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INTELLIGENT CONTROL OF THE REGULATORS ADJUSTMENT OF THE DISTRIBUTED GENERATION INSTALLATION

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Abstract

In the power supply systems of railways (PSSR), which include distributed generation systems (DG), intelligent technologies for controlling modes are fully applicable. To form the necessary characteristics of the transient process, the DG installations must be equipped with automatic control systems, the optimal adjustment of which allows improving the quality of electricity and improving the reliability of the electricity supply to consumers. The article describes the technique of coordinated tuning of automatic excitation regulators (AER) and the rotation speed (ARRS) of synchronous generators in

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relation to the installation of a DG operating in the PSSR. A feature of the proposed methodology is the use of the following intelligent technologies: a genetic algorithm (GA) to optimize the settings of AER and ARRS; fuzzy logic for adaptive control of the coordinated tuning of AER and ARRS. On the basis of the simulation, the efficiency of using the proposed adaptive AER and ARRS control unit of the generator of the RG setup is shown, which consists in reducing the transient time and the voltage overshooting and rotational speed of the generator rotor, and in providing the necessary stability margin and in the system's ability to maintain the standard voltage and quality of electric power at consumers at disturbances in system.

1. Introduction

At the present stage of the development of civilization, technical systems (TS) become self-controlled through the use of intellectual components, as a result of which the transfer of managerial functions from man to the built-in subsystems, that are part of the TS, is realized. In addition to the intellectualization of the TS, the use of intelligent information technologies (IIT) is expanding, the application of which in practice implies taking into account the specifics of the problem area.

Rail transport is a fairly capacious consumer of energy resources. In electrical networks, feeding traction substations of main railways, as well as in power supply systems of railways (PSSR), intelligent technologies are fully applicable.

Intellectual PSSRs may include the following segments:

- Developed complexes that monitor the condition of electrical equipment, including devices operating on-line;
- Automatic control devices based on digital technologies;
- Phase-controlled sources of reactive power;
- Distributed generation devices (DG) and power storage units;
- Direct current insertions (DCI);

- A set of devices for improving the quality of electricity, including active conditioners of harmonics (ACG), symmetry transformers and other devices.

At present, a lot of research has been done on the application of IIT in power supply systems [1-7]. In this paper, the methods and algorithms using IIT are presented for tuning the regulators and controlling the DG installations based on synchronous generators operating in the PSSR.

2. Intelligent Controllers for Distributed Generation Installations

When solving the problems of using distributed generation technologies on railways, it is necessary to consider the peculiarities of the PSSR, that distinguish them from general-purpose power supply systems: the sharply variable nature of single-phase traction loads, the presence of asymmetry and harmonic distortion. In this connection, it is better to connect the DG installations to the PSSR through the direct current insertions (DCI) using modern conversion technology. This makes it possible to limit the short-circuit power on the buses of the DG sources, improves the quality of electric power and gives the electric power supply to consumers the nature of the guaranteed power supply [8].

To form the necessary characteristics of the transient process, the DG installations must be equipped with automatic control systems, the optimal adjustment of which allows improving the quality of electricity and improving the reliability of the electricity supply to consumers. Below is described the technique of coordinated setting of automatic excitation regulators (AER) and rotational speed (ARRS) of synchronous generators [9, 10] with reference to DG the installation, operating in the PSSR. A feature of the proposed methodology is the use of the following intelligent technologies: a genetic algorithm (GA) for optimizing the settings of AER and ARRS [11]; fuzzy logic for adaptive control of the coordinated tuning of AER and ARRS. In addition, the following methods of digital signal processing are used in the proposed technique: wavelet transform to isolate the noise of regulators, used in object identification [11]; fast Fourier transformation for obtaining the spectra of signals, used in identification; technology to smooth out the empirical evaluation of the complex transfer factor of the system, based on the use of weighted windows.

In view of the relatively low power of the DG installations and the low constant inertia of the rotors of their generators, the task of coordinating adjustment of AER and ARRS is of particular relevance. The importance of this task can be illustrated on the basis of the classical circuit of a generator operating on an infinite power bus (Figure 1).

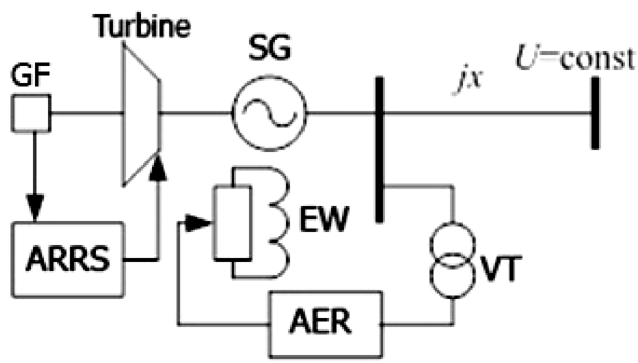


Figure 1. A generator working on infinite power bus: SG - synchronous generator; GF - the gauge of rotation frequency; VT - voltage transformer; EW - excitation winding.

The equation of the rotor motion for this circuit can be written as follows:

$$\frac{d\Delta\omega(t)}{dt} = \frac{1}{T_J}\left[M_T(\omega_0 + \Delta\omega(t)) - \frac{E_q(i_f)U_G}{x}\sin\left(\delta_0 + \int_0^T \Delta\omega(t)dt\right)\right], \quad (1)$$

where T_J is the generator's inertia constant, M_T is the mechanical moment of the turbine, E_q is the EMF of the generator, ω_0 is the synchronous rotor speed, i_f is the current in the excitation winding, x is the generator resistance and communication with the system, δ_0 is the initial value of the load angle (the angle between the EMF vectors E_q and the generator voltage U_G).

Voltage on the generator bus is determined by the expression:

$$\dot{U}_G = \dot{E}_q - j\dot{I}_G x_G,$$

where I_G is the generator current, x_G is the generator resistance.

It follows from equation (1) that the acceleration $\frac{d\Delta\omega(t)}{dt}$ of the rotor is inversely proportional to the moment of inertia. For DG installations with small values, the variations in speed will be significant. Therefore, for DG installations, coordinated regulation of electrical and mechanical parameters is required. Such regulation can be realized on the basis of the ideas of [10]. The principle of consistent tuning is to determine the adjustment coefficients of the AER and ARRS providing minimum deviations of the generator parameters from the nominal values, high damping properties for electromechanical transient processes and the required stability margin.

Determination of optimal control factors for AER and ARRS systems with their coordinated tuning presupposes obtaining a mathematical description of the system under investigation in the form of a characteristic polynomial. For this, the method of nonparametric identification is used, according to which the system is regarded as a "black box", and on the basis of priori information about the process, the numerical values of the complex transfer coefficient are determined, as a ratio of the spectra of the output and input signals of the object [10]. The characterization of the characteristic polynomial of a closed regulated system "turbine-generator" is performed according to the following expression:

$$D^M(j\omega) = \det[E + W_G(j\omega) \cdot W_R(j\omega)], \tag{2}$$

where E is the identity matrix, $W_G(j\omega)$ is the matrix transfer function of the regulation object ("turbine-generator" system), which is proposed to be determined experimentally, $W_R(j\omega)$ is the matrix transfer function of the regulator, taking into account the relationship between AER and ARRS: $W_R(j\omega) = \begin{bmatrix} W_{\text{ARRS}}(j\omega) & W_{\text{AER}}^{\omega}(j\omega) \\ 0 & W_{\text{AER}}^{U}(j\omega) \end{bmatrix}$, $W_{\text{ARRS}}(j\omega)$ is the complex ARRS transfer coefficient $W_{\text{AER}}^{\omega}(j\omega)$ is the complex transmission factor of the ARE control channel by frequency, $W_{\text{AER}}^{U}(j\omega)$ is the complex transmission factor of the ARE control channel by voltage.

To obtain accurate transfer functions of the control object during identification, it is expedient to use test broadband signals. Since interference in the operation of power supply systems is undesirable, it is proposed to use an approach in which the test effect is performed on the basis of the allocated noise of the regulators using wavelet transform [11], which allows localizing the signal both in frequency and in time:

$$W(s,\ \tau) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} f(t) \cdot \psi\left(\frac{t-\tau}{s}\right) dt, \tag{3}$$

where $f(t)$ is the original signal, $\psi(t)$ is the wavelet, taken as the basis, τ is the shift, s is scale, t is the time.

In wavelet analysis, the signal is decomposed into components representing a smoothed signal and oscillations determined by the detail coefficients that are processed when the noise is extracted. In real systems, the noise amplitudes are smaller than the amplitudes of the main signal. Therefore, to remove noise, zero values of the coefficients can be made, which do not exceed the preset threshold level. The choice of the threshold level determines the quality of noise reduction, which is estimated as a signal-to-noise ratio.

The frequency characteristics constructed from the transmission functions obtained in this way turn out to be not sufficiently smooth. Therefore, in order to generate more reliable estimates of system parameters, it is necessary to carry out additional processing of the obtained models. To do this, you can use the method of smoothing the empirical evaluation of the complex transfer coefficient of the system, based on the use of weighted windows [12]. This technique assumes the use of an estimate based on a consistent averaging of the frequency characteristics for each spectrum of a discrete sample of the system signals under study, instead of the complex transfer coefficient obtained in the identification:

$$W'(j\omega) = \frac{\int_0^{\omega} W_\gamma(\omega) \cdot |U(j\omega)|^2 \cdot W_S(j\omega) d\omega}{\int_0^{\omega} W_\gamma(\omega) \cdot |U(j\omega)|^2 d\omega}, \quad (4)$$

where $W_S(j\omega) = \dfrac{Y(j\omega)}{U(j\omega)}$ is the complex transfer coefficient of the system obtained during identification, $U(j\omega)$ is the noise spectrum of the input signal of the system being identified, $Y(j\omega)$ is the noise spectrum of the output signal of the system being identified, $W_\gamma(\omega)$ is the weight function or weight window.

After identifying the control object, it is possible to determine the optimum regulator adjustment factors by solving the optimization problem with the help of GA, which minimizes the following quadratic criterion:

$$J = \int_0^{\Omega} e^2(j\omega) \to \min, \quad (5)$$

where $e(j\omega) = D^D(j\omega) - D^M(j\omega)$ is the discrepancy between the desired and the model sets of coefficients of the characteristic polynomials, ω is current frequency value from the range $[0; \Omega]$, which determines the “bandwidth” of the system. As desired polynomials, Butterworth polynomials or others can be used.

In connection with the fact that the magnitude of the error $e(j\omega) = \mathrm{Re}(\omega) + j\mathrm{Im}(\omega)$ is complex, difficulties arise in minimizing the functional (5). Therefore, it is expedient to use linear convolution:

$$J = \frac{1}{2} J_{\mathrm{Re}} + \frac{1}{2} J_{\mathrm{Im}} \to \min, \quad (6)$$

where J_{Re}, J_{Im} are the criteria corresponding to the closeness of the hodographs in ranges of real and imaginary values. These criteria are formed as follows:

$$J_{\text{Re}} = \int_0^{\Omega} (\text{Re}\, D^D(\omega) - \text{Re}\, D^M(\omega))^2 d\omega,$$

$$J_{\text{Im}} = \int_0^{\Omega} (\text{Im}\, D^D(\omega) - \text{Im}\, D^M(\omega))^2 d\omega. \quad (7)$$

The minimized functional (5) has a large number of local extrema, therefore it is advisable to perform the search for a global minimum in the presented problem by means of a genetic algorithm. The works aimed at implementing various modifications of GA are devoted to the tasks aimed at optimizing the settings of automatic regulators with the help of GA [13, 14] and the use of known GA variants for tuning automatic control systems [15-17], as well as research on the effectiveness of GA and its search properties improvement. The difference between this work is that the GA is used to solve the problem of reconciling the settings of the AER and ARRS of the generators of the DG installations, as well as the use of the proposed adaptive GA. Adaptivity of the algorithm consists in automatic selection of the initial population, the optimal value of the probability of crossing and mutation for a particular task.

The proposed algorithms for the coordinated tuning of AER and ARRS of generator of the DG installations were implemented in a specialized software complex [18].

It should be noted that identification and consistent configuration of the AER and ARRS systems of the generators of the DG installation for several operating modes of the PSSR (for example, for the minimum and maximum load modes). As a result, you can get a set of optimal settings for all predicted modes, which will create a basis for the rules of the adaptive regulator of the DG installation. Such adaptive control system can be based on fuzzy logic technology and artificial neural networks, which allows to determine the operating mode of the PSSR and change the adjustment coefficients of the AER and ARRS to the optimal for the current mode.

In this paper, as an adaptive system that changes the adjustment ratios of AER and ARRS, it is proposed to use a fuzzy control system, integral parts of which are: a fuzzy logic inference system consisting of blocks of phasing and dephasing, and a knowledge base containing a rule base and an output block. The rule base of the proposed system is formed according to the "If-then" form using the technique of consistent setting of AER and ARRS [9, 10].

3. Description of the Model and the Research Results

The studies were carried out in the MATLAB environment in the context of structural diagram of the PSSR, shown in Figure 2. A separate region of power supply for non-traction consumers (RPS) was modeled, including the installation of a DG, which feeds a group of loads with a capacity of 5.5 MV·A, combined into a network cluster based on the DCI. The power of the DG setup was 3 MV·A. Automatic control of the active and reactive power of the DG installation was carried out using AER and ARRS, controlled by a fuzzy controller.

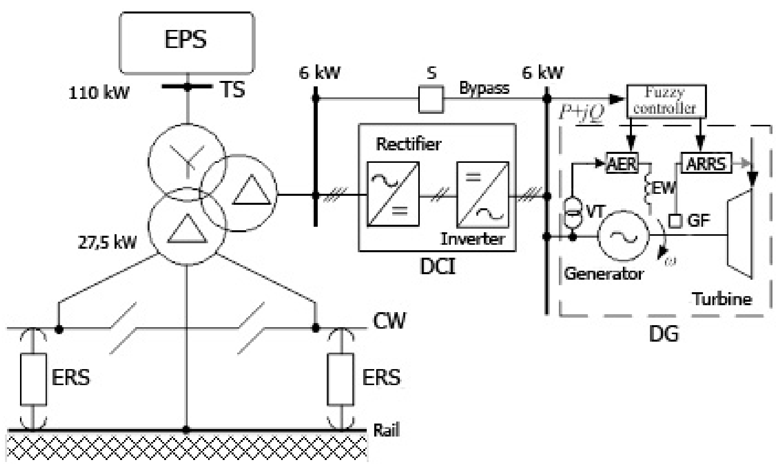


Figure 2. Fragment of the power supply system of the railway: EPS - electric power system; TS - traction substation; ERS - electric rolling stock; CW - contact wire; AER - automatic excitation regulator; ARRS - automatic regulator of rotation speed; GF - gauge of rotation frequency; EW - excitation winding; VT - voltage transformer; S - switch.

The model of the system under investigation was created using the Simulink and SimPowerSystems packages in the MATLAB environment.

The generator of the DG installation was simulated by the standard block of the SimPowerSystems library of the MATLAB system - Synchronous Machine p.u. Fundamental. The steam turbine model is represented by the following transfer function:

$$W(s) = \frac{P_T}{\mu} = \frac{1}{T_T s + 1},$$

where P_T is the turbine power, μ is the opening of the regulatory body, T_T is the turbine time constant, determined by the delay in the conversion of steam energy into mechanical energy (in the simulation it was assumed equal to 0.2 s), s is the complex variable.

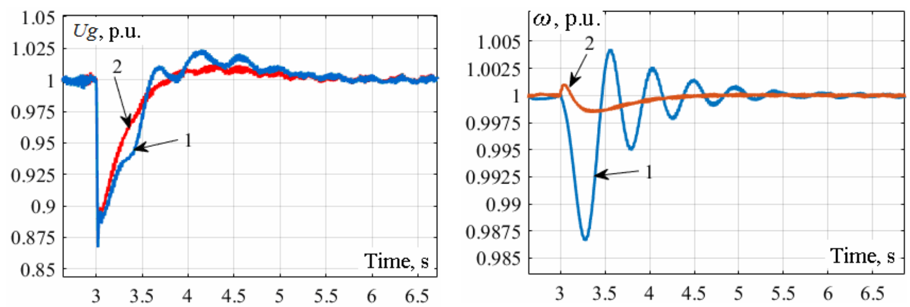
The thyristor exciter was modeled by a first-order aperiodic link with a coefficient k_e, a time constant T_e, and a voltage-limiting block. At modeling the following values of parameters were accepted: $k_e = 1$; $T_e = 0.025$ s.

To regulate the frequency and voltage of the generator, microprocessor AER and ARRS are used in the model, the description of which is given in [9, 10]. The reconciliation of the AER and ARRS settings of the generator of the DG setup, as well as the formation of the base of the fuzzy regulator rules, was carried out with the help of a specialized software package [18]. AER and ARRS settings were defined for two modes: minimum mode (generator loaded to 50%) and maximum mode (generator load is 100%). The model provided for the possibility of introducing disturbances in the form of switching off or connecting an additional load and simulating a three-phase short circuit (SC), which was considered by the control system as the maximum mode.

To analyze the effect of the proposed adaptive control system on the coordinated tuning of AER and ARRS on the parameters of electromagnetic and electromechanical transients, the following regimes were considered:

- connection of additional load;
- occurrence of short circuit on 6 kV buses and its disconnection by relay protection after 0.5 s.

The results of computer simulation show the effectiveness of using the proposed adaptive control unit for AER and ARRS parameters of the generator of the DG setup, consisting in reducing the transient time and overshooting the voltage and rotational speed of the generator rotor, and in providing the necessary stability margin and in the system's ability to maintain the standard voltage and power quality at consumers at disturbances in system. The simulation results confirming these conclusions are shown in Figures 3 and 4.



(a) (b)

Figure 3. Oscillograms of the voltage (a) and rotor speed (b) of the generator when additional load is connected: 1 - without changing the adjustment factors of AER and ARRS; 2 - using a fuzzy controller that changes the settings of the AER and ARRS.

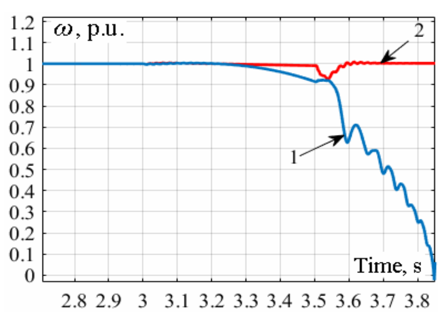


Figure 4. Oscillograms of the rotor speed of the generator when a short-circuit with duration 0.5 s appears on the tires of a non-traction consumer at time 3: 1 - without changing the adjustment factors of AER and ARRS; 2 - using a fuzzy controller that changes the settings of the AER and ARRS.

Thus, used in the methodology of coordinated adjustment of digital signal processing controllers and intelligent technologies, it became possible to form the knowledge base of adaptive control system for a distributed generation installation, operating as part of the power supply system of railway. The intellectuality of the proposed system can be increased through the use of artificial neural networks and more detailed ranking of the possible modes of operation of the distributed generation system when compiling a knowledge base.

Conclusion

1. An adaptive control system for the parameters of the regulators of a distributed generation installation is proposed, based on the application of the harmonized tuning technique and intelligent technologies.

2. The results of computer simulation allow us to make conclusion about the effectiveness of the fuzzy adaptive control unit application by the coordinated setting of automatic regulators of the generator of the distributed generation system. When using an intelligent control system, the transient time and voltage overshooting and rotor speed of the generator are reduced, and the stability and survivability of the power supply system under various operating modes are ensured.

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