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Power Systems Oscillations Damping with Regard the Finite Speed of Propagation the Electromechanical Waves

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Abstract: Damping of the power system electromechanical oscillations with magnitude-phase excitation controller (*MPH-EC*), which is responsive to the deviations of the magnitude and phase of the terminal voltage phasor, and taking into account the finite speed of propagation the electromechanical waves, caused perturbation the power balance are considered in this paper. The structure of an integrated excitation control system of synchronous machines (*IECS SM*) using a remote phasor measurement units (*PMU's*) to identify the cross-sections (tie lines) of electromechanical oscillations and putting into operation the function of power system stabilizer, installed on the revealed cross-sections of electromechanical oscillations has been proposed. A significant advantage of the proposed method and technology of damping the low-frequency electromechanical oscillations in the power system is its selectivity in relation to the main modes, with the lowest damping ratio, making the greatest contribution to the development of the power system instability, due to the action of the optimal number of *MPH-EC* located taking into account the given grid topology.

Keywords: Power System, Synchronous Generator, Terminal Voltage Phasor, Automatic Voltage Regulator, Power System Stabilizer, Synchrophasor Vector Processor, Mode of Electromechanical Oscillation

1. Introduction

The major blackouts in large extended power systems of the world occurred in the recent past [1] show the need to continue work on the development, as a mathematical model of occurring transients, and practical applications to ensure safe, reliable and efficient operation of the interconnected systems. Contributes to this goal recently active development of remote measurement, monitoring, protection and control systems: *WAMS* - wide area measurement system, *WAPS* - wide area protection system, *WACS* - wide area control system, *WAMPC* - wide area monitoring, protection, and control system [2-4], which are based on phasor measurement unit (*PMU*). At the same time, currently with sufficient hardware development of the above systems, the main obstacle to their further development is the lack of control algorithms based on the use of phasors measurements [4].

Application of the above systems in the United States [3, 5-7] allowed the practice to reveal the existence of electromechanical wave's propagation in the power system with a finite speed, much less than the speed of electromagnetic waves propagation. Experiments with load shedding, conducted in the United States [5] revealed a delay of about *0.5 s* with the measured values of the frequency in the transient (with the help of *PMU*) between the nearest and remote power system buses. This is allowing estimating the propagation speed of the electromechanical waves about *500-1000 km/s*, as a much smaller compared to the speed of electromagnetic waves, depending on the tie lines parameters and the inertia of synchronous generators. Distribution of electromechanical waves in the event of disturbances in the power system is not considered as a classical model of electromechanical oscillations of synchronous machines in a power system, and the development of protection and control. At the same time, accounting of this physical phenomenon, and the use of remote measurement systems (*WAMPC*) allow, as shown in the paper, to develop an integrated excitation control system of synchronous machines (*IECS SM*), revealing the cross-sections of electromechanical oscillations (*CSEO*), and the selective introducing the function of power system stabilizer on the synchronous machines, located in the *CSEO*. This allows us to suppress the main electromechanical oscillation modes, with the lowest damping ratio, that make the greatest contribution to the development of the instability of the power system. Thus, an effective damping of electromechanical oscillations and better dynamic properties of the power system is attained by the action of an optimal amount of *ECS SM*, located with account the grid topology.

This paper presents the sections with the following contents. In the *second section* consider the main existing models of electromechanical wave propagation in large power systems. The key assumptions used in these models and it main conclusions are given. The attention is focused on the applicability of the obtained results for the development of *IECS SM*. S*ection three* presents the main elements of *WAMPC*. The structural and functional diagrams of this system are presented. Discussed in detail the synchrophasor vector processor *(SVP)*, those obtain the input data from *PMU's*. *SVP* provides the calculation of *CSEO* with the subsequent formation of the necessary control signals to *ECS SM* for damping the most dangerous electromechanical modes. In the *fourth section*, we consider a block diagram and the algorithm of *IECS SM* with magnitude-phase excitation controller *(MPH-EC)*, which receives the control signals from *SVP*. In the *fifth section* shows an example the design of *IECS SM* for 6-machines power system model, in which we investigate the static and dynamic stability of the *SM*. In the *conclusions* summarizes the main points and results of this paper.

2. Main Provisions of the Existing Models of Electromechanical Wave Propagation in Large Power Systems

Operating experience has revealed that the perturbations in the large extended power systems caused by an imbalance of power consumption and generation propagate with finite speed. Obviously, the speed boundedness of electromechanical waves propagation in the power system with values *500-1000 km/s*, much lower than the speed of electromagnetic wave propagation, was identified with the use of *PMU's*, synchronized in time with the help of global positioning system *GPS* [2, 5-7]. This fact is not reflected in the classical theory of electromechanical oscillations, based on ordinary differential equations (*ODE*) the motion of synchronous machine rotor, depending only on the time [8, 9]. Therefore, the models, that describe the motion of the synchronous machines rotors depending on the time, and the spatial coordinates, based on partial differential equation (*PDE*) have been developed [6, 7, 10-12]. These models are based on the representation of the basic parameters of the power system as continuous variables, distributed in a certain spatial coordinate system. For example, defined by the distributed inertia of synchronous machine rotor per unit length. Directly homogeneous model of power system for study the electromechanical wave propagation represented as a grid of connected nodes, shown on Figure 1:

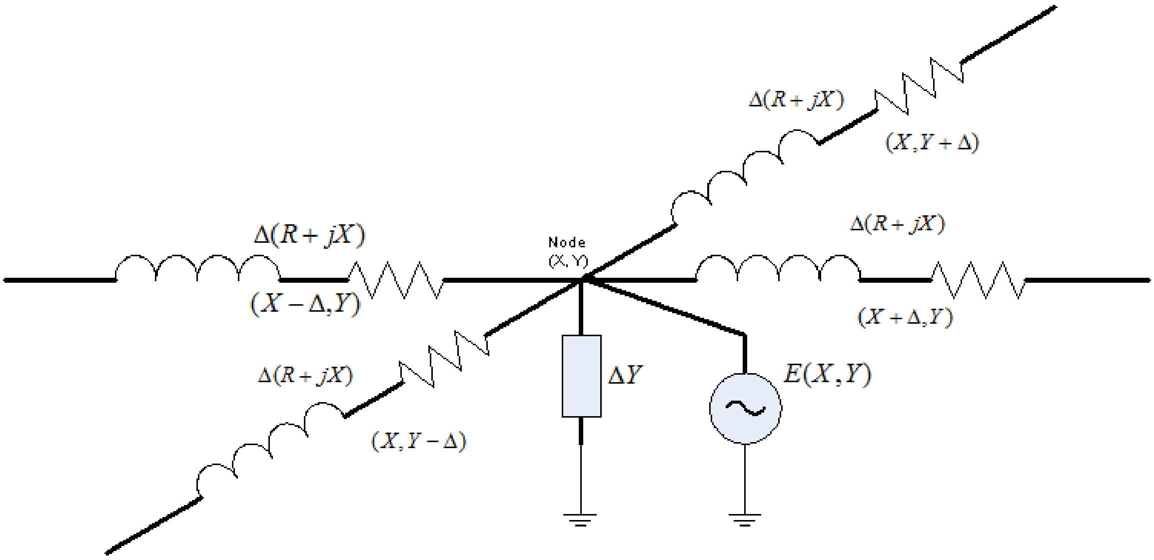


Figure 1. *Diagram of simulated grid node with the coordinates (X, Y).*

Each node can be modeled in two-dimensional space *(X, Y)* of grid coordinate system, that characterized by a certain constant voltage $E(X,Y)$ with phase δ and conductivity ΔY. At displacement Δ relative to the given node along the selected axes *(X, Y)* parameters of transmission lines linking it with other nodes receive an increment $\Delta(R+jX)$. Connecting a set of nodes (Figure 1) in ring, was examined the physical processes of electromechanical wave propagation in the event of disturbances in the homogeneous 64-machines power system model [6, 7, 10-12]. In equation of motion the synchronous machine rotor:

$$\frac{2H}{\omega}\ddot{\delta}+\omega D\dot{\delta}=P_m-P_e=P_a\,, \qquad (1)$$

where H - inertia constant, *s*, ω - angular rotor speed of *SM*, *rad/s*, D - damping coefficient, s^2, P_m, P_e, P_a - mechanical, electrical, and accelerating power, *p. u.* In equation (1) its parameters are also considered as distributed parameters that depend on the spatial coordinates *(X, Y)*:

$$H \to \Delta h(X,Y), D \to \Delta d(X,Y),$$
$$P_m \to \Delta p_m(X,Y), P_e \to \Delta p_e(X,Y), P_a \to \Delta p_a(X,Y) \quad (2)$$

Passing to the limit $\Delta \to 0$, the equation (1) reduces to the form [6]:

$$\ddot{\delta} + \gamma\dot{\delta} - v^2\nabla^2\delta + u^2(\nabla\delta)^2 = P \quad (3)$$

where

$$v^2 = \frac{\omega V^2 \sin\Theta}{2h|z|}, u^2 = \frac{\omega V^2 \cos\Theta}{2h|z|}, P = \frac{\omega\left(P_m - GV^2\right)}{2h},$$
$$\gamma = \frac{\omega^2 d}{2h}, z = R + jX, G = \mathrm{Re}[\Delta Y], \nabla = \frac{\partial}{\partial X}\vec{i} + \frac{\partial}{\partial Y}\vec{j}$$

Equation (3) is a hyperbolic wave equation of 2nd order in partial derivatives.

Local frequency measured on the tie line or any bus of power system is defined as:

$$f = f_0 + \frac{1}{2\pi}\frac{d\delta}{dt}, \Delta f = f_0 - f = -\frac{1}{2\pi}\frac{d\delta}{dt} \quad (4)$$

Accordingly, when the electromechanical wave passes through the *PMU* location (the bus of power system, tie line, etc.), a local phase angle of the voltage in this location will vary depending on the time. The velocity of electromechanical wave propagation, and accordingly the phase angle change in the local voltage in this location depend on the magnitude voltage, power system frequency, inertia of synchronous machines, and impedance of tie lines. For the above homogeneous model of grid in the form of a ring was determined the speed estimate of electromechanical wave propagation:

$$v^2 = \frac{\omega_0 V^2 \sin\Theta}{2h|z|}, \quad (5)$$

where ω_0 - power system nominal frequency, V - voltage magnitude, Θ - phase angle of the tie line impedance ($\Theta \approx 90^\circ \to \sin\Theta \approx 1$), h - inertia constant per unit length, z - impedance of the tie line per unit length.

In the above power system homogeneous model the spatial distribution the inertia constant of *SM,* and the impedance of tie lines (links) along the coordinate axes *X-Y* assumed to be identical. The orientation of branches, connecting the nodes determined 0^o or 90^o with respect to the chosen coordinate system *X-Y*. In a heterogeneous power system model for study the electromechanical waves propagation the distributions of parameters (inertia constants, tie lines impedances, and others), as well as the spatial arrangement of branches relative to the selected coordinate system is assumed to be arbitrary. For this model in [12], the electromechanical wave in power system described by a system of equations similar to the telegraph equations:

$$\frac{\partial^2\omega(x,t)}{\partial t^2} = \frac{1}{m(x)}\frac{\partial}{\partial x}\left[b(x)\frac{\partial\omega(x,t)}{\partial x}\right],$$
$$\frac{\partial^2 p(x,t)}{\partial t^2} = b(x)\frac{\partial}{\partial x}\left[\frac{1}{m(x)}\frac{\partial p(x,t)}{\partial x}\right] \quad (6)$$

where $m(x)$ - inertia constant, *p. u.*, $b(x)$ - susceptance of tie lines per unit length, *p. u.*, $\omega(x,t)$ - angular rotor velocity, *p. u.*, $p(x,t)$ - electric power, *p. u.*, x - 1-dimensional spatial coordinate. This system of equations for $\omega(x,t) = \Omega(x)e^{j\overline{\omega}t}$, $p(x,t) = P(x)e^{j\overline{\omega}t}$ where $\Omega(x), P(x)$ - complex functions, has an analytical solution:

$$\omega(x,t) = \Omega_0(x_0)\sqrt{\frac{v(x)}{v_0(x)}} \cdot \exp\left[j\overline{\omega}\left(t \mp \int_{x_0}^{x}\frac{1}{v(\xi)}d\xi\right)\right],$$
$$p(x,t) = P_0(x_0)\sqrt{\frac{v(x)}{v_0(x)}} \cdot \exp\left[j\overline{\omega}\left(t \mp \int_{x_0}^{x}\frac{1}{v(\xi)}d\xi\right)\right] \quad (7)$$

where $v(x)$ - speed of electromechanical wave propagation.

Effective damping of power system oscillations can be significantly improved if the algorithms of power system stabilizers will take into account the limitation of speed (5) of distribution the electromechanical waves (and hence the delay) in the event of disturbances to determine the optimal impacts of *ECS SM*. The following section describes the main elements of *WAMPC* system, necessary for the solving given problem.

3. Wide area Measurement, Protection and Control System

Currently, the synchronized phasor measurements have been widely used in power systems around the world for checking the accuracy of developed power systems models, transient analysis, and parameters estimation in real time. However, the synchrophasor measurements are still significant untapped potential to provide a safe, reliable and economic operation of power systems by it control taken into account the phase relations between their operation mode parameters, which can be measured and processed in real time. Synchrophasor measurement based on the use of *PMU*. For communication between *PMU's* and their top-level devices using protocol by standard *IEEE C37. 118* [13]. Processing of synchrophasor measurements and their use for controlling includes the next steps:

1. Sending the synchrophasor measurements data from *PMU*;
2. Time coordination for received synchrophasor measurements data taking into account the delays in each of the communication channels;

3. Perform the vector complex mathematical operations for processing synchronized data;

4. Perform the programmed logic operations based on the synchrophasor measurements data;

5. Formation and sending the control commands to the corresponding output relay, or control unit of power system in a time short period to ensure control in real time.

Block diagram of the power system control in real time using synchrophasor measurement data is shown in Figure 2:

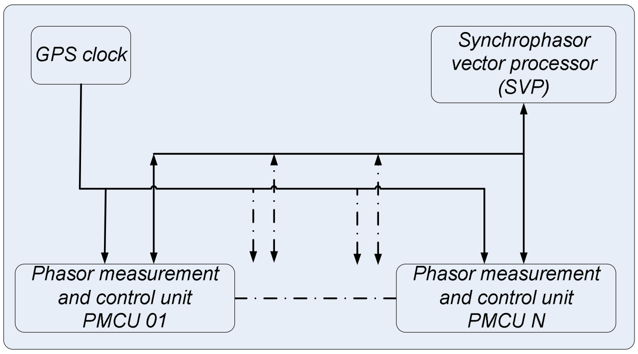


Figure 2. *Block diagram of real time synchrophasor power system control.*

Task of synchrophasor vector processor (*SVP*) [3, 14] is to collect data from *PMU's*, reception of digital input signals from the protection relays and system automation, the implementation of vector and scalar calculations, the formation of the control signals, and sending them to the actuating elements, recording and archiving of power system data in transients. For example, one of the *SVP* tasks may be collect data from *PMU's*, established at the tie line ends, the comparison of the voltage phase angles at its ends, and the forming the alarm, and control signals to reduce the active power flow above a certain critical value.

An important issue to ensure the correct control of the power system in real time, using the synchrophasor measurement data, is accuracy of the time measurement. So, for example, one electrical degree (*1º el.*) for frequency *50 Hz* corresponds to the time interval in *55.5 µs*. Therefore, the error in the time measurement, approximated to *10-20 µs*, may be considered acceptable. Working with such small time intervals for processing the synchrophasor measurement data defines the requirements for the data transmission. Considered as acceptable the speed that determines at least one packet data transmission over the period. In some cases the use of a serial data transmission protocol at speed 9600 bit/s answered for these requirements. For applications requiring higher data rates need to use the *Ethernet protocol*, or similar. A block diagram of the *SVP* inputs-outputs shown in Figure 3. [3]:

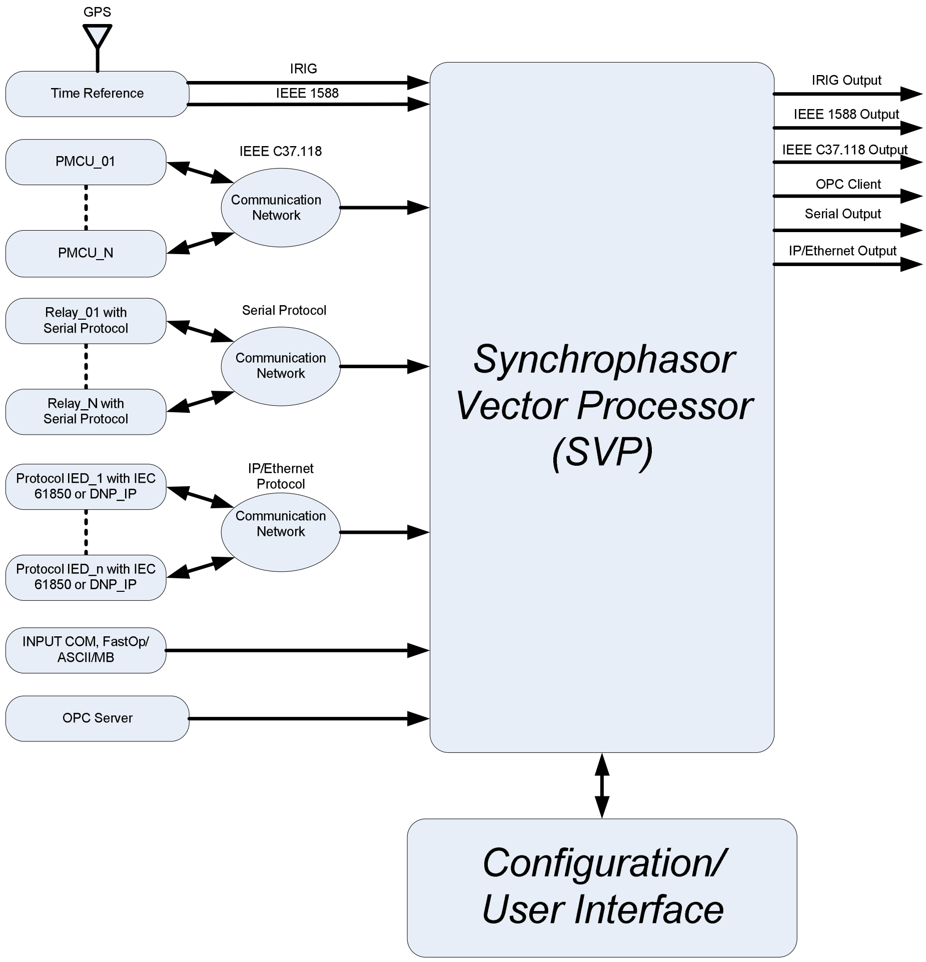


Figure 3. *SVP Input/Output Block Diagram.*

The appointment of *SVP* inputs and outputs described in [3, 14]. Software *SVP* based on the standard *IEC 61131-3*, which includes the functions for performing matrix and complex calculations, can be used for the following tasks:

1. Monitoring the dynamics of the power system states by calculating the difference between the voltage phasors angles in its main reference points (buses), the slip frequency, and acceleration in order to predict the state of the angular grid instability.

2. Modal analysis in real time based on synchrophasor measurements data for identification the undamped electromechanical oscillation modes in order to perform the necessary compensation actions to prevent violations of the power system stability. One of these actions can be coordinated excitation control of synchronous machines using *SVP* determining the cross-sections of electromechanical oscillations (*CSEO*), as will be discussed below.

3. Develop and implement a differential buses protection, covering several switching power supply system to ensure the maximum performance and selective clearance of faults.

4. Identification and compensation the data measurement error from *PMU's*.

Next, consider the hardware functional block diagram of the *SVP* [3, 14], is shown in Figure 4.:

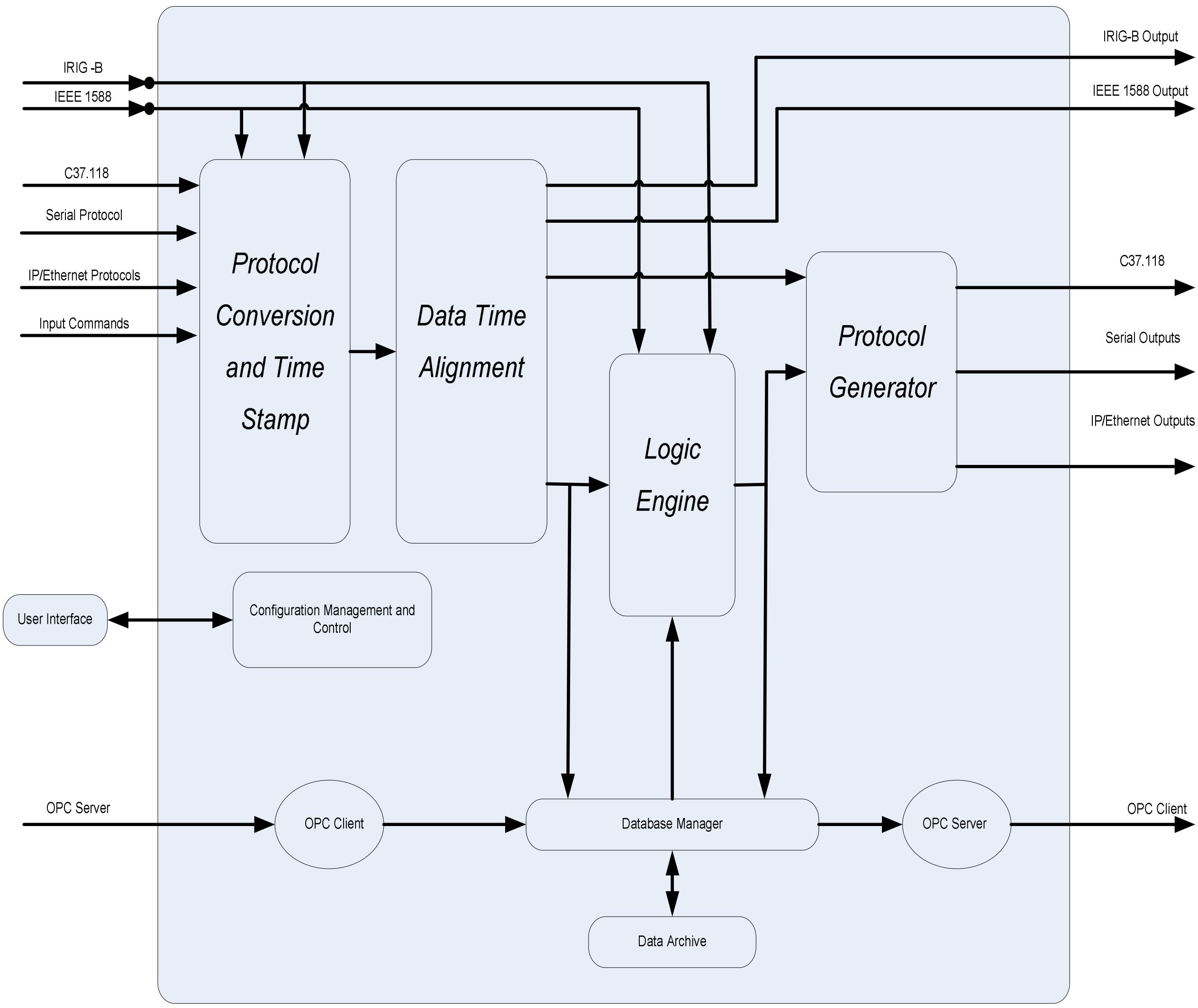


Figure 4. *SVP Hardware Functional Block Diagram.*

The main elements of *SVP* are [3]:

- *Protocol Conversion and Timestamp.* This block translates *IEEE C37.118*, serial data, IP/Ethernet protocols, and input commands into a common data format/structure. For protocols that do not support time information, a timestamp for the data is added. Examples of protocols that do not have time information are *Modbus*, and *SEL Fast Message*. IEEE protocols such as *C37.118, IEC 61850*, and *SEL Synchrophasor Fast Message* already have a timestamp.
- *Data Time Alignment.* Data may be measured at the same time but delayed during communication. The Data Time Alignment block correlates data blocks based on time to compensate for unequal communications delays.
- *Logic Engine.* The Logic Engine is a soft-core programmable logic controller (*PLC*) with vector and

complex math capabilities. Data inputs to the Logic Engine are from the Data Time Alignment block. The Logic Engine can also access the Database Manager to retrieve stored data, as required for logic processing.

- *Protocol Generator*. Outputs from the Logic Engine are sent to the Protocol Generator. It converts the results into appropriate protocols such as *IEEE C37.118, DNP3 LAN/WAN, Modbus RTU, SEL MIRRORED BITS* communications, *SEL Fast Message*, etc.
- *Database Manager*. The Database Manager interfaces to the Data Time Alignment block and the output of the Logic Engine. The Database Manager formats data for storage, performs the *OPC* Client query, and provides *OPC* Server responses. It also provides data to the Logic Engine for use in control algorithms.
- *OPC Client*. The *OPC* Client performs *OPC* requests for data as defined by user setting or the Logic Engine.
- *OPC Server*. The *OPC* Server serves data to external *OPC* clients. The data may be raw data from the Data Time Alignment block, Logic Engine, or Data Archive block.
- *Configuration Manager and Control (CMC)*. The *CMC* provides a user interface to configure the various communications inputs, Logic Engine algorithms, communications output format configurations, database management, and other various configuration duties.

As mentioned above, an object of the *SVP* is fast execution of mathematical operations by complex vectors for control of the power system mode. For it the computation cycle should not exceed one period of the frequency. Algorithmic functional diagram of *SVP* shown in Figure 5:

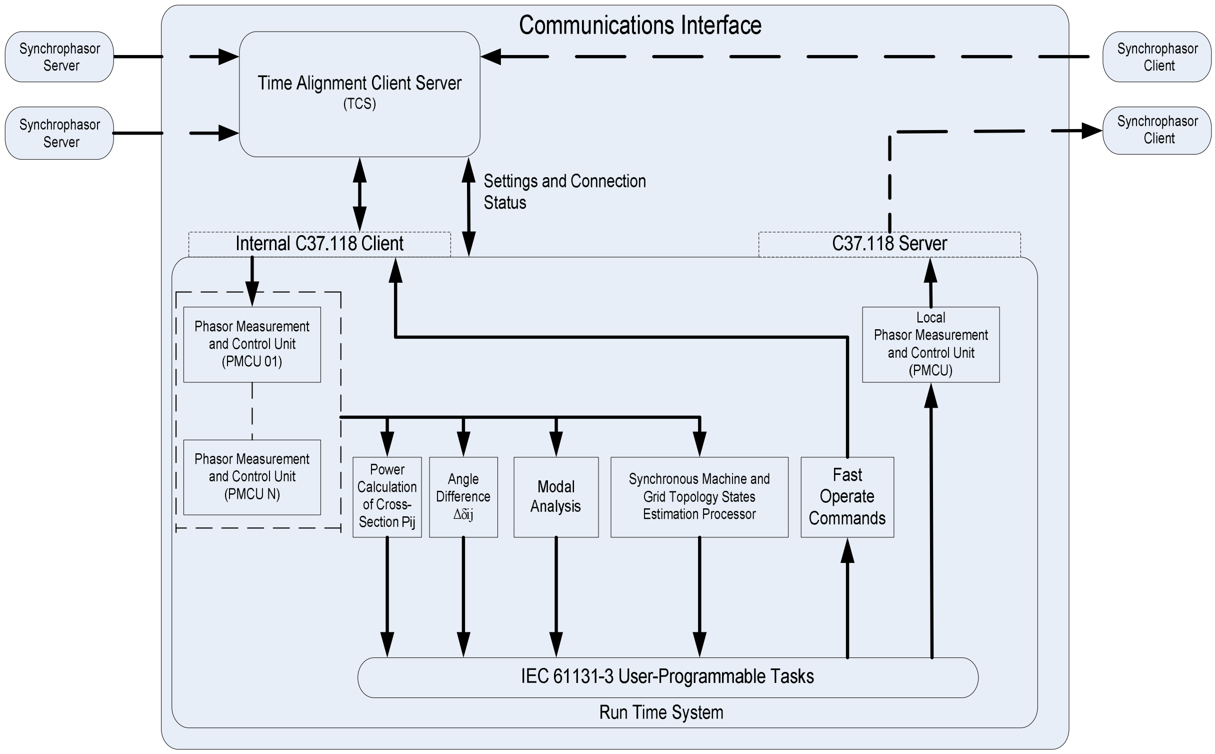


Figure 5. *SVP Algorithmic Functional Block Diagram.*

In addition to the above given hardware functional block diagram of the *SVP* in this figure marked the following algorithmic function blocks, that can be modified or expanded:

- *Power Calculation*: the calculation of active P and reactive Q power using the voltage $\overline{U}$ and current $\overline{I}$ phasors.
- *Monitoring of Phase Angle Difference*: the calculation of the phase angle difference for voltage phasors between two points (buses) of controlled grid, and forming alarm when it exceeds a predetermined value for a given cross-section to prevent angular instability.
- *Modal Analysis (MA)*: the calculation in real time the parameters of the observed electromechanical oscillation modes, based on data received from the *PMCU's*.
- *Synchronous Machine and Grid Topology States Estimation Processor*: receiving information from the previously mentioned algorithmic function blocks, this processor calculates the integral state of a synchronous machine with regard to its stability, thermal and vibration conditions, work of power system automation, limiters (*OEL* – overexcitation limiter, *UEL* – underexcitation limiter, etc.), and generates the control inputs to *ECS SM* and turbine controller. One of these actions may be the control of power system stabilizer (*PSS*) of *ECS SM*, using *SVP* that defining the cross-sections of electromechanical oscillations (*CSEO*), enable or disable

them from working on corresponding synchronous machines. It is thus possible to provide an integral selective stabilizing effect of *PSS*, mounted on all *ECS SM*.

- *Formation of output signals and commands*: *SVP*, using fast protocols and communication cannels, sends commands to the remote and local control devices of the power system (such as *ECS SM*, turbine controllers, compensators, shunt reactors and other).

As an example of the modern *SVP*, can be considered the unit *SEL-3378* [14], manufactured by Schweitzer Engineering Laboratories (*USA*). This *SVP* provides for the collection of information from 20 *PMU's* with all the above mentioned protocols for data transfer, the transfer of control commands and processing of algorithmic problems, except for the above-described the processor for synchronous machine and grid topology states estimation.

In concluding this section, it should be noted that the implementation of such a control principle is based on the previously discussed concepts, defining the electromechanical oscillations as electromechanical wave in power system, having a finite, and a much lower speed of propagation compared with an electromagnetic wave.

4. Damping of Low-Frequency Electromechanical Oscillations in the Power System Using a Complex "*PMU's – SVP – ECS SM*"

Using devices *PMU's* and *SVP*, taking into account the finite speed propagation of electromechanical waves, allows to execute a modal analysis of emerging electromechanical oscillations in the power system in real time. Identifying the dangerous oscillation modes, and ways of their distribution is possible optimally provide the necessary control actions (signals) for their damping.

The traditional approach to prevent and damping of electromechanical oscillations in the power system is based on the modal analysis (*MA*) implementation, studying the dynamic properties of the grid model at the stage of it design (not in real time). The inaccuracy of the constructed grid model, and therefore a reflection of its dynamic properties, the inability to complete the modeling of all perturbations and modes of operation that may occur in the power system, limited the method of *MA*. Using the *PMU's* and *SVP* is possible to identify and optimally dampen the electromechanical oscillations in real time, due to selectively chosen *ECS SM* for the identified cross-section(s) of power system oscillations. For it in *SVP* used the algorithm of modified Prony analysis (*MPA*). At the core of the *MPA* is the superposition principle by which the initial measurement signal (phasor voltage, current, power, or another physical quantity) is replaced by a linear combination of a set of exponential oscillation modes in a finite time interval. To sample the measured data $\{x[1], x[2], \ldots x[N]\}$ *MPA* estimates the value $\hat{x}[n]$ accordingly both for $1 < n < N$ [3]:

$$\hat{x}[n] = \sum_{m=1}^{M} A_m e^{\sigma_m (m-1)T} \cos(2\pi f_m (m-1)T + \varphi_m) \quad (8)$$

where:

T - sampling interval, *s*;
A_m - amplitude of m^{th} exponential function, *p. u.*;
σ_m - damping constant for the m^{th} exponential function, s^{-1};
f_m - frequency, *Hz*;
φ_m - initial phase, rad.;
M - number of modes.

An important parameter that determines the objectivity of the calculations is the *SNR* – "signal-to-noise ratio":

$$SNR = 10\log_{10}\left(\frac{\sum_{n=0}^{N} x^2[n]}{\sum_{n=0}^{N} (x[n] - \hat{x}[n])^2}\right) \quad (9)$$

Since *MPA* is based on a linear superposition of the modes, it has a low *SNR*, if the sample data contain the results of nonlinear perturbations (for example, the on-off generators or loads, tie lines, or the like). The *SNR* has a sufficient value *(~ 80 dB)*, if the disturbances of this kind are not included in the reporting sampling interval, corresponding to the mode of the following electromechanical oscillations in the power system.

Electromechanical oscillations (waves) in the power system can be observed in the parameters deviations of the operation mode, such as bus voltage V_i, the difference of buses voltage angles δ_{ij}, flows of active ΔP and reactive ΔQ power in tie lines. In *MA* used the synchrophasor measurements data as input signals. As result, *MA* determinates the main existing (or observed by *MPA*) electromechanical oscillation modes, and their value *SNR*. Each detected mode of electromechanical oscillations characterized by a structure which is based on the following key parameters [3]:

1. Amplitude of mode A_m (named or relative units of corresponding physical parameter);
2. Frequency of mode f_m, *Hz*;
3. Damping constant σ_m, s^{-1};
4. Damping ratio ς_m, *p. u.* or *%*;
5. Initial phase of mode φ_m, ^{o} or *rad*.

The damping ratio ς_m calculated from the known values damping constant σ_m and frequency f_m:

$$\varsigma_m = \frac{-\sigma_m}{\sqrt{\sigma^2{}_m + (2\pi f_m)^2}} \quad (10)$$

The negative value of the damping ratio ς_m (positive damping constant σ_m) characterizes that the corresponding mode leads to an instability the power system. Since the *MPA* uses a numerical approximation (8), the calculated values of the observed frequencies of the modes in various places of the grid may be different at frequency main, most dangerous mode of the electromechanical oscillation. Therefore, to identify a common system mode of electromechanical oscillation, that must be dampening primarily, used a predetermined threshold Π deviation of frequency i mode from the average frequency value f_m of observed electromechanical oscillation modes:

$$f_m = \frac{\sum_{i=1}^{M} f_i}{M} \tag{11}$$

SVP calculates the total electromechanical oscillation mode, if the difference between the calculated average value of the frequency f_m and the frequency f_i i mode is less Π :

$$|f_m - f_i| \leq \Pi \tag{12}$$

In accordance with the above, in *SVP* is implemented the logic unit for detection, and damping the dangerous mode of electromechanical oscillations in the power system, Figure 6. [3]:

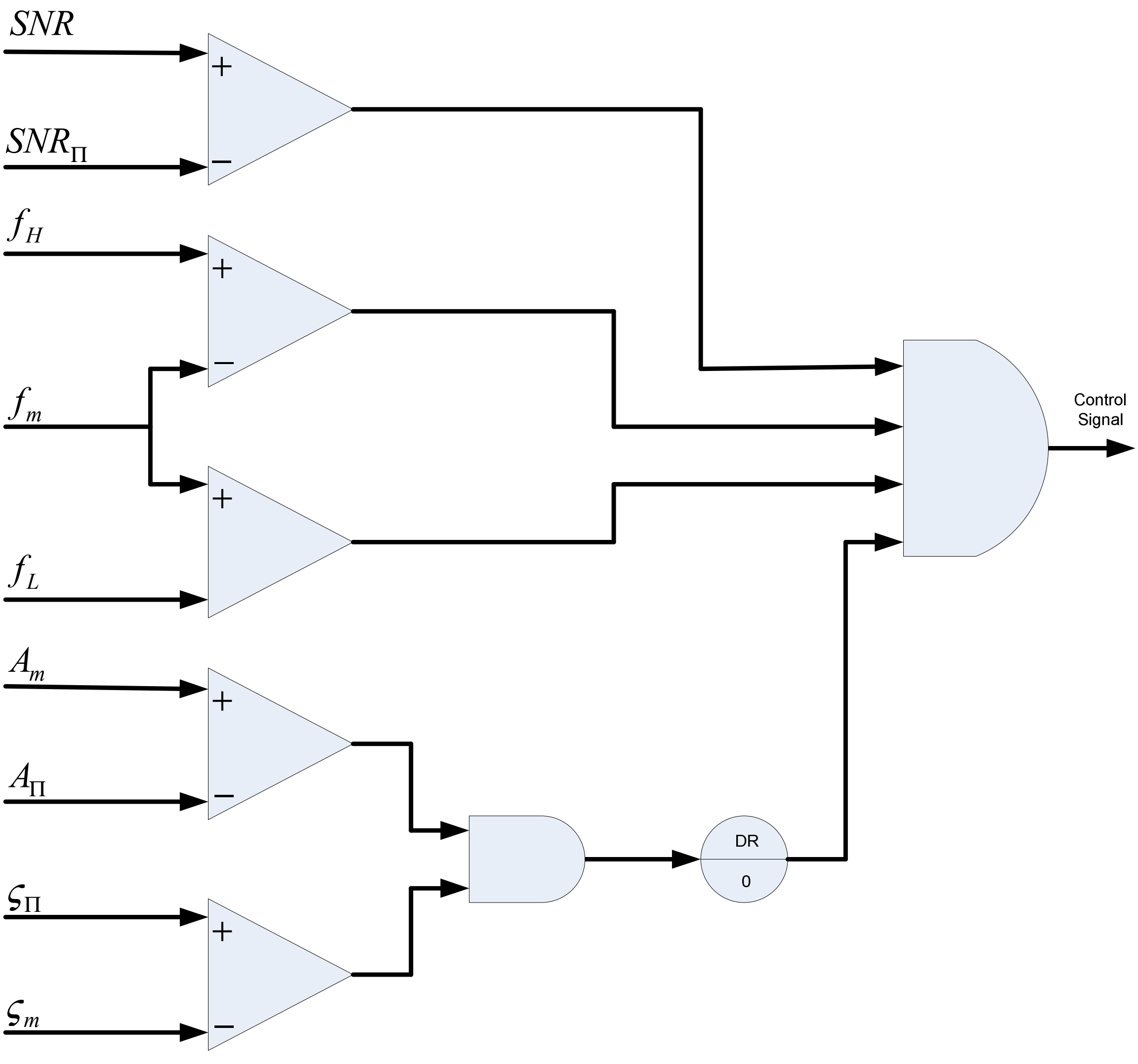


Figure 6. *Logic unit for the detection and damping of dangerous mode of electromechanical oscillations in the power system.*

For generating a control signal from the *SVP* to *ECS SM* must satisfy the following conditions (Π - lower index for a given threshold):

- "Signal – to – noise" ratio $SNR > SNR_\Pi$;
- The upper f_H and lower f_L values define a predetermined frequency range of electromechanical oscillation typical for given power system. The frequency of the observed dangerous mode $f_L \leq f_m \leq f_H$;
- If the structure of observed mode of electromechanical oscillation with frequency f_m is characterized by the parameters: amplitude $A_m \geq A_\Pi$, and damping ratio (*DR*) $\varsigma_m \leq \varsigma_\Pi$, control signal from *SVP* activates the power system stabilizers in those *ECS SM*, which are located at the buses of power system, connectable the

CSEO.

Let us now consider how to ensure optimum damping effect of low-frequency electromechanical oscillations in the power system using the complex *"PMU-SVP-ECS SM"*. To solve the problems of voltage regulation and damping of electromechanical oscillations in *ECS SM* used the structure of magnitude-phase excitation controller (*MPH-EC*) [15-17]. Block diagram of the proposed complex *"PMU-SVP-ECS SM"* is shown in Figure 7:

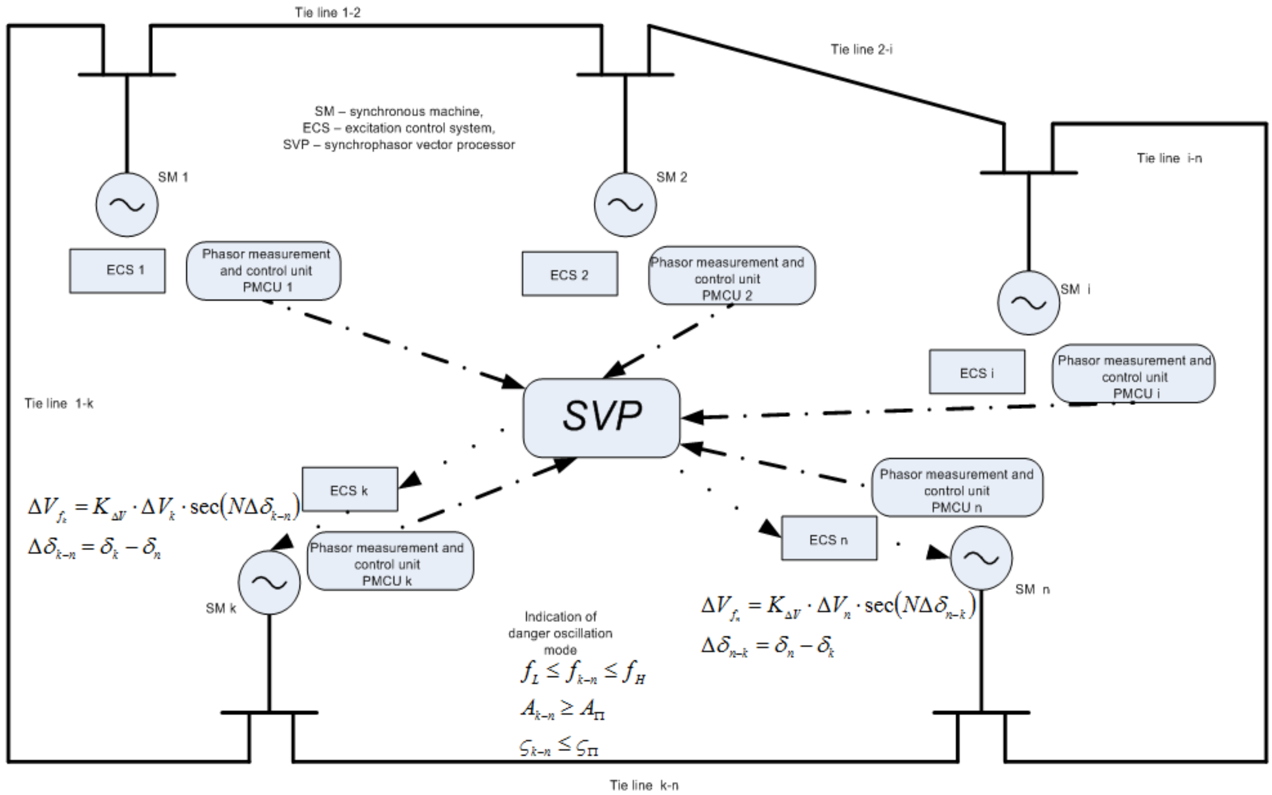


Figure 7. *Damping of low-frequency electromechanical oscillations in the power system through an integrated excitation control system of synchronous machines (IECS SM) "PMU – SVP – ECS SM".*

SVP, using the information from *PMU's*, determines the cross-section (-s) of power system in which it extends a dangerous for the stability electromechanical oscillation mode, assume this cross-section $k-n$ as shown in Figure 7. For it cross-section detects the conditions:

$$f_L \le f_{k-n} \le f_H, \quad A_{k-n} \ge A_\Pi, \quad \varsigma_{k-n} \le \varsigma_\Pi \tag{13}$$

In determining the conditions (13), *SVP* generates the control signals for *ECS SM*, connected to the k th and n th buses of power system, connected the cross-section $k-n$ (this can be one or more tie-lines). When receiving these control signals in *ECS SM*$_k$ and *ECS SM*$_n$ introduced the power system stabilizers from the angles deviations at the ends of the cross-section in accordance with the law of *MPH-EC*:

$$\Delta V_{f_k} = K_{\Delta V} \cdot \Delta V_k \cdot \sec(N\Delta\delta_{k-n}), \Delta\delta_{k-n} = \delta_k - \delta_n, \quad \Delta V_{f_n} = K_{\Delta V} \cdot \Delta V_n \cdot \sec(N\Delta\delta_{n-k}), \Delta\delta_{n-k} = \delta_n - \delta_k, \tag{14}$$

or gain N changes to enhance the action on angles deviations $\Delta\delta_{k-n}, \Delta\delta_{n-k}$.

A significant advantage of the proposed method and technology of damping the low-frequency electromechanical oscillations in the power system is its *selectivity* in relation to the main modes, with the lowest damping ratio, making the greatest contribution to the development of the power system instability, due to the action of the optimal number of ECS SM, located taking into account the given grid topology.

5. Example of Construction the Integrated *ECS SM* to Study the Steady-State and Transient Stability

To estimate the stability and dynamic properties of multi-machine power system with integrated *ECS SM* consider a model of 6-machine system, Figure 8:

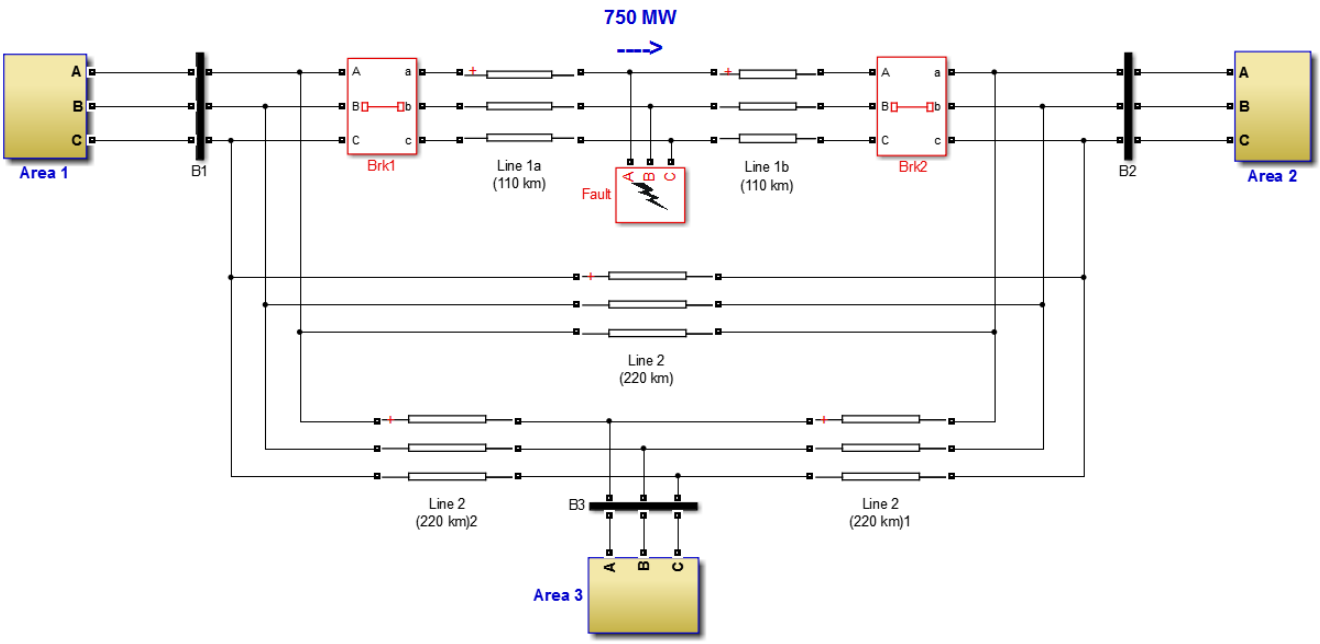


Figure 8. *6-machine power system model.*

In each of the areas *1-3*, connected by tie lines *230 kV*, installed two synchronous turbogenerator with parameters given in Table 1:

Table 1. *Parameters of the models of synchronous turbogenerators in 6 - machine system.*

Parameter	Value					
	G1	**G2**	**G3**	**G4**	**G5**	**G6**
x_d, *p. u.*				1.8		
x'_d, *p. u.*				0.3		
x''_d, *p. u.*				0.25		
x_q, *p. u.*				1.7		
x'_q, *p. u.*				0.55		
x''_q, *p. u.*				0.25		
x_l, *p. u.*				0.2		
T'_{d0}, *s.*				8		
T''_{d0}, *s.*				0.03		
T'_{q0}, *s.*				0.4		
T''_{q0}, *s.*				0.05		
R_s, *p. u.*				0.0025		
H, s.	6.5	6.5	6.17	6.17	6.17	6.17
K_F (friction gain), *p. u.*				0		
p (number of poles pairs)				4		
f, Hz				60		
Parameters of the initial steady state						
$d\omega$, %	0	0	0	0	0	0
δ,°	0	-12.7	-46.1	-56.7	-36	-46.6
I_s, *p. u.*	0.9	0.82	0.8	0.79	0.8	0.78
φ_a,°	-11.5	-30.7	-53.4	-65.5	-41.8	-51.5
φ_b,°	-131.5	-151	-173	174.5	-162	-171
φ_c,°	108.5	89.2	66.6	54.5	78.2	68.5
V_f, *p. u.*	2.07	2.02	1.86	1.85	1.84	1.79

In *ECS SM* modelled *MPH-EC* with parameters $K_{0V} = 3.3, N = 1 \rightarrow 180$. In the initial steady-state mode, the loads of power system areas are:

$$P_1 = 967 \text{ MW}, Q_1 = -287 \text{ MVAr};$$

$$P_2 = 1767 \text{ MW}, Q_2 = -437 \text{ MVAr};$$

$$P_3 = 1767 \text{ MW}, Q_3 = -437 \text{ MVAr}$$

that causes the active power flow *750 MW* between the first and second areas.

To study the steady-state and transient stability of power system under consideration are simulated following perturbations:

1. Submission a step signal *0.05 p. u.* at the input of voltage setting V_{ref1} of the first turbogenerator duration *200 ms* at *2 s* of simulated transient;

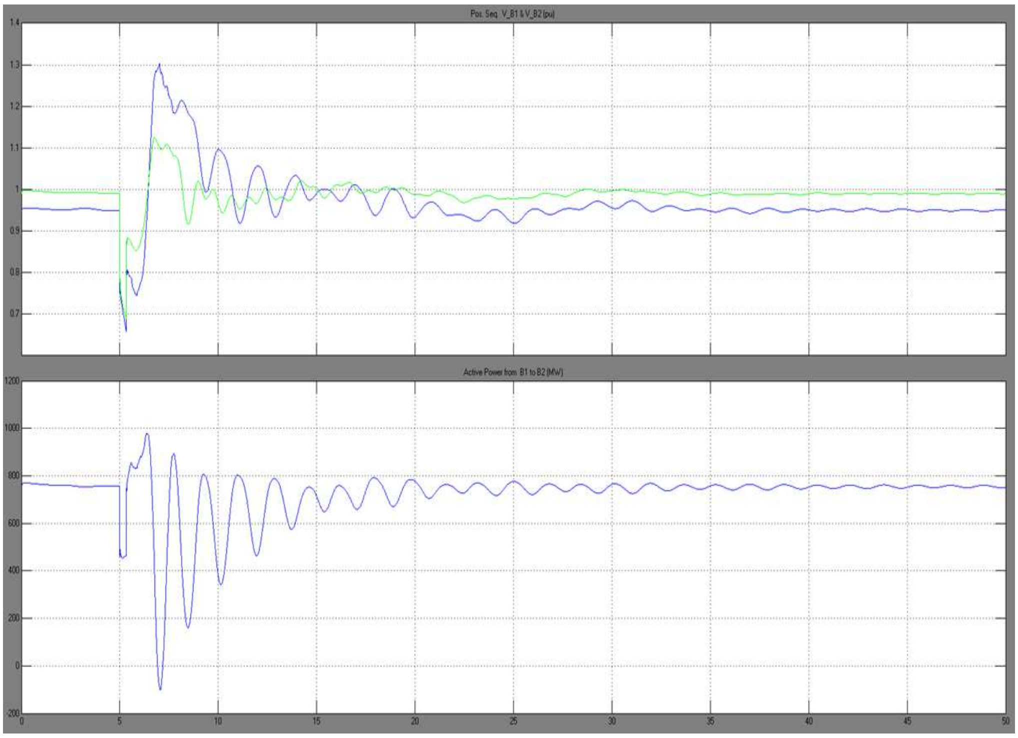
2. The three-phase short circuit on the tie line, connecting area *1* and area *2*, in a time moment $t = 5$ *s*, and duration *0. 33 s*.

After the appearance of dynamic disturbance (three-phase short-circuit), and the identification of a dangerous mode of electromechanical oscillations simulated different combinations of control actions from *SVP* in the time interval *5.3-10.3 s* (taking into account the delays in data transmission from the *PMU*, and the computation time of the *SVP* for conditions (13)), increases the gain of *MPH-EC* on the deviation rotor angle $N = 1 \rightarrow 180$. In this case, as a result of computational experiments, it was determined that the stability of the simulated multimachine power system at a given hard dynamic perturbation is provided only for the case of increasing the gain $N = 1 \rightarrow 180$ of *MPH-EC* for *SM G1* and *G2*, installed on the revealed cross-section of the power system oscillations between area 1 and area 2, from the sending area 1. For other combinations of control actions from *SVP*, the stability of simulated multimachine power system is not guaranteed. In the annex Figure 9 and 10 shows the obtained transients in the time domain.

6. Conclusions

Modern state development of power systems is characterized by intensive introduction the remote measurement data system, such as *WAMPC*, allowing the use, in addition to the magnitude of state parameters, their angle (phase) information. These systems allow in practice to identify the existence of electromechanical waves propagating with finite speed in power systems at its perturbations. Using this fact, offer an integrated *ECS SM*, to identify the electromechanical oscillation modes with the lowest damping ratio, makes the greatest contribution to the development of the power system instability. Putting into operation the power system stabilizers of *ECS SM* with *MPH-EC*, located in the arising cross-sections of electromechanical oscillations from the transmitting side, allows achieving an optimal damping of power system. Computational experiments carried out on the model, have shown the effectiveness of the proposed integrated *ECS SM* to increase the stability, and dynamic properties of the power system.

Annex



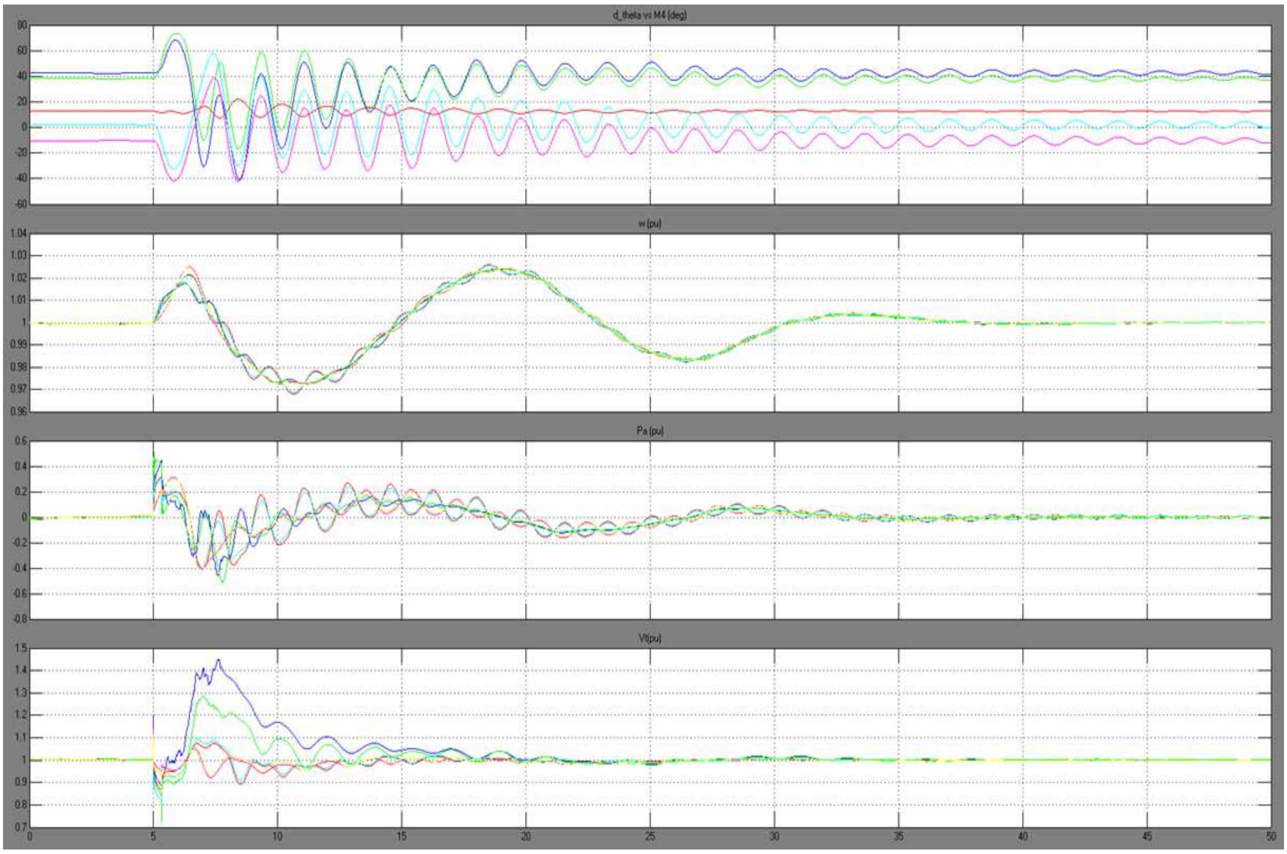
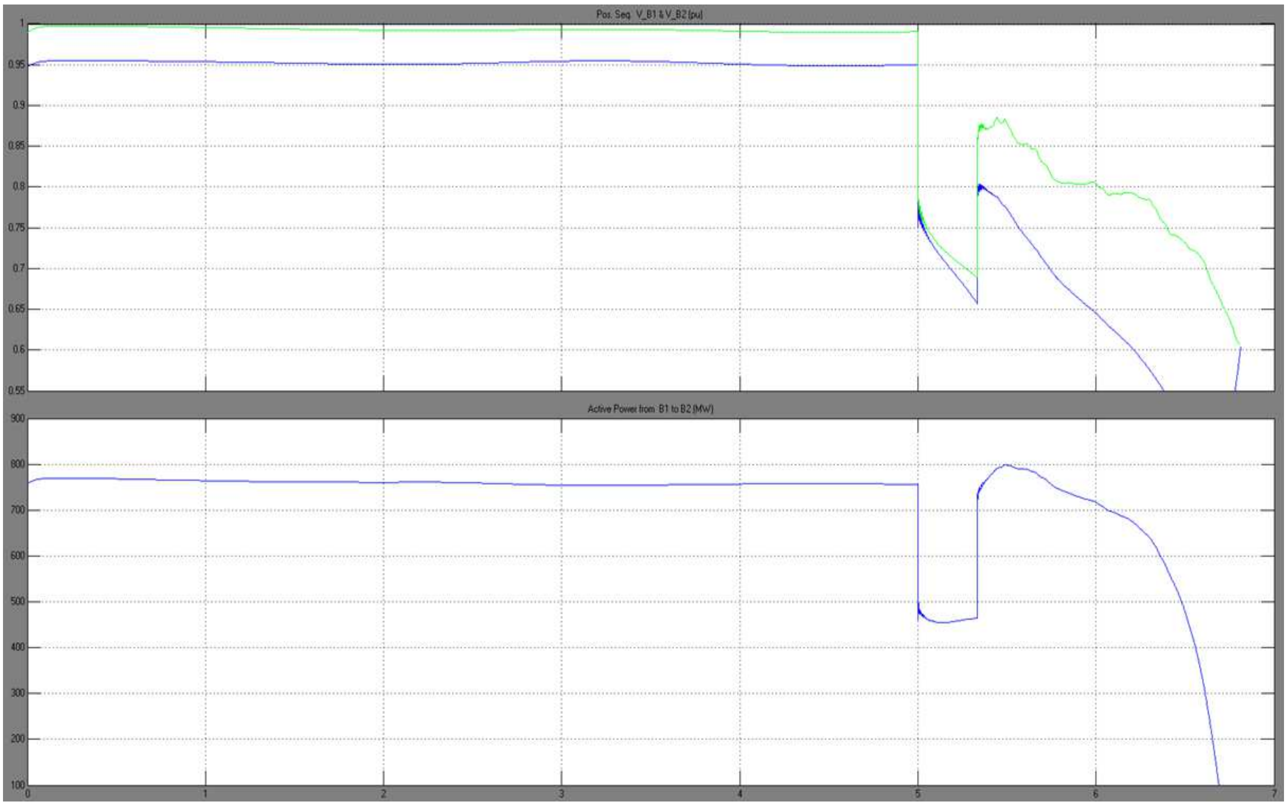


Figure 9. *Transient in the 6-machine power system model, K_{0v} = 3.3, N = 180 is inputted to the SM G1 and G2 in the area 1.*



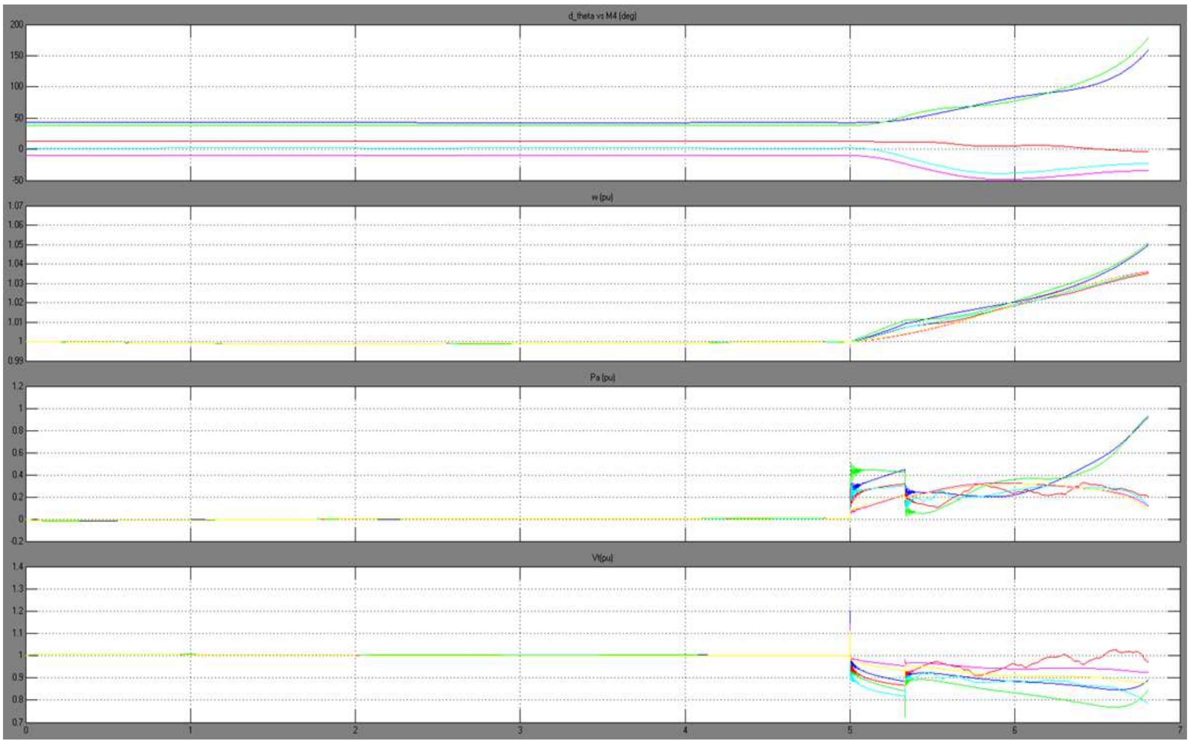


Figure 10. *Transient in the 6-machine power system model, K_{0v} = 3.3, N = 180 is inputted to the SM G3-G6 in the areas 2, 3.*

References

[1] U.S.-Canada Power System Outage Task Force, Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations, April 2004, Available at www.nerc.com.

[2] Phadke A. G., Thorp J. S., *"Synchronized Phasor Measurements and Their Applications"*, Springer Science + Business Media LLC, 2008, p. 248, ISBN 978-0-387-76535-8

[3] Schweitzer E. O. *Advanced Real-Time Synchrophasor Application* / E. O. Schweitzer, III, D. Whitehead, A. Guzman, Y. Gong, M. Donolo// Journal of Reliable Power. – 2011. – Vol. 2. – № 2. –May. – p. 16-28.

[4] Machowski J., Bialek J. W., Bumby J. R., *"Power System Dynamics: Stability and Control", 2nd* Edition, John Wiley & Sons, Ltd., 2008, p. 629.

[5] Faulk D., Murphy R. J., *"Comanche peak unit no. 2 100% load rejection test – underfrequency and system phasor measurement across TU electric system"*, Proc. Annu. Conf. Protective Relay Engineers, March, 1994, College Station, TX, USA.

[6] Thorp J. S., Seyler C. E., Phadke A. G., *"Electromechanical Wave Propagation in Large Electric Power Systems"*, IEEE Transactions on Circuits and System-I: Fundamental Theory and Applications, Vol. 45, № 6, pp. 614-622, June 1998.

[7] Huang L., Parashar M., Phadke A., Thorp J., *"Impact of electromechanical wave propagation on power system protection and control"*, Cigre Session 2002, Paris, France, no. 34, pp. 201-206, August 2002.

[8] Kundur P. *Power System Stability and Control* / P. Kundur. – New York: McGraw-Hill, 1994. – 1176 p.

[9] *Analysis and Control of Power System Oscillations*: CIGRE TF 38.01.07, Brochure 111, 1996. – 119 p.

[10] Semlyen, A., *"Analysis of Disturbance Propagation in Power Systems Based on a Homogeneous Dynamic Model"*, IEEE Transactions on Power Apparatus and Systems, Vol. 93, № 2, pp. 676-684, 1974.

[11] Lesieutre B. C., Scholtz E., Verghese G. C., *"A Zero-Reflection Controller for Electromechanical Disturbances in Power Networks"*, 14th PSCC, Seville, 24-28 June 2002, p. 7.

[12] Xu Y., Wen F., Ledwich G., Xue Y., *"Electromechanical Wave in Power System: Theory and Applications"*, Journal Modern Power System Clean Energy, 2014, no. 2(2), p. 163-172.

[13] *IEEE Standard for Synchrophasor for Power Systems"*, IEEE Standard C37. 118-2005. Available at http://standards.ieee.org/.

[14] *SEL-3378 Synchrophasor Vector Processor Data Sheet*, Schweitzer Engineering Laboratories, available at http:// www.selinc.com/sel-3378.htm.

[15] Agamalov O. N. *Magnitude-Phase Controller (MPHC)* / O. N. Agamalov // The 2012 International Conference on Control Engineering and Communication Technology (ICCECT 2012), Shenyang, China, 2012.

[16] Agamalov O. *Control systems structures of synchronous machines excitation* / O. Agamalov. – Lambert Academic Publishing, 2013. – 177 p. ISBN: 978-3-659-34203-5.

[17] Agamalov O. Physical Processes in the Damping of Electromechanical Oscillations of the Synchronous Machine with Magnitude-Phase Excitation Controller / O. Agamalov // International Journal of Energy and Power Engineering. ISSN: 2326-960X (Online) – 2013. – Vol. 2. – № 4. – p. 164-171.