The Development of an Isolated Electric Power System Model to Determine the Voltage Dips During the Induction Motor Start

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Abstract: - The article develops a model of an isolated electric power system with three diesel-generator units to calculate the voltage dip when the induction motor is connected. The necessity to estimate the voltage dip when connecting the induction motor to the generator is substantiated, and for this purpose a model experiment is proposed to be used. A block diagram of a power plant model for calculating voltage dips is presented. Algorithms of the synchronization system and power distribution system between generators in the form of digital automata have been developed. The use of transition graphs as a specification language for the description of operation algorithms of automation tools allows their software implementation on the basis of microprocessor technology. The modeling of the power plant operation in dynamic modes was carried out; oscillograph records of voltage dips when connecting induction motors of various rating were obtained. A software shell has been developed allowing the power station operator to estimate the magnitude of the voltage dip when an induction motor is connected, and, if necessary, to change the power station operation mode by connecting an additional generator to provide power reserve.

Key-Words: - isolated power plant, diesel-generator, induction motor, voltage dip, modeling, digital automaton, transition graph.

1 Introduction

The alternating current generators of isolated electric power systems (IEPS) shall meet certain requirements to ensure high quality of voltage maintenance and regulation at load connection and rejection, especially when squirrel-cage induction motors are started. Normal operating conditions for current-using equipment and its switching and controlling equipment, reliable starting of electric motors and generators stability depend on fast and accurate voltage maintenance at generator terminals within the specified limits. A squirrel-cage induction motor (IM) is the main type of motors in isolated AC power stations. The power of some induction motors is 15-25% of the power capacity of the power plant generator. The normal operating conditions of an isolated power plant are mostly characterized not by static, but by dynamic modes of operation. It is known that the value of the initial starting current of an induction motor is determined by the very low resistance of its windings, and if the motor is turned on at full supply voltage, a significant “peak” of current is obtained corresponding to the short circuit mode in the network downstream the motor resistance. A voltage dip which appears when starting electric motors commensurable in their power to the generator, at isolated power plants conditions, is an undesirable phenomenon. Studies have shown that deep voltage dips (over 20%) with a long voltage recovery period are unacceptable, since the mechanical characteristics of the engine deteriorate so much that it cannot overcome the moment resistance of its mechanism. The speed of previously switched on electric motors can decrease up to “stalling” of some electric motors. This will lead to a further decrease in the generator voltage due to a sharp increase in reactive power consumption by stopping induction motors, and the stable operation of the entire system may be disrupted. Therefore, it is urgent to pre-assess the magnitude of the voltage dip, which occurs when the IM is started, in order to prevent emergency conditions in the IEPS. The electric power system model may be part of the automated control system, and the modeling of the IM start-up can be triggered from the software of the automated working station of the IEPS operator. On completion of the modeling process, the power plant operator will receive information about the predicted value of the voltage dip, and, if necessary, can change the IEPS operating mode by connecting a subsidiary generator, and if there is no power reserve, disconnect some electricity consumers. Thus, it is necessary to develop the power plant model which is an integral part of the information support system for the IEPS operator's actions, and is distinguished by the most accurate reproduction of the features of relevant electric power processes.

2 Problem Formulation

to develop a model of an isolated electric power system, which incorporates the models of generators synchronization and power distribution system, to calculate the magnitude and duration of a voltage dip when an induction motor is connected.

To achieve this goal, it is necessary:

1. develop a block-diagram of an isolated electric power system model, which includes several diesel-generators and automation systems, in order to simulate the start-up mode of an induction motor, to estimate the magnitude and duration of the voltage dip occurring in this case; to develop an IEPS model in Matlab Simulink on the basis of the block-diagram;
2. develop operating procedures for automation equipment – generators synchronization systems and systems distributing active power between generators, which shall be represented as transition graphs of finite state automata; integrate the developed procedures into the IEPS model using Matlab State flow;
3. simulate the start-up processes of induction motors of various rating and obtain the values of the magnitude and duration of the voltage dip; draw conclusions on the admissibility of the voltage dip magnitude in IEPS.

3.Analysis of Publications on the Research Topic

Powerful induction motors start-up leads to significant voltage dips [1, 2], which, as noted in [3, 4], can lead to the activation of protective equipment due to prolonged transients, and have a negative impact on the quality of electricity [5]. In addition, the interconnected operation of synchronous generators [6] may be disrupted, which will lead to an emergency situation and de-energizing of the entire power plant. To reduce the magnitude of voltage dips, IM soft starters [7, 8], anticipatory control of the excitation of a synchronous generator [9], and adaptive voltage regulators [10] are often used. At the same time, many IEPS use the direct starting mode for IM, especially if IM is an integral part of pumps [11]. However, voltage dip calculation is associated with significant computational costs and requires solving a differential equation system [12, 13]. At the same time, it is not always possible to obtain an adequate description of IEPS with several operating generators, which also contain operating IM, automation systems, non-linear loads and other motors connected to the network, as noted in [14]. In this regard, modeling can be successfully used to estimate the magnitude of voltage dips, which is confirmed by [15, 16]. The disadvantage of the existing IEPS models, in particular [17–20], is that they simulate energy processes, but not control systems. Therefore, IM start-up modeling does not take into account IEPS control processes which can lead to a change in the power plant operating mode and, as a result, affect the modeling results. In other words, such models are idealized. In particular, the model of a power plant with one isolated generator and an induction motor, considered in [20], can be used in a very limited set of real situations, and is rather theoretical than practical. IEPS [21]. Recently, there has been a trend in the intellectualization of IEPS control processes. Information on the consequences of IM direct start-up is important when building and operating intelligent control systems. Intellectual support systems for operator's actions [22, 23] in managing IEPS are becoming increasingly common. Analysis of [15, 24] showed that the use of a modeling system with an IEPS model together with IEPS control software, which is an automated working station, allows to obtain qualitatively new solutions for assessing the effects of IM direct start-up. At the same time, the issue of the model structure that could be used for these purposes remains unclear, as well as the equipment configuration. IEPS automation tools play an important role and must be considered in the model. But the difficulty lies in the fact that modern automation systems are microprocessor-based ones, i.e. discrete, and controlled objects – diesel-generators and induction motors are continuous. Therefore, the IEPS model is to be used, which contains continuous controlled objects and discrete automation systems. If we present a generators synchronization system, a system of power distribution between generators in the form of digital automata, then it will be possible to create models of such systems and incorporate them into the IEPS. As shown in [25, 26], representing automation tools in the form of digital automata has several advantages, in particular, it allows conversion of the program code into the transition graph of a finite automaton, and vice versa. In addition, such a model will be reconfigurable in real time and will correct the weak points of the known models and modeling approaches discussed in [17, 18, 20, 24].

4. The Development of a Model of an Isolated Electric Power System

We shall consider a synchronous generator operating in idle mode, the voltage on which equals nominal. This voltage is equal to the EMF induced along the longitudinal axis in the stator winding:

$$E_d = U_d \, .$$

After connecting some reactive load to the generator, neglecting the active resistance of the stator, we find that the EMF induced in this winding equals the sum of voltages at the generator's terminals and the voltage drop on the internal resistance:

$$E_d^{'} = u_{st} + I_d x_d^{'}$$

$$u_{st} = E_d^{'} - I_d x_d^{'} \, ,$$

where E'd is transient EMF of the generator along the longitudinal axis; $u_{нач}$ is voltage at the terminals of the generator until it is turned on; Id is a component of load current along the longitudinal axis.

The physical meaning of E'd is that it remains unchanged at the initial moment of a sudden operational breakdown. For the initial moment, you can take Ed=E'd. Then, from equation (1) it can be inferred that ust is less than ud by the amount of internal voltage drop $I_d x_d^{'}$. The excitation winding has active resistance, the current will gradually attenuate and the resistance x'd will gradually increase and strive for xd, and the generator voltage will decrease. In the absence of an automatic voltage regulator, the voltage drops until the engine starts. Steady-state voltage is equal to:

$$u_{fin} = E_d - I_d x_d \, ,$$

where Ed is idle EMF; xd is longitudinal synchronous inductive resistance.

The magnitude of the voltage dip depends on many parameters, in particular on cosφ and x'd. If we neglect the transients of the actuator, then the voltage change on generator from the initial value Ust to the steady-state voltage Ufin will occur almost exponentially:

$$u = U_{\text{st}} - (U_{\text{fin}} - U_{\text{st}}) e^{-\frac{t}{T_d^{'}}} \, .$$

Time constant of the transient when starting the engine together with the load is determined by the formula

$$T_d^{'} = T_{d0}^{'} \frac{x_d^{'} + x_{\text{mot}}}{x_d + x_{\text{mot}}} \, ,$$

where $T_{d0}^{'}$ is time constant of the transient with the open stator winding; $x_d^{'}$ is transient longitudinal inductive resistance of the generator; xd is longitudinal inductive resistance of the generator; xmot is engine equivalent resistance.

The initial voltage value is found by the transition EMF of E'd at the time of the engine start:

$$U_{\text{st}} = \frac{E_{dst}^{'} x_{\text{mot}}}{x_d^{'} + x_{\text{mot}}} \, .$$

The magnitude of the initial voltage dip of the generator in percent is calculated by the equation:

$$\Delta U = (1 - U_{\text{st}}) \cdot 100\% \, .$$

From the known calculation of the engine equivalent inductive resistance [3] we get:

$$x_{\text{mot}} = (1-\mu)x + \frac{\mu \cdot x}{1 + (s_{\text{im}} T_r)^2} \, ,$$

where sim is engine slip, sim=1 at the start; x is stator inductive resistance; μ is coupling factor of stator and rotor windings of the engine; T_r is time constant of the rotor.

The resulting equation can be used to estimate the magnitude of the voltage dip when an induction motor is connected to a single-running synchronous generator. However, this is an idealized case which does not take into account the work of other motors that can also be connected to the generator, the current load of the generator, the resistance of the cables. Also, this equation is not applicable in the case of the power plant operation mode when several generators are connected to a common load. For such a case, the calculation of the voltage dip requires solving a differential equation system and involves the use of numerical methods that are well implemented in Matlab Simulink and Scilab Scicos. These packages have interfaces for interacting with C++ external applications, and can describe the power plant structure as a graphical block-diagram.

It is proposed to create a block-diagram with the corresponding power units, automation tools (frequency and voltage controllers, synchronizing devices and load sharers), equivalent active-inductive load and an induction motor, which connection modeling will be performed. If it is necessary to calculate the expected voltage dip when starting an induction motor of a given power, a model can be activated with arguments determining the state of the generator switches, the current active-inductive load of the power plant and the power of the connected induction motor, and with a return value – the magnitude of voltage dip. Fig. 1 presents a block-diagram of a power plant model for calculating the expected voltage dip.

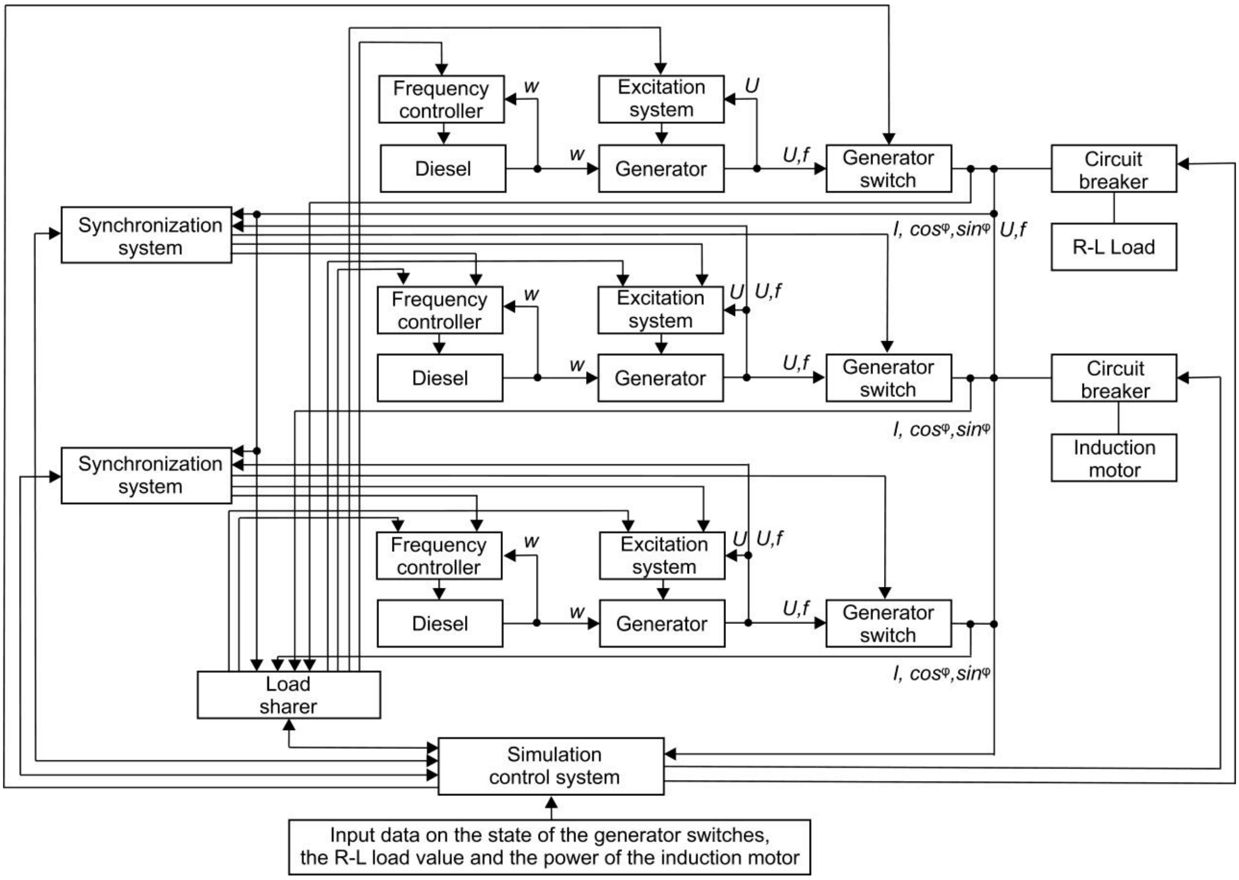

Fig. 1. The block-diagram of the power plant model for calculating the voltage dip when connecting IM

Fig. 2 shows the power plant model, compiled in accordance with the above requirements. This model can be used to calculate the expected voltage dip when an induction motor of a given power is connected to an autonomic network, for which a given number of paralleled diesel generators are operating. The model consists of three diesel generators with automatic frequency and voltage controllers, a load equivalent in power to paralleled power consumers at a given moment, and an induction motor. All units, except for the main DGU and load, can be controlled by connecting to the autonomic network.

The IEPS control system can be represented as a complex automaton, which by decomposition can be transformed into a complex hierarchy of finite automata with a specific functional purpose. To ensure parallel operation of diesel generators in IEPS, synchronization systems and load sharers are used whose operating procedures in the form of transition graphs of the A1-A4 finite automata are shown in Fig. 3 and Fig. 4.

Since the proposed model is suggested to be used when operating a power plant in real time, after connecting an induction motor, the derivative sign of voltage of an autonomic network is calculated with respect to time: when it reaches a zero (or first positive) value, a time point with a minimum voltage value will be obtained, after which the voltage dip value can be calculated and the modeling can be stopped. The software interacts with the model (creating and initializing variables of the Matlab workspace required for modeling – loads and states of generator switches of each DGU, power of the connected inductive motor; modeling performance; dip calculation and returning the obtained value to the program) using the Matlab Engine interface.

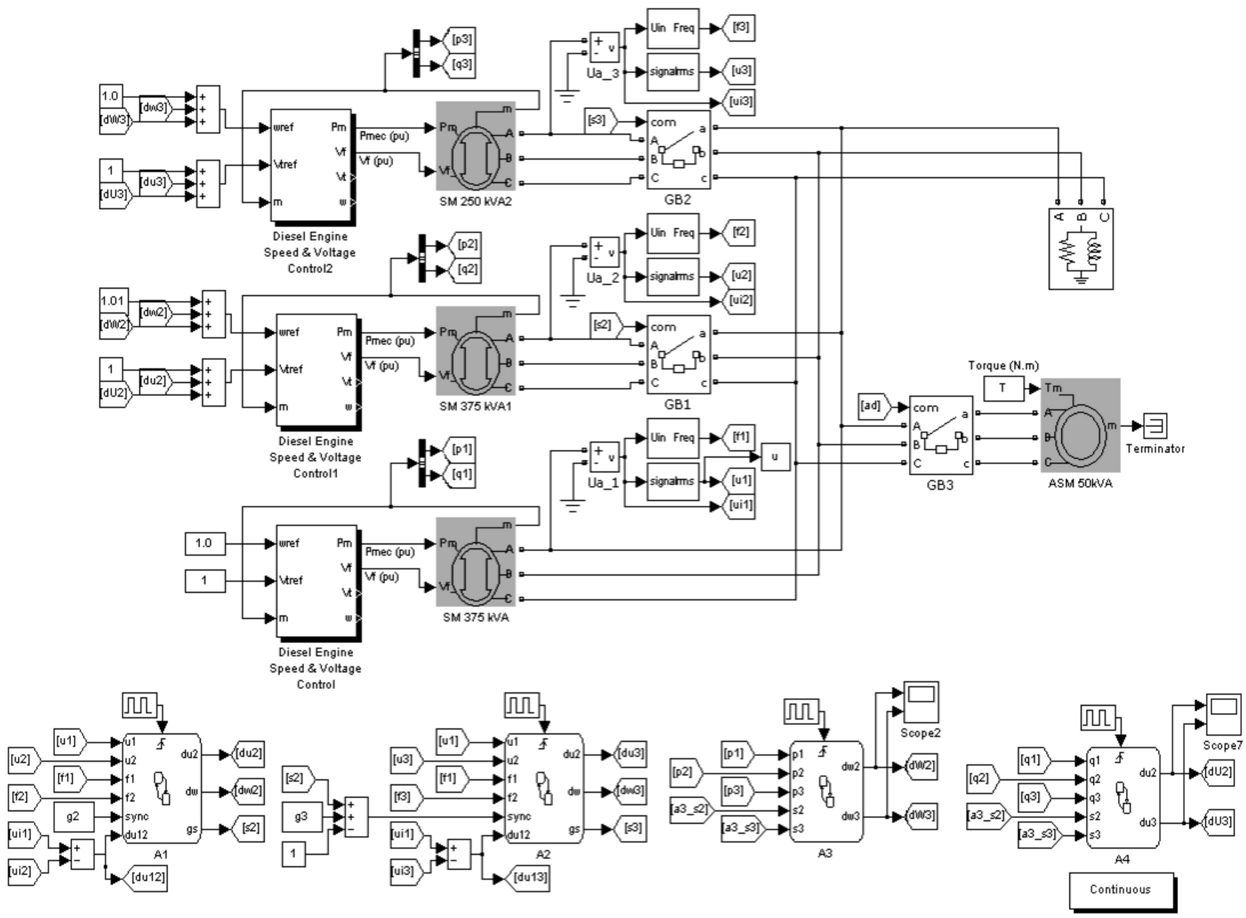

Fig. 2. Isolated electric power system model

The scheme of autonomous electric power system presented in Fig. 2 uses models of synchronous generators from the Sim Power Systems library. In this case, IEPS is considered, which includes two main generators with a rated power of 375 kVA each, and one standby generator with a rated power of 250 kVA. The generators' nominal power values are determined at the design stage of IEPS and remain unchangeable in the process of work. In other words, changeable are the values of active and reactive power generated by each of the power units, but not the values of their nominal powers. At the same time, a separate control system (Simulation control system) is used to control the modeling process. In essence, this system is a software module, which main functions are setting the initial conditions of the modeling process, obtaining modeling results and their transfer to the IEPS automated control system in order to display the received information to the operator. In this case, the IEPS operator has the possibility to set the power of each of the generators separately and simulate the start of the induction motor for any configuration of the power plant. Thus, before the start of the simulation process, the rated power can be set individually for each of the IEPS generators. At that, the values of the nominal powers of the generators can be arbitrary and differ from those indicated in Fig. 2.

Fig. 3 shows a graph-scheme of a finite automaton, which is a generator synchronization system. The graph-scheme is created using Matlab State flow. Automata are created on the basis of the analysis of [26]. The generator synchronization system generates pulse signals to correct the excitation of the connected generator and the speed of its drive diesel. To equalize the voltage of the connected generator with the voltage of the operating one, impulses are generated to increase (x1) or decrease (x2) excitation:

$$x_1 = \frac{1}{2}(1 + sign(U_1 - U_2)),$$

$$x_2 = \frac{1}{2}(1 + sign(U_2 - U_1)),$$

$$sign(0) = -1.$$

In the above formulas, x1 and x2 are logical variables that represent the states of the discrete excitation control signals of the generator, which is connected to the generator already operating under load. The sign function recovers –1 value, if the argument is negative, and the value of 1, if the argument is positive:

$$sign(\Delta U) = -1, \Delta U < 0,$$

$$sign(\Delta U) = 1, \Delta U > 0.$$

Thus, at each time point, one variable, either x1 or x2 can assume the value of 1, while another variable assumes the value of 0. Accordingly, if x1=1 (while x2=0) the excitation of the connected generator will increase, because the voltage U2 on its buses is less than the voltage U1 of the working generator. If x2=1 (while x1= 0), the excitation of the connected generator will decrease, since the voltage U2 on its buses is higher than the voltage U1 of the operating generator. The situation in which x1 = 0 and x2= 0 is possible with equal voltages of both generators, i.e. U1 = U2. The situation in which x1 = 1 and x2 = 1 is impossible in principle. Fig. 3 shows oscillograms of voltage changes of operating (curve 1) and connected (curve 2) generators.

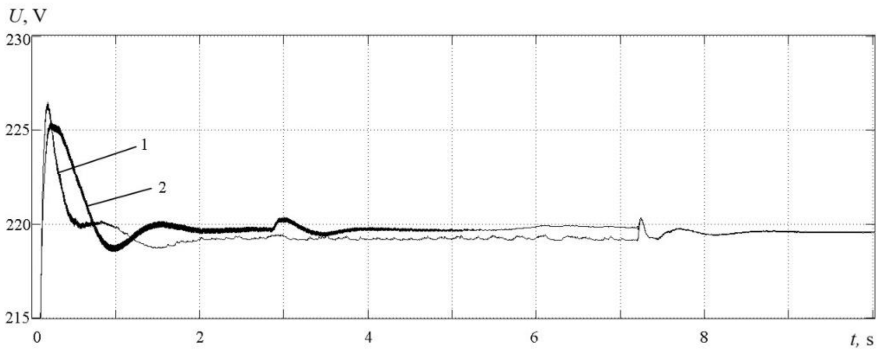

Fig. 3. Oscillograms of operating (curve 1) and connected (curve 2) generator voltage changes

When sflag=1, the circuit breaker contacts are closed.

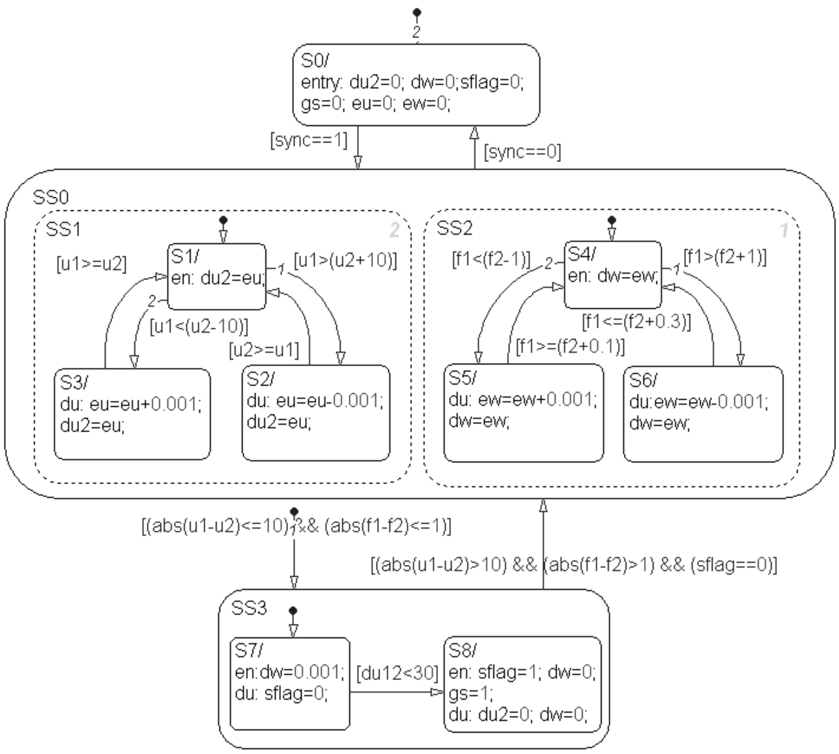

Fig. 4. Graph-schemes of A1 and A2 finite automata controlling the process of generator synchronization

The following designations are used in Fig. 4:
S0 – is the digital machine initial state;

SS0 – is a super-state of two parallel digital machines, which operate in accordance with transition graphs SS1 and SS2;
SS1 – is a super-state in which operates the digital machine, which controls the excitation of the connected synchronous generator by generating control signals to the excitation system;
SS2 – is a super-state in which operates the digital machine, which controls the frequency of the connected synchronous generator by generating control signals to the drive motor;
SS3 – is a super-state in which the analysis of the phase difference between the voltages of the operating and connected generators is performed;
S1 – is the machine state when the effective voltages of both generators are equal;
S2 – is the machine state when the effective voltage of the operating generator exceeds the effective voltage of the connected generator by more than 10 V;
S3 – is the machine state when the current voltage of the operating generator is less than the current voltage of the connected generator by 10 V or more;

S4 – is the machine state when the voltage frequencies of both generators are equal;
S5 – is the machine state when the voltage frequency of the operating generator exceeds the voltage frequency of the connected generator by more than 1 Hz;
S6 – is the machine state when the voltage frequency of the operating generator is less than voltage frequency of the connected generator by 1 Hz or more;
S7 – is the machine state when the phase difference between the voltages of both generators is more than 30°;
S8 – is the state, into which the machine enters when the phase difference between the voltages of both generators is less than 30°; in this state, the signal is generated to the circuit of the circuit breaker (sflag = 1), which connects additional generator to the total load;
u1 – is the effective value of the operating generator voltage;
u2 – is the effective value of the connected generator voltage;
f1 – is the operating generator voltage frequency;
f2 – is the connected generator voltage frequency;
du2 – is the difference between the effective voltages of the operating and connected generators;
dw – is the difference between the frequencies of the voltages of the operating and connected generators;
sflag – is a logical variable, which indicates whether the circuit breaker GB1 or GB2 is open (sflag = 0) or closed (sflag = 1) in the model in Figure 2;
gs – is the control signal, which closes the contacts of the circuit breaker GB1 (or GB2), and connects an additional generator to the load;
eu – is the voltage value, by which the excitation of the operating generator changes during its synchronization with another generator;
ew – is the increment value of the drive engine revolutions, by which the generator rotor rate of rotation changes during its synchronization with another generator;
en, entry – is an action performed once at the machine entry into a new state;
du – is an action performed at the time (during the time) the machine is in a certain state;
abs – is a function, which recovers the module of number.

When in S0 state, the system waits for an external signal to perform automatic accurate synchronization. After receiving the command to start the synchronization process, the system enters the SS0 state in which two automata are operating simultaneously. In the SS1 state, the excitation of the connected generator is corrected, and in the SS2 state, the speed of the power-driven diesel engine is corrected. To correct the voltage of the connected generator, in addition to the idle voltage in the excitation circuit a voltage increment from the controller will occur [10]:

$$U_f(p) = U_{f_0} + \Delta U_f(p),$$

$$\Delta U_f(p) = K_U(1 - U_d),$$

where Ud is nominal voltage of the synchronous generator in p.u.; KU is control factor by deviation, in the above model is 0.001. To determine the phase difference between the generator voltages, the effective value of the beat voltage is used Ub. In the model, the signal to turn on the automaton is formed when Ub<30B, which corresponds to the permissible phase difference between the voltages of generators. The pulses for voltage correction of the connected generator are generated until the difference between the voltages is less than 10V. Pulses to correct diesel engine speed are generated if frequency difference exceeds 1 Hz. At the same time, a hysteresis is introduced into the automaton in order to avoid “chatter” at the indicated interval boundaries. In the SS3 state, the beat voltage is controlled and its value determines the signal output for the circuit breaker contact closure. In the S7 state, the GSS generates a signal to increase the speed of the power-driven diesel engine. This is to avoid the system "hang" when the frequencies of both generators coincide, and also to shift part of the load to the connected generator.

On completion of the generators synchronization, the active power distribution system comes into operation, the transition graph of which is shown in Fig. 5.

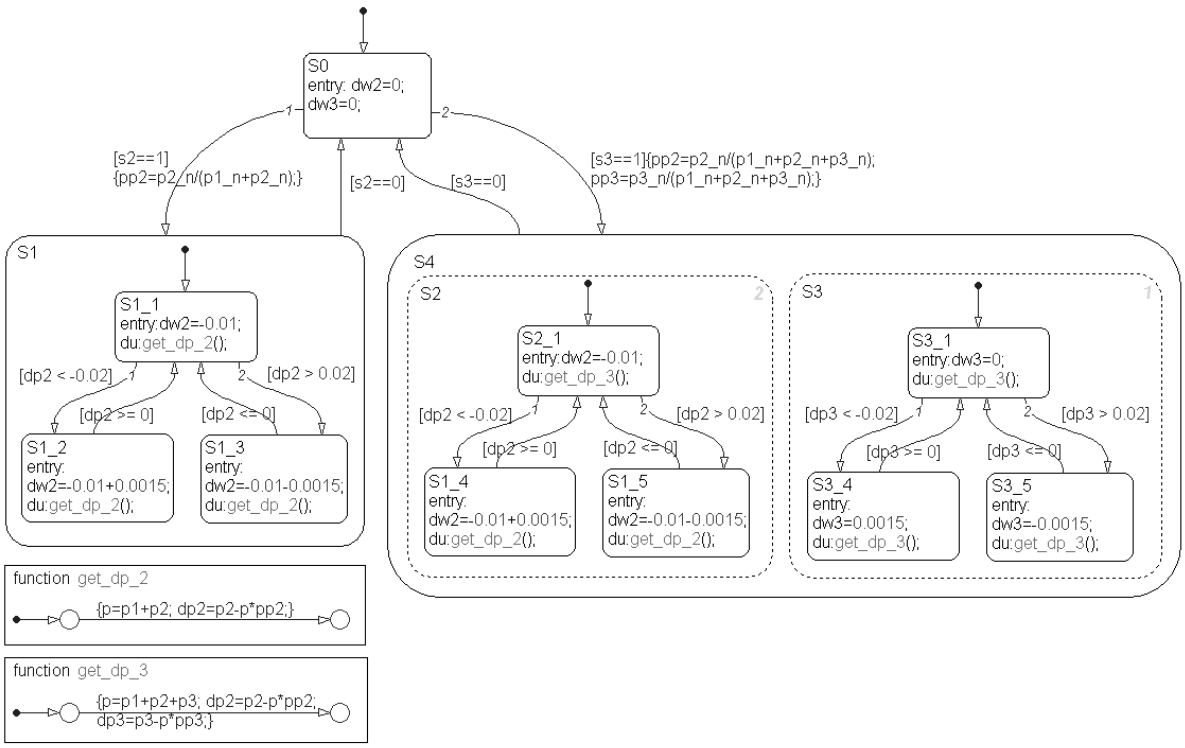

Fig. 5. Graph-scheme of the A3 and A4 finite automata, controlling the process of active loads distribution between paralleled generators

The following designations are used in Fig. 5:
S0 – is the initial machine state from which the execution of the algorithm of its operation begins;
S1 – is a separate machine super-state in which it performs power distribution between two generators operating on the total load;
S2 – is a super-state of the machine functioning while performing control of the generated active power of the second generator;
S3 – is a super-state of the machine functioning while performing control of the generated active power of the third generator;
S4 – is a super-state of the machine functioning when all three generators operate simultaneously on the total load;
S1_1 – is the machine state when the power between the first and second generators is distributed in proportion to their nominal capacities;
S1_2 – is the machine state when the active power of the first generator exceeds by more than 2% the active power delivered to the load by the second generator (when two generators operate simultaneously on the total load);
S1_3 – is the machine state when the active power of the second generator exceeds by more than 2% the active power delivered to the load by the first generator (when two generators operate simultaneously on the total load);
S1_4 – is the machine state when the active power of the first generator exceeds by more than 2% the active power delivered to the load by the second generator (when three generators operate simultaneously on the total load);
S1_5 – is the machine state when the active power of the second generator exceeds by more than 2% the active power delivered to the load by the first generator (when three generators operate simultaneously on the total load);
S2_1 – is the machine state when the power between the first and the second generator is distributed in proportion to their nominal capacities (when three generators operate simultaneously on the total load);
S3_1 – is the machine state when the power between the first and the third generator is distributed in proportion to their nominal capacities

(when three generators operate simultaneously on the total load);
S3_4 – is the machine state when the active power of the first generator exceeds by more than 2% the active power delivered to the load by the third generator (when three generators operate simultaneously on the total load);
S3_5 – is the machine state when the active power of the third generator exceeds by more than 2% the active power delivered to the load by the first generator (when three generators operate simultaneously on the total load);
dp2 – is the difference between the active powers of the first and the second generator;
dp3 – is the difference between the active powers of the first and the third generator;
dw2 – the value of the increment frequency of revolutions of the drive motor of the second generator;
dw3 – the value of the rate of rotation increment of the drive motor of the third generator;
s2 – is a logical variable that indicates whether the second generator is connected to the total load;
s3 – is a logical variable that indicates whether the third generator is connected to the total load;
p1_n – is the value of the first generator rated power;
p2_n – is the value of the second generator rated power;
p3_n – is the value of the third generator rated power;
pp2 – is the power value at which the proportional load distribution between the first and the second generator is ensured (when two generators operate simultaneously on the total load);
pp3 – is the power value at which the proportional load distribution between the first and the third generator is ensured (when three generators operate simultaneously on the total load);
p, p1, p2, p3 – variables that are used in functions for calculating the load values of the generators, which ensure the proportional distribution of power between them during their parallel operation;
entry – is the action performed once at the entry of the machine into a new state;
du is the action performed at the time (during the time) the machine is in a certain state;
get_dp_2, get_dp_3 – the names of functions that are used for calculating the load of the generators, in which it is distributed in proportion to the nominal capacities of the generators.

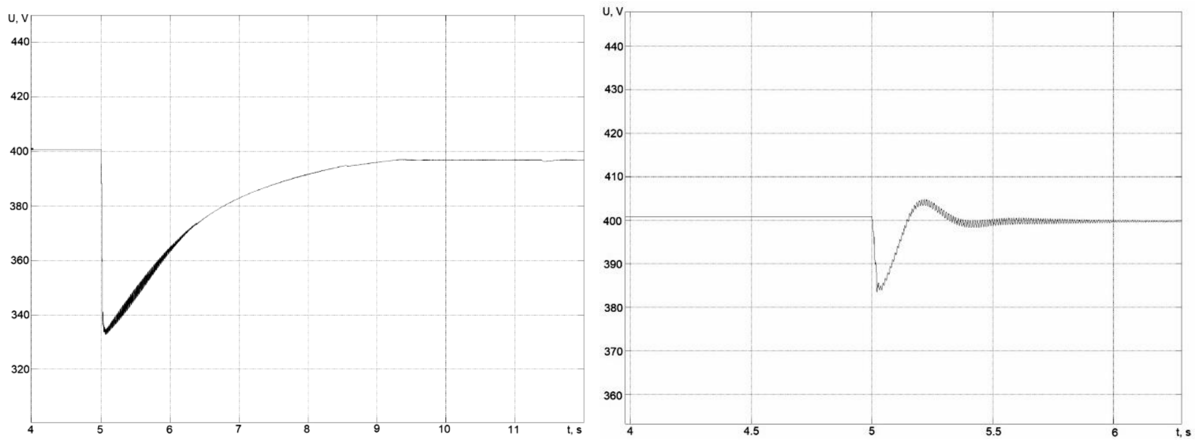

Fig. 6. Oscillograph records of voltages at the start-up of induction motors of various capacities: a – 55 kW; b – 14 kW

On the model development, the 55 kW and 14 kW induction motors start-up modeling were performed. The modeling results are presented in Fig. 6, a, b, respectively.

Based on modeling results, it was determined that the magnitudes of voltage dips at IM start are approximately 67 V and 16 V, respectively. Based on the data obtained, it is decided to change the IEPS operating mode, in particular, to connect an additional generator to the total load to provide power reserve and prevent significant voltage dips during IM direct start.

5 Conclusion

On conducting the study, the following results have been obtained:

1. A block-diagram of the IEPS simulation model with a configuration modified in real-time for the implementation of the above task has been developed. This solution allows, while monitoring the operation of the electric power system, to assess the possible consequences of an induction motor direct start under current conditions and, based on them, to decide on connection of an additional diesel generator to the network or disconnection of the least responsible consumers from the network. The developed IEPS model allows for a deep study of static properties and dynamic characteristics of generating units based on modeling, and for the development of necessary measures, hardware and software tools ensuring voltage stability in a wide range of loads.

2. The operating procedures of IEPS automation tools have been developed, which are presented in the form of transition graphs of finite automata. The methodology for modeling power plant automation tools based on an automate approach was further developed. The main advantage of the proposed approach is the complete documentation of the algorithm based on the functional decomposition of the control problem, as well as the simplicity of programs implementation for microcontrollers. The automate approach can be effectively used in the development of models and software for controllers designed to control various processes. The program design is based on an algorithm – a finite automaton in the form of a state diagram, intended for the formal description of the program logic. To describe the behavior of complex systems, not one automaton but a system of interconnected automata is usually used, which enables, in particular, the description of parallel processes, which was demonstrated in this paper.

3. The IM start-up modeling was performed and the oscillograph records of the voltage change in the electric grid were obtained. The information obtained as a result of modeling is the source information for taking measures to ensure the reliable operation of the electric power system and uninterrupted power supply to consumers. To prevent emergency situations, the developed IEPS and automation tools model can be used together with the means of the automated working station as part of the decision support information system in operating IEPS.

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