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EVALUATION OF DYNAMIC CHARACTERISTICS OF MULTIMACHINE ELECTRIC POWER SYSTEMS ON THE BASE OF DATA OF TRANSIENT MODES MONITORING SYSTEM

The aim of introduction of transient mode monitoring system is the increase of reliability and energy supply quality by means of decision making in real time rate on the base of synchronized measurement analysis. Processing of the data, obtained from the system of transient modes monitoring (STMM) provides the account of dynamic properties of electric power system (EPS). The character of electromechanical transient processes of multimachine EPS is determined, to a great extent, by the inertia of rotating masses of generators, motors and complex resistances of electric couplings between them.

Modern trends in the development of power industry revealed problems, dealing with further integration of renewable sources of energy (RSE). Inverter connection of RSE does not provide the feedback of energy sources with electric grid, that results in reduction of kinetic energy store (KES) of rotating masses of energy system. In its turn, KES is fast acting reserve of power, that provides stability of electric system operation to reaction of primary regulators of frequency and active. Taking into account the fact that RSE, connected by means of inverters do not have inertia response (IR),in order to maintain stable operation of EPS it is necessary to develop methods and tools for increasing IR of RSE.

Thus, the analysis of transient processes in EPS with RSE and development of methods, aimed at increase of kinetic energy stores of rotating masses of electric power system is an urgent problem.

Key words: *electric power system, transient modes monitoring system, frequency regulation, kinetic energy store, inertia response, virtual inertia, renewable sources of energy, coherent groups of generators.*

Introduction

One of the priority lines in the development of the world largest EPS is creation and introduction of the systems for transient modes monitoring. These systems are used for improvement of information support and quality of EPS and energy enterprises modes operation. Characteristic feature of STMM, unlike the existing telemetering systems, is time synchronization of modes measured parameters by means of using the exact time signals transmitted from the satellites and high discreteness of parameters registration, that determines wide range of technology application. In unified energy system (UES) of Ukraine (Fig. 1) systems of transient modes monitoring are effective for the analysis of reasons and consequences of technological faults and system failures, for verification of EPS dynamic models, evaluation of EPS states, solution of the problems dealing with the information support of on-line-dispatching control.

Introduction of the system of transient modes monitoring pursues the following aims of their practical usage:

1. Verification of digital models of UES and their separate elements:

- Models of the devices of automatic regulation and control;
- Refinement of models of generation and load, their static and dynamic characteristics;
- Digital model of UES on the whole.

2. Analysis of already happened failures:

- Development of methodological analysis of system failures and regional level failures;

3. Obtaining quality approximation for mode calculation in real time: usage of voltage vectors in grid nodes, where STPM registrators are installed, enables to create «the framework» of mathematical model, considerably reduce the problem of convergence and decrease the time of mode calculation.

4. Detection and analysis of low frequency oscillations.

Fig. 1. Scheme of STPM devices location in UES of Ukraine

Digital mathematical model of EPS is the system of non-linear differential equations with the set initial conditions.

Multimachine ES is described by the system of non-linear differential equations (1)

$$\frac{\partial \delta_i}{\partial t} = \omega_i$$

$$\frac{2H_i\,\omega_i\,S_{\text{ins.}}}{\omega_s^2}\frac{\partial \omega_i}{\partial t} + D_i\omega_i = P_{\text{mec.}} - \left(E_i^2 G_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{n} E_i E_j Y_{ij}\cos\left(\theta_{ij} - \delta_i - \delta_j\right) \right) \tag{1}$$

where δ_i, δ_j – deviation of rotors turning angles from synchronized rectangular coordinates of i^{th} and j^{th} generators, correspondingly [rad.]; ω_i – deviations of i^{th} generator frequency from synchronized rectangular coordinate [rad/s]; H_i – constant inertia of i^{th} generator [s]; D_i – damping factor of i^{th} generator [MW·s/rad]; $S_{ins.}, P_{mec.}$ – installed and mechanical powers, correspondingly [MW]; E_i, E_j – EMF of i^{th} and j^{th} generators, correspondingly [V]; G_{ii} – active self-conductance of the node *i,* to which i^{th} generator is connected [S].

Power in the node *i* equals electric power of i^{th} synchronous machine (SM) and is determined as

$$P_{ei} = E_i^2 G_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{n} E_i E_j Y_{ij}\,cos\left(\theta_{ij} - \delta_i - \delta_j\right), i = 1,2,\dots,n \tag{2}$$

where Y_{ij} – mutual admittance between i^{th} and j^{th} nodes [S]; θ_{ij} – argument of complex admittance between i^{th} and j^{th} nodes [rad].

The parameter of the model (1) H_i – constant inertia of EPS, characterizing kinetic energy store of rotating masses of electrically connected sets of power stations. Depending of the mode of EPS the composition and list of power stations, connected to EPS, as a result, change in time of the inertia value is quite natural property of EPS. In case of emergency power imbalance kinetic energy, accumulated in synchronous rotating masses, provides fast acting reaction on the disturbance, prior the action of primary frequency regulators. Taking into account the above-mentioned, the problem of the development of control methods of existing, KES is very important, their control will allow to forecast the character of transient modes in EPS.

Impact of renewable sources of energy on kinetic energy store of EPS

Analysis of the trends of power industry development, based on SmartGrid, showed that in the near future the dominating factors influencing the changes of EPS operation will be:

- large volume of RSE introduction and promotion of the integration of large-scale projects of renewable power generation with high share of generators, connected across power converters;
- application of technologies, dealing with storage and accumulation of energy with various time constants, considerable part of which will use inverter connection to the network;
- distribution of electric energy from new generation capacities on the base of high voltage direct current networks, using power semiconductor converters, that separate new primary sources of energy from the existing electric system.

Renewable sources of energy (RSE), wind energy being the primary source of energy, for instance, wind turbines with constant rotation frequency, use synchronous generators, and, as a consequence, kinetic energy of these generators is added to KES of EPS. On the other hand, sources of energy, such as photovoltaic solar power station (SPS), using the inverters for alternating current generation, do not have the feedback between the frequency of the system and their own stores of kinetic energy. Power converters, used in these systems, are oriented as a rule, only for optimization of energy extraction process. Power of SPS, in this case, is only the function of solar radiation and does not depend on mode parameters of the network [1].

Characteristic feature of RSE, such as wind stations, is that the speed of wind turbine rotation may decrease from nominal rotation frequency to minimal value, regardless of the network frequency. Besides, as a result of connection by means of inverters, generators result in the decrease of inertia response. However the latest studies [2] showed the possibility to provide efficient inertia response (IR) of RSE by means of virtual inertia regulators.

That is why, determination of admissible volumes of RSE usage in energy balance, maintaining of safe level of EPS KES, improvement of EPS dynamic characteristics by means of usage of rotating parts of wind turbines kinetic energy and SES power reserves is very important problem.

Estimation of KES of multimachine electric energy systems

For estimation of dynamic characteristics of multimachine EPS in the case of imbalance transient modes could be conventially divided into 3 parts (Fig. 2):

- t0-> t1 when EPS dynamics is determined by electromagnetic transient processes;
- t1-> t2 when EPS dynamics is determined by electromechanical transient processes;
- t2 + when EPS dynamic is determined by the systems of automatic control.

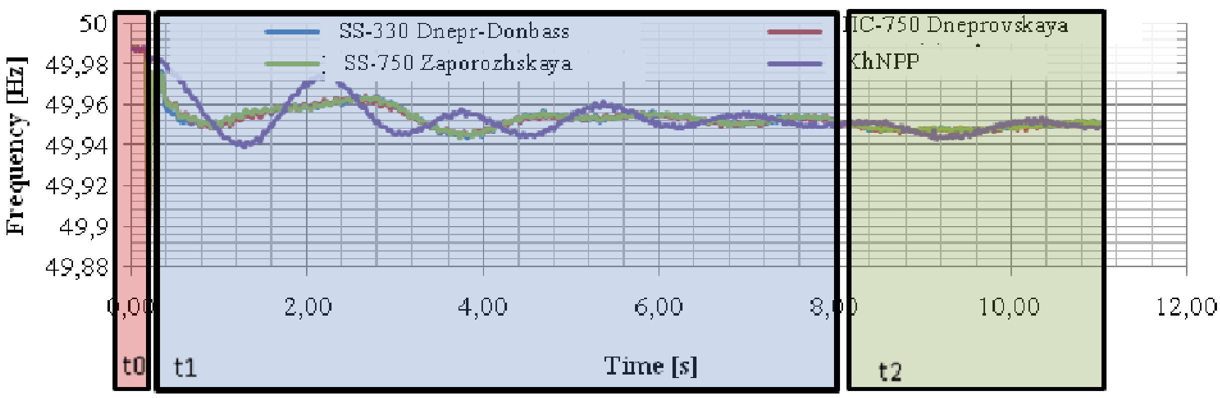

Fig. 2. Transient process of frequency change at the buses of EPS in case of emergency disconnection of 1 GW unit at Zaporizhia NPP

It is expedient to perform estimation of EPS dynamic characteristics on the base of the data of electromechanical transient processes, because in this time interval the impact of the systems of frequency primary regulation is missing.

After imbalance of active power in EPS occurs, frequency in separate parts of energy system changes differently (Fig. 2). Analysis of transient process of frequency change on EPS buses in case of emergency disconnection of 1 GW unit at Zaporizhia NPP (Fig. 2), showed that the rate of frequency change of generators, located closer to the place where imbalance originated(PIO). It is stipulated by initial distribution of imbalance in accordance with electric distance from the generator to PIO (Fig. 3).

During transient process in EPS, synchronizing power maintains electric frequency of synchronous generators stator field rotation the same for all generators, connected to the network. However, due to different distribution of imbalance per units and weak system couplings, in case of disturbance groups of generators with instantaneous frequencies are formed, these groups in transient mode slightly differ, without violating general synchronism of the system. Such groups are called coherent groups of generators (CGG) [1] (be frequency) or clusters. Coherence can be manifested in short time intervals (rapid coherence) and in long time intervals (slow coherence). For estimation of dynamic characteristics of CGG it is expedient to use groups with slow coherence.

Analysis of transient process (TP) by frequency in case of emergency disconnection of 1 GW unit of Zaporizhia NPP determined three coherent groups of generators in UES of Ukraine (Fig. 3). The composition of CGG is mainly stipulated by the structure of couplings of EPS elements and does not depend on the type and place of the disturbance, if this disturbance does not change the basic structure of system couplings.

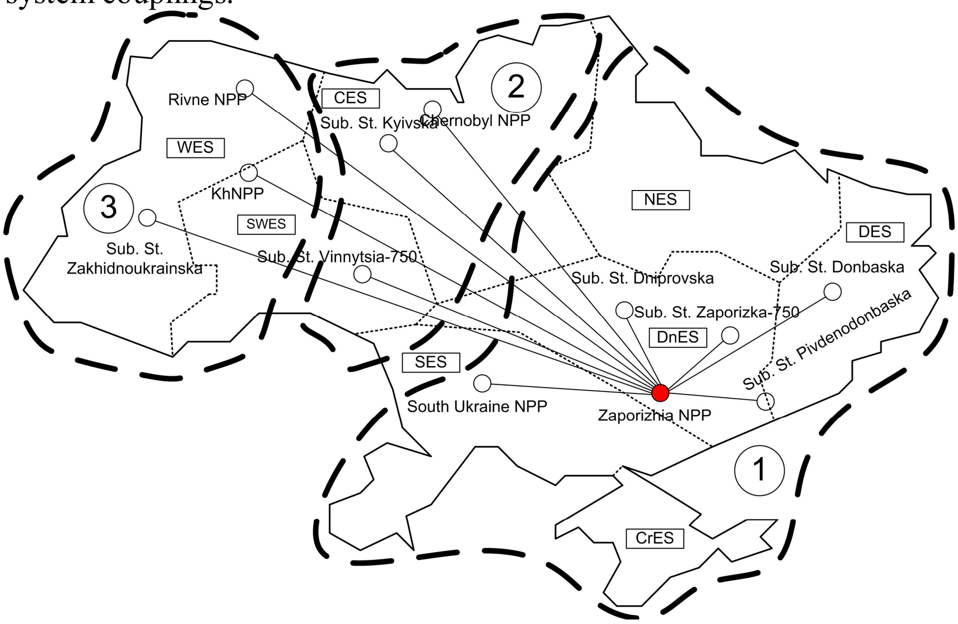

Fig. 3. Coherent groups of generators in case of disconnection of the unit at Zaporizhia NPP

Characteristic instantaneous frequencies of the clusters are called frequencies of inertia centers. The problem of determination of inertia centre frequency according to the STPM data is reduced to filtration of intersystem oscillations [3] by the approximation of transient processes curves, applying the method of least squares, Fourier filtration or wavelet filtration.

For determination of the frequencies of clusters inertia centers filtration, applying the methods of discrete wavelet transformation (DWT) [4] and Fourier transform, taking into account possible absence of STPM data on all the generators of the group, was carried out (Fig. 4).

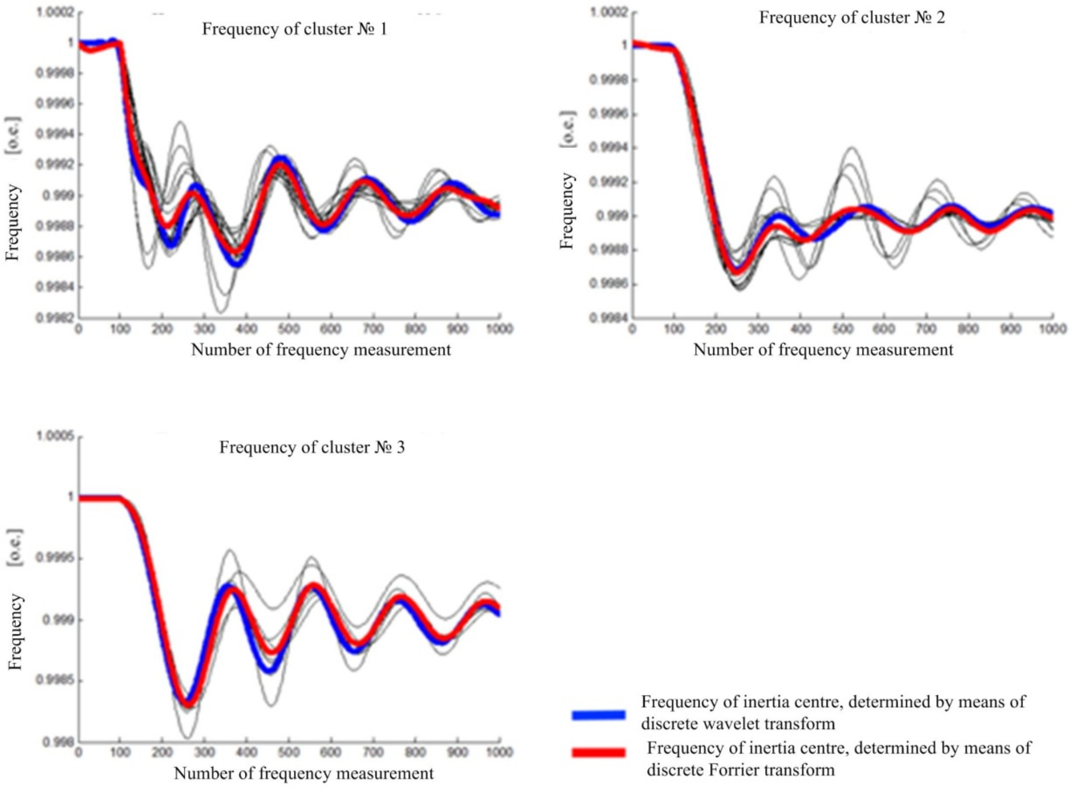

Fig. 4. Frequencies of inertia centers of three clusters in case of disturbance and Zaporizhia NPP

Absence of STPM data regarding all the generators of the group was compensated by valuation of spectral power of generators oscillations in coherent groups. Thus, oscillations with different amplitude but opposite phase (internal oscillations of CGG) in case of reverse transformation of Fourier spectra into oscillations signals will be completely compensated.

As it was mentioned above, initial distribution of the imbalance in EPS occurs according to the value of electric distance to PIO. Determination of electrical distance from generators toPIO is expedient to perform by reducing graph model of flux distribution in steady-state modes (Fig. 5). Direct proportional relation between equivalent conductances to the place of disturbance determines the imbalance distribution by generators.

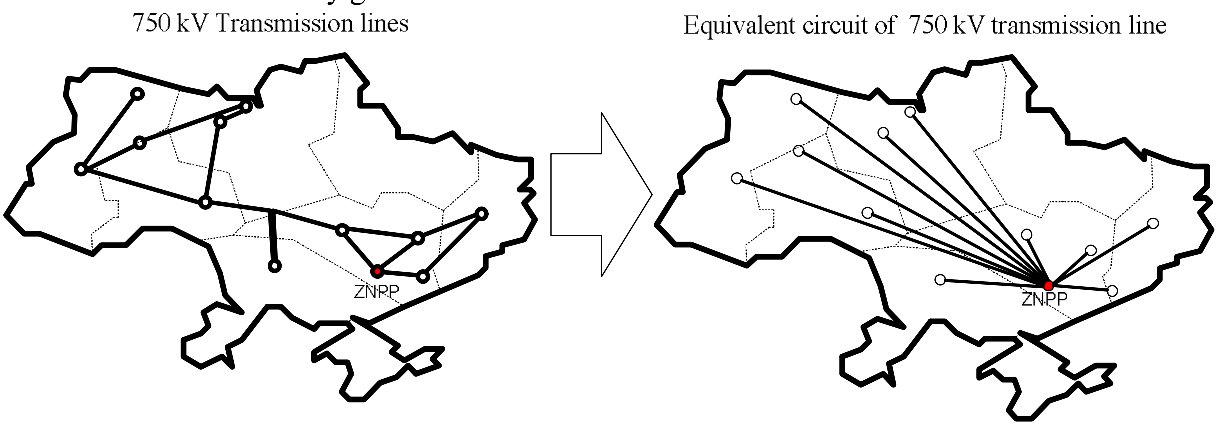

Fig. 5. Electrical distance to the place of imbalance origin at Zaparizhia NPP

Generators, having smaller input resistance relatively the place of disturbance, take greater part of imbalance load. The obtained distribution of load power corresponds to the component $Pprec_i - Pel_i = Pa_i$ of the model (1).

Thus, having determined all the necessary components of dynamic equation, the value of inertia constant of CGG equivalent generator [5, 6] is determined by the dependence (3).

$$H_i = \frac{Pa}{2 \cdot Srated} \cdot \frac{\omega s^2}{\omega r} \cdot \frac{1}{\frac{\partial^2 \delta}{\partial t^2}} \tag{3}$$

where S_{rated} – installed power of CGG equivalent generator [MW]; δ – operating angle of CGG equivalent generator [rad]; ω_r – angular frequency of equivalent generator rotor [rad/s]; ω_s – synchronous angular frequency of equivalent generator rotor [rad/s]; H_i inertia constant of equivalent generator [s].

As it was mentioned above, the rate of EPS frequency change during the first seconds after the disturbance is determined by the value of the stored kinetic energy of the system. The system with high inertia has low rate of change and higher frequency minimum as the systems of primary regulation of turbine frequency have more time for activation. If the frequency is below certain critical level, automatic devices switch renewable sources of energy into autonomous operation, that, in its turn, will lead to further loading of the operation mode, frequency decrease and, in worse case, to system failure. It was determined experimentally [7], that in case of considerable disturbances, increased levels of frequency change rate with increased levels of wind generation, not all the generators (wind and synchronous) could remain in synchronism with the grid (dynamic stability is violated).

Research showed [7], that considerable disturbances in great cluster of wind electric stations (WES) can be caused by switching of WES into autonomous operation, that creates large imbalance of active power in the system. This can lead to more serious failure, if WES are not connected to the network and restore the generation of active power.

Thus, the solution of given problem is either in decreasing frequency change rate or in of speed increase of primary regulators of power. However, decrease of frequency change rate or increase of kinetic energy store of rotating masses is considered as more flexible and economically efficient solution [7].

Inertia response and modeling of system inertia change processes

Rotating parts of the units, connected to EPS, accumulate kinetic energy, that is released during frequency change in the system. Increase of synchronous machine power in the first seconds of transient mode (inertia response) ΔPi is the function of inertia constant, installed power of SM, system frequency and is described by the dependence (4).

$$\Delta P_i = H_i \cdot P_i \frac{\partial f_{sys}}{\partial t} \tag{4}$$

where H_i – inertia constant of j^{th} generator [s]; P_i – installed power of the unit [MW]; f_{sys} - system frequency [e. u.].

If KES in generating unit is not available, for instance, in case of solar power plants, it is necessary to provide inertia response of the unit by means of rapid regulation of active power. Controller, providing IR of the generators without KES, is called the controller of virtual inertia (CVI) [7]. In case of SES, the simplest control law for CVI is differential one, by the value $\frac{\partial f_{sys}}{\partial t}$. If generation powers are lost or in case of sudden increase of the load, the power to provide IR by means of SES, is obtained from spinning reserve for load of power station. Nowadays, networking codes, regulating for RSE automatic support of reserves for loading at preset level, are developed [8]. Reserves for off-loading for solar electric stations [SES] correspond to current power of the station and are used by CVI, for instance, while disconnection of powerful transmission lines, that is equivalent to load loss in EPS. Taking into account the above-mentioned, the structure of differential CVI in the system of SPP control has been developed (Fig. 6).

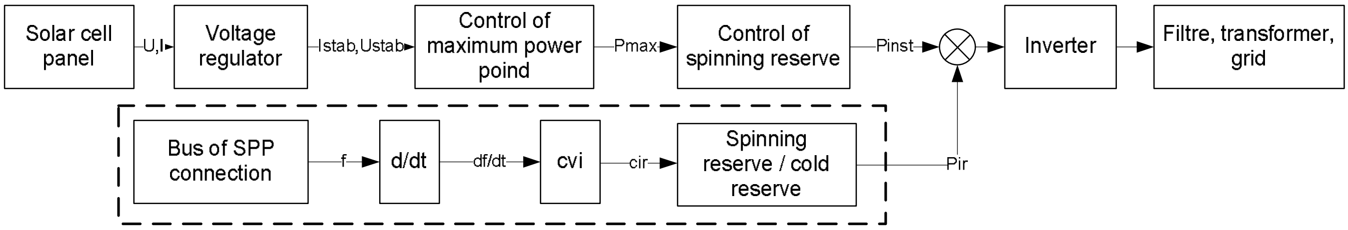

Fig. 6. Differential controller of virtual inertia in the structure of SES

Main parameter, determining the value of CVI IR is the coefficient of virtual inertia k_{vi}, making part of the controller as proportional unit (Fig. 6). Power of inertia response P_{ir} is formed, taking into account the sign $\frac{\partial f_{sys}}{\partial t}$ and available on-line reserves.

For investigation of the character of transient processes while the change of inertia value of PS as a result of substitution of considerable share of synchronous generators by RSE, 4 node test circuit, shown in Fig. 7 is used. All synchronous generators, used in the model, have the same power (100 MW) and inertia constant H_i *(8 s)*, total inertia constant of the network section changed from 32 s (Fig. 7 a) to 16 s (Fig. 7 b).

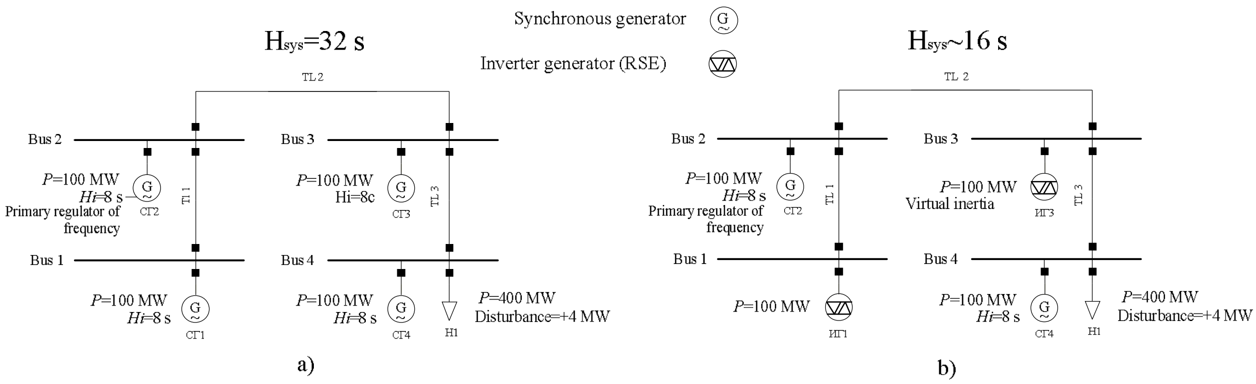

Fig. 7. Test circuit for study the impact of inertia constant on the character of transient process by frequency

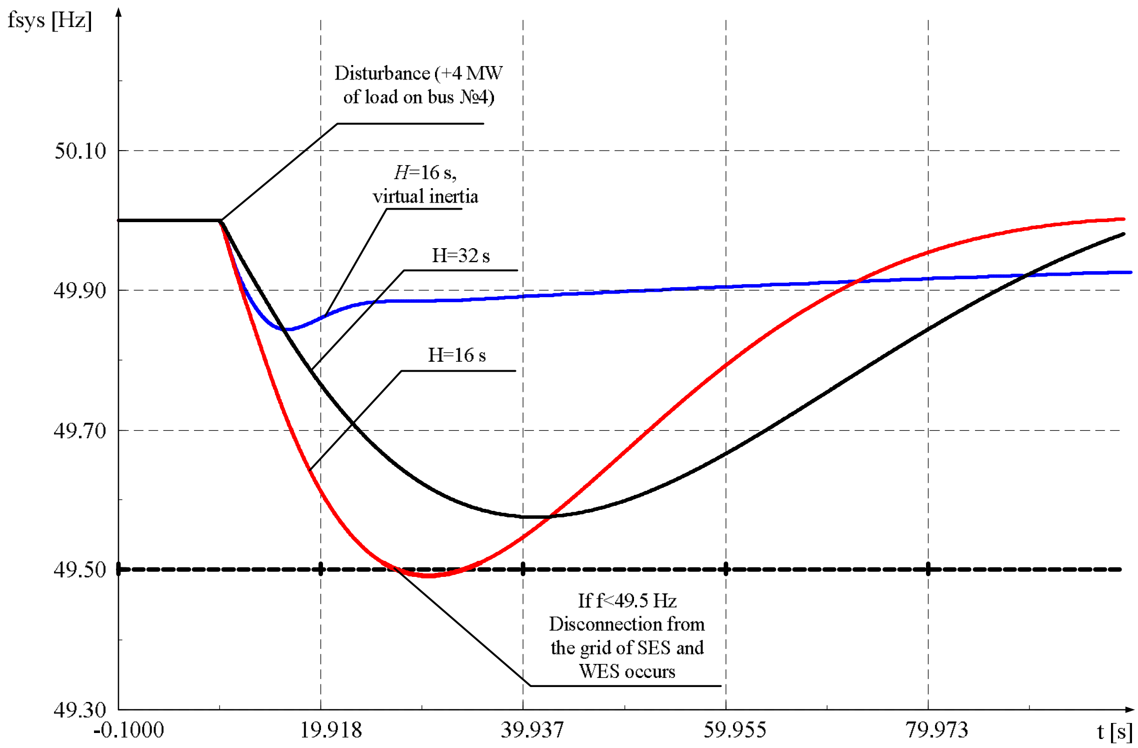

Fig. 8. Results of disturbance simulation on the bus №4 at various inertia constants of the system

Disturbance in EPS was introduced at the bus №4 (+ 4 MW), the results of frequency calculation in transient mode are given in Fig. 8.

The analysis of the obtained results showed considerable change of frequency deviation from 49.56 Hz ($\Delta f = 0.44$ Hz) in case of absence of RSE with inverter connection to the frequency 49.49 Hz ($\Delta f = 0.51$ Hz) if the number of connected synchronous generators is decreased by 50% (with their equivalent replacement for RSE with inverter connection (IG1, IG3)). It is important to note, that according to networking codes of European EPS frequency deviation for more than 0.5 Hz from nominal leads to disconnection of solar and wind power plants from the grid, that may cause deficit of power [8]. When CVI is used frequency deviation decreased 3 times ($\Delta f = 0.159$ Hz), that prevented the disconnection of generating powers.

Conclusions

Method of estimation of kinetic energy store of coherent groups of generators and EPS on the base of SMTP is suggested in the paper. For determination of initial distribution of imbalance it was suggested to use the data of flux distribution graph model, that enables to determine input resistances of EPS generators relatively the place of imbalance origin.

On the example of transient mode data in case of disturbance at Zaporizhia NPP according to SMTP data, filtration of internal oscillations of CGG is carried out, frequency forms of CGG inertia centers of UES of Ukraine are determined.

The research carried out, showed the necessity of solving the problem of decreasing the levels of kinetic energy store of electric power system in case of RSE integration. Further introduction of RSE must be accompanied with the development of efficient methods, aimed to provide inertia response for main types of renewable sources of energy. For RSE with inverter connection the efficiency of CVI usage to provide IR is showed. For optimization of transient process quality by the frequency of IR from CVI must be coordinated with dynamic properties of EPS and operation of already existing system of automatic control.

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