Proceedings of the 8th IEEE Mediterranean Conference
on Control and Automation (MED 2000)
Rio Patras, GREECE 17-19 July 2000

NEW APPROACH OF ADAPTIVE AUTOMATIC LOAD SHEDDING

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Abstract. In the paper a new approach of adaptive automatic load shedding, a procedure for protecting electric power systems from dynamic instability and frequency collapse is presented. It is consisted of two main stages. In the first stage the frequency and the rate of its change are estimated by nonrecursive Newton Type Algorithm and Least Error Squares Method. In the second stage the magnitude of disturbance, i.e. the difference between generated and consumed active power is estimated by applying the simplest form of generator swing equation. Results of multimachine test system computer simulations are presented.

Key Words. Adaptive algorithm, automatic load shedding, nonlinear estimation, Newton Type Algorithm.

1. INTRODUCTION

Automatic load shedding (ALS) is an efficient measure for preventing frequency drop in power systems after large disturbances causing imbalance between the generated and consumed active power. The main aim of ALS is to disconnect a portion of load if the system frequency reaches values lower than prescribed one (e.g. disconnection of 0.1 p.u. load if $f < 49.2$ Hz). Every power system has its own plan of ALS, which is coordinated with the plans of the neighboring power systems. Nowadays the existing plans of ALS are deterministic, not taking into account the actual system topology, operating point and the nature and the magnitude of disturbance causing the activity of ALS. By this, ALS can disconnect more or less load, than required, to prevent the system from the frequency collapse, or dangerous and unreliable operating states. This causes undesired damages and serious costs. The appearance of modern microprocessor technology, new efficient and intelligent digital processing numerical algorithms, even the application of satellite technology, influenced the directions of development of modern devices and methods implemented in power engineering, in particular in power system control, measurement applications, protection, monitoring etc. In this paper a new method for the estimation of power imbalance, i.e. the estimation of the difference between the generated and consumed electrical active power (abbreviated: the **E**stimation of the **M**agnitude of **D**isturbance – **EMD**), occurring after a large disturbance (short circuits, islanding, failures on generating units, etc.) in power systems will be presented. The method introduce a new adaptive approach of ALS in which the ALS plan is on-line, just after the disturbance and EMD, created and applied. The EMD requires the frequency and the rate of frequency change of all generators operating in a multimachine system and supplying the customers with the electrical energy. The actual generator frequency and its rate of change are estimated from the digitized generator output voltage by using **N**ewton **T**ype **A**lgorithm (**NTA**) a nonlinear estimator, applied in nonrecursive form.

2. THE CLASSICAL AND ADAPTIVE ALS

Today are used deterministic ALS plans. An example of deterministic ALS plan of German Electric Power System (VDE) [1] is given in Table 1 in which three steps (three frequencies f_k and disconnected power Δp_k, respectively) are given. At $f = 49.8$ Hz follows alarm signal, whereas at $f = 47.5$ Hz underfrequency protection disconnects generators from the network to protect them from dangerous resonant phenomena. Any ALS plan must be simple, efficient, fast and robust. The disconnected loads are uniformly distributed through the system and per steps. It is locally controlled, since it depends on the locally measured frequency.

Table 1: ALS plan of German Electric Power System (VDE).

Step	1.	2.	3.
f_k (Hz)	49.0	48.7	48.4
Δp_k (p.u.)	0.10-0.15	0.10-0.15	0.15-0.20

Some plans include defined time delays, Δt_k (s), to avoid unnecessary load disconnection. Delay can be also calculated from the rate of change of frequency.

The new, adaptive approach of ALS can be divided into the following separate procedures:

1. Estimation of the Magnitude of Disturbance – **EMD**,
2. Disturbance localization,
3. Generation of control action and
4. Distribution of control action.

The first two procedures are estimation problems, whereas the last two are the control problems. In this paper the first, estimation problem: *the estimation of magnitude of disturbance* (**EMD**) will be solved.

One of the starting points in designing the new EMD procedure is the analysis of the generator swing equation, suitable for the analyses of the electromechanical transient processes of one machine power systems at the instance just after disturbance ($t = 0^+$ s):

$$\frac{2H}{\omega_n}\frac{d\omega}{dt} = p_m - p_e = \Delta p \tag{1}$$

where: p_m is the mechanical turbine power (p.u.), p_e is the electrical power (p.u.), Δp is the power imbalance (p.u.), H is the inertia constant (s), ω is the angular velocity, (proportional to frequency) (rad/s) and ω_n is the rated angular velocity (rad/s). The detailed theoretical description of the processes occurring in power systems after sudden and large disturbances can be found in [2,3]. Figure 1 depicts frequency changes of a real power system after sudden disconnection of a generating unit [4]. It can be observed that at $t = 23$ s a portion of load is disconnected from the network, so the frequency was temporarily recovered.

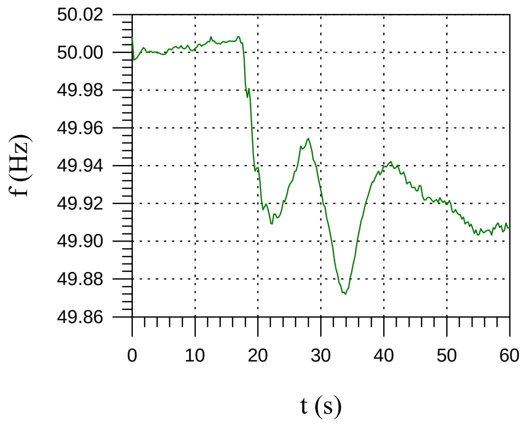

Fig. 1: Power system frequency after the disconnection of a generating unit from the network.

For the further development of EMD it is essential to notice that with the exact measured generator rate of frequency changes df/dt and with in advance known the inertia constant H, one can simply estimate the value of power imbalance Δp from Eq. (1). This value represents the magnitude of disturbance, from which the ALS strategy and protection of the system from the frequency collapse can be adaptively and on-line designed. Nowadays power systems are consisted of many generators, so the method should be derived for a multimachine power system. In the next paper Section nonrecursive Newton Type Algorithm for frequency and its rate of change estimation will be presented.

3. NONRECURSIVE NEWTON TYPE ALGORITHM

The starting point of Newton Type Algorithm (NTA) [5] is in advance assumed mathematical model of the generator output voltage which caries the information of its (generator) frequency:

$$h(\mathbf{x}, t) = \sum_{k=1}^{M} C_k \sin(k\omega t + \theta_k) \tag{2}$$

Here the vector of unknown parameters is $\mathbf{x} = [\omega, C_1, \ldots, C_M, \theta_1, \ldots, \theta_M]^T$. In Eq. (2) C_k and θ_k ($k = 1, \cdots, M$) are the amplitude and the phase angle of the k-th harmonic, respectively, whereas ω is frequency and M is the maximal number of harmonics taken into account. NTA is capable to estimate the unknown vector $\mathbf{x}$, i.e. power system frequency and the power spectrum simultaneously. It is based on the following vector equation:

$$\hat{\mathbf{x}}_{k+1} = \hat{\mathbf{x}}_k + \mathbf{J}_k^{\#}(\mathbf{s} - \mathbf{h}(\hat{\mathbf{x}}_k)) \tag{3}$$

where: $\hat{\mathbf{x}}$ is an $(n \cdot 1)$ vector of estimated unknown parameters, $\mathbf{s}$ is an $(m \cdot 1)$ observation vector (m samples of the input signal, belonging to the data window), **h(.)** is the nonlinear signal model (an $(n \cdot 1)$ vector), $\mathbf{J}^{\#}$ is an $(n \cdot m)$ pseudoinverse matrix of the Jacobi matrix (its elements are the first derivatives of the signal model through the unknowns) and k is the iteration index. In [5] it is shown that for the prefiltered input voltage the sampling frequency and data window size selected should be $f_s = 800$ Hz and $T_{dw} = 40$ ms, respectively. One of the main features of NTA algorithm is that it is capable of estimating power spectrum and frequency simultaneously. In other applications, e.g. for the purpose of electrical power quality indices estimation, power spectrum could be estimated during off-nominal frequency conditions.

For the purpose of the rate of frequency change estimation, a simple frequency linear model $f = a + bt$, where b is the unknown rate of frequency change, and the application of Least Error Squares Method satisfied the accuracy requirements.

4. ESTIMATION OF THE MAGNITUDE OF DISTURBANCE

In the single machine power system the problem of EMD is trivial what is not the case in a multimachine power system in which every machine has its own parameters and its own behavior after disturbance inception. Now the problem should be considered by analyzing all machines separately and coupled. Here the swing equation for the *i*-th (i = 1...N) machine has the following form:

$$\frac{2H_i}{\omega_n}\frac{d\omega_i}{dt} = p_{mi} - p_{ei} = \Delta p_i \tag{4}$$

By addition N swing equations, one obtains:

$$\Delta p = \frac{2\sum_{i=1}^{N} H_i}{\omega_n}\frac{d\omega_c}{dt} \tag{5}$$

where:

$$\omega_c = \frac{\sum_{i=1}^{N} H_i \omega_i}{\sum_{i=1}^{N} H_i} \tag{6}$$

is the *frequency of the equivalent center of inertia*, ω_c (average frequency, equivalent frequency). If all machines have the same frequencies, than $\omega_c = \omega_n$.

The new procedure of EMD can be divided into the following steps:

1. Synchronous machines frequency and rate of frequency change estimation.
2. Frequency of equivalent center of inertia, ω_c, estimation (using results of Step 1).
3. EMD, by processing L values of estimated frequency (e.g. L = 16, in a time period shorter than 0.1 s).

The quality of EMD depends on the quality of rate of frequency change estimation. A technical problem in the real time estimation of frequency of equivalent center of inertia can be the acquisition of all frequencies estimated on the remote generators at one central point in the power system. The problem can be solved by using the modern satellite technology, e.g. GPS system, or any other equivalent telecommunication infrastructure on the earth capable of fast data transmission from the remote sensors (e.g. Internet). The time constants describing the frequency changes and electromechanical transient processes occurring in a huge power systems are relatively big enough (1-5 seconds), so the speed of data transmission through the system to the control center, in which ω_c is estimated, is not critical. Without suitable infrastructure for data transmission through the network, the problem of ω_c estimation can be solved by using the frequency of the largest synchronous machine in the system instead of ω_c in EMD procedure.

In order to create a new ALS plan adapted to the current system state and its dynamics, the EMD can be now used as an input to adaptive ALS plan. Here the estimated difference between generated and consumed powers, Δp, i.e. EMD, should determine the number of steps, frequencies, the amounth of load to be disconnected from the network in every step and the time delays. In other words, ALS plan is adapted to the disturbance which provoked the frequency drop.

The problem in creating a suitable control action using the EMD must be based on the knowledge of the disturbance location, as well.

5. CASE STUDY THROUGH COMPUTER SIMULATION OF POWER SYSTEM

In Figure 2 one line diagram of 60 Hz 3-machine test power system [3], very suitable for the testing of adaptive Automatic Load Shedding based on the estimated magnitude of disturbance, is presented. Two typical examples are investigated: 1) generator outage and 2) power impact. In both cases generator frequencies are estimated from generator output voltages, by using NTA algorithm.

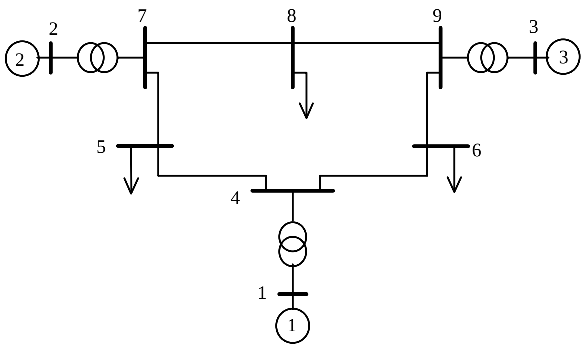

Fig. 2: One line diagram of the test system

In the first example generator #2 is suddenly disconnected from the network. Generator #2, supplying the network with $P_{g2} = 150\,\text{MW}$ is disconnected at $t = 0.01$ s. Two characteristic cases are be presented: 1) ALS blocked and 2) adaptive ALS activated (uniformly disconnection of estimated Δp load in one stage, at $f_1 = 59.6$ Hz with time delay $\Delta t_1 = 0.25$ s). In Figures 3 and 4 the frequencies of generators #1 and #3 and estimated frequencies of equivalent center of inertia (Eq. (6)) are presented. With ALS blocked (ALS = 0), the new forbidden state with $f = 59$ Hz is reached. Contrary, with adaptive ALS (ALS = 1), the new state with the nominal power system frequency is reached. In Figure 5 the estimated power Δp for both cases are presented. At the very beginning of the estimation procedure at $t = 0^+$ s, just after the disturbance inception, the exact values of disconnected power ($\Delta p = 150$ MW) are estimated. The swing equation (1) is the simplest model of slow transient processes in power system, but it is valid very short period after the inception of the disturbance. Later on, some other factors influences the motion of generator rotors (damping factors, changes in electrical (consumed) power, turbine governor, power system stabilizers, spinning reserve, etc.). That is why the EMD is correct only at $t = 0^+$ s. But it is sufficient for the further adaptation of ALS and adaptive disconnection of loads. In Figure 5 the instant when a portion of load was disconnected from the network to preserve the system stability and to recover the system frequency to its nominal value can be also noticed.

In the second test example, 70 MW load is suddenly connected to the network at node 8 at $t = 0.01$ s. In Figures 6-8 the results equivalent to the results from the first test example are presented. Here the adaptive ALS disconnected estimated Δp load in one stage, at $f_1 = 59.7$ Hz with time delay $\Delta t_1 = 0.25$ s. In this example the exact estimate of power Δp is obtained in both cases, with and without ALS.

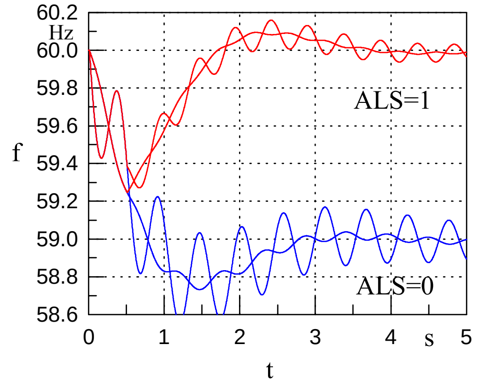

Fig. 3: Frequencies of generators #1 and #3.

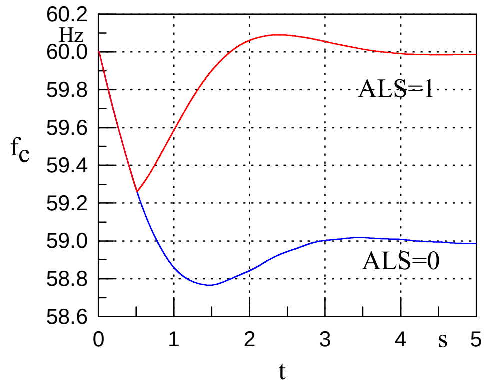

Fig. 4: Frequencies of equivalent centers of inertia.

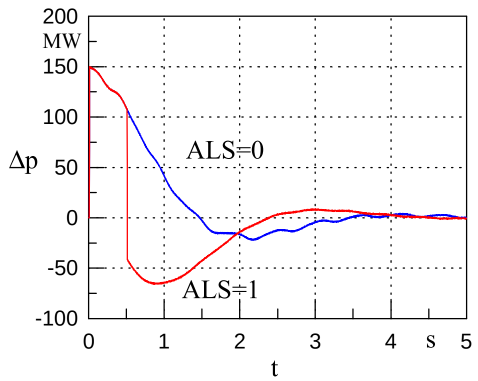

Fig. 5: Estimated power imbalances.

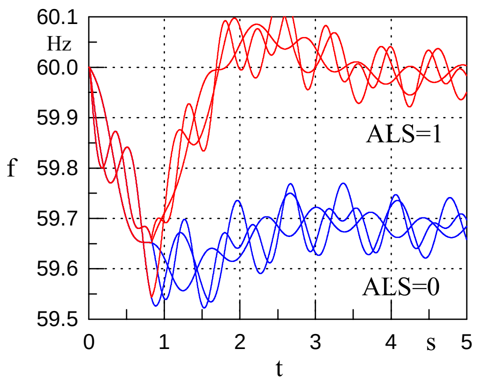

Fig. 6: Generator frequencies.

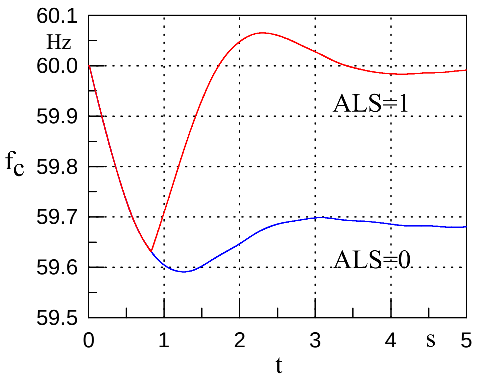

Fig. 7: Frequency of equivalent center of inertia.

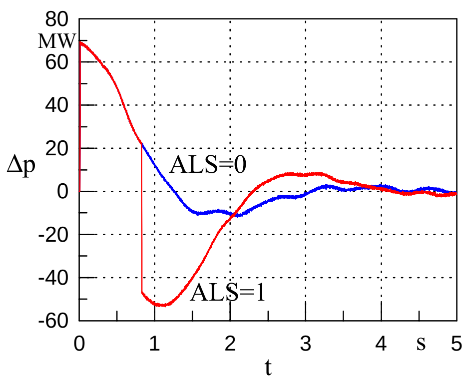

Fig. 8: Estimated power imbalance.

From the results obtained through the simulation tests, the following can be concluded:

1. The magnitude of disturbance, i.e. the difference between the generated and the consumed powers, Δp, can be efficiently estimated by using the elementary swing equation (Eq. (1)) for the one machine, or Eq. (6) for multimachine power systems.
2. The prerequisite for efficiently estimation of Δp are the precise measured frequencies of all parallel operating generators. Nonrecursive Newton Type Algorithm is a suitable nonlinear estimator for the purpose of frequency measurement.
3. With the new adaptive ALS more reliable power system operation can be provided. The damages and the costs can be significantly reduced.

In the next stage of this research it is planed to provide an investigation of the new adaptive ALS under laboratory conditions and by using field data records.

5. CONCLUSION

A new strategy of adaptive automatic load shedding, as a last step in protecting power system from instability is presented. The strategy is based on precise estimation of frequency and its rate of change on every generator unit. Estimation is provided by using nonrecursive nonlinear Newton Type Algorithm and linear Least Error Squares Method. Further, the power system frequency of equivalent center of inertia is estimated from the estimated generators' frequencies. Finally, the magnitude of disturbance is estimated and used for the determination of the amount of disconnected load. The new adaptive strategy is tested through computer simulated tests provided on a multimachine power system. An essential effort is reached when an adaptive approach is applied.

6. REFERENCES

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7. ACKNOWLEDGEMENTS

The authors are gratefully acknowledged to Alexander von Humboldt Foundation for supporting this research and to Miss. Borka Milošević (Georgia Tech, GA, USA) for the cooperation during early stages of this research.