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RESEARCH OF COMPACT ELECTRICAL POWER SYSTEMS SYNCHRONOUS GENERATORS SYNCHRONIZATION AND PARALLEL OPERATION CHARACTERISTICS UNDER VARIABLE LOAD CONDITIONS

Summary of Doctoral Thesis

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CONFIRMATION

Hereby I confirm that I have worked out the present Doctoral Thesis, which is submitted for consideration at Riga Technical University for the degree of Doctor of engineering sciences. This work is not submitted in any other university for obtaining the doctor’s degree.

Kristina Berzina …………………………….(Signature)

Date: ………………………

Doctoral thesis is written in English, it contains preface, 6 chapters, and conclusions. Total amount of this work is 119 pages, with 59 illustrations. Bibliography includes 92 literature sources.

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TOPICALITY OF THE THESIS

Feasibility of small local energy development identification is justified by specifications through the range of its objects functionalities such as:

- Application of dispatching principles that are characteristic for high power systems can not be ensured fully in this case;
- Priority of electrical power generation on the basis of compact electrical power plants;
- No availability or poor application of emergency control or emergency automation control systems;
- Domination of overhead power lines on wooden poles over cable lines;
- Heat utilization is not entirely applied and consequently low efficiency factor of power plant is observed.

Under such conditions the tasks of effective control and management of compact electrical power station (CEPS) - remain the most significant. Out of the diversity of these tasks systems efficiency increase of generators synchronization and sub-systems of compact electrical plants is one of the most topical.

The issue is described in the aspect that the existing synchronization systems are not always capable to provide immediate and of respective quality of transition process actuation of generators and subsystems of CEPS to parallel operation mode to network but algorithm schemes and elements of these systems are obsolete technologically. The tasks solution of synchronization systems efficiency increase could be achieved by different methods including application of flexibly controlled technical devices of deviation (changes) of active and reactive power.

Currently the attention to such technical hardware is dictated by intensive and widely implemented concept of application of flexibly controlled power lines of alternative current that in technical literature have acquired the name Flexible AC Transmission systems (FACTS)*. In power industry the term FACTS covers a number of technologies that enhance the reliability, capacity and flexibility of power transmission systems. FACTS solutions enable power grid owners to increase existing transmission network capacity while maintaining or improving the operating margins necessary for grid stability.

*-G Davis - California energy commission, 1999 - ecourses.dbnet.ntua.gr.

As a result, more power can reach consumers with a minimum impact on the environment, after substantially shorter project implementation times, and at lower investment costs - all compared to the alternative of building new transmission lines or power generation facilities.

Local, compact systems of power supply are interpreted as independent isolated power supply systems of separate entities or residential areas incorporating autonomous power plants and distribution systems of limited length. The consumed power in such systems does not exceed 0,5-2 MW in rare cases 5-10 MW.

In several regions the power supply of industrial objects and residential areas is provided simultaneously by autonomous power plants and centralized networks. Besides the range of specific issues appeared due to integrated operation of a local system and centralized network.

Autonomous power energy sources (APES), represented by several primary motors - drives such as: diesel generators, gas combustion motors, gas turbine engines and some other types, are not technically adequate to generate electrical power energy with the parameters meeting the requirements of modern standards.

This doctoral thesis is focused on investigation and development of electrical power engineering equipment for local power supply system's providing efficient operation mode.

The realization of extended implementation of local power supply systems requires additional researches in the following trends:

- Investigation of methods how to improve efficiency of autonomous power plants operation;
- Provision of efficient integrated operation of local systems with centralized networks.

Having summarized all the above mentioned, the conclusion is obvious that there are difficulties to reach the required efficiency of electrical power complexes for production and conversion of electrical power energy and to ensure required level of indicators characterizing its quality by specific consumption of primary fuel, stability of frequency and voltage under the conditions of inconsistent consumption. The mentioned indicators remain relatively low and require considerable improvement. Thus a significant issue is identified as a development of local systems of electrical power systems with efficiency improved by structural changes of generating part of autonomous electrical power plant, application of new methods of primary motor regulation, application of power converting technique and provision of basic parameter of generating voltage – frequency.

The solution of the mentioned problem would allow to reduce the costs of electrical power generation and heat production, as well as to raise the stability of frequency and voltage in more extended area of parameters of load and operation modes.

THE OBJECTIVE OF THE THESIS

The objective of the thesis is a development of effective algorithms and structural functional schemes of precise synchronization systems for generators and sub-systems of compact electrical power plants on the theoretical basis of automatic control of objects relocation programming.

To achieve the objective the following tasks have been formulated:

- Statement of effective task solution on control of precise automatic synchronization for generators and sub-systems of compact EPP on the theoretical basis of automatic control of objects relocation programming;
- Development of an algorithm of adaptive control of the process of precise automatic synchronization for generators and sub-systems of compact EPP;
- Synthesis of basic functional units of generators synchronization adaptive systems and sub-systems of compact EPP as the components of formed structural-functional schemes.

SCIENTIFIC NOVELTY

Scientific novelty of the doctoral thesis reported and implemented for the first time:

– The tasks of effective system synthesis of automatic synchronization for synchronous generators and sub-systems of compact EPP are identified and solved;
– The method of compiling equations for compact EPP is developed based on the Park-Gorev differential equations using the investigated system models for design synthesis of structural components in principle;

- the methodology is developed for the research of compact EPP with synchronous generator, based on structural modeling approach using the Park-Gorev element equations;
- functional models of compact EPP with synchronous generator are developed, that are incorporated into a united system; simulation is provided in relative units where parameters of applied elements are expressed in their base unit;
- the mathematical model is developed that allows studying the change of synchronous generator parameters and generator load in different modes of operation, including the interaction.

METHODS AND INSTRUMENTS OF THE RESEARCH

The following research methods are used in the thesis:

- General theoretical research methods;
- Structural modeling.

The following tools are used in the thesis:

- the similarity theory, the theory of electrical machines, and mathematical description of electrical machines;
- Park-Gorev differential equations;
- numerical integration methods for solving system of non-linear differential equations;
- the software FORTRAN, Microsoft Excel;
- UNITROL 1000 equipment.

1. PROBLEMS OF CONTROL OPERATION MODES OF COMPACT ELECTRICAL POWER SYSTEMS

Compact electrical power systems differ by their operation modes either as independent or integrated with entire consolidated electrical power system.

There are three following groups:

- Parallel operation with integrated power system by direct link with allowable output and input of capacity which is equivalent to full capacity of compact power systems, including in the repair regime;
- Parallel operation with integrated power system by flexible link with allowable output and input of capacity up to 30% of full capacity of compact power system;
- Autonomous operation mode with no connection with integrated power system.

Each group presents its own characteristics and consequently operation and maintenance problems related specifically with control of compact power systems (CPS) operation modes. Tasks of stability of the synchronous generator synchronization process are formulated based on analysis of this issue.

2. MODELLING OF SYNCHRONOUS GENERATOR PARALLEL OPERERATION

2.1. Specific features of mathematical modeling of electrical power plants

Mathematical models of alternating current generators should consider the effect of current displacement in circuits of rotor representing rotor either by multi-circuit system on the basis of synthesis of constant parameters either by double-circuit system with variable parameters of equivalent circuit.

Mathematical models of valve system of excitation of synchronous generators should consider switching processes in static converters.

Mathematical models of excitation regulators of generators must incorporate requirements on multichannel of regulators, limiting characteristics of channels and acceptable coefficients of regulation. It is required to observe frequency regulation of rotor rotation of steam and gas turbines, as well as dynamic characteristics of energy carrier sources.

Mathematical models of dynamic systems must be capable to alter designed assumed conditions as well as parameters of network, machines parametres.

2.2. Simulation of synchronization process of combustion engine and thermogenerator by application of mathematical model

For check of stability of any synchronization method it is necessary to determine first of all allowable angular speed of rotor slip at the connected machine, and at exact synchronization with restriction of an angle of switch-on and a limiting angle of switch-on. For opinion about size of the currents proceeding in system during synchronization, it is necessary to find an angle on which the generator deviates at switch-on, and also to analyze the influence of superfluous moment changes, rotation frequency and excitation on synchronization process.

For an estimation of synchronization stability the mathematical model is developed. The model includes the synchronous generator model with use of the full differential Park-Gorev equations and the primary engines differential equations.

It is necessary to have the voltage equilibrium equations of electric loops both on stator and rotor and the rotor's equation of motion in the differential form for the research of rotating electric machines transient processes, in particular synchronous generators. The kind of these equations depends on a choice of coordinate axes positive directions and a direction of a current in loops.

All the equations are written down in relative unit's system "system X_{ad}" or "per unit system" there both the mutual induction reactances and magnetomotive forces are equal among themselves.

The synchronous generator's mathematical model in *d*-*q*-0 coordinate system is:

$$\left.\begin{aligned} u_d &= \frac{d\Psi_d}{d\tau} - \Psi_q\,\omega + i_d\,R; \\ u_q &= \frac{d\Psi_q}{d\tau} + \Psi_d\omega + i_q\,R; \\ u_f &= \frac{d\Psi_f}{d\tau} + i_f\,R_f; \\ 0 &= \frac{d\Psi_D}{d\tau} + i_D\,R_D; \\ 0 &= \frac{d\Psi_Q}{d\tau} + i_Q\,R_Q. \end{aligned}\right\} \qquad (2.1)$$

where Ψ_d, Ψ_q – are the components of full flux linkages in *d*-*q*-0 coordinate system;

u_d, u_q – are the components of instantaneous values of phase voltages in *d*-*q*-0 coordinate system;

i_d, i_q – are components of instantaneous values of phase currents in *d*-*q*-0 coordinate system;

R_d , R_q – are the active resistances of phase windings (R_d = R_q = R in case of stator symmetry);

u_f, i_f, Ψ_f, R_f – are the components of voltage at excitation winding, current in it, full flux linkage with it and active resistance of this winding correspondingly.

Flux linkages of all loops which have been written down in *d*-*q*-0 coordinate system, contain only the constants independent on time of inductance:

$$\left.\begin{aligned} \Psi_0 &= X_0 i_0; \\ \Psi_d &= X_d i_d + X_{ad} i_f + X_{ad} i_D; \\ \Psi_q &= X_q i_q + X_{aq} i_Q; \\ \Psi_f &= X_{ad} i_d + X_f i_f + X_{ad} i_D; \\ \Psi_D &= X_{ad} i_d + X_{ad} i_f + X_D i_D; \\ \Psi_Q &= X_{aq} i_q + X_Q i_Q. \end{aligned}\right\} \qquad (2.2)$$

Substituting (2.1) and (2.2), and resolving relatively currents derivatives, the modeling algorithm of the synchronous generator in alternating currents is recievied.

In the matrix form:

$$\frac{d}{d\tau}\begin{bmatrix} i_d \\ i_q \\ i_f \\ i_D \\ i_Q \end{bmatrix} = \begin{bmatrix} Q_1 & 0 & 0 & 0 & 0 \\ 0 & Q_2 & 0 & 0 & 0 \\ 0 & 0 & Q_3 & 0 & 0 \\ 0 & 0 & 0 & Q_4 & 0 \\ 0 & 0 & 0 & 0 & Q_5 \end{bmatrix} \times \begin{bmatrix} u_d \\ u_q \\ u_f \\ u_d \\ u_q \end{bmatrix} + \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{bmatrix} \times \begin{bmatrix} i_d \\ i_q \\ i_f \\ i_D \\ i_Q \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix}$$

or

$$\frac{d}{dt}[I_{SG}] = [Q_{SG}][U_{SG}] + [H_{SG}] \qquad (2.3)$$

where elements of a matrix $[A]$:

$$a_{11} = -R_a Q_1, \quad a_{12} = X_q \omega Q_1, \quad a_{13} = -R_f Q_3, \quad a_{14} = -R_D Q_4, \quad a_{15} = X_{aq}\omega Q_1;$$

$$a_{21} = -\omega X_d Q_2, \quad a_{22} = -R_a Q_2, \quad a_{23} = -X_{ad}\omega Q_2, \quad a_{24} = -X_{ad}\omega Q_2, \quad a_{25} = -R_Q Q_5;$$

$$a_{31} = -R_a Q_3, \quad a_{32} = X_q \omega Q_3, \quad a_{33} = -\frac{X_d X_D - X_{ad}^2}{\Delta d} R_f, \quad a_{34} = \frac{X_s X_{ad}}{\Delta d} X_D, \quad a_{35} = X_{aq}\omega Q_3;$$

$$a_{41} = -R_a Q_4, \quad a_{42} = X_q \omega Q_4' \quad a_{43} = \frac{X_s X_{ad}}{\Delta d} R_f, \quad a_{44} = -\frac{X_d X_B - X_{ad}^2}{\Delta d} R_D, \quad a_{45} = X_{aq}\omega Q_4;$$

$$a_{51} = -X_d \omega Q_5, \quad a_{52} = -R_a Q_5, \quad a_{53} = -X_{ad}\omega Q_5, \quad a_{54} = -X_{ad}\omega Q_5, \quad a_{55} = -\frac{X_q}{\Delta q} R_Q.$$

elements of a matrix $[Q_{SD}]$:

$$Q_1 = \frac{X_D X_f - X_{ad}^2}{\Delta d}; \quad Q_2 = \frac{X_Q}{\Delta q}; \quad Q_3 = -\frac{X_{sD} X_{ad}}{\Delta d}; \quad Q_4 = -\frac{X_{sf} X_{ad}}{\Delta d}; \quad Q_5 = -\frac{X_{aq}}{\Delta q},$$

$$\Delta d = X_d X_f X_D - X_{ad}^2 (X_d + X_D + X_B - 2X_{ad}),$$

$$\Delta q = X_q X_Q - X_{aq}^2$$

elements of a matrix $[B]$:

$$B_1 = Q_3 u_B; \quad B_2 = 0; \quad B_3 = \frac{X_d X_D - X_{ad}^2}{\Delta d} u_B; \quad B_4 = -\frac{X_s X_{ad}}{\Delta d} u_B; \quad B_5 = 0.$$

Equations system (2.1) is supplemented with the equation of motion:

$$\frac{d\omega}{d\tau} = \frac{1}{T_M}\left[M_{diz} - \left(\Psi_q i_d - \Psi_d i_q\right)\right] \qquad (2.4)$$

where M_{diz} – determine from prime mover's mathematical model of internal combustion engine;

T_M - the resulted time constant of a diesel engine in per unit's system.

It is necessary to transform a network voltage to *d*-*q*-0 coordinate system, U_{sd}, U_{sq} rotating together with a rotor of the synchronous machine, as shown in Fig.2.0 and equation (2.5).

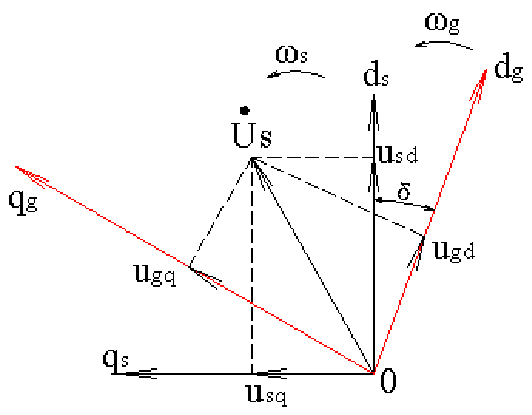


Fig.2.0. Vector diagramm

$$U_d = U_{sd}\cos\delta - U_{sq}\sin\delta ,$$
$$U_q = U_{sd}\sin\delta + U_{sq}\cos\delta . \qquad (2.5)$$

Also it is necessary to consider the change of an angle δ as function of a difference of frequencies of rotation of coordinate systems of a network and the synchronous generator.

Automatic speed regulators of synchronous generators' prime movers are under construction the usual regulators' schemes. In direct action regulators the deviation of rotation speed will be transformed to centrifugal mechanism's coupling translational motion and through the system of levers is transferred to the fuel pump rack. Such regulators are applied to diesel engines of small and average power.

When compact generating installation of the small and average power is required, the most suitable type of a drive are internal combustion engines which are more economic, and, the main thing, are always ready to start-up in this connection a diesel engine - generators can serve as reserve (emergency) sources of the electric power.

Static and dynamic properties of automatic control system of a diesel engine operating mode are determined by properties of systems' elements both the engine, and an automatic speed regulator. The engine's work under operating conditions develops of set of the established and transitive modes.

The established mode, as is known, is characterized by that, as the adjustable parameter, and the parameters describing an overall performance of the engine, remain constant in time.

The engine's work in the established mode is possible under condition of energy quantity equality, developed a diesel engine, to the energy quantity used by the consumer, in this case the synchronous generator. If to replace this equality of energy with the equality of the torgue m_{diz} and the generator's torgue $m_{\text{eм}}$ in static balance the condition the established mode can be written down

$$m_{diz} + m_{em} = 0 \qquad (2.6)$$

Thus it is necessary to take into account, that for the basic operating mode of the synchronous machine it is accepted generator, and accordingly in the established mode the electromagnetic torgue is characterized with "minus" sign.

If in system "diesel engine - generator" there is a surplus or lack of energy the established mode is broken. Thus all change in time or only those parameters which define an overall performance of a diesel engine. Thus the diesel engine - generator shaft receives positive or negative acceleration, and the system passes to work in the unsteady (transitive) mode. If J - the resulted inertia moment of a diesel engine and the synchronous generator the dynamic balance condition describing an unsteady operating mode of a diesel engine, can be written down according to Dalamber's principle:

$$J\frac{d\omega}{dt} = m_{diz} + m_{em} \qquad (2.7)$$

In per unit's this equation will look like:

$$T_M \frac{d\omega}{dt} = M_{diz} + M_{em} \qquad (2.8)$$

Due to existence of diesel engines' various types: not direct and direct action, with turbocharger and without it, considering a question of prevalence of those or other types of diesel engines and comparing with their mathematical models, in work as initial model is accepted the direct action diesel engine of with turbo – supercharding. The differential equations' system describing behaviour of a rotation frequency regulator of a diesel engine, in Coshie form is following:

$$\begin{aligned} &\frac{d\mu_p}{d\tau} = k; \\ &\frac{dk}{d\tau} = -\frac{1}{T_2''}\left[T_K k + \delta\mu_p + \delta i\left(\mu_p - \xi\right) + \left(\omega - \omega_0\right)\right]; \\ &\frac{d\xi}{d\tau} = \frac{1}{T_i}\left(\mu_p - \xi\right). \end{aligned} \qquad (2.9)$$

where T_2'' – a time constant of a sensitive element of a rotation frequency regulator;

T_k – a viscous friction time constant of a rotation frequency regulator;

T_i – a dash-pot time constant of a rotation frequency regulator;

μ_p – moving of regulating body of a rotation frequency regulator;

δ – constant-error response of a rotation frequency regulator;

δ_i –temporary (additional) constant-error response of a rotation frequency regulator;

ξ – a dash-pot moving of a rotation frequency regulator;

ω_0 – a rotation frequency regulator setting;

ω – a rotation frequency of the synchronous generator with a drive from the internal combustion engine (diesel engine).

The turbocharger turbine impact on dynamic properties of a diesel engine, improving them, but only for the chosen operating mode. At change of optimum conditions setting accordingly elements characteristics of diesel engine or turbo-compressor are broken and teamwork's quality declines.

The turbine impact on diesel engine work is taken into account by introduction of the equation

$$\frac{d\omega_T}{dt} = \frac{1}{T_T}\left(\mu_p - \omega_T\right) \qquad (2.10)$$

where T_T - a turbine time constant;

ω_T - the turbo-supercharging turbine rotation speed .

The engine torgue of diesel engine M_{diz} is defined as

$$M_{diz} = \eta_e \cdot \mu_p \qquad (2.11)$$

where η_e – effective efficiency of a diesel engine.

Dependence $\eta_e = f(\beta)$ is submitted in table 1 as follow:

Table1. *Dependence's* $\eta_e = f(\beta)$ *definition*

η_e	1,13	1,09	0,96	0,46	0,4514
β	0	0,625	1,18	2,825	3,0

Graphically dependence $\eta_e = f(\beta)$ is submitted on Fig.2.1.

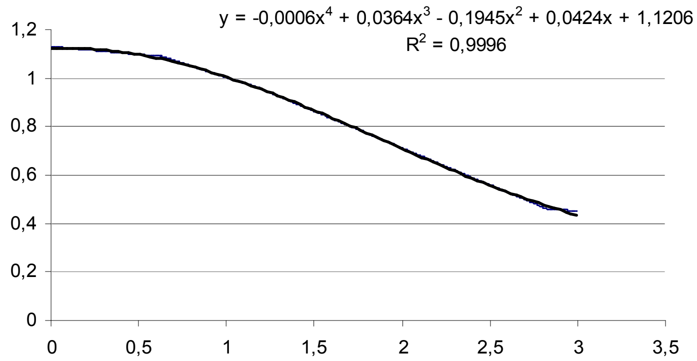


Fig.2.1. Dependence $\eta_e = f(\beta)$ and its trendline

Using computer technologies, according to the table the nonlinear regress equation (trendline) is determined:

$$\eta_e = -0{,}0006\beta^4 + 0{,}0364\beta^3 - 0{,}1645\beta^2 + 0{,}0424\beta + 1{,}1206$$

$$\beta = \frac{q_{cikl}}{q_B} = \frac{\mu_p}{q_B}; \quad q_B = 0{,}8 + 0{,}2\omega_T \tag{2.12}$$

where q_B - of the supercharger air consumption;

q_{cikl} - the cyclic submission of fuel. It is equal to μ_P in relative units.

Restrictions are imposed on regulating body moving of a rotation frequency regulator:

$$-0{,}25 \le \mu_p \le 1{,}1 \; .$$

After analysis of the received results from mathematical model in an operating mode, it has been determined that T_2'' is rather small (1-5s). Thus in the given circumstances allows to accept that $T_2'' = 0$.

Finally mathematical model for a diesel generator is:

$$\begin{aligned} \frac{d\mu_p}{dt} &= -\frac{1}{T_k}\left[\delta \cdot \mu_p + \delta_i(\mu_p - \xi) + (\omega - \omega_0)\right]; \\ \frac{d\xi}{dt} &= \frac{1}{T_i}(\mu_p - \xi); \\ \frac{d\omega_T}{dt} &= \frac{1}{T_T}(\mu_p - \omega_T). \end{aligned} \tag{2.13}$$

To show serviceability of the generator model with a drive from the internal combustion engine (diesel engine) the analysis of a synchronization regime with a infinite power network is carried out.

In Fig. 2.2-2.3 results of the generators switching on in a network with breaking synchronization conditions are given. The beginning regime is the same in all the cases.

In Fig. 2.4.-2.5. modelling results for cases of coming into a synchronous work are resulted at a deviation from synchronization conditions with a shift angle $\delta = +0{,}8\ el.rad$ and $\delta = -0{,}8\,el.\,rad$. In first case maximal current is 5 p.u., and maximal moment 2.07 p.u.; in the second case maximal current 4.05 p.u. and moment: -3,6 p.u.

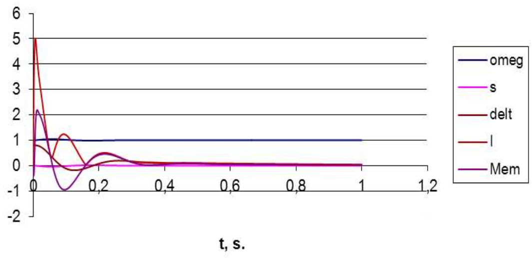


Fig. 2.2. Results of synchronization with mismatch angle $\delta = +0{,}8\ el.rad$, moment, current, rotation frequency, shift angle in time.

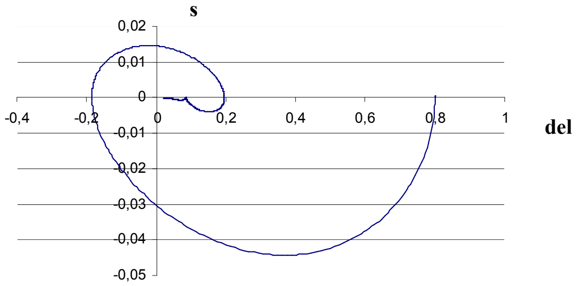


Fig. 2.3. Results of synchronization with mismatch angle $\delta = +0{,}8\ el.rad$, phase's trajectory.

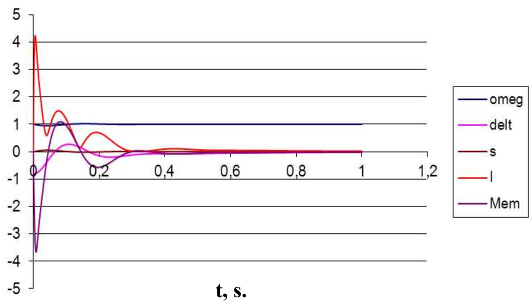


Fig. 2.4. Results of synchronization with mismatch angle $\delta = -0{,}8\,el.\,rad$, moment, current, rotation frequency, shiftangle in time.

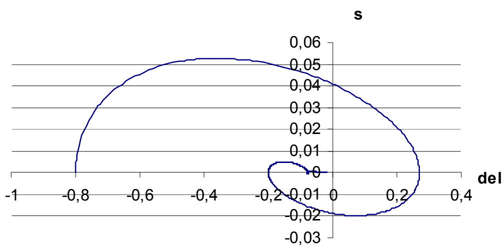
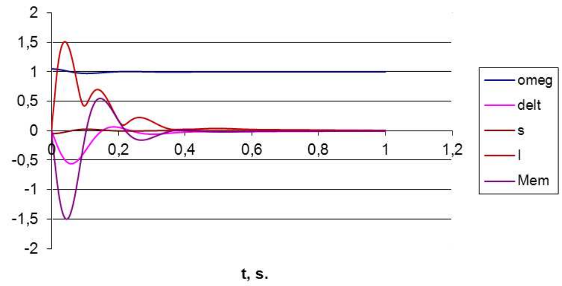


Fig. 2.5. Results of synchronization with mismatch angle $\delta = -0{,}8\,el.\,rad$, phase's trajectory.

In Fig. 2.6.-2.7. calculation results of a regime are resulted at nonsynchronous switching with generator's rotation frequency more than a network's frequency $\omega = 1{,}05$. The analysis of curves shows, that the machine pulling into synchronism. Currents have maximal size 1,45 p.u. The maximal size of generator's electromagnetic moment is equal -1,5 p.u.



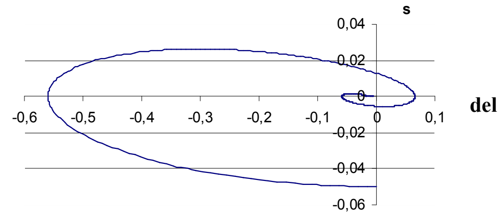
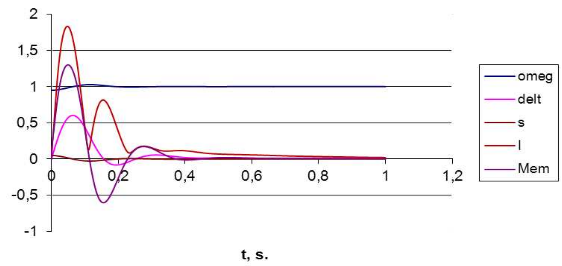


Fig. 2.6. Results of synchronization with frequency $\omega = 1{,}05$, moment, current, rotation frequency, shift angle in time.

Fig. 2.7. Results of synchronization with frequency $\omega = 1{,}05$, phase's trajectory.

In Fig. 2.8.-2.9. is the opposite picture. Calculation results of this regime are resulted with generator's rotation frequency smaller than a networks frequency $\omega = 0{,}95$. Thus it is visible, that the generator also is pulling into synchronism. Maximum size of a current is 1,78 p.u., and maximal moment is 1,25 p.u.



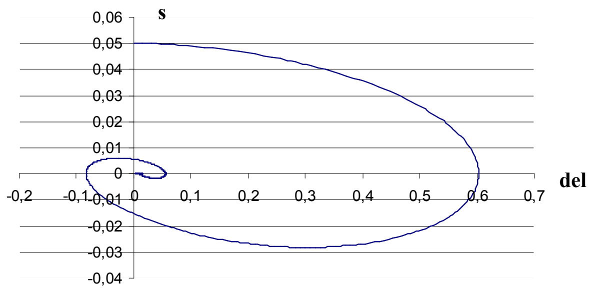


Fig. 2.8. Results of synchronization with frequency $\omega = 0{,}95$, moment, current, rotation frequency, shift angle in time

Fig. 2.9. Results of synchronization with frequency $\omega = 0{,}95$, phase's trajectory.

This case study proves the serviceability of the model. In all cases synchronous generator is coming into synchronism.

On the developed program's basis there is possible with high degree of reliability to define synchronization conditions of generator with a drive from the internal combustion engine (diesel engine). To determine possible deviation limits on rotation frequency and shift angle of exact synchronization. Also the offered program allows to estimate a size of stator currents and electromagnetic moment of synchronous generator.

2.3. Simulation of synchronization process of two generators by application of mathematical model

Less analyzed, and one of the most complex is synchronization process of generators in autonomous power system. At that part a power system model containiny two synchronous generators with primary engines is offered. The load is presented with statically active – inductive load (Fig. 2.10.).

Mathematical modeling of synchronization process consists of two consequtive steps:

- First step – SG1 generator stationary condition calculation to active – inductive load;
- Second step – SG2 generator connection without synchronization conditions compliance.

For an estimation of synchronization stability the mathematical model is developed. The model includes the synchronous generator model with use of the Park-Gorev full differential equations and the statically active – inductive load's equations.

The mathematical model of synchronous generator is represented on the basis of Park-Gorev differential equations on active-induction loads in *d*-*q*-0 coordinate system.

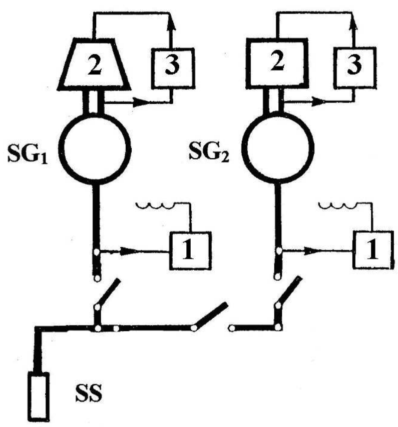


Fig. 2.10. Scheme of mathematical model. (1.- excitation; 2.- the engine; 3.- the engine control; SS - load).

Mathematical model of synchronous generator in *d-q-0* coordinate system:

$$\left.\begin{aligned} u_d &= \frac{d\Psi_d}{d\tau} - \Psi_q \omega + i_d R; \\ u_q &= \frac{d\Psi_q}{d\tau} + \Psi_d\ \omega + i_q\ R; \\ u_f &= \frac{d\Psi_f}{d\tau} + i_f\ R_f\ ; \\ 0 &= \frac{d\Psi_D}{d\tau} + i_D\ R_D; \\ 0 &= \frac{d\Psi_Q}{d\tau} + i_Q\ R_Q; \\ T_M \frac{d\omega}{d\tau} &= M_T - (\Psi_q i_d - \Psi_d i_q). \end{aligned}\right\} \qquad (2.14)$$

where $\Psi_d = X_d i_d + X_{ad} i_f + X_{ad} i_D;$

$\Psi_q = X_q i_q + X_{aq} i_Q;$

$\Psi_f = X_{ad} i_d + X_f i_f + X_{ad} i_D;$

$\Psi_D = X_{ad} i_d + X_{ad} i_f + X_D i_D;$

$\Psi_Q = X_{aq} i_q + X_Q i_q;$

Equations (2.14), with the exception of equation of motion, can be transformed into matrix form as shown in (2.3).

Equation (2.15) is devised for considering the load of autonomous power system in the mathematical model.

$$[u_1] = -[L_{StL}]\frac{d}{dt}[I_{StL}] - [Z_{StL}] \times [I_{StL}], \qquad (2.15)$$

where $[u_1] = -\begin{bmatrix} u_{d1} \\ u_{g1} \end{bmatrix}; [L_{StL}] = \begin{bmatrix} X_{StL} & 0 \\ 0 & X_{StL} \end{bmatrix}; [Z_{StL}] = \begin{bmatrix} R_{StL} & -X_{StL} \\ X_{StL} & R_{StL} \end{bmatrix}.$

Applying of all systems elements of expressions (2.16) ensures the system of current equations of synchronous generator stator. Equation according to Kirchoff's law for estimated point:

$$[I_{SG1}] + [I_{SG2}] = [I_{StL}]. \qquad (2.16)$$

For mathematical model there are complete equations of synchronous generator therefore currents are expressed by differentiated functions and equations (2.16) have to be differentiated.

$$\frac{d[I_{SG1}]}{dt}+\frac{d[I_{SG2}]}{dt}=\frac{d[I_{StL}]}{dt} \tag{2.17}$$

The mathematical model is supplemented with equations of current flows of stator (2.18), in the main expression form:

$$\frac{d[I_{SGi}]}{dt}=[Q_{SGi}]\times[U_1]+[H_{SGi}]. \tag{2.18}$$

In expression (2.17) instead of $\frac{d[I_{StL}]}{dt}$ expressions from equations (2.18) are used and inserted to obtain equation (2.19)

$$\begin{gathered}[U_1]=-[L_{StL}]\times[m_{SG1}Q_{SG1}+m_{SG2}Q_{SG2}]\times[U_1]-[L_{StL}]\times[m_{SG1}H_{SG1}+m_{SG2}H_{SG2}]-\\ -[Z_{StL}]\times[m_{SG1}I_{SG1}+m_{SG2}I_{SG2}]\end{gathered} \tag{2.19}$$

Under transformation the following expression is obtained:

$$\begin{gathered}([1]+[L_{StL}]\times[m_{SG1}Q_{SG1}+m_{SG2}Q_{SG2}]\ )\times[U_1]=-[L_{StL}]\times[m_{SG1}H_{SG1}+m_{SG2}H_{SG2}]-\\ -[Z_{StL}]\times[m_{SG1}I_{SG1}+m_{SG2}I_{SG2}]\end{gathered} \tag{2.20}$$

Solving equation (2.20) in relation to $[U_1]$, the system of variables of voltage for mathematical model of synchronous generators is obtained

$$\begin{gathered}[U_1]=[([1]+[L_{StL}]\times[m_{SG1}Q_{SG1}+m_{SG2}Q_{SG2}])]^{-1}\times(-[L_{StL}]\times[m_{SG1}H_{SG1}+m_{SG2}H_{SG2}]-\\ -[Z_{StL}]\times[m_{SG1}I_{SG1}+m_{SG2}I_{SG2}]).\end{gathered} \tag{2.21}$$

For modelling of system shown in Fig. 2.10. the parameters of synchronous generator are used in per units (p.u.)

$$\sum m_{SGi}=1 \text{ or } m_{SG1}+m_{SG2}=1. \tag{2.22}$$

Under constant load on the first generator SG1 $m_{SG1}=1.0$. By connecting a second generator SG2, the load distribution assumed for calculations is the following: $m_{SG1}=0.9$, a $m_{SG2}=0.1$. The process of synchronization under such circumstances is represented below in Fig. 2.12. - 2.14.

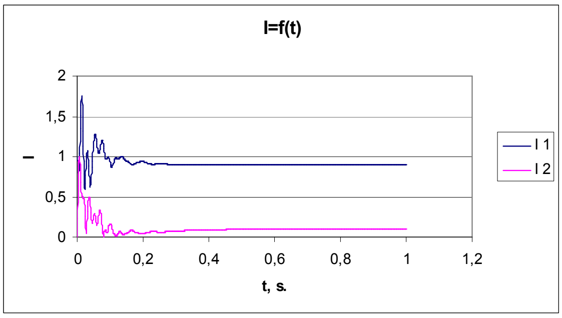


Fig. 2.11. Syncronization results of two

generators – currents by time:

I1- the first generator current;

I2- second generator current.

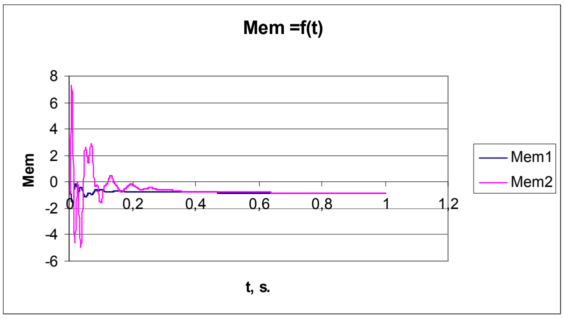


Fig. 2.12. Syncronization results of two

generators – moments by time:

Mem1- the first generator moment;

Mem2- second generator moment.

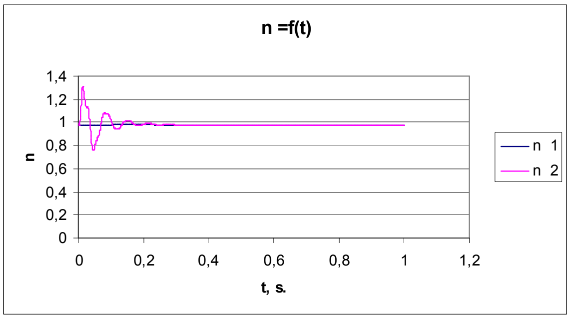


Fig. 2.13. Synchronization results of two

generators – frequency by time:

n1 – the first generator;

n2 – second generator.

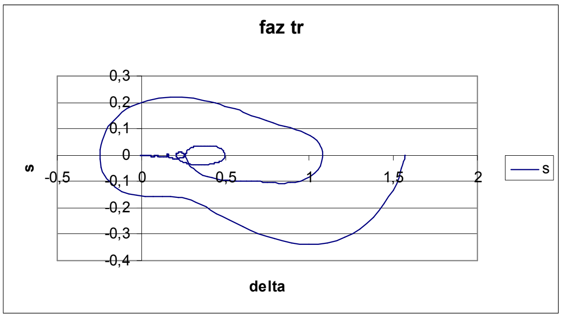


Fig. 2.14. Synchronization results of two

generators – phase trajectory.

This case study proves the serviceability of the model of two generators.

On the developed program's basis there is possible with high degree of reliability to define synchronization conditions of two generators. To determine possible deviation limits on rotation frequency and shift angle of exact synchronization. Also the offered program allows to estimate a size of stator currents and electromagnetic moments of synchronous generators.

3. THE SYNCHRONIZATION PROCESS OF SYNCHRONOUS GENERATOR, PRACTICAL AND THEORETICAL DATA FOR COMPARISON

3.1. Synchronous generator synchronization with UNITROL 1000 system

UNITROL 1000 is automatic regulator of voltage for upgrading of synchronous generators models and synchronous generators. The estimated sample of regulator includes integrated macroprocessing technology on semiconductor base elements.

Parameters of the stated equipment allow to monitor data variations of generator and network both at synchronization moment and at the definite assigned time period. UNITROL 1000 integrates built-in oscillograph function.

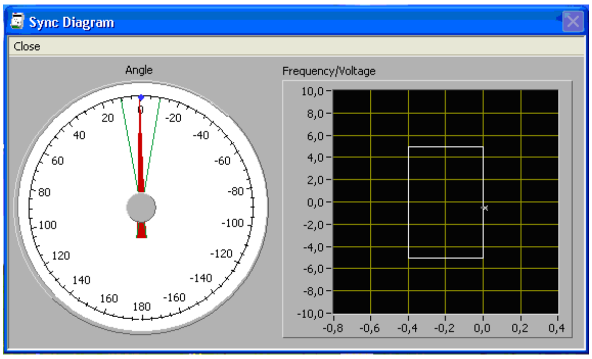


Fig.3.1. Synchronization diagram.

Management window.

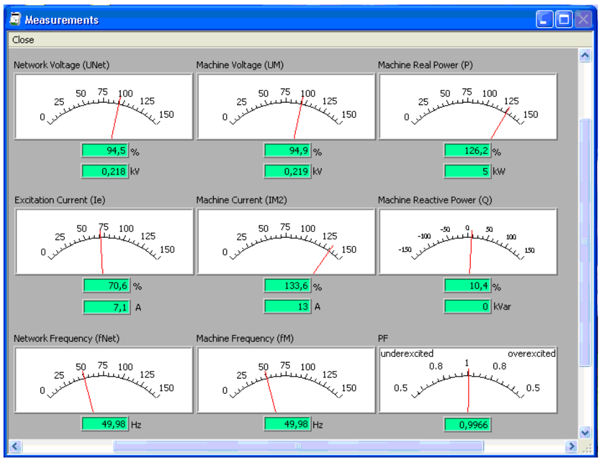


Fig.3.2. Values measured in real time.

Management window.

Fig. 3.1 visualizes a management window in which the parameters are displayed being measured in real time: frequency; voltage; shift angle at synchronization moment. Fig.3.2 shows the parameters measured in real time: voltage of network; voltage of generator; active power; reactive power; excitation current; current of generator; frequency of network; frequency of generator; angle of phases deviation.

To show emergency conditions of the exciting generator model the analysis of a synchronization regime with an infinite power network is carried out.

In Fig. 3.3. – 3.5. the results are given for normal cases of coming into a synchronous work resulted at a deviation from synchronization conditions generator-network, generator-load 2,2 A and generator- double as much load 4,4A.

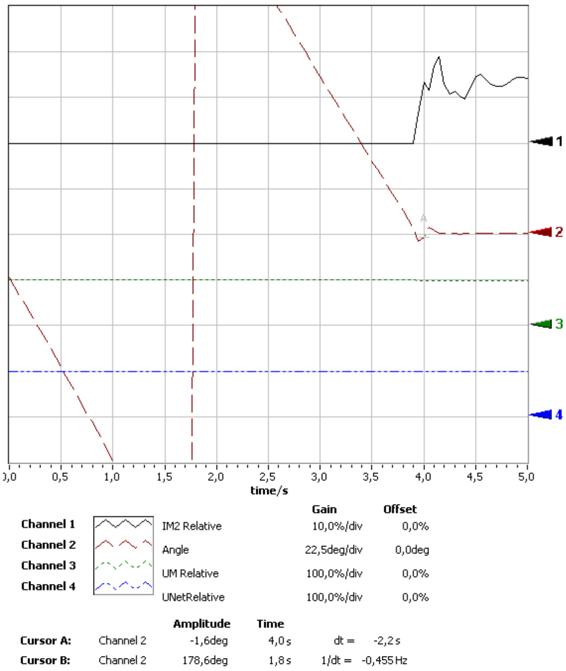


Fig.3.3. The results obtained at the moment of synchronization under condition– generator-network.

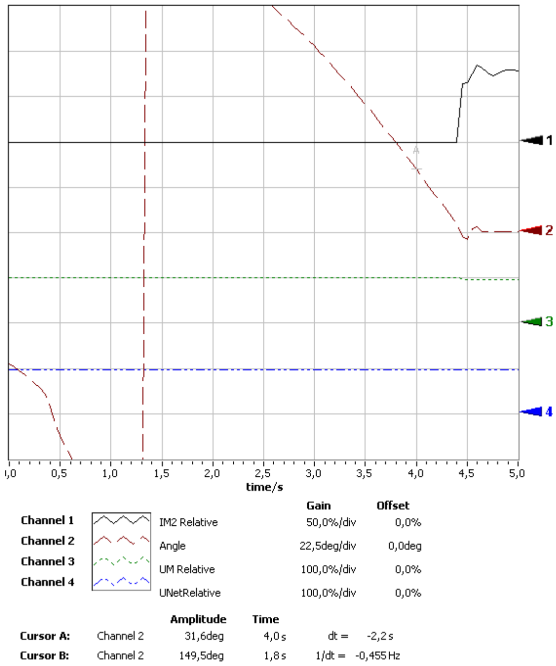
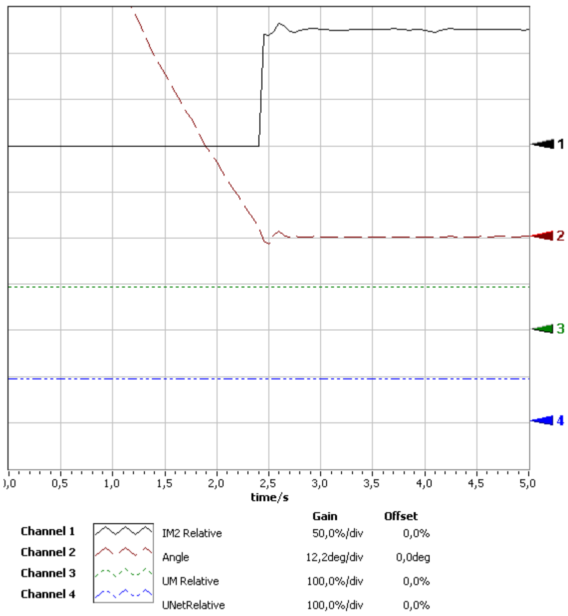


Fig.3.4. The results obtained at the moment synchronization under condition– generator-load.



On the Unitrol's basis there is possible to define synchronization conditions of generator. To determine possible deviation limits on rotation frequency and shift angle of exact synchronization.

Fig.3.5. The results obtained at the moment of synchronization under condition– generator-double load.

From Unitrol data synchronization conditions (current p.u. dependence in time) generator-network with different frequency can be seen (Fig. 3.6.).

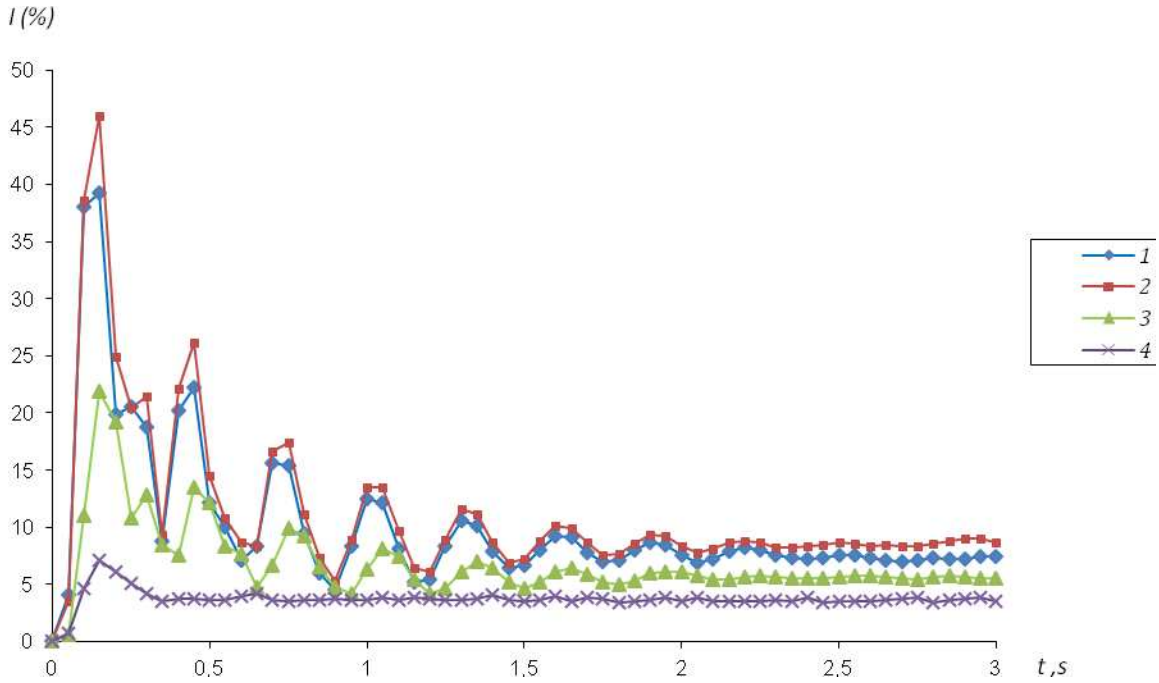


Fig.3.6. Results for cases of coming into a synchronous work are resulted at a deviation from synchronization conditions generator-network (no load) I=f(t), (Unet=Ug, δ=0);

1 – I (f_{net}<f_g, Δf= 0,75 Hz);

2 – I (f_{net}<f_g, Δf= 0,1 Hz);

3 – I (f_{net}<f_g, Δf= 0,5 Hz);

4 – I(f_{net}=f_g);

where

f_{net} - frequency of network;

f_g - frequency of generator;

Δf - frequency diference;

U_{net} - voltage of network;

U_g - voltage of generator;

δ - shift angle.

It is easy to follow how the changing of a parameter affects the overall behavior of the regulator by referring to the power chart and the oscilloscope function. This means, that the optimum settings are found within a short time. The applied model has shown the serviceability.

Also the device allows comparing the networks and generators currents and voltage in the real time.

Four signals can be selected for graphic display parameter files and graphs can be saved in numerical form for later analysis the resolution of the oscilloscope is 50 ms, and a total of 20 channels are recorded.

In this thesis emergency situations of coming into a synchronous work are resulted at a deviation from synchronization conditions generator-network, generator-load and generator-double load, when generator was initiated into engine conditions.

The Unitrol 1000 makes possible to control, analyze and compare theoretical current, power, shift angle results which was received from mathematical models and all components' practical results. It gives possible to check if the mathematical model and its calculating results are correct.

3.2. Comparison of practical and theoretical data

The mathematical model of synchronous generator has been developed and testing the data on synchronization of synchronous generator obtained practically with the help of previously described system UNITROL 1000.

In the dated chapter the results are visualized and represented on startup and synchronization of synchronous generator with network, generator with load, generator with double load.

Mathematical model was constructed in compliance with the principle described above applying equations.

For saturation record on the way of the main flux linkage is required in expressions for currents i_d and i_q to use depending on saturation value of mutual induction impedance which maybe determined by magnetization curve of the machine depending on resulting flux linkage in air clearance of the machine: $x_m=f(\Psi_\delta)$.

For this purpose characteristics of idle run of machine is used. Tables 3.1.- 3.3 present normal (regular) characteristics of idle run and characteristics obtained by experimental method for synchronous machine under research.

Table3.1. *Regular characteristics data of idle run of generator*

i_f, p.u.	0,5	1,0	1,5	2,0	2,5	3,0	3,5
E_0, p.u.	0,58	1,0	1,21	1,33	1,4	1,46	1,51

Table3.2. *Estimated characteristics data of idle run of generator*

i_f, p.u.	0,18	0,25	0,309	0,41	0,57	0,72	0,97	1,39
E_0, p.u.	0,24	0,29	0,41	0,53	0,56	0,74	0,0,99	1,11

Table3.3. *Obtained by practical approach characteristics data of idle run of generator*

i_f, p.u.	0,18	0,25	0,309	0,41	0,57	0,72	0,97	1,39
E_0, p.u.	0,25	0,3	0,4	0,53	0,55	0,73	0,98	1,1

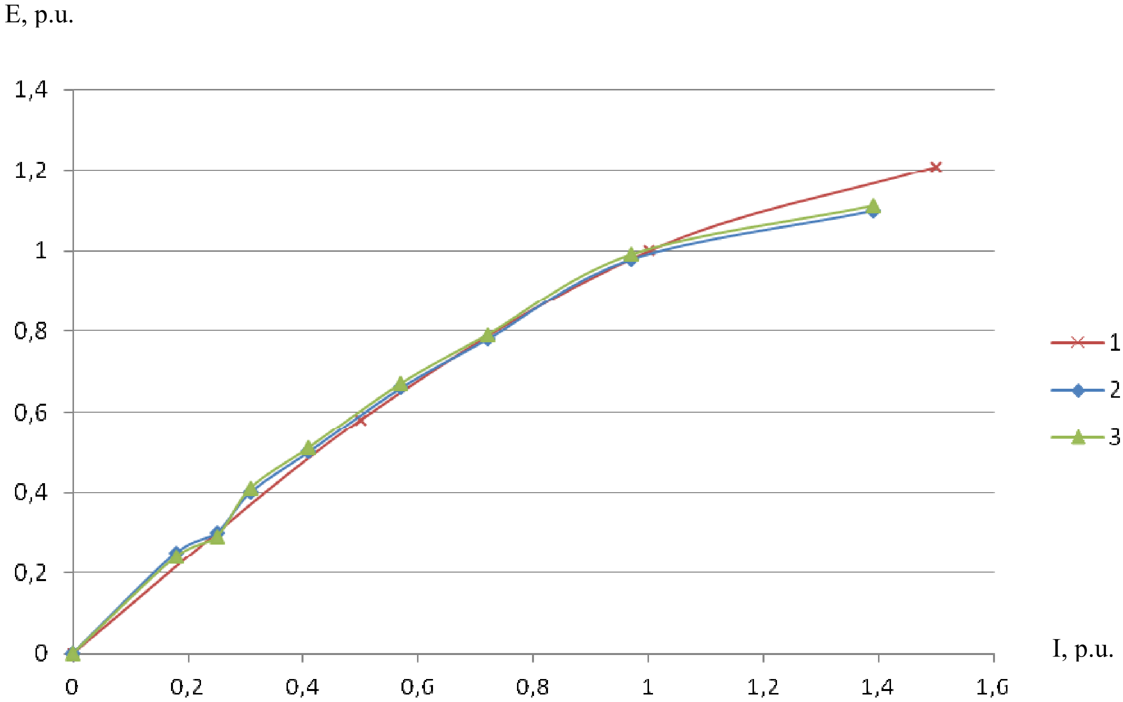
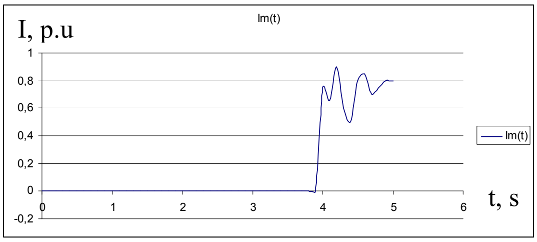


Fig.3.7. Regular(1) obtained by practical approach (3)and estimated (2) characteristics of idle run of the generator.

Lets consider the obtained characteristics of generator current by time. Fig. 3.8 presents characteristics of generator current by time under the first conditions of synchronization generator- network.

Fig. 3.9 presents the characteristics of generator current by time under the second conditions of synchronization generator- load.



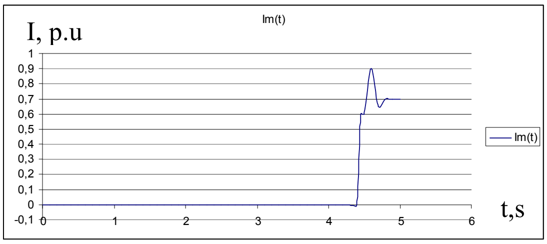


Fig.3.8. Characteristics of generator current by time. Condition - generator-network.

Fig.3.9. Characteristics of generator current by time. Condition generator- load.

Fig. 3.10 shows the characteristics of generator current by time under the third conditions of synchronization generator – double load.

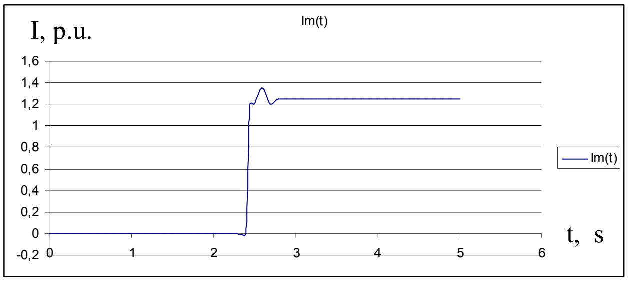


Fig.3.10. Characteristics of generator current by time.

Condition – generator – double load.

Thus the results obtained in the process of mathematical modelling in comparison with practical method obtained characteristics proves the accuracy of model results. The model is operable and obtained results are close to practical results – this solution is coming after respective test. The developed model allows to estimate and analyse parameters of synchronization of synchronous generators under different conditions.

THE MAIN RESULTS OF THE RESEARCH AND CONCLUSIONS

Future development trends of compact electrical power systems prescribe the necessity of research and analysis of control methods of synchronization for generators and sub-systems as one of the most significant tasks to increase operation efficiency. As a theoretical research it is relevant to prove compliance of mathematical methods for solving problems of synchronization of synchronous generators and compact electrical power systems. Recently, control of power system can be provided through flexible control equipment that allows analyzing the problem of direct synchronization of compact electrical power system from different point of view the power compact direct synchronization problems of the new lines.

The main results of the research are summarized in the concluding section of the doctoral thesis. The main results are:

1. The methodology for research of synchronous generators of compact electrical power systems is developed, based on structural modeling approach by using Park-Gorev equations.
2. Proposed models of synchronous generators of compact power system are incorporated into a single system. It is proposed to perform modeling in the system of relative units, where parameters of applied elements are expressed in their base unit. The mathematical model of synchronous generator allows studying the change of synchronous generator parameters at different generator operating modes, including the interaction;
3. On the basis of mathematical models of synchronous generators and static load individual program modules are developed that can be used for the analysis of operation modes as well as for determining of optimal mode parameters of the machine;
4. For the research of transient process the proposed mathematical model allows obtaining the values, that are required during design and operation of electrical machine for choosing devices of relay protection and automation and their proper settings;
5. The developed mathematical model can be used for including compact electrical power system as a component in overall model of power system;
6. Boundary values for stable and efficient parallel operation of components of compact electrical power system are established: the phase shift angle should be from -10 degrees to 10 degrees in the case of generator-grid (connection of a compact power system to an integrated power system);
7. Admissible torque limits from 0.75 to 0.95 relative units are estimated for autonomous compact power system with two or more synchronous generators.

The results obtained in the process of mathematical modelling in comparison with the characteristics obtained practically prove accuracy of the proposed mathematical model. The developed model allows analyzing synchronization parameters of generators under different conditions. Thus, in future for development of synchronizers by using these principles, it will be possible to control movement processes to fulfil precise synchronization.

APPROBATION OF RESEARCH OUTCOMES

List of publications

1. Berziņa K., Ketnere E. The research of mathematical models of local power supply systems with synchronous generator**.** // Scientific Journal of RTU. 4. series., Enerģētika un elektrotehnika. - …vol. (2012) (accepted for publication).
2. Bērziņa K., Ketnere E. Simulation of Gas-Turbine Driven Device // Scientific Journal of RTU. 4. series., Enerģētika un elektrotehnika. - 25. vol. (2009), pp 27-30.
3. Mesņajevs A., Ketnere E., Bērziņa K., Orlovskis G. The Research of Stability of Synchronization Process with Unitrol 1000 Application // Scientific Journal of RTU. 4. series., Enerģētika un elektrotehnika. - 25. vol. (2009), pp 81-86.
4. Ketners K., Ketnere E., Bērziņa K., Latve-Sļesarenoka I. The Research of Stability of Synchronization Process with Mathematical Model's Application of Two Generators // Scientific Journal of RTU. 4. series., Enerģētika un elektrotehnika. - 20. vol. (2007), pp 115-121.
5. Ketners K., Ketnere E., Bērziņa K. Modelling of Stability of Synchronization Process with Various Primary Engines // Scientific Journal of RTU. 4. series., Enerģētika un elektrotehnika. - 19. vol. (2007), pp 115-121.
6. Berzina K., Ketnere E., Ketners K. The Research of Stability of Synchronization Process with Mathematical Model's Application. // Scientific Proceedings of RTU. 4. series. Enerģētika un elektrotehnika 18. vol. (2006), pp 10-18.

List of conferences

1. Ketner K., Berzina K., Ketnere E. The Research of Stability of Synchronization Process with Mathematical Model's Application. 2005. y. Latvija, Riga. 46th International Scientific Conference Power and Electrical Engineering. RTU;
2. Berzina K., Ketnere E. Modeling of stability of synchronization process with various primary engines. 2006. y. Latvija, Riga. 47th International Scientific Conference Power and Electrical Engineering; RTU;
3. Berzina K., Ketnere E. The Research of Stability of Synchronization Process with Mathematical Model's Application of turbogenerator and Diesel engine. 2007. y. Latvija, Riga. 48th International Scientific Conference Power and Electrical Engineering. RTU;
4. Berzina K., Ketnere E. The research of stability of synchronization process with Unitrol 1000 aplication. 2008.y. Latvija, Riga. 49th International Scientific Conference Power and Electrical Engineering. RTU;
5. Berziņa K., Ketnere E. Simulation of gas-turbine driver device. 2008. y. Latvija Riga. 50th International Scientific Conference Power and Electrical Engineering. RTU.