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Frequency and Active Power Control in Islanded Power Systems Based on the Magnitude of the Disturbance Estimation

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***Abstract*--Paper presents the difficulties of existing anti-emergency automation when operating in islanded power system. The operation of existing anti-emergency automation is apprized from the point of view of elimination of active power deficiency or surplus. Shortages of existing anti-emergency automation as well as necessary areas for improvements are shown. New method for estimation of active power deficiency or surplus is proposed. It is based on the use of the mathematical description of the considered system to provide more accurate operation of anti-emergency automation, for instance, when shedding load or starting generation reserves. The analysis as well as possible application of the proposed method for estimation of active power deficiency or surplus is presented.**

***Index Terms*--Frequency, adaptive control, islanding.**

I. Introduction

POWER system ranks among the most complicated artificial technical systems created by mankind. For a number of reasons and in common with any other technical device it can get into emergency operation mode characterized by inadmissible deviations of frequency or voltage from their rated values, unarranged disconnection of transmission lines, electrical or mechanical damages of equipment etc.

From the point of view of frequency and active power control one of the most dangerous and complicated situations arose when some part of power system gets into islanded operation mode.

Power system islanding can occur unexpectedly during emergency operation mode or deliberately in case of interference of dispatcher service or power system splitting automation. Such islanded system can include single steam turbine operating in house-load mode or cover the territory of several countries.

Lately the increasing interest has been drawn to islanding of distributed generation (DG) resources as a result of ongoing penetration of wind, solar, fuel cell and other small scale power plants in distribution networks.

Islanded system can be formed intentionally as well. In some remote areas hybrid stand-alone power systems are often more cost effective than utility grid extensions, mainly due to the high cost of transmission lines.

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The emphasis in the paper is put on the islanded power systems for a variety of reasons discussed in the following subdivisions.

A. Unsatisfactory operation of islanded regions during cascading failures

A lot of accidents in power systems have shown the inability of islanded regions to secure their operation.

Thus, for example, during the cascading power failures in USA and Canada at 9th of November 1965, in most of the islanded areas power generation ceased within a matter of three to twelve minutes [1, 2].

In spite of never-ceasing improvement of relay protection and automation devices and use of microprocessor based units which can be programmed for complicated algorithms, nothing has changed substantially. Thus, during the last phase of cascading failures at 14th of August 2003 in the USA and Canada, several islanded areas have formed. Most of them went black soon afterwards [3].

The continuous operation of such islanded areas would preserve the generating units and power supply. It would hold down the extension of emergency and would facilitate the power system restoration process.

B. Competing objectives in DG interconnection standards

Most state interconnection standards mandate control and protection measures to minimize the probability of an inadvertent island, and to minimize the duration of an island's existence, if one should occur. These measures, however, also have their own impact on power system performance, primarily on the system dynamic behavior during and following system disturbances.

With the small penetration level of DG resources the impact will normally be insignificant. With higher values of penetration, compared to local load and system capacity, measures intended to limit unintentional islanding can aggravate local disturbances. If DG penetration becomes widespread, the anti-islanding measures may also impact bulk power system voltage and frequency stability [4].

The need to quickly detect and eliminate inadvertent DG supported islands and the desire to minimize DG impact on system dynamic performance, are conflicting objectives using the protective functions required today. As DG penetration grows, industry attention is needed to reconcile these competing objectives and develop new approaches to island avoidance or tolerance which minimize consequential system impact.

C. Deterministic character of anti-emergency automation

Nowadays, the existing plans of different automation devices are predominantly deterministic, not taking into account the actual system state and topology, operating point, and the nature and the magnitude of the disturbance. As a consequence, for example, under-frequency load shedding very often disconnects more or less load than is required. This causes undesired damages and serious costs [5].

Several methods for islanded systems have been proposed to estimate active power deficiency or surplus that would make automation devices more adaptive and precise (hereafter for the sake of the simplicity only active power deficiency will be mentioned). These methods, however, have some shortages.

From the previous the necessity for new means and methods for automated control of islanded power systems can be concluded.

II. Existing Methods Based on the Magnitude of the Disturbance Estimation

Overall the methods for direct active power deficiency estimation in islanded power systems can be divided into two groups:

1) Active power deficiency estimation using the rate of change of frequency;

2) Active power deficiency estimation by collecting the actual data from the power system.

A. Active power deficiency estimation using the rate of change of frequency

The frequency deviation that accompanies system islanding disturbances is caused by the imbalance between load and generation. This effect is most serious in the island that has excess load, since speed governing is usually effective in reducing the generation in islands that have an excess of generation. Therefore, most of the concern is for the island with an excess of load. Since there is no direct control of utility load, the primary method of restoring frequency is to shed load in appropriate amounts. This must be done with considerable planning, since there is no merit in shedding excessive amounts of load and thereby creating a need for reducing generation [6].

To estimate the necessary amount of load to be shed the rate of change of frequency indication is used. Interconnection between the amount of disturbance and the rate of change of frequency can be observed from the rotor swing equation (1) [7]:

$$\frac{2\cdot H}{f_{rated}}\cdot\frac{df}{dt}=P_{mech}(f)-P_{el}(f)=\Delta P \qquad (1)$$

where H is combined mechanical inertia time constant of the generator and turbine [MW·s/MVA]; f is frequency [Hz]; f_{rated} is rated frequency (50 Hz); $P_{mech}(f)$ is mechanical power [p.u.]; $P_{el}(f)$ is electrical power [p.u.]; ΔP is disturbance (active power deficiency or surplus) [p.u.].

From the equation it is obvious that the rate of change of frequency during a system overload is directly proportional to the amount of overload.

It should be noted, however, that after the appearance of active power deficiency and the resulting decrease of frequency the turbine speed controllers will be actuated and will increase the generated power. At the same time the load power will decrease according to its frequency characteristic. In addition to these two factors other events may also take place such as operation of under-frequency load shedding or starting of generation reserves. Therefore power imbalance ΔP is proportional only to the initial rate of frequency change. It also depends on the electric power system inertia (2):

$$\left.\frac{df}{dt}\right|_{t=0}=\frac{\Delta P\cdot f_{rated}}{2\cdot H} \qquad (2)$$

From the point of view of active power deficiency estimation in the islanded power system the considered method has several shortcomings (even though various approaches by different authors have been tried to overcome them [5, 6, 8, and 9]):

1) The amount of active power deficiency can be precisely estimated exclusively at the initial instant of the transient process (assuming the mechanical inertia time constant is assigned accurately). The method is subordinated to the single moment of emergency situation.

2) Most frequently under-frequency load shedding sheds the load with some time delay, waiting for the frequency to decline below its pre-set value. Additional time delay is formed because of operation time of automation device and a circuit breaker. As a result the load is shed at a time when the actual active power deficiency might have different value from the initial one.

3) Obviously, all of the load that should be dropped to correct for the anticipated overload could be dropped at one time. However, it is safer to increase the number of steps and divide load among the steps. As more steps are included in the load-shedding scheme, the amount of load that is shed can more accurately correct the overload. The considered method is not appropriate for multiple load shedding steps though.

4) It is not possible to estimate the amount of active power deficiency in the situations when frequency is settled below its rated value (the rate of change of frequency is equal to zero).

5) The considered method is not effective for slow decrease of frequency and is problematic for cascading power failures.

6) The considered method is analyzed mostly for islanded power system with thermal power plants. It is not contemplated for power systems where hydro power plants predominate (with their water-hammer trademark). It is not contemplated for hybrid power systems with different distributed energy resources as well. Every power system has its own specifics that should be taken into account – it can be

substantially deficiency (Latvia, Finland) and import power from neighboring countries, it can comprise mostly thermal power plants (Japan) or hydro power plants (Brazil). It can be dissipated (Russia) or concentrated (Europe) etc.

B. Active power deficiency estimation by collecting the actual data from the power system

In addition to the use of rate of frequency change the active power deficiency can be estimated by unitary collection of power system data.

As a practical example of unitary collection of power system data the so called adaptive matrix of Latvian Pļaviņu hydro power plant can be mentioned (adaptive matrix operates in the united power system as well as in islanded mode). It collects the data from power system and estimates the necessary control action.

An excerpt from the adaptive matrix of Pļaviņu HPP is shown in Fig. 1. In case of frequency decline below 49.4 Hz, the control action depends on the situation in Kruonio pumped storage power plant and on the situation in Pļaviņu HPP.

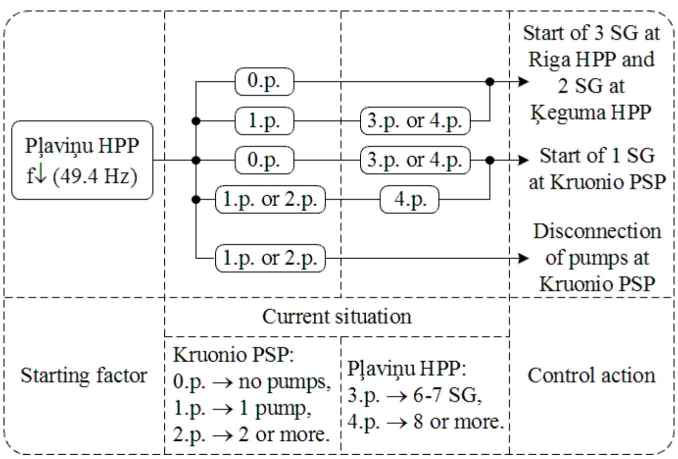

Fig. 1. Excerpt from the adaptive matrix of Latvian Pļaviņu HPP

The main shortcoming of the considered approach is linked with the pre-determined control actions of the adaptive matrix. These control actions and settings are chosen in advance according to some previously calculated possible emergency situations. However, it is not possible to foresee all the possible power system failures and cascading events. Therefore the considered approach is most effective when the emergency situation corresponds or is close to the foreseen one. In other cases it can produce wrong control actions.

III. Development of a New Method for Active Power Deficiency Estimation

Revising the shortcomings of existing methods for active power deficiency estimation it can be concluded that the new method should accomplish the following tasks:

1) It should be able to estimate the active power deficiency not only at the initial moment but during the whole transient process;

2) It should adapt itself to the emergency process by changing accordingly the necessary amount of control action;

3) It should effectively operate during slow frequency variations as well as in situations when frequency is settled below its rated value;

4) It should take into consideration the specifics of every local object (for instance, the operational particularities of fuel cell power plant).

General methodology for active power deficiency estimation is summarized below:

1) Creation of the mathematical description for the considered system taking into account only the electromechanical transient processes. For example, for single isolated synchronous generator (for the sake of simplicity excluding the differential equations of turbine speed governor):

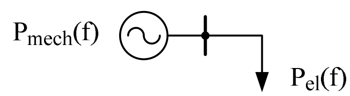

Fig. 2. Single isolated synchronous generator

$$\frac{2\cdot H}{f_{rated}}\cdot\frac{df}{dt}=\left[P_{mech}(f_{rated})-\frac{\Delta f}{R}\right]-\left[P_{el}(f_{rated})+D\cdot\Delta f\right] \quad (3)$$

where Δf is frequency deviation from its rated value [p.u.]; R is droop coefficient; D is load damping constant.

2) Assignation of the parameters for the mathematical description. Some of the parameters are known (f_{rated}), can be measured (f), calculated (df/dt), read from the given settings (R) or from the technical data (H). Some parameters can be taken approximately (D) or estimated by different estimation procedures.

3) Continuous measurement/calculation of f, df/dt un $P_{el}(f)$ at the generator bus.

4) Calculation of $P_{el}(f_{rated})$ using the measurements of frequency and $P_{el}(f)$:

$$P_{el}(f_{rated})=P_{el}(f)-D\cdot\Delta f \quad (4)$$

5) Estimation of $P_{mech}(f_{rated})$ as the only remaining unknown quantity from the equation (3).

6) Computation of active power deficiency (surplus). It shows the necessary control action to restore the frequency back to its rated value:

$$DEF=P_{el}(f_{rated})-P_{mech}(f_{rated}) \quad (5)$$

7) In case of multiple power plants the estimation procedure is performed in each of them.

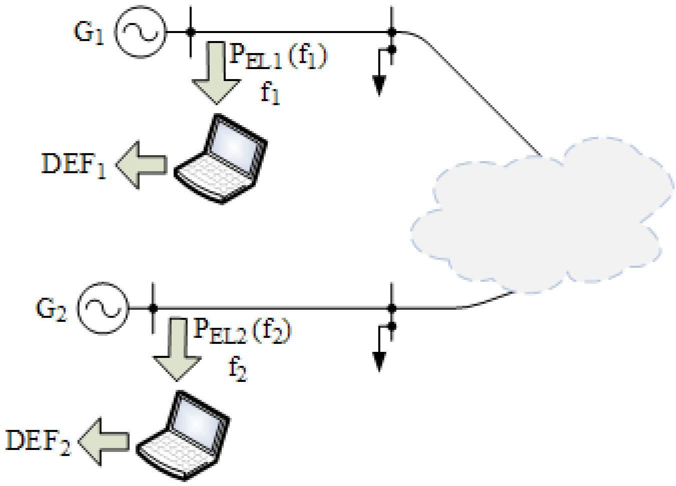

Fig. 3. General structure of active power deficiency estimation

Fig. 4 presents specific quality of the considered method – the sum of all estimated active power deficiencies (if they are estimated at all power plants) corresponds to the actual deficiency (surplus) in the considered system at every time instant.

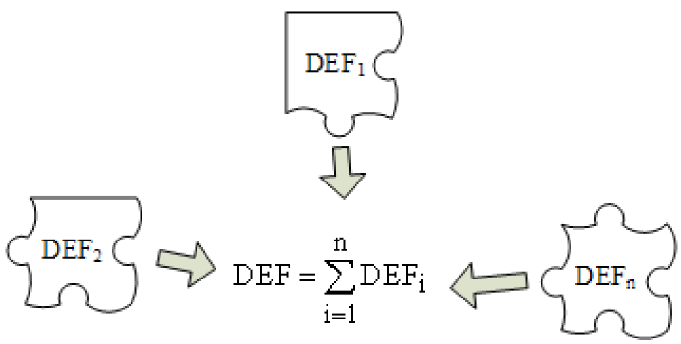

Fig. 4. Summation of individual active power deficiencies (surpluses)

8) Afterwards, according to the considered object, the necessary control action is chosen (load shedding and/or starting of generators, number of steps, time delays etc.).

IV. Overview of the Constraints and Possible Inaccuracies of the New Method's Operation

The proposed new method for active power deficiency estimation should be checked for a number of specific situations:

1) Not all of the mathematical description's parameters are always precisely known. There might be inaccuracies, for example, in the technical data of the power equipment. Difficulties are presented also by parameters such as load damping constant which depends on the load and therefore is continuously alternating. Therefore it is very significant to evaluate how these inaccuracies affect the precision of estimated active power deficiency.

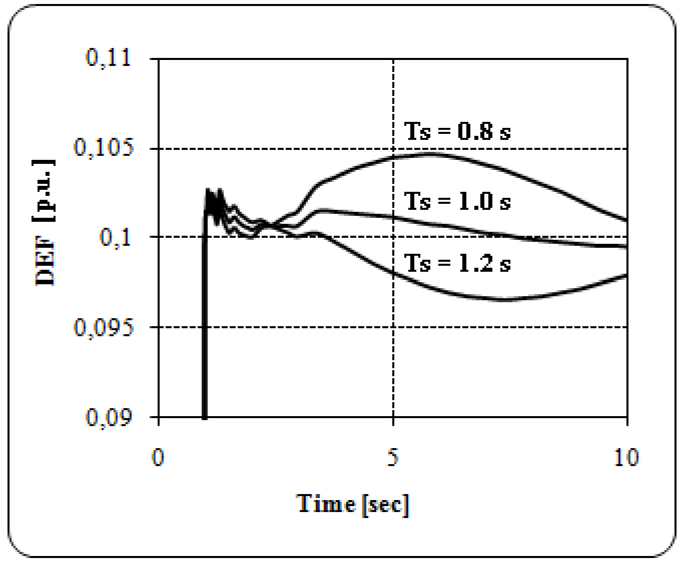

Fig. 5. Estimation of active power deficiency (DEF = 0.1 p.u.) for three different values of time constant Ts of servomotor (the correct value of Ts is 1.0 sec)

Let us take as an example three machine system with identical hydro power plants and turbine speed governors. Examining three different values of time constant Ts of servomotor (one correct and two inaccurate) it can be concluded that inaccuracies of Ts does not substantially affect the results if the control action is applied soon enough (see Fig. 5).

The situation is more problematic in case of mechanical inertia time constant H. From the Fig. 6 it is obvious that calculation mistakes expresses instantly. Therefore this parameter should be closely watched.

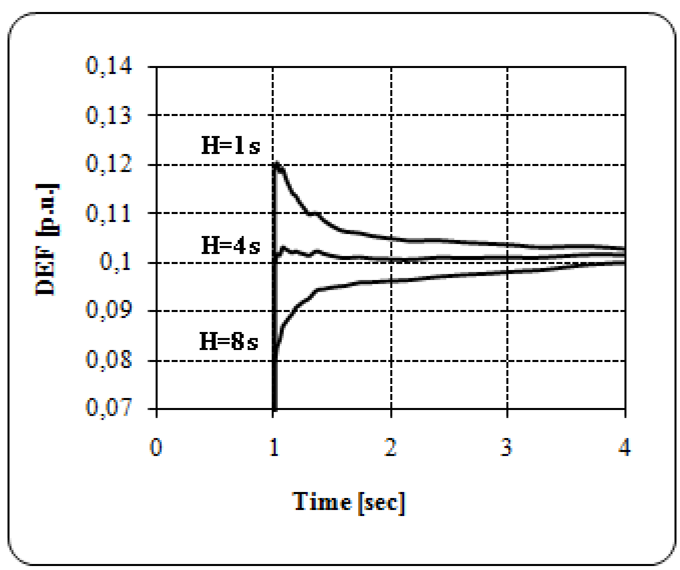

Fig. 6. Estimation of active power deficiency (DEF = 0.1 p.u.) for three different values of mechanical inertia time constant (the correct value of H is 4.0 sec)

2) It should be noted, that in real isolated power system there will be more than one power plant. As a result the

deficiency can be estimated at all the power plants or just in a few of them. The point of estimation can affect the effectiveness of the new method.

Every power plant feels only a part of the actual value of deficiency. Therefore, if possible, it is better to estimate and apply the control action from every power plant for a faster and more effective preclusion of emergency situation.

3) The possible applications of estimated control action should also be carefully inspected. Information about the estimated active power deficiency can be used for load shedding or starting of generators. Control action can be applied at one power plant or at all of them. It can be applied at once or divided into several steps, with or without a time delay etc. These topics are planned for the future work.

One particular problem is related to the control action which includes shedding of load. Even if the necessary amount of load which should be shed is estimated, it is difficult to enforce the precise control action since the load is varying parameter and actual load behind circuit breakers (feeders) might be unknown.

4) Physical and technological constraints of power system elements should also be considered. Constraints such as limited carrying capacity of transmission lines, the dependence of distributed energy resources on intermittent natural resources can influence the operation and effectiveness of the new method.

Thus, for example, MCFC and SOFC types of fuel cells typically operate at 650ºC and 1000ºC respectively. High-temperature operation requires a significant start-up time (hours) and results in a worse dispatching ability. Therefore these types of power plants cannot be used for quick changes of generated active power according to the estimated deficiency or surplus.

5) Existing relay protection and automation devices when operating in parallel with the proposed new method can also have some unwanted influence. The influence of voltage and reactive power should also be considered.

V. Example of Possible Application of the Proposed New Method

In this chapter example of possible application of the proposed method is shown. While developing the new method the emphasis was mostly put on very small systems with one or several machines and transmission lines in them. At the same time a possibility to extend the obtained results to larger systems is not eliminated.

To show the operation of the proposed new method in larger system the mathematical model of Baltic region (see Fig. 7) is used in which the first stage of power system splitting experiment in 2003 is reproduced (disconnection of the last 330 kV intersystem's tie therefore provoking the active power deficiency of 169 MW and subsequent decrease of frequency).

Fig. 7. Islanding of Baltic region during the power system splitting experiment in 2003

The simulated frequency transient process is presented in the Fig. 8 which matches the actual frequency transient process during the power system splitting experiment.

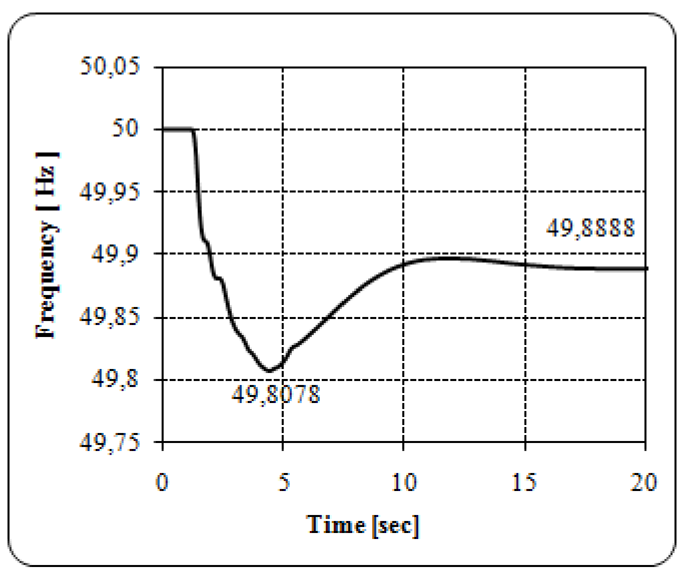

Fig. 8. Frequency transient process after the disconnection of the last 330 kV intersystem's tie

Active power deficiency of 169 MW distributes among the whole islanded region. By placing the active power deficiency estimation devices at every power plant in the region it is possible to see this distribution for every moment of time. The active power deficiency values at Estonian power plants are shown in Fig. 9.

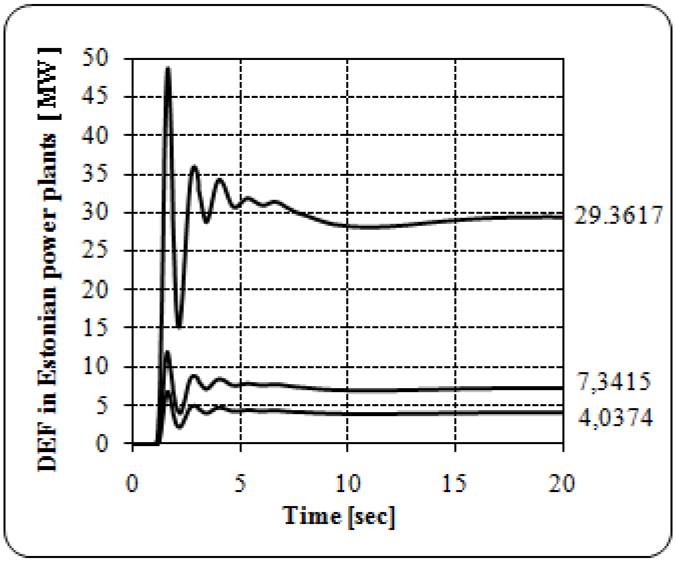

Fig. 9. The active power deficiency values at Estonian power plants

Summing the values of deficiency at every instant (in the power plants of Latvia, Estonia, Lithuania, Belorussia and Kaliningrad) it is possible to ascertain that the resulting value is 169 MW and it corresponds to the actual disturbance. Knowing the deficiency at every plant, it can be eliminated more efficiently than using only indirect indications such as frequency decline.

VI. Conclusions

1) From the point of view of frequency and active power control one of the most dangerous and complicated situations arose when some part of power system gets into islanded operation mode. As DG penetration grows, it is necessary to analyze in more detail the islanded operation subjects of DG.

2) Existing automation devices operate predominantly in a deterministic manner, not taking into account the actual system state and topology, operating point, and the nature and the magnitude of the disturbance (or they are capable to estimate the disturbance exclusively at the initial instant of the transient process). Therefore new means and methods for automated control of islanded power systems should be developed.

3) New method for active power deficiency (surplus) estimation is developed. The results can be used for the further expansion of the subject. Realization of the proposed method on the microprocessor-based devices is also possible.

4) In the future work existing mathematical models of power system elements can be improved and new ones developed. Especially significant is the creation of models for distributed generation sources. These are relatively new and fast-changing technologies for which the mathematical models sometimes are not even developed yet (or kept in secret by power equipment manufacturers).

5) Significant feature of the considered new method is its adaptive operation.

6) There is a possibility to extend a proposed new method to larger power systems.

7) The proposed new method for active power deficiency (surplus) estimation can be improved by the help of different optimization procedures (for example, for the estimation of more effective amount and number of control action's steps).

VII. References

[1] Report of the U.S. Federal Power Commission, "Report to the President by the Federal Power Commission on the Failure in the Northeastern United States and the Province of Ontario on November 9-10, 1965," Washington, DC: U.S. Government Printing Office, December 6, 1965.

[2] Report of the U.S. Federal Power Commission, "Prevention of Power Failures: An Analysis and Recommendations Pertaining to the Northeast Failure and the Reliability of U.S. Power Systems," Volume I: Washington, DC: U.S. Government Printing Office, July 1967.

[3] "Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations," U.S.-Canada Power System Outage Task Force, April 2004.

[4] Walling R. A., Miller N. W, "Distributed Generation Islanding - Implications on Power System Dynamic Performance," IEEE Power Engineering Society Summer Meeting, Vol. 1, pp. 92 – 96, July 2002.

[5] Terzija V. V., "Adaptive Under-frequency Load Shedding Based on the Magnitude of the Disturbance Estimation," IEEE Transactions on Power Systems, Vol. 21, No. 3, pp. 1260 – 1266, August 2006.

[6] Anderson P. M., Mirheydar M., "An Adaptive Method for Setting Under-frequency Load Shedding Relays," IEEE Transactions on Power Systems, Vol. 7, No. 2, pp. 647 - 655, May 1992.

[7] Kundur P., *Power System Stability and Control*, McGraw-Hill, Inc., 1994, 1176 pp.

[8] Haibo You, Vijay Vittal, and Zhong Yang, „Self-Healing in Power Systems: An Approach Using Islanding and Rate of Frequency Decline-Based Load Shedding," IEEE Transactions on Power Systems, Vol. 18, No. 1, pp. 174 - 181, February 2003.

[9] Thalassinakis E. J., Dialynas E. N., "A Monte-Carlo Simulation Method for Setting the Under-frequency Load Shedding Relays and Selecting the Spinning Reserve Policy in Autonomous Power Systems," IEEE Transactions on Power Systems Vol. 19, No 4, pp. 2044 - 2052, November 2004.

VIII. Biographies

Vladimir Chuvychin (M'1979, SM'1990) was born in Russia on January 17, 1941. He received diploma engineer degree in 1965, Candidate of Technical Science degree (PhD) in 1975 and Dr. habil. sc. degree in 1997 from Riga Technical University, Riga, Latvia.

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