A mathematical model for the virtual simulator of the power unit electrical part

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Abstract. The mathematical model is developed for a virtual training system (simulator) of the power unit electrical part operators of a thermal (nuclear) power plant. The model is used to simulating the main operating conditions of the power unit electrical part: generator idling, generator synchronization with the power system, excitation shifting from the main unit to the backup one and vice versa, switching in the power unit auxiliary system, and others. Furthermore, it has been implemented modelling some probable emergency conditions within a power plant: incomplete phase switching, damage to standard power unit equipment, synchronous oscillations, asynchronous mode, etc. The model of the power unit electrical part consists of two interacting software units: models of power equipment (turbine, generator with excitation systems, auxiliary system) and models of its control systems, automation, relay protection and signalling. The models are represented by the corresponding algebraic-differential equations that provide real-time mapping power unit processes at the operator's request. The developed model uses optimal solving algebraic-differential equations to ensure the virtual process behaviour in real-time. In particular, the implicit Euler method is used to solve differential equations, which is stable when simulating processes in significant disturbances, such as accidental disconnection of the unit from the power system, tripping and energizing loads, generator excitation loss, etc.

1. Introduction
Safe, reliable and efficient operation of a power plant can only be achieved with qualified service personnel. Their theoretical knowledge and practical experience assess the qualifications of the personnel. The operator experience allows avoiding mistakes and wrong decisions in planned or emergency scenarios of the power plant operation, excluding the possible production losses, equipment damage and even the power system blackout. Therefore, the operator must determine the correct sequence of actions in various operating situations. Suppose the operator did not faced some possible situations during the station operation. In that case, a virtual simulator can design them artificially in real time and display the process on the mnemonic control panel of the power plant or power unit. To this aim, various training systems have been created, ranging from the simplest, which studies the technical characteristics of power plant equipment, the basics of power unit management and improved training systems that reflect the behaviour of power units during operational management. The latest training systems, the so-called full-scale simulators or high-fidelity power plant simulators, utilize real-time scenarios as in an actual power plant [1, 2]. These simulators use...
powerful servers and can be adapted to create different challenges during actual power plant operations. The cost of development, creation and operation of such complexes reaches several million dollars [1].

It is possible to improve the quality of training of operational personnel of power plants due to the use of specialized (local) training systems [3]. These systems allow you to practice operational management of individual systems of the power unit, such as a steam generator (or its particular elements), a nuclear reactor, turbine, generator, etc. [4, 5].

2. Virtual training simulator outline

The authors have developed a virtual training simulator (VTS) to train operational personnel to control the electrical part of the power unit of both thermal and nuclear power plants [6]. Using a personal computer (PC) for the VTS operation essentially reduces its cost. In the presented system, in contrast to the full-scale simulator, there are no special technical means (control keys, switches, control devices, etc.) that reproduced the instruments of the control, monitoring and signalling of an actual power plant unit. The absence of these traditional control and monitoring bodies is not an essential shortcoming of the proposed system because PC control is widely used at modern power plants.

The developed VTS consists of two subsystems. The first subsystem carries out modelling technological processes in the power unit electric part. Such modelling should reproduce the unit electrical part behaviour in real-time at long-lasting intervals. For operational control, virtual models of panels and motor fields have been created. The VTS allows training the managing the electrical part of the unit during normal, abnormal and emergency operating conditions: generator idling, generator synchronization with the power system (manual, automatic), control of active and reactive power during unit operation, excitation shifting from the primary unit to the backup one and vice versa, shifting power supply of auxiliaries bus sections from the main transformer to the backup and vice versa, partial and complete loss of the generator excitation, power system synchronous oscillations, load asymmetry, etc.

The training subsystem implements the following operations: auto-simulator, demonstration, self-training, self-checking.

**Auto-simulator mode** is an operation without a scenario under the initial conditions defined by the selected exercise. The operator carries out any free actions, limited only by the technology requirements of the power unit electrical part (parametric restrictions, operation of relay protection devices and automation, etc.).

**Demonstration mode** is a step-by-step implementation of the selected exercise. All actions to control the unit electrical part are performed automatically; the operator only contemplates the consequences of acting.

**Self-training mode** is an operation by the scenario without a time limit with the indication of mistakes and the ability to seek help from the training subsystem.

**Self-checking mode** is an operation by the time-limited scenario, analyzing the number and importance of mistakes with quantitative assessment of the trainee for a given exercise.

Scenarios represent a sequence of actions that the operator must perform during the execution of a given exercise. A system of encoding and decoding actions to perform a given exercise has been developed to generate scenarios.

3. The mathematical model for virtual simulator

The mathematical model is developed for a virtual training system (simulator) of the power unit electrical part operators of a thermal (nuclear) power plant. The model of the power unit electrical part consists of two interacting software units: models of power equipment (turbine, generator with excitation systems, auxiliary system) and models of its control systems, automation, relay protection and signalling. The models are represented by the corresponding algebraic-differential equations that provide real-time mapping power unit processes at the operator's request. The developed model uses optimal methods for solving algebraic-differential equations to ensure the virtual process behaviour in
real-time. In particular, the implicit Euler method is used to solve differential equations, which is stable when simulating processes in significant disturbances, such as accidental disconnection of the unit from the power system, tripping and energizing loads, generator excitation loss, etc.

3.1. Turbine model

A simplified turbine model with automatic speed control has been developed to simulate the generator idling, its synchronization with the power system, active power control during regular operation. The model is written for per unit variables as follows:

$$TP\frac{d\psi}{dt} = \begin{cases} 0, \mod(\psi - \mu_p) \leq b_{ZH}; \\ \text{sign}(\psi - \mu_p - b_{ZH}) \cdot \mod(\psi - \mu_p); \end{cases}$$

$$\psi = \frac{(\omega_0 - \omega_G)}{\delta};$$

$$MT = \mu_p,$$

where $TP, b_{ZH}, \delta$ is time constant, characteristic of the insensitivity and automatic speed controller slope, respectively; $\mu_p$ is rod move of the servomotor controlling the turbine control valves, in per units; $\omega_0$ is frequency setpoint for the automatic speed controller; $\omega_G$ is turbogenerator rotor speed; $\psi$ is a position of the centrifugal pendulum clutch for automatic speed controller; $MT$ is the turbine torque.

3.2. Turbogenerator electromagnetic model

The turbogenerator model implements Park equations of the synchronous machine in $d$, $q$ coordinates. The model accounts for rotation e.m.f., without the impact of transformation e.m.f. and equivalent damping circuits on the generator stator voltage because they present only in transients. Rotor damping circuits is used in the generator rotor swing equations. Therefore, the electromagnetic model of the turbogenerator is as follows:

$$\begin{bmatrix} Ud \\ Ud \end{bmatrix} - \begin{bmatrix} r & 0 & \omega_G L_q \\ 0 & r_f & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} 0 \\ -\omega_G L_d - \sqrt{3/2} \omega_G L_{ad} \end{bmatrix},$$

where $U_d, U_q, I_d, I_q$ is components of turbogenerator stator voltage and current vectors for the $d$ and $q$ axis; $U_f, I_f$ is excitation winding voltage and current; $r, r_f$ is resistances of the stator and excitation windings; $L_d, L_q$ is $d$ and $q$ stator winding inductance components; $L_{ad}$ is the mutual inductance between the stator and the excitation windings for the $d$ axis.

3.3. Turbogenerator electromechanical model

Changing rotation speed of the turbine-generator shaft accompanies electromechanical operating conditions (for example, the unit idling, asynchronous mode, power unit synchronization). To modelling those conditions, the turbogenerator swing equation supplements the VTS mathematical model:

$$T_J \frac{d\omega_s}{dt} = M_T - M_{EM} - M_0,$$

where $T_J$ is the inertia constant of the power unit; $M_T$ is turbine torque; $M_{EM}$ is electromagnetic torque; $M_0$ is the mechanical loss torque.

The electromagnetic torque in the per units considering equal inductances along the $d$ and $q$ axis is as follows:

$$M_{EM} = \frac{1}{3} \left( L_{ad} I_q (I_d + I_f) - L_{ad} I_d I_q \right) + M_D \omega_s,$$

where $M_D$ is a damping factor; $\omega_s$ is the slip frequency.
The mechanical loss torque accounts for the purely mechanical power loss due to friction in the bearings:

\[ M_0 = a_1 \omega_G + a_2 \omega_G^2 + \frac{a_3}{a_4 + a_5 \omega_G}, \]  

(5)

where the coefficients \( a_1, a_2, a_3, a_4, a_5 \) are constant for the specific turbine.

The following equations relate the generator stator \( d, q \) voltage components and the power system voltage:

\[ U_d = U_c \cdot \sin \delta + x_c I_{cq}; \]
\[ U_q = U_c \cdot \cos \delta + x_c I_{cd}, \]  

(6)

where \( U_c \) is the power system voltage reduced to the generator voltage; \( x_c \) is the power system reactance; \( \delta \) is the rotor angle; \( I_{cq}, I_{cd} \) is longitudinal and transverse current components supplied by to the system, and

\[ I_{cl} = I_d - I_{dBB}; \]
\[ I_{cq} = I_q - I_{qBB}, \]  

(7)

where \( I_{BB}, I_{BB} \) – power unit auxiliaries current components.

When supplying power unit auxiliaries from an auxiliary transformer, the current of the transformer is determined within the unit auxiliary model. In the case of connecting electric drives of the unit auxiliary to the standby transformer, \( I_{BB}, I_{BB} \) are assumed to be equal to zero. Equations (6) and (7) are supplemented by an equation that relates the generator angular frequency and the system angular frequency:

\[ \frac{1}{\omega_{nom}} \frac{d\delta}{dt} = \omega_G - \omega_c, \]  

(8)

where \( \omega_{nom} \) is the nominal angular frequency, \( \omega_c \) is the system angular frequency.

3.4. Turbogenerator excitation system model

Modern power units use, as a rule, thyristor or brushless excitation systems for powering the generator field winding. The automatic control of the excitation systems is equipped with power system stabilizers (PSS). The model of such an excitation system is presented as follows:

\[ e = k_{0U} \cdot (U_G - U_0) + k_{1U} \frac{dU}{dt} + k_{1f} \frac{df}{dt}; \]
\[ e_{min} \leq e \leq e_{max}; \]
\[ U_f = e, \]  

(9)

where \( e \) is the signal at the output of the controller; \( U_0 \) is controller voltage setting of the generator; \( k_{0U}, k_{1U}, k_{1f} \) are gains of the corresponding controller channels, \( e_{min}, e_{max} \) are the controller output signal limits.

Because the power system within the model is presented as a source of constant frequency and voltage, the model of the controller has no channels for frequency deviation and frequency derivative. The controller model can perform several other functions: excitation forcing, rotor current limiting when forcing at double level, automatic generator unloading when excitation overcurrent, automatic setpoint change during synchronization, limiting field current when reactive power consumption, and generator overvoltage protection at unexpected load tripping.

3.5. Auxiliaries model
The main components of the power unit electrical part are powerful induction motors (IM). The following equation presents the IM rotor electromechanical motion:

\[ F(s_i, t) = T_{ji} \frac{d}{dt} s_i - M_{EMi} + M_{Ci} = 0, \]  

(10)

where \( T_{ji} \) is the mechanical time constant of the \( i \)-th drive; \( M_{EMi} \) is the motor shaft electromagnetic torque; \( s_i \) is the \( i \)-th IM rotor slip.

In the general case, a mechanical moment of a drive is a nonlinear dependence on the IM rotor rotation speed [7]. In the elaborated model, the mechanical moment is determined by a function:

\[ M_{Ci} = k_{zi} \left( M_{CTi} + (1 - M_{CTi}) \left( \frac{1 - s_i}{1 - s_{nomi}} \right)^{n_i} \right), \]  

(11)

where \( k_{zi} \) is the degree of the \( i \)-th mechanism loading; \( M_{CTi} \) is the initial mechanical moment of the \( i \)-th drive (at slip frequency \( s_i = 1 \)); \( s_{nomi} \) is the IM nominal slip; \( n_i \) is the \( i \)-th mechanism type exponent (for mechanism with a non-slip dependence \( n_i = 0 \), for fan \( n_i = 2 \), for different pump types, the value of \( n_i \) varies between 2 – 4).

To the IM shaft electromagnetic torque model \( M_{EMi} \) we used a multi-contour electrical circuit, accounting for the rotor current skin effect [8].

3.6. Solving Model Equations

The developed model uses optimal methods to solving algebraic-differential equations ensuring the virtual process behaviour in real-time. In particular, the implicit Euler method is used to solve differential equations, which is stable when simulating processes in significant disturbances, such as accidental disconnection of the unit from the power system, tripping and energizing loads, generator excitation loss, etc.

The system of differential equations of the developed model in the implicit Euler method can be represented as:

\[ \dot{\mathbf{y}}_{k+1} - h \cdot \mathbf{f}(\mathbf{y}_{k+1}, t) = 0, \]  

(12)

where \( \mathbf{y}_{k+1} \) is a vector of the operating condition parameters at a given integration step; \( \dot{\mathbf{y}}_k \) is a vector of the operating condition parameters at the previous integration step; \( \mathbf{f}(\mathbf{y}_{k+1}, t) \) is a vector-function of these operating condition parameters; \( h \) is an integration step.

The vector of the operating condition parameters for the mathematical model of the power unit electric part (without auxiliaries), concerning which the algebraic-differential equations is solved, can be presented as follows:

\[ \mathbf{y} = (\mu_p, \omega_G, \delta, U_d, U_q, I_d, I_q, I_f, U_p). \]  

(13)

Newton’s method with the following iterative formula is used to solve the equations (11):

\[ \mathbf{W}(\mathbf{y}_{k+1}^{(l)}) \cdot \mathbf{A}_{k+1}^{(l)} = \mathbf{y}_{k+1}^{(l)} - h \cdot \mathbf{f}(\mathbf{y}_{k+1}^{(l)}, t); \]

\[ \mathbf{y}_{k+1}^{(l+1)} = \mathbf{y}_{k+1}^{(l)} - \mathbf{A}_{k+1}^{(l)} \]  

(14)

where \( \mathbf{y}_{k+1}^{(l)} \) is a vector of the operating condition parameters for the \( l \)- iteration at the \( k+1 \) integration step; \( \mathbf{W}(\mathbf{y}_{k+1}^{(l)}) \cdot \mathbf{A}_{k+1}^{(l)} \cdot \mathbf{f}(\mathbf{y}_{k+1}^{(l)}, t) \) is the Jacobi matrix of the equations (12).

The solution of the equations (14) is carried out by the LDU transformation algorithm based on the Gaussian method. According to this algorithm, the original system of equations is rearranged to obtain the minimum number of non-zero coefficients during the transformation of the Jacobi matrix; trivial operations are excluded (multiplication and addition of zero, multiplication by 1, etc.). In order to optimize the solution of the equations (14), the Jacobi matrix is written in tape form. This solution
optimization is primarily aimed to achieve real-time simulations. Software implementation of digital models was carried out in the programming environment Lazarus [9]. The use of this software environment allows compiling a program to work in different operating systems.

4. Modelling virtual simulator interface

The power unit electrical part model is managed by the model of the power block control panel, which displays on the computer monitor a mnemonic control panel with monitoring and signalling devices. Based on object-oriented programming technologies has been created a specialized editor for designing a power unit control panel, including the location and appearance of control devices and switches, their connection to the power circuit, as well as the emergency and process signalling boards. Then the appearance of the managing, monitoring and signalling devices on the control panel model and their mutual placement corresponds as much as possible to the prototype of the actual control panel.

A blender package for 3D graphics modelling was used to create graphic images of control panel components [10]. To simulating the control, monitoring and signalling devices of the power unit electrical part control panel, a library of the model components has been created.

The use of cyclic rendering (Cycles Render) provided high-quality images of the model components on the LCD monitor, as close as possible to their actual appearance. To visualize the labels and device arrows, the additional module BGRABitmap was used, and antialiasing and transparency effects were applied, which significantly improved the realism of displaying control and monitoring devices on the LCD monitor.

The developed virtual training simulator for a 300 MW power unit of a thermal power plant was commissioned in the Ukrainian power system. Figure 1 depicts a display of the turbo generator TGV-300 control panel fragment on a liquid crystal PC monitor of the Virtual Training Simulator.

![Figure 1. PC monitor display of the turbo generator TGV-300 control panel fragment.](image)

5. Conclusions
The developed virtual training system (VTS) aims to train operational personnel to manage the power unit electrical part of a thermal or nuclear power plant. The mathematical model of the power unit electrical part, including its digital implementation, allows simulating electromechanical processes in real-time at long intervals with the required accuracy. The use of special programming tools has allowed obtaining high-quality graphic images of the control panel components on a PC monitor, enhancing the sense of reality when working with the virtual training system. The developed virtual training system can be used in the curriculum of power engineering students to gain knowledge in the field of operational management of power plants.

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