УДК 621.311

ANALYSIS OF ELECTROMECHANICAL OSCILLATION IN THE IPS OF UKRAINE USING EUROSTAG AND DIGSILENT POWERFACTORY SOFTWARE TOOLS

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Poorly damped low frequency oscillations – is one of the most complex and significant problems arising in large-scale power systems. The appearance of such oscillations in the power system can lead to system collapse. In the article the possible low-frequency electromechanical oscillations in IPS of Ukraine have been considered. Analysis was performed for three scenarios: 1 – IPS of Ukraine interconnected with united power system of Commonwealth States, 2 – Ukraine operating in isolated (island) mode, 3 – Ukraine interconnected to ENTSO-E. Research was performed involving real practice software. The poorly damped low frequency inter-area oscillations have been determined and compared for each of the scenarios of IPS of Ukraine. References 10, table 3, figures 9.
Key words: Low-frequency oscillations, small signal stability, methodology of study, interconnected to ENTSO-E.

1. Introduction. Poorly damped low frequency inter-area oscillations are of major concern in operation planning and control of large-scale power systems. In the past decade, many cases of such oscillations have been recorded with the aid of Wide-Area Measurement System (WAMS) technologies [3, 4, 10] and investigated using modern software tools all over the world.

The last recorded incident caused by poorly damped inter-area oscillations in Continental Europe power system occurred in February 2011. Due to the high active power oscillations on the Swiss border tie-lines, Swissgrid has blocked the operation of the Automatic Generation Control (AGC) four times (time windows of about two minutes) [1]. The unexpected interaction among various system controls like AGCs, speed governors, HVDCs, etc. initiated by low frequency oscillations can be extremely dangerous. Therefore, the possible poorly damped oscillations might hazard the system security.

It should be noted that the Ukrainian TSO has never faced with such a phenomenon until today. Unfortunately, there were not significant achievements in practical methods and tools of small-signal stability in traditional “Russian school” of power system analysis. The main attention was paid to study aperiodic steady state (static) stability and transient (dynamic) stability of synchronous machines. An exception case is the oscillation stability described in [2]. However, a very small test system has been used to demonstrate modal analysis techniques in that paper.

Recently, several modern PMUs have been installed and commissioned in IPS of Ukraine [9]. However, no low frequency oscillations have been recorded since that. The possible reason might be in the high damping ratio of inter-area modes in the IPS of Ukraine. Power system operation with quite high stability margin (about 20% for normal condition) contributes for keeping sufficiently damped electromechanical oscillations. However, current market rules push the system operator to operate the power system closer to its stability limits. In such a scenario, the study of inter-area oscillations may be of high importance for the IPS of Ukraine. It should also be taken into account the future plans for synchronously interconnecting the IPS of Ukraine with the ENTSO-E system.

Basically, the power system oscillations study is based on the linear systems and modern control theory. Today, different software vendors that provide various implementations of the mathematical principles and algorithms use different simplifications and assumptions in their tools. Many engineers have different visions on modal technique indices like mode shape, observability, controllability etc. Therefore, the brief theoretical background is presented in this article and it outlines the main steps usually employed in power system small-signal stability analysis.

2. Model and Methodology of study. In this paper, small-signal stability studies are performed for the perspective (2020Y horizon) model of IPS of Ukraine for winter peak load condition. The correspondent overview diagram of IPS of Ukraine is presented at Fig. **1**. Two nuclear units with installed capacity of 1000 MW at Khmelnitska Nuclear Power Plant (NPP), four units at Dnestrovska Pumped Storage Hydro Power Plant (PSHPP) and a large amount of renewable energy sources are planned to be installed before 2020 in Ukraine, which makes this target-year very challenging from the power system stability point of view.

The objective of this study is to assess the possible inter-area oscillation modes for Ukrainian power system in different network configurations in 2020. The local oscillation modes are also computed, but not analysed in details in this study, unless if they indicate system instability.

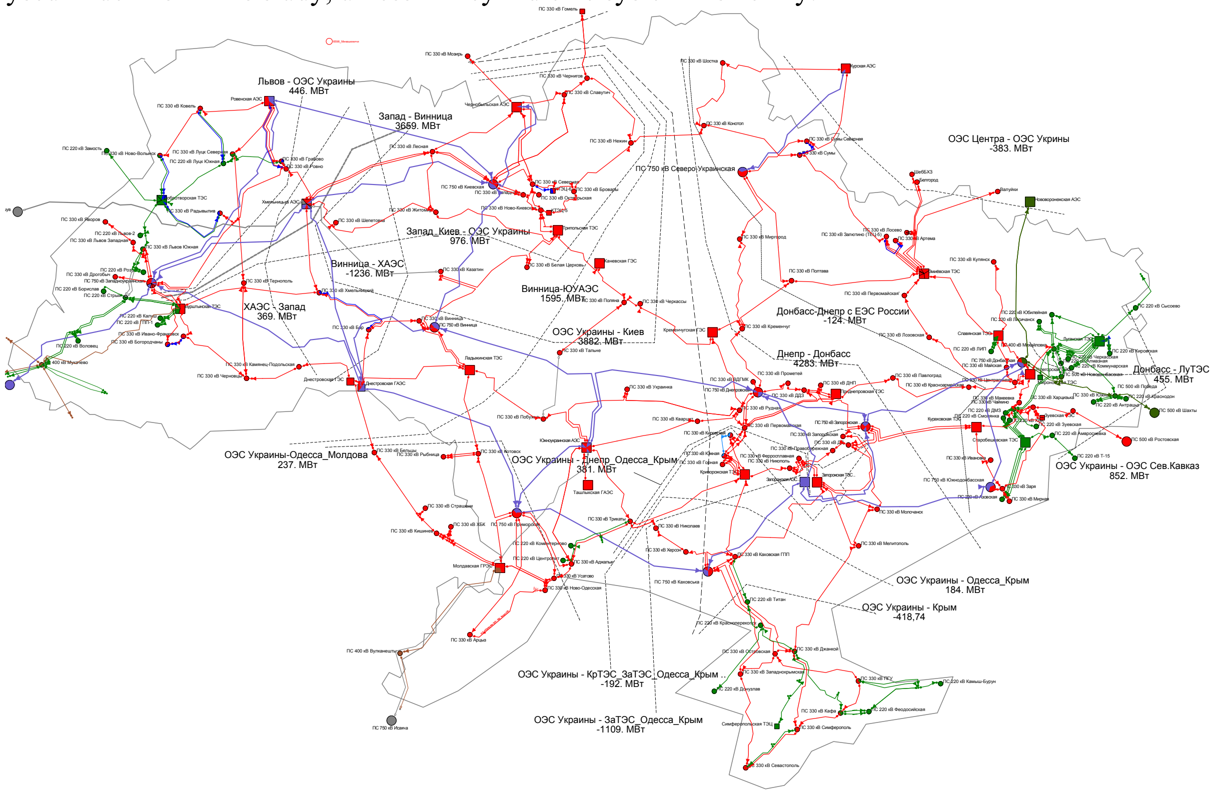

Fig. 1

Taking into account the numerous of development alternatives of the Ukrainian power system, the analysis is carried out for the following network configurations:

i. IPS of Ukraine interconnected with united power system of Commonwealth States;
ii. Ukraine operating in isolated (island) mode;
iii. Ukraine interconnected to ENTSO-E.

It should be noted that such comprehensive study has never been performed for the IPS of Ukraine before. In order to achieve adequate results, proper models of the IPS of Ukraine are needed, especially for the regulations of generating units, including the well-known “strong action automatic excitation regulator with relay forcing action” commonly used in Russian power stations [6].

Another feature of this study is the use of different simulation software, according to the network configuration: DIgSILENT PowerFactory (configurations i and ii) and Eurostag (configuration iii).

3. Theoretical background of small-signal stability analysis. The majority of power system components, such as generators, excitation systems, governors and loads, have nonlinear characteristics. These components and their associated controls may include saturation and output limiters. Despite the fact that nonlinear systems theory can be used to study such a system, this is only applicable for small and simple systems.

On the other hand, the linear systems theory can provide useful insights into the operating behaviour of an interconnected power system. The use of this theory is based on the principle that the dynamic behaviour of the system is linear (or quasi-linear) around an equilibrium point. Fortunately, low frequency oscillations in a power system are fairly linear when caused by disturbances of small magnitude such as random fluctuations of generation and load. The variations in system dynamic variables such as machine rotor angle and speed are also small under these circumstances and the assumption of a linear system model around a given operating point provides valid results. These conclusions are generally consistent with what is observed in the field under similar operating conditions [7].

The advantage of assuming a linear model for the system is that the theory of linear systems is in a mature state, meaning that methodologies, algorithms and tools able to deal with very large systems in reasonable computation time are available.

In power systems, the study of system stability using linear models is commonly referred to as "small-signal stability analysis". This type of study allows the analysis of the so-called steady-state stability. The following types of oscillation modes can be detected and identified through small-signal stability analysis [8]:

- *Local modes*: associated with the oscillations of units at a power station with respect to the rest of the system (oscillation frequency between 1 Hz and 2 Hz). These oscillations are located at one station or a small part of the system.
- *Inter-area modes*: associated with the swing of many machines in one part of the system against machines in the other parts (oscillation frequency between 0,1 Hz and 1 Hz). Caused by two or more groups of coherent (electrically close) machines being interconnected by a weak transmission network.
- *Control modes*: associated with generating units and their controls. The usual causes of instability of such modes are improperly tuned excitation systems, speed governors, HVDC converters and SVCs.
- *Torsional modes*: associated with the rotational components of turbine-generator shaft systems. The usual causes of instability of such modes are interactions with excitation controls, speed governors, HVDC controls, and series-compensated lines.

It must be emphasized that the stability in the small-signal sense is a necessary (but not sufficient) condition for the power system operation. As consequence of not being a sufficient condition, the results of small-signal stability analyses must be assessed through nonlinear time-domain simulations (electromechanical transients simulations).

The following section presents a set of definitions related to linear systems theory and small-signal stability that will be used for the definition of the methodology to be adopted in this study.

3.1 Linear system theory aspects applied to power systems small-signal stability problem. Low-frequency electromechanical oscillations usually range from 0,1 Hz to 3 Hz other than those with sub-synchronous resonance (SSR). multi-machine power system dynamic behaviour in this frequency range is usually represented by a set of nonlinear differential and algebraic equations (DAE) in the form of

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},\mathbf{z},\mathbf{u}), \qquad \mathbf{0} = \mathbf{g}(\mathbf{x},\mathbf{z},\mathbf{u}), \qquad \mathbf{y} = \mathbf{h}(\mathbf{x},\mathbf{z},\mathbf{u}),$$

where **f** and **g** are sets of differential and algebraic equations and **h** is a set of output equations. **x**, **z**, **u** and **y** are vectors of state variables, algebraic variables, inputs and outputs, respectively.

The linearization around an equilibrium point and Gaussian elimination of the algebraic variables of this system of nonlinear DAEs results in a linear system in the form of

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}, \qquad \mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}.$$

3.1.1 Eigenvalues and oscillation modes. The eigenvalues (λ_i) of the state matrix (A) characterize the dynamic behaviour of the linearized system. These eigenvalues may be real or complex numbers. Complex eigenvalues always occur in conjugate pairs $\lambda_i = \sigma_i \pm j\omega_i$.

The eigenvalues of the state matrix correspond to the system modes (oscillation mode, if λ_i is complex). The real part (σ) relates to the mode damping and the imaginary part ($\pm j\omega$) relates to its oscillation frequency.

The relationship between the eigenvalues and the system stability is defined by the absolute stability criteria, which follows [7]: "A system is stable according to the absolute stability criteria if all eigenvalues of the system are located in the left semi-plane of the complex plane (all eigenvalues must have negative real parts)".

The analysis of the eigenvalues indicates the damping level and the oscillation frequency of the modes. The requirement for minimum damping level varies from system to system (usual criteria is to assume a minimum damping ratio of 5% [8]). The oscillation frequency of a mode, in Hertz, is given by

$$f_i = \omega_i / 2\pi .$$

The damping ratio of a mode is given by $\zeta_i = -\sigma_i(\sigma_i^2 + \omega_i^2)^{-1/2}$.

3.1.2 Eigenvectors and mode shapes. In power systems literature, the right eigenvector associated to an eigenvalue λ_i is known as the mode shape of λ_i. The mode shape provides valuable information on the participation of a given state variable in a particular mode. It allows the identification of the participation of an individual machine or a group of machines in a particular mode.

The mode shapes are very useful for the identification of coherent groups of machines, as well as for the identification of inter-area modes.

3.1.3 Participation factors. In large power systems it is important to quantify the role of each generator on each mode. A method generally employed for this purpose is the computation of the participation factors for each mode. The participation factor is a measure of the relative participation of the *k*-th state variable on the *i*-th mode, and vice-versa.

The participation factor of a state variable in a given mode is calculated by means of combining the left and right eigenvectors associated to that mode. Through this combination it is possible to produce a dimensionless index, which is essential when comparing state variables of different physical units.

Through the calculation of the participation factors it is possible to determine the machines that have more contribution to a given oscillation mode. The generators with highest participation factor on poorly damped low frequency modes are potential candidates for installing a power system stabilizer (PSS).

A drawback of the participation factors is that they relate only to the state and do not take into account the input/output (I/O) relationship. Therefore, it cannot effectively identify a controller site and an optimal feedback signal without information on the most adequate input and output when feedback control is employed. The effectiveness of control can be indicated through controllability and observability factors, as described in the following.

3.1.4 Modal controllability and observability. Considering the linearized dynamic system given by

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}, \qquad \mathbf{y} = \mathbf{Cx},$$

where **x** is the system state vector, **u** is the input vector and **y** is the output vector.

Denoting by $\mathbf{\Phi}$ the matrix where each column is a right eigenvector of **A** then the change of variable $\mathbf{z} = \mathbf{\Phi x}$ leads to the following system:

$$\dot{\mathbf{z}} = \mathbf{\Lambda z} + \mathbf{\Phi}^{-1}\mathbf{Bu}, \qquad \mathbf{y} = \mathbf{C\Phi\, x},$$

where $\mathbf{\Lambda}$ is a diagonal matrix composed by the eigenvalues of **A**, one can see that:

- If the *i*-th row of $\mathbf{\Phi}^{-1}\mathbf{B}$ is not null, then it is possible to control the *i*-th mode through the control **u**. If there are different potential controls (**u** is a vector), then the different elements of the *i*-th row give indication on which inputs have the largest impacts on the *i*-th mode.
- If the *i*-th column of $\mathbf{C\Phi}$ is not null, then it is possible to observe the *i*-th mode trough the output **y**. If there are different potential observers (**y** is a vector) then the different elements of the *i*-th column give indication on which output provides the more information on the *i*-th mode.

This means that the controllability of the input signal and the observability of the feedback signal are basic requirements for PSS allocation.

4. Methodology for small-signal stability analysis. The first step for the small-signal stability analysis is the linearization of the power system dynamic model around a given operating condition. The linearized system is then used to compute the following parameters:

- System eigenvalues and eigenvectors (both right and left);
- Participation factors;
- Controllability and observability indices.

4.1 Identification of inter-area and critical oscillation modes. Critical oscillation modes are defined as modes with low damping level (a cigré "task force" on electromechanical oscillations in power systems recommends a minimum damping of 5%). the identification of critical oscillation modes starts by the computation of the system eigenvalues. as the power system model is very large, the computation of all system eigenvalues through orthogonal decomposition-based methods (i.e. qr factorization) is not recommended due to the large computational time and memory usage required by these methods [5].

In this study, the method used for eigenvalue calculation is based on the calculation of all eigenvalues within a predefined region of the complex plane (Arnoldi method) [5]. This region is defined by the user and must comprise the modes with oscillation frequency up to 3,5 Hz and damping ratios at least up to 35%. This guarantees the calculation of all critical electromechanical modes of the system, as well as the inter-area modes.

The result of eigenvalues computation is a table containing all information related to the modes: real and imaginary parts, damping ratio and oscillation frequency.

4.2 Critical modes are identified as the ones whose damping ratio is less than 5%. Inter-area modes are pre-identified by selecting the modes whose frequency lie in the range between 0,1 Hz and 1 Hz. To get the final decision on which modes are in fact inter-area modes a second step is needed: analysis of the mode shapes, which is explained in the sequel.

4.3 Participation factor and mode shape analysis. The goals of participation factor and mode shape analysis are twofold:

Identify the machines associated to the critical oscillation modes (analysis of participation factors);

Identify the inter-area modes within the modes with frequency between 0,05 Hz and 2 Hz.

4.4 Analysis of participation factors. The participation factors provide an indication of the contribution of the machines in a given mode. This is very useful for identifying the machines that have major contributions to the critical modes as well as to the inter-area modes.

In this study, the participation factors of all modes classified as critical (ζ < 5%) in the eigenvalue computation phase are calculated and analysed in order to provide indications on which machines have most participation on the critical modes.

4.5 Analysis of mode shapes. As previously described, the mode shapes give the relative magnitude and phase of the oscillations as seen from a given state variable. Since the objective of this project is to analyse electromechanical oscillations, the rotor speed or angle must be chosen as state variable.

In this study, the mode shapes of all oscillation modes with frequency between 0,05 Hz and 2 Hz are calculated and analysed in order to identify all inter-area modes. After the identification of these modes, their respective damping ratios are carefully analysed. In case of poorly damped inter-area modes, the necessary measures to improve the damping are recommended.

4.6 Determination of candidate machines for avr retuning aiming at improving oscillation damping. In case of the presence of critical inter-area modes, the identification of the candidate machines for avr parameters retuning is performed.

The choice of the machine and the input signals to be used for the improving the damping of critical modes is not straightforward. It depends on the calculation of the controllability and observability indices.

In this study, if any critical inter-area mode is detected at a certain operating condition, the necessary recommendations for AVR parameters retuning are given.

5. Study cases. All simulations related to the scenarios "i" and "ii" are performed in DIgSILENT PowerFactory, while the simulations for the scenario "iii" are performed in EUROSTAG.

5.1. IPS Ukraine interconnected with united power system of Commonwealth States. The results of small-signal stability analysis for this scenario show that there exist two main inter-area modes, as presented in Table 1.

Table 1

Mode	Real part	Imaginary part	Damping Ratio [%]	Oscillation Frequency [Hz]	Characterization of the Mode
"Ukr-Rus"	-0,172	±3,196	5,360	0,509	Ukrainian PS vs Russian PS inter-area mode
"North-South"	-0,2259	±4,002	5,636	0,637	Zaporizhs'ka NPP, Juzhno-Ukrainskaja NPP vs Khmelnitska NPP, Rovenskaya NPP, Kurskaya NPP (rus), Smolenskaya NPP (rus) inter-area mode

To detail these inter-area oscillations and to check the correction of our result, the time domain simulation has been performed. Figure 2 presents results of time-domain simulations that clearly depicts the "Ukr-Rus" inter-area mode. The oscillation frequency taken from the time domain simulation results (1/T = =1/ 1,933 = 0,517 Hz) is very close to the value obtained in the small-signal stability analysis (0,509 Hz).

Figure 3 presents results of time-domain simulations that clearly depicts the "North-South" inter-area mode. The oscillation frequency taken from the simulation results (1/T = 1/1,561 = 0,640 Hz) is very close to the value obtained in the small-signal stability analysis (0,637 Hz).

5.2. Isolated operation of the IPS Ukraine. The results of small-signal stability analysis for "Isolated operation of IPS of Ukraine" show that there are two main inter-area modes, as presented in Table 2.

Table 2

Mode #	Real part	Imaginary part	Damping Ratio [%]	Oscillation Frequency [Hz]	Characterization of the Mode
"North-South"	-0,3250	±5,3884	6,020	0,858	North vs South inter-area mode
"East-West"	-0,2564	±3,5618	7,179	0,567	East vs West inter-area mode

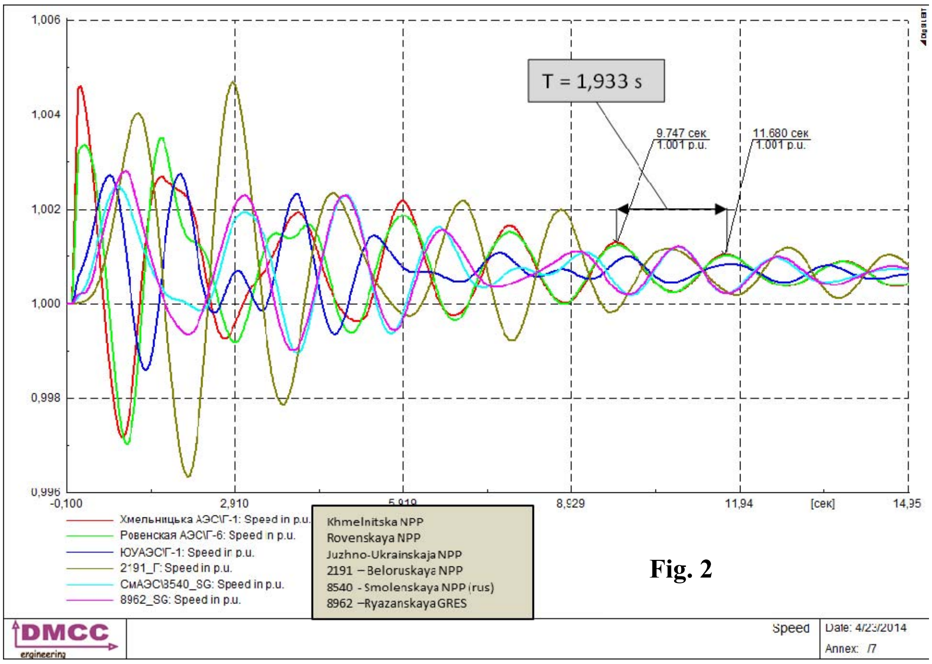

Fig. 2

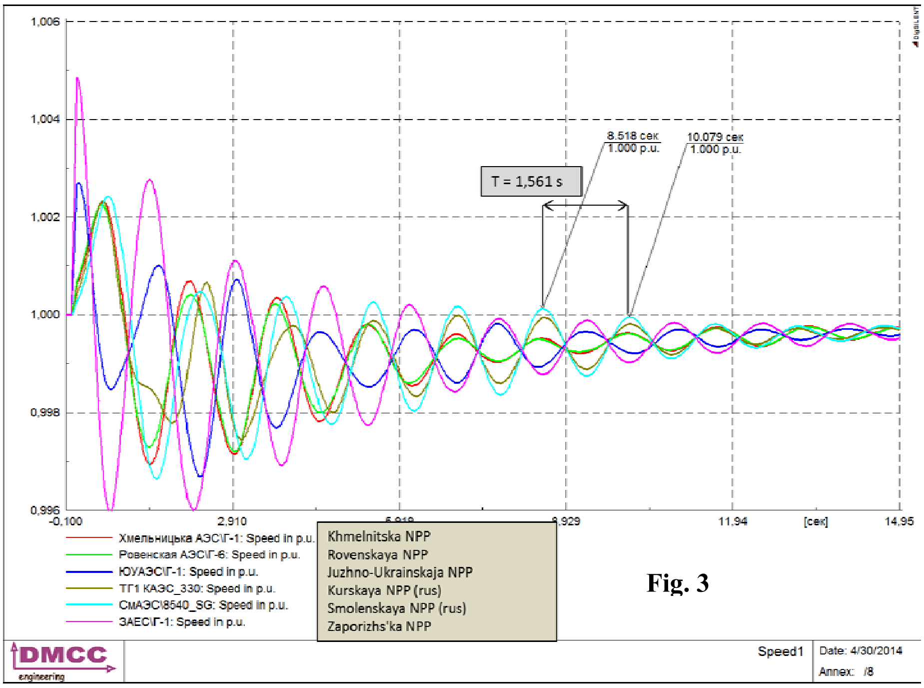

Fig. 3

Figure 4 presents results of time-domain simulations that clearly depicts the "North-South" inter-area mode. The oscillation frequency taken from the simulation results (1/T=1/1,154=0,867 Hz) is very close to the value obtained in the small-signal stability analysis (0,858 Hz**).**

Figure 5 presents results of time-domain simulations that clearly depicts the “East-West” inter-area mode. The oscillation frequency taken from the simulation results (1/T = 1/1,744 = 0,573 Hz) is very close to the value obtained in the small-signal stability analysis (0,567 Hz**).**

5.3. IPS Ukraine interconnected with ENTSO-E. The results of small-signal stability analysis for this scenario show that there exist two inter-area modes, as presented in Table 3.

Table 3

Mode #	**Real**	**Imaginary**	**Damping Ratio [%]**	**Oscillation Frequency [Hz]**	**Characterization of the Mode**
1	-0,3623	±1,7088	20,739	0,272	Ukraine x ENTSO-E inter-area mode
2	-0,1671	±3,8123	4,379	0,607	East x West inter-area mode

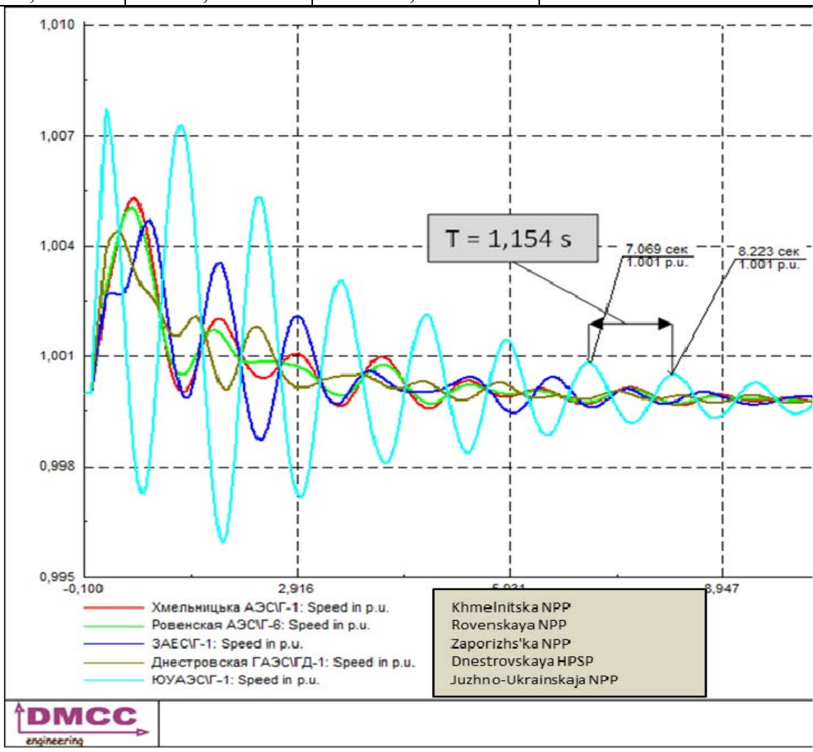

Fig. 4

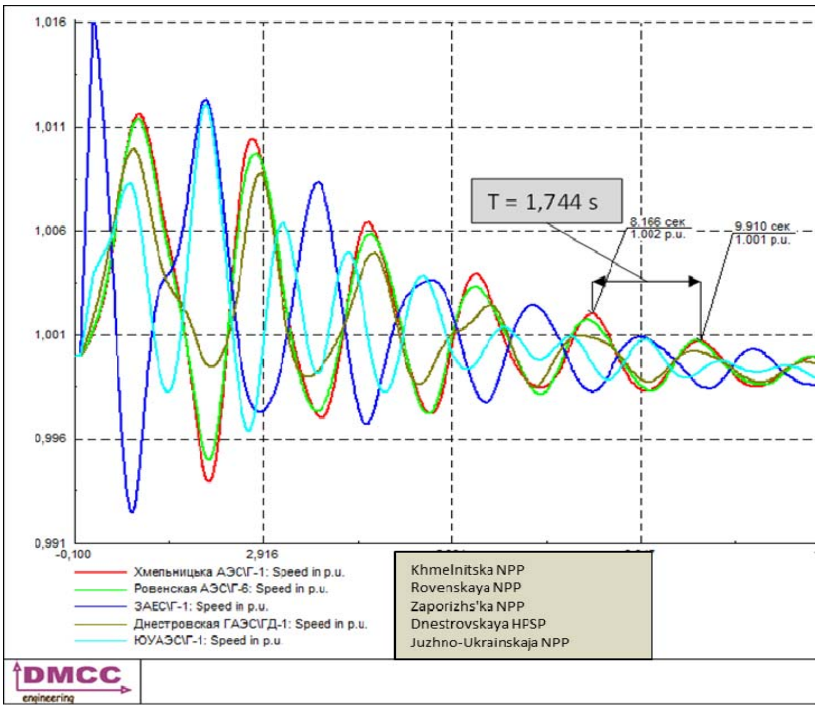

Fig. 5

Mode 1 is an inter-area mode associated to the machines of the Ukrainian system oscillating against the machines of the ENTSO-E system. Figure 6 shows the mode shape plot for this mode. It clearly depicts the phase opposition between the ENTSO-E system equivalent machine and the coherent group of machines of the Ukrainian system. For this mode, the oscillation frequency is equal to 0,272 Hz and the damping ratio is about 20,7%, which is considered an adequate damping ratio for an inter-area mode.

Mode 2 is an inter-area mode associated to the machines of the Western part of the Ukrainian power system oscillating against the machines of the Eastern part of the system. Figure 7 shows the mode shape plot for this mode. It clearly depicts the phase opposition between the Eastern and Western groups of machines. For this mode, the oscillation frequency is equal to 0,607 Hz and the damping ratio is about 4,4%.

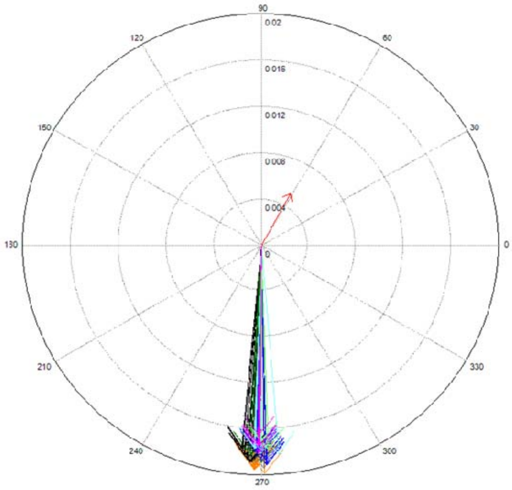

Fig. 6

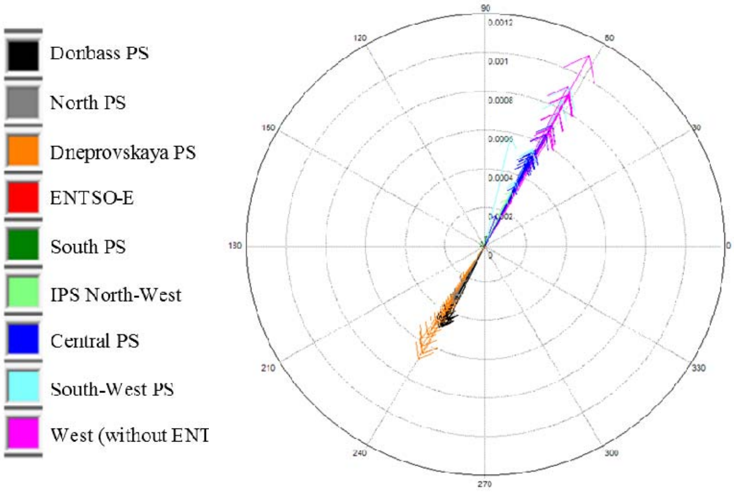

Fig. 7

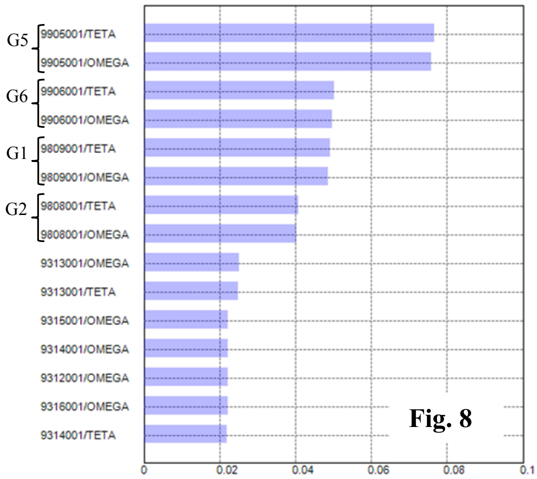

Fig. 8

This inter-area mode is considered as insufficiently damped.

Figure 8 shows the participation factors for "Mode 2". The machines with major contribution to this oscillation mode are Rovenskaya AES (G5 and G6) and Khmelnitska (G1 and G2). The analysis of controllability and observability indices indicates that this mode is more effectively observable and controllable through the machines G5 and G6 of Rovenskaya NPP. It is then recommended to retune the parameters of the AVR system of these two machines in order to improve the damping of this inter-area mode. Attention has to be taken on tuning this AVR system ("Strong Action Automatic Excitation Regulator - SAAER") because of its particular structure, which does not allow the employment of classical PSS tuning methods to retune the AVR parameters. It is worth noticing that retuning AVR systems to improve damping of inter-area modes is out of the scope of this study.

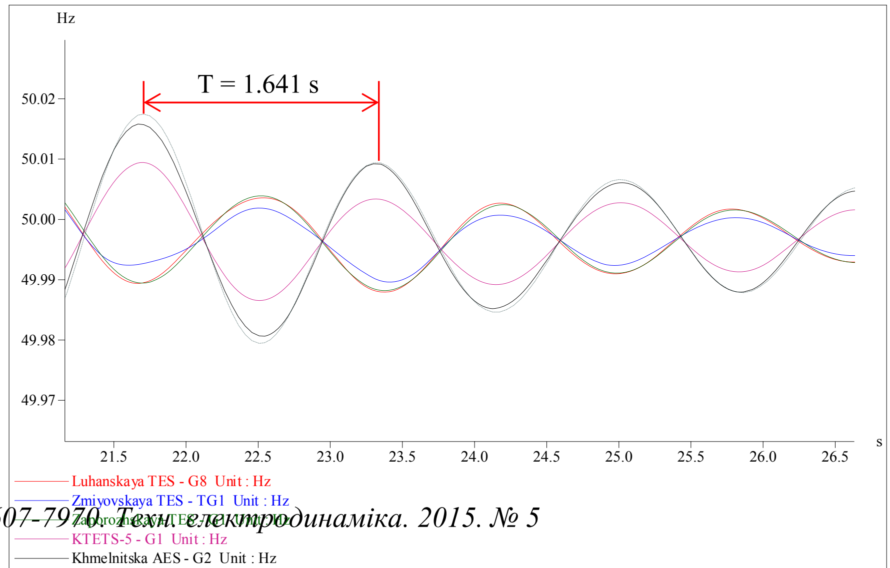

Fig. 9

Figure 9 present results of time-domain simulations that clearly depicts the East-West inter-area mode.

The oscillation frequency measured on the simulation results (1/T=1/1,641=0,609 Hz) is very close to the value obtained in the small-signal stability analysis (0.607 Hz**).**

6. Conclusion

Small-signal stability analysis has been performed for the interconnected power system of Ukraine for time horizon of 2020Y. The oscillations have been identified for three different scenarios of power system operations: "IPS of Ukraine is interconnected with UPS of Commonwealth State", "Isolated operation of IPS of Ukraine" and "IPS of Ukraine is interconnected with ENTSO-E system". The small-signal stability analysis for the first and second scenarios has been performed using DIgSILENT PowerFactory software tool, while the simulation for the third scenario has been carried in EUROSTAG.

There are two inter-area modes in the first operating scenario with damping ratios of about 5% (5,35% and 5,64%) and low oscillation frequencies (0,51 Hz and 0,64 Hz). The first mode is associated to the machines of the Ukrainian power system oscillating against the machines of the Russian power system. The second mode is associated to the machines Southern part oscillating against the machines of the Northern part of the Ukrainian system.

In the second scenario the last mentioned oscillation mode (machines of the Southern part oscillating against the machines of the Northern part of the system) is slightly different. The damping ratio increases (from 5,64% to 6,02%) and frequency of oscillation is also increased (from 0,64 Hz to 0,86 Hz). In addition to that, in this scenario another inter-area mode has been identified. This mode is associated to the machines of the Eastern part of the system oscillating against the machines of the Western part (damping ratio equal to 7,18% and oscillation frequency of 0,57 Hz).

For the scenario "IPS of Ukraine interconnected with ENTSO-E system", also two inter-area modes are identified. The first one is associated to the machines of the Eastern part of the Ukrainian power system oscillating against the machines of the Western part, whose damping ratio is lower than 5% (oscillation frequency equal to 0,61 Hz). Further investigation aiming at improving the damping of this mode is recommended, but is outside of the scope of this paper. The second mode is related to the machines of the Ukrainian system oscillating against the machines of the ENTSO-E system. This mode has a very low oscillation frequency (0,27 Hz) and is well damped (damping ratio equal to 20,7%).

The results of this small-signal stability analysis show necessity of preventing measure for damping oscillations in inter area mode within Ukraine for scenario of parallel operation with ENTSO-E system. In addition, it should be noted that same additional study is advisable to perform after validation/calibration of Ukrainian power system dynamic model.

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УДК 621.311

АНАЛІЗ ЕЛЕКТРОМЕХАНІЧНИХ КОЛИВАНЬ В ОЕС УКРАЇНИ З ВИКОРИСТАННЯМ ПРОГРАМНИХ ЗАСОБІВ EUROSTAG ТА DIGSILENT POWERFACTORY

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Низькочастотні коливання потужності – це одна із найбільш складних і значних проблем, які виникають у великих енергооб'єднаннях. Поява таких коливань у енергосистемі може призвести до розвитку системних аварій. У статті розглянуто можливі електромеханічні низькочастотні коливання в ОЕС України. Аналіз виконано для трьох сценаріїв роботи: 1 − паралельна робота ОЕС України з енергооб'єднанням ЄЕС Росії/ Білорусії, 2 − ізольована від енергосистем сусідніх країн робота ОЕС України, 3 – паралельна робота ОЕС України з ENTSO-E. Дослідження виконані із залученням перевірених на практиці програмних засобів. За результатами проведених розрахунків було визначено небезпечні, погано демпфовані моди коливань для кожного із сценаріїв роботи ОЕС України та проаналізовано, як ці моди можуть змінюватися в залежності від сценарію роботи ОЕС України. Бібл. 10, рис. 9, табл. 3.

Ключові слова: низькочастотні коливання, розрахунки, коливна стійкість, методика розрахунку, інтеграція до ENTSO-E.

УДК 621.311

АНАЛИЗ ЭЛЕКТРОМЕХАНИЧЕСКИХ КОЛЕБАНИЙ В ОЭС УКРАИНЫ С ИСПОЛЬЗОВАНИЕМ ПРОГРАММНЫХ СРЕДСТВ EUROSTAG И DIGSILENT POWERFACTORY

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Низкочастотные колебания мощности – это одна из самых сложных и серьезных проблем, которые возникают в больших энергообъединениях. Появление таких колебаний в энергосистеме может привести к развитию системных аварий. В статье рассмотрены возможные электромеханические низкочастотные колебания в ОЭС Украины. Анализ выполнен для трех возможных сценариев работы: 1 − параллельная работа ОЭС Украины с энергообъединением ЕЭС России / Белоруссии, 2 – изолированная от энергосистем соседних стран работа ОЭС Украины, 3 – параллельная работа ОЭС Украины с ENTSO-E. Исследования выполнены с привлечением проверенных на практике программных средств. По результатам проведенных расчетов были определены опасные, плохо демпфированные моды колебаний для каждого из сценариев работы ОЭС Украины и проанализировано, как эти моды могут изменяться в зависимости от сценария работы ОЭС Украины.
Библ. 10, рис. 9. табл. 3.

Ключевые слова: низкочастотные колебания, расчеты, колебательная устойчивость, методика расчета, интеграция в ENTSO-E.

Надійшла 19.06.2015