct indicator of the system's active power imbalance. In normal operation the system frequency hardly deviates from 50 Hz in Union for the Coordination of Transmission of Electricity - UCTE. On the other hand, during abnormal system conditions the UFLS must assure that the frequency does not drop below 47.5 Hz. According to [1] this is the lowest acceptable limit for the frequency, before the generating units are tripped due to their underfrequency protection.

In the following chapter, the basic UFLS principle is described. Next, the suggested UFLS scheme is explained and highlighted with some dynamic simulation examples. Main problematic aspects that consider UFLS are also stressed. Following, the results of testing the suggested scheme on the test system is presented. Finally, the conclusions are drawn.

2. Underfrequency load shedding

Smaller frequency deviations in the EPS are handled by turbine governors across the system. However, its response time makes it unable to prevent the island collapse in case of more serious frequency deviations. Frequency gradient might namely reach higher values that create the need for an automatic procedure of disconnecting the parts of the system (island) load. This is namely the only applicable measure that is able to restore the balance between the active power generation and consumption before the frequency reaches a critical level. Such an automatic procedure is called an underfrequency load shedding (UFLS).

UFLS schemes can be categorized according to [2] into three groups:

- the traditional UFLS schemes,
- the semi-adaptive UFLS schemes,
- the adaptive UFLS schemes.

This paper deals with the latter. The adaptive schemes can be divided into two functional joints: active power deficit determination and the actual load shedding (Fig. 2). The effectiveness of the second part depends on the accuracy of the first part. The realization of the load shedding is namely based on the estimated active power deficit.

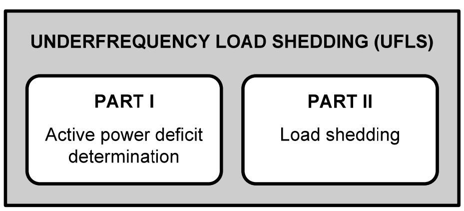

Fig. 2: Underfrequency load shedding

The importance of an UFLS scheme determines that the scheme must be reliable, simple, efficient, fast and robust [3]. The fast advance in the recent years in the area of communication technologies makes an opportunity to upgrade the traditional UFLS schemes. Authors (e.g. in [4]) usually assume the availability of the secure, efficient and fast communication link between the underfrequency relays and the control center (e.g. fiberoptic communication, global positioning system - GPS). The same assumption is made in this paper.

The following subsection describes the main principles of the suggested UFLS scheme, presented in this paper. All figures are obtained from the dynamic simulations of a small island in the Gorenjska region in Slovenian EPS (the test system) with four generating hydro units and four load centers [5].

3. Suggested UFLS scheme

3.1 Part I – Active power deficit determination

Two problematic aspects of the adaptive UFLS schemes will be addressed in this section:

- frequency measurement,
- voltage dependence of the load.

Frequency measurement is not a trivial task, neither during normal operation, neither (and especially) during transients. The same applies for the frequency gradient. Under transient conditions and off-nominal frequencies even the use of Phasor Measurement Units (PMUs) brings a significant error into the measurement [6]. Therefore, before the measurement can be considered trustworthy, at least the transient must be ended. This makes us unable to measure the frequency gradient just at the moment of the island separation.

Theoretically, it is possible to determine the active power deficit in MW (ΔP_{MW}) in the island only by measuring the frequency gradient df/dt at $t = 0^+$, where t denotes time, knowing the island inertia constant H_{isl} and the sum of the generator's rated apparent powers S_{isl} in the island (f_N is the rated system frequency).

$$\Delta P_{MW} = \frac{2 \cdot H_{isl} \cdot S_{isl}}{f_N} \cdot \left.\frac{df}{dt}\right|_{t=0^+} . \quad (1)$$

It has been shown in [7] that (1) must be corrected due to voltage drops on the load busses. Namely, in reality the load's active and reactive powers change with the voltage deviation. For the simulations in this paper, the loads are modeled as a voltage dependent redraw of active and reactive power.

$$P_L = \sum_{i=1}^{m} P_{L0,i} \cdot \left(\frac{U_i}{U_{0,i}}\right)^{\alpha_i} \qquad Q_L = \sum_{i=1}^{m} Q_{L0,i} \cdot \left(\frac{U_i}{U_{0,i}}\right)^{\beta_i} . \quad (2)$$

In (2) P_L and Q_L represent the current values of the system load's active and reactive power, respectively, $P_{L0,i}$ and $Q_{L0,i}$ the i-th load's initial active and reactive power just before the disturbance, U_i is the current voltage on the i-th load bus, $U_{0,i}$ is the voltage of the i-th load bus just before the disturbance, m is the number of load busses in the system, α_i is the factor depicting the active power dependence of the i-th load and the β_i factor depicting the reactive power dependence of the i-th load on voltage deviations.

It has been shown that the voltage drop on the load busses at the moment of the island formation can not be neglected, as it might be considerable and it directly influences the active and reactive power imbalance in the island [7]. For simulations in this paper, values $\alpha = 1$ and $\beta = 2$ have been selected. On the other hand, the frequency gradient measurement that is used for the active power deficit determination is made as soon as possible after the separation of the island. Frequency at that point does not deviate much from its nominal value of 50 Hz. Therefore the frequency dependence of the loads has not been modeled.

If (1) is corrected by considering load's voltage dependence, it is possible to obtain:

$$P_{\text{trip}} = \left[\frac{2 \cdot H_{\text{isl}} \cdot S_{\text{isl}}}{f_{\text{N}} \cdot P_{\text{L0}}} \cdot 100 \right] \cdot \frac{\mathrm{d}f}{\mathrm{d}t} + \left[\sum_{i=1}^{m} P_{\text{L0,i}} \cdot \left(\left(\frac{U_{\text{i}}}{U_{\text{i,0}}} \right)^{\alpha_{\text{i}}} - 1 \right) \cdot \frac{100}{P_{\text{L0}}} \right] = g_1 \cdot \frac{\mathrm{d}f}{\mathrm{d}t} + g_2 \quad (3)$$

P_{trip} is the active power deficit in the island, expressed in percent of the total load in the system just before the separation of an island (sum of all $P_{\text{L0,i}}$ in the island) P_{L0}. Functions g_1 and g_2 determine the so called "gradient curve", which not only differs from island to island but also varies in time. Therefore, to correctly determine the active power deficit, many system parameters should be known (according to (3)), otherwise frequency gradient could give very misleading information about the active power deficit. For simulations presented in section 4, two different gradient curves were considered known, each corresponding to the current island parameters. In this way, the active power deficit estimation is done with high precision.

The other important aspect of frequency measurement is the different generator responses to the active power deficit. Generator responses of all four generators in the test system are depicted in Fig. 3.

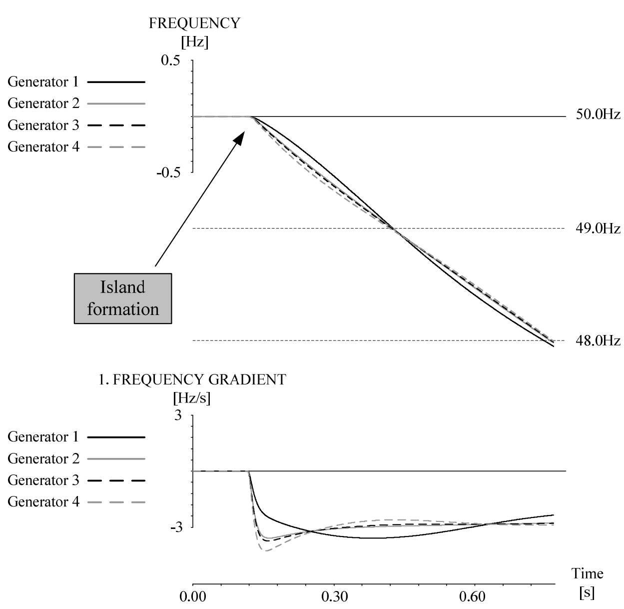

Fig. 3: Different generator responses to the active power deficit

From Fig. 3 can be seen, that the frequency can not be considered as the global parameter, as the electrical distance from the disturbance determines the frequency response of the generator [3]. From the individual generator frequency responses f_{i} (where the denotation i represent the i-th generator of the total n generators in the island) the average frequency response f_{average} can be calculated by using generator's inertia constants H_{i}:

$$f_{\text{average}} = \frac{\sum_{i=1}^{n} f_{\text{i}} \cdot H_{\text{i}}}{\sum_{i=1}^{n} H_{\text{i}}} . \quad (4)$$

Nevertheless, some oscillation still remains, which can be best seen from depicting the second frequency gradient (Fig. 4). This is one of the drawbacks for using the second frequency gradient in UFLS. Nevertheless, by constructing an appropriate filter, we would be able to usefully apply the direct component of the second frequency gradient signal.

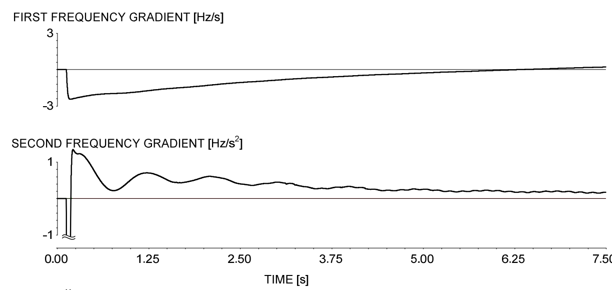

Fig. 4: Second frequency gradient oscillation

3.2 Part II – Load shedding

Actual load shedding, discussed in this subsection, depends on the active power determination, made in the Part I of the UFLS procedure. As the frequency starts to drop (after the island separation), its trajectory passes the predefined values of frequency, where the load shedding is to be executed. Individual shedding steps are defined as the fixed percentage of the total active power deficit. In the worst case scenario, the total shedding amount (the sum of all individual shedding steps) would therefore be equal to the estimation, determined in Part I.

In the suggested UFLS scheme, the milestones in Table 1 are used for load shedding. The first shedding step is determined at 49.0 Hz, meanwhile the following 6 steps are 0.2 Hz apart. Two different cases are simulated: Case 1 and Case 2. The only difference is a different distribution of the total estimated shedding amount into individual steps. Both cases follow the proposal that the greater shedding steps are to be executed prior to lower steps.

An important feature of the suggested UFLS scheme is the fact, that not all shedding steps are unconditionally executed. Minimizing the total shedding amount is one of the objectives that the suggested UFLS scheme is trying to reach. In order to achieve this goal, in the steps from II. to VII. a conditional criteria has been introduced. Its purpose is to leave out the shedding step if a certain condition is met. In order to understand the criteria mentioned, Fig. 5 must be first explained.

Table 1: Shedding steps, used in the suggested UFLS scheme

Shedding step	Frequency [Hz]	Shedding amount (Case 1) [% P_{trip}]	Shedding amount (Case 2) [% P_{trip}]
I.	49.0	35	35
II.	48.8	15	15
III.	48.6	15	10
IV.	48.4	15	10
V.	48.2	10	10
VI.	48.0	5	10
VII.	47.8	5	10

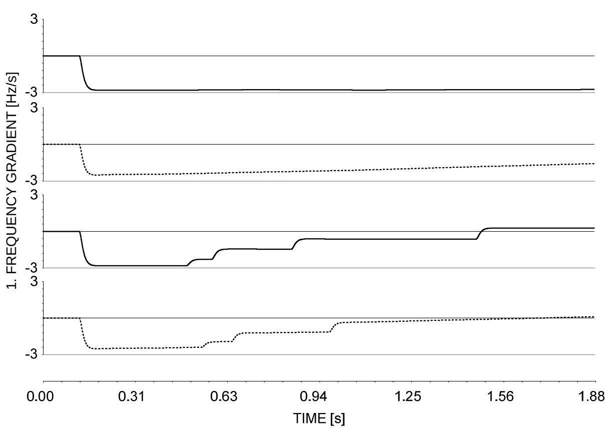

Fig. 5: Control mechanisms and load shedding influence on the first frequency gradient

All four graphs on Fig. 5 depict the first frequency gradient of the test system. The differences between the four graphs are:

- **the first graph** is a simulation with no turbine and voltage control in addition to constant active and reactive power load consumption,
- **the second graph** is a simulation with standard parameters of the turbine and voltage control in addition to load parameters $\alpha = 1$ and $\beta = 2$,
- **the third graph** is a simulation with no turbine and voltage control in addition to constant active and reactive power load consumption and standard load shedding applied,
- **the fourth graph** is a simulation with standard parameters of the turbine and voltage control in addition to load parameters $\alpha = 1$ and $\beta = 2$ and standard load shedding applied.

As it can be seen from graphs 1 and 3, with the exception of the first frequency gradient change due to load shedding, the gradient value remains constant (i.e. between the two shedding steps). On the other hand, the applied control mechanisms in simulations shown on graphs 2 and 4 are changing (reducing) the value of frequency gradient between the shedding steps as well. Measuring the difference between frequency gradient in several measuring points gives us the information regarding the quantity of used control mechanisms. As the voltage control and the "self-regulating effect" of the load are contradictive and there is reasonable to assume that after the frequency stabilizes, the remained load will return to its pre-fault values, only the turbine control can be monitored in this manner. Finally, the total shedding quantity can be minimized only in the account of using the available spinning reserve (turbine control).

The second frequency gradient would be an ideal indicator of different control mechanisms response to the lack of active power generation. But in reality it is difficult to measure it, especially due to the oscillations that occur in the real EPS (Fig. 4). However, by measuring the differences between the values of the first gradient in two distinct measuring points, we are able to partly use the information, that the second frequency gradient caries. Namely:

$$\frac{\mathrm{d}y(t)}{\mathrm{d}t} = \lim_{\Delta t \to 0} \frac{y(t_n + \Delta t) - y(t_n)}{\Delta t}, \qquad (5)$$

where $y(t)$ can be considered as the frequency gradient function, dependent on time ($y(t) = \mathrm{d}f(t)/\mathrm{d}t$).

The idea behind the conditional criteria is the linearity of the gradient curve. It is assumed that without any control mechanisms (the third graph on Fig. 5) the x % P_{trip} shedding results in x % of lowering the frequency gradient. The steepness of the gradient curve remains constant as long as the function g_1 does not change. After each load shedding the system's operating point is fictitiously moving towards the gradient curves with higher steepness (P_{L0} is getting smaller with each load shedding). The consequence is smaller frequency gradient sensitivity to shedding amount (Fig. 6).

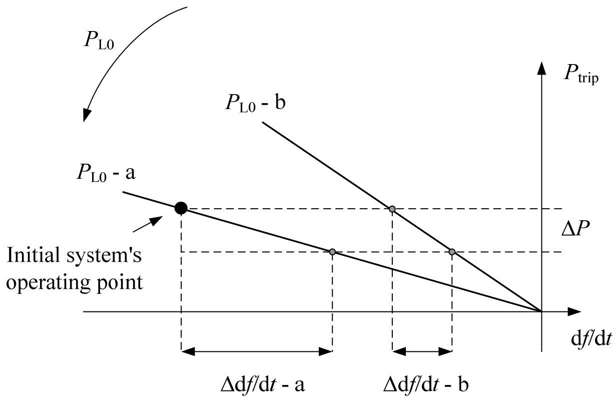

Fig. 6: Transition between the gradient curves due to the load shedding

Considering load shedding in the amount of x % P_{trip}, this results in a smaller actual frequency gradient change than x %. Only the increasing generation (turbine control) can enlarge the frequency change between shedding steps to a value of x % (or above this value). Consequently, measuring and comparing the frequency gradient at each of the shedding steps milestones with the initial frequency gradient (maximum value) can give us the information about the turbine control reaction. If the following condition is satisfied, the shedding step is left out, otherwise it is executed:

$$\frac{|\mathrm{d}f_{\mathrm{k}} / \mathrm{d}t| - |\mathrm{d}f_0 / \mathrm{d}t|}{|\mathrm{d}f_0 / \mathrm{d}t|} \geq \mathrm{UCLS}, \qquad (6)$$

where the index k represents the current shedding milestone, index 0 the moment of measuring the initial frequency gradient (as soon as possible after the transient is ended) and UCLS the percentage of the P_{step} that would be executed until the k-th milestone in case of all load shedding steps being unconditional (**U**n**C**onditional **L**oad **S**hed).

An example of a time domain dynamic simulation is shown in Fig. 7, using the suggested UFLS scheme – Case 2 (see Table 1). The upper graph depicts the frequency in Hz, the middle graph the value of the first frequency gradient in Hz/s and the lowest graph the left hand side of (6) – the so called "condition parameter" in percent.

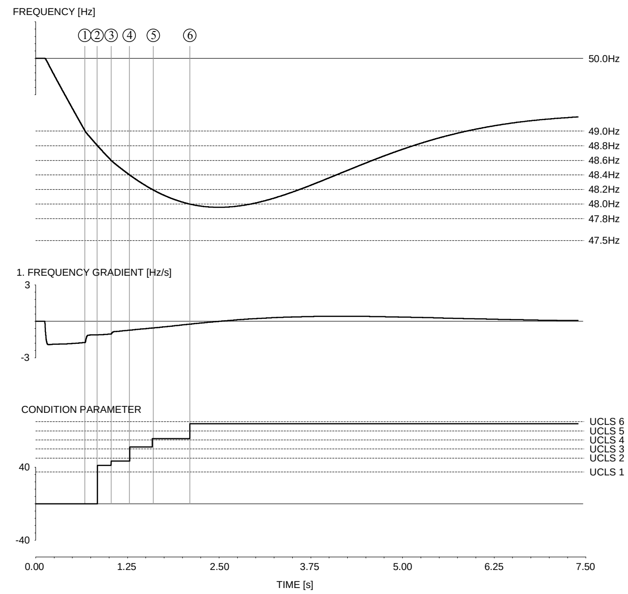

Fig. 7: The example of using the conditional criteria for leaving out the shedding steps

At the first shedding step (marked with circled number 1 at the top of the figure), load shedding in the amount of 35 % P_{trip} is unconditional. In all the shedding steps that follow, the condition (6) is applied. At the second shedding step condition parameter exceeds the value of UCLS 1 (35 %), therefore the shedding step is left out. At the third step UCLS 2 is not exceeded, therefore load shedding in the amount of 10 % occurs. In case of steps 4, 5 and 6, the values of UCLS 3, UCLS 4 and UCLS 5 are exceeded, respectively. Therefore, all three shedding steps are left out.

An additional feature of the suggested UFLS scheme that strongly contributes to the reliability of the scheme is the introduction of the final shedding step at 47.5 Hz. It is executed unconditionally in the amount of all shedding steps, which were left out during frequency falling. Assuming that the active power deficit estimation was done accurately enough, in this way frequency never falls bellow the lowest acceptable limit.

4. Testing of the suggested UFLS scheme

The examples presented in this section were carried out by applying software for simulating the EPS dynamics and the dynamic model of the test system, presented in [5]. The test system consists of four generating hydro units and four load centres. Two different loadings of the system were observed, namely P_{L0} = 152 MW (scenario 1) and P_{L0} = 81 MW (scenario 2). The active power deficit estimation is done by knowing the gradient curve, which is equal for:

- scenario 1:

$$P_{trip} = -16.201 \cdot \mathrm{d}f/\mathrm{d}t + 7.8221$$

- scenario 2:

$$P_{trip} = -29.052 \cdot \mathrm{d}f/\mathrm{d}t + 5.8899$$

To show the importance of the distribution pattern of the deficit value into individual shedding steps, two different distribution patterns were considered, according to Table 1. The effect of the suggested UFLS scheme has been compared to the traditional scheme, currently used in the Slovenian EPS [7]. It is based merely on measuring the value of the frequency and shedding the predefined amount of load at each shedding step (10 % P_{L0} at 49.0 Hz, 15 % P_{L0} at 48.8 Hz, 15 % P_{L0} at 48.4 Hz and 15 % P_{L0} at 48.0 Hz). The results, depicting the total shedding amount in each of the simulated cases, are given for scenario 1 in Fig. 8 and scenario 2 in Fig. 9.

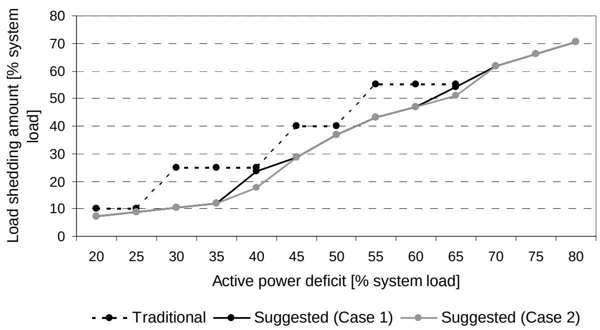

Fig. 8: Total shedding amount, traditional scheme and the suggested scheme (case 1 and case 2), scenario 1

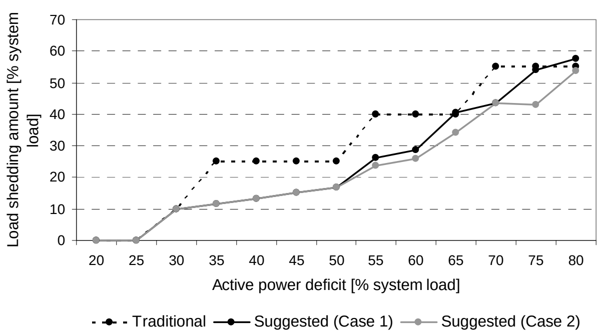

Fig. 9: Total shedding amount, traditional scheme and the suggested scheme (case 1 and case 2), scenario 2

As can be seen from the graphs, in certain values of the deficit, an improvement regarding the total shedding amount is substantial. It reaches even up to 58 % in scenario 1 (at the deficit 30 % P_{L0}) and up to 53 % in scenario 2 (at the deficit 35 % P_{L0}). Two advantages of the suggested scheme are of great importance, compared to the traditional scheme:

- system collapse never occurs. Collapse namely does occur in case of the deficit higher than 70 % in scenario 1 in the case of applying the traditional scheme with the fixed amount of the maximum load shedding,
- the total shedding amount is usually lower, due to the better use of turbine control.

The latter aspect clearly needs to be additionally addressed. The influence of the different distribution patterns of the estimated deficit into individual shedding steps has an important impact on the scheme effectiveness. As can be seen from Fig. 8 and Fig. 9, even though the active power deficit is exact in both situations (Case 1 and Case 2) the total shedding amount might be different and is some cases even higher than the one using the traditional scheme (Fig. 9 – 80 % deficit). Therefore, the distribution patterns need to be determined carefully. Authors suggest the pattern, marked as the Case 2.

On the other hand, a different "self-regulating effect" of the load does not influence the scheme performance. Namely, the deficit determination is done according to the corresponding value of α and β and therefore the deficit is always estimated correctly. In addition, a condition in (6) considers all changes in a frequency gradient – also the "self-regulating effect" of the load.

5. Conclusion

Frequency gradient might give very misleading information regarding the active power deficit value in the isolated system (island). In order to override this difficulty, many system parameters that vary from island to island and from time to time must be known. Only then the active power deficit can be estimated accurately enough.

Introducing the conditional criteria for shedding steps execution, it is possible to keep track of the amount of the turbine governor control reaction. In this way, it is possible to lower the total shedding amount and therefore to keep more consumers supplied. This is namely very important feature of the suggested underfrequency load shedding scheme, as the secure power supply is getting more important every day. By applying the suggested scheme, it is possible to lower the shedding amount up to 58 %.

Further work on this subject will include the research, how to extract even more information from the second frequency gradient. It might be namely very valuable, as long as the suitable filter is applied.

Acknowledgement

This work was supported by a Slovenian Research Agency as a part of a research programme Electric Power Systems, P2-356.

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