







Software and Hardware Decision Support System for Operators of Electrical Power Systems

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Abstract—The transience and unpredictability of processes in electric power systems (EPS) determine complexity of its control. This problem is especially relevant for EPS with renewable energy sources and flexible alternating current transmission systems technologies. Automatic control systems simplify the solution of this problem. Despite this, many issues related to EPS state control are solved by power system operators. Decision support systems (DSS) are applying to increase efficiency of operators work. However, existing algorithms in practice are inoperable in some cases: unrealizable decisions are formed, or decision cannot be found at all, etc. Another important problem is impossibility to preliminarily verify the proposed solution. In this regard, operators can additionally use EPS simulators, which are usually limited either by the size of simulated scheme or by the details of equipment mathematical models. The limitations are a consequence of numerical methods using, which are badly applicable for large-scale power systems simulation. In this article, a novel DSS has been developed based on a hybrid approach to EPS modeling combining properties and capabilities of several simulation techniques: analog, physical and digital. The implicit integration of differential equations in analog way makes possible modeling faster than real time. Such opportunity allows operator to verify more decisions and select the most effective ones. The algorithm for DSS application has been developed and described in the article. The properties and capabilities of the developed DSS are confirmed by experimental studies and tests in a real EPS.

Index Terms—Decision support systems, hybrid simulation, real-time systems, HRTSim.

I. INTRODUCTION

ELECTRIC power systems (EPS) are among the most complex technical systems. The development of power systems and the integration of new types of equipment lead to a deviation

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Fig. 1. The main phases of the blackout development.

of the modes and processes in the EPS from existing regulations, and also makes them even more unpredictable. The generating capacity increasing leads to the operation of electrical networks in critical conditions, which contributes to the increased probability of cascade accidents occurrence, including blackouts [1]–[6]. The existing practice of control by individual parts of an EPS without monitoring the broad picture as a whole can lead to even greater risks of large blackouts. In this regard, the methods and means of modern EPS controlling should become much more comprehensive to effectively counter the growing threat of large blackouts.

The development of system accidents, as a rule, includes five main parts: the pre-emergency condition, the initiating event, the cascade development of the accident, the final state of the system, and restoration (Fig. 1). A critical point, after which it is impossible to stop the development of the blackout, is the occurrence of a triggering event. Initiating events (short circuits, equipment overload, false tripping or failure of relay protection, etc.) have a direct impact on large blackouts or can lead to the decline of the current operating state. After the initiating event during the phase of a slow development of an accident in an EPS, the balance between generation and consumption is maintained for an approximately ten of minutes or more. In this case, the main problem is the multiple overloading of network elements. At this stage, the slow rate of state changing allows the operator to realize operational actions that will prevent further cascade events. After the occurrence of the triggering event, the balance between generation and consumption is broken, that leads to a rapid cascade shutdown of a large amount of network elements and collapse in the EPS. In the phase of rapid development of an accident, duration of which is several minutes or less, it is often too late to stop a cascade of events.

Thus, only during a slow phase of accident development operator can prevent the occurrence of blackout. However, this requires appropriate methods and means that allow operators not only to obtain quickly comprehensive, adequate and reliable information about processes in an EPS, but also to evaluate

the possible consequences of their actions and choose the most effective ones. In this regard, the article is devoted to the urgent task of methods and means development of DSS for operators and it is organized as follows: Section II is devoted to the analysis of existing methods and means for operator's decisions support. Section III contains the approach proposed by the authors for mentioned problem solution, as well as the hardware and software basis of the developed system. Section IV describes the decision support algorithm for operators using the developed system. Section V presents the results of experimental studies and field testing of the developed tool in a real large-scale EPS.

II. STATE-OF-THE-ART OF DECISION SUPPORT SYSTEMS

The main difficulty is associated with a large amount of data that the operator needs to analyze before making a decision [7]. An effective support tool for the operator is the DSS, which allows to identify key parameters of the changing EPS state and to offer the operator variants for events development.

There are different approaches to solve the decision support problem, for example, in [8], [9] an analysis of possible situations in an EPS is performed and the dynamic stability of the system is assessed. This allows the EPS operator in turn to assess the current and upcoming state of the EPS in terms of its stability. In [10] a unified approach based on the pattern recognition system is presented for assessing the EPS state reliability in real time. In [11] the results of the study of various artificial intelligence algorithms applicability to ensure EPS reliability are reviewed. However, it has been proven [12] that most of the pre-emergency conditions are unique and there is no single algorithm for their detection. Therefore, with the help of these methods and algorithms, despite their development, the decision support of the operator is not feasible in all possible states of EPS.

At the same time, the operator may need a help in restoring the EPS operation after an accident. This is due to the fact that the post-accident restoration of the EPS is a complex and difficult task [13]. The problem of restoration is solved in the literature by various methods, such as fuzzy logic [14], heuristic algorithms [13], rough sets method [15], quasi steady-state simulation [16], genetic algorithm [17], neural networks [18] and multi-agent approach [19], [20]. The main and currently unsolved drawback of these methods is that, in some cases, the solution may not be found at all and the probability of this is unknown [13].

The most reliable method that gives the information about the processes in an EPS is the detailed simulation. However, the calculation procedure becomes more complicated and long-term because the number of solution variables increases. This is due to the fact that conventional tools for EPS modes and processes calculation use numerical methods for solving nonlinear equations describing these processes. Due to the combinatorial nature of the problem, these approaches require a lot of computation time and, therefore, cannot be effectively used in real time [18].

In this regard, there is a need to develop a more efficient tool that provides the solution of these problems in real time or faster. The best variant is detail large-scale power systems modeling, since the impact of individual elements or their small groups on

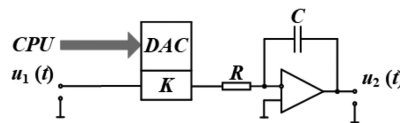


Fig. 2. The continuous implicit integration method description.

the EPS operating state is lost with significant equivalence of EPS schemes [21]. Obviously, the software programs cannot be used for these purposes, since they are limited by the resources of a single computer, consequently, the solution of a detailed EPS model is time-consuming and is not feasible in the real time of the processes. The hardware-software simulators dividing resources between individual processors do not have such problems. However, appropriate limitations and simplifications are valid for digital hardware-software simulators in case of large-scale EPS modeling (methodological error of the solution, the dilemma between the need to simplify mathematical models of EPS equipment or change the integrating step of differential equations, etc.) [22]. An alternative way to solve the problem of DSS implementation for operators is hybrid EPS modeling tools usage as the basis, such as HRTSim [23], combining different approaches for EPS modeling and allowing to achieve the necessary technical and economic indicators.

III. SOFTWARE AND HARDWARE DESCRIPTION OF DECISION SUPPORT SYSTEM BASED ON HYBRID SIMULATION

A hybrid approach of EPS modeling, which consists of analog, physical and digital parts is developed and realized at the HRTSim. The HRTSim is proposed by authors as a hardware basis of the DSS, because it has the following key properties and capabilities required to solve the mentioned problem of decision making for operators described below.

A. Analog Part

The range of significant processes in the EPS equipment, which does not contain switching elements, is described by systems of differential equations. The continuous implicit integration method (Fig. 2) is used to provide the methodologically accurate, parallel solution in real time and on an unlimited time interval of these stiff, high-order non-linear differential equations. In this case, only the instrumental error of the integrated microelectronic elements has the impact on simulation accuracy. However, the error in the proposed DSS is no more than 1% [24] for simulation of a significant spectrum (up to 1 kHz) of processes in an EPS.

For the effective solution of decision support tasks the adequate modeling of processes in EPS is required not only in real time, but also faster. The simulation speed, or in other words, the timescale (M_t) in the analog method for solution of systems of differential equations is determined by (1):

$$M_t = t/t_n, \quad (1)$$

where t is a machine time, t_n is a natural time.

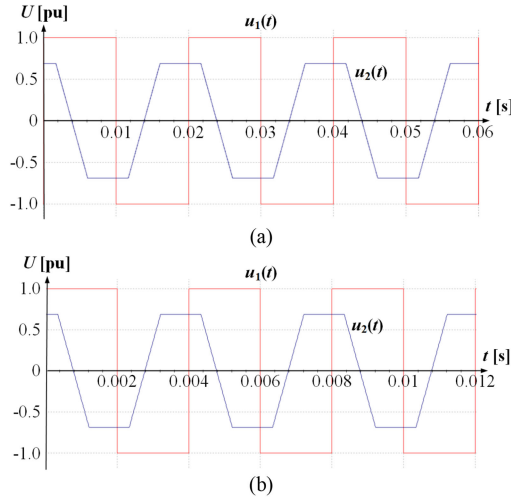


Fig. 3. Oscillograms of the $u_1(t)$ and $u_2(t)$ in case of different fundamental frequencies. (a) $f = 50$ Hz. (b) $f = 250$ Hz.

The integration is implemented by using an operational amplifier integrator to eliminate the need for matching and interaction of voltages of input-output circuits.

According to the Fig. 2, the output (u_2) and input (u_1) voltages of integrator are related by (2) to eliminate the need for matching voltage levels and mutual influence of input-output circuits:

$$u_2 = - (K/RC) \int u_1 dt, \quad (2)$$

where K is an acceleration factor, R and C are values of resistance and capacitance respectively, determining time constant ($\tau = RC$) of the integrator.

The procedure of variable scaling is implemented for wider use of the input-output voltage limits of microelectronic elements (in this case $u_{\max} = \pm 10$ V). The variable scaling is defined as the ratio of the maximum voltage of the microelectronic element to the maximum value of the simulated physical parameters. For the case shown in the Fig. 2, the scale of the input and output variables is determined by (3):

$$\begin{cases} M_{in} = u_{\max}/x_{\max}(t) \\ M_{out} = u_{\max}/y_{\max}(t) \end{cases} \quad (3)$$

The value of u_2 , u_1 , t can be found through the value of $x_{\max}(t)$, $y_{\max}(t)$ and t_n , consequently, (2) will be:

$$M_{in} y_{\max}(t) = - (K/RC) \int M_{out} x_{\max}(t) M_t dt_n \quad (4)$$

For the determining of the parameters by (2) to the Fig. 3, there must be equality $K M_{out} M_t / R C M_{in} = 1$, in such way:

$$RC/K = y_{\max}(t) \cdot M_t / x_{\max}(t) \quad (5)$$

For a real-time solution, it is necessary to provide $M_t = 1$ and $K = 1$, while the values of the resistor and capacitor are selected based on the smallest voltage drop across the resistor and the smallest dimensions of the capacitor.

To speed up the modeling process, it is necessary to proportionally reduce τ . A digital-to-analog converter (DAC) allows

to programmatically change τ . If the User via DAC increases $K > 1$, the solution of equations will be in K -times faster than real time [25].

The validation tests were made to proof the proposed approach. Fig. 3 shows the oscillograms of $u_1(t)$ and $u_2(t)$ for the circuit shown in the Fig. 2, obtained via experimental studies. In the first case, a pulse signal with a frequency of 50 Hz (with $K = 1$), then with a frequency of 250 Hz (with $K = 5$) is supplied to the test circuit. The voltages were obtained for the real integrator based on OP2177 ($R = 31.8$ k Ω , $C = 0.1$ μ F).

From the obtained oscillograms (Fig. 3) it follows that the $u_2(t)$ in the studied cases reaches the same value at different times, which corresponds to the acceleration of the modeling process, consequently, the fundamental frequency (50 Hz) is 'replaced' by 250 Hz. Moreover, the value of the output signal and its waveform does not change, which indicates the adequacy of the simulation results with an accelerated solution.

Thus, the analog solution method allows to implement any solution speed or otherwise any time scale that is determined by the User depending on the solving tasks.

The acceleration factor K is not only specified for an analog solution, it is also automatically taken into account in the time step of numerical integration, which is used to solve mathematical models of control and regulation systems in peripheral processors [23], in different time settings in the relay protection and automation system (RPA), as well as in the $dq \leftrightarrow ABC$ conversion equations.

The mathematical variables of currents formed as a result of continuous implicit integration, which are represented at the analog level by continuous voltages, are input signal for voltage-to-current converters (u -to- i). These mathematical variables of the currents are converted by voltage-to-current converters into the corresponding model physical currents. This operation is carried out via the signal multiplier [26], based on the AD534 scheme.

B. Physical Interaction

The physical simulation approach is used to provide: (1) the interconnection between models of EPS equipment, (2) the possibility of an almost unlimited scaling of the EPS model, and (3) adequate modeling of the spectrum of various three-phase commutations similar to real EPSs. Interaction between analog part of DSS and physically simulated EPS equipment of this system is provided by converting continuous mathematical variable of currents of the simulated EPS elements into their corresponding physical model currents. The simulation of EPS equipment containing switching elements (circuit breaker or power semiconductor device) is carried out with the series and shunt digitally controlled three-phase switches (SSDCS). Due to technical characteristics of modern SSDCS [27], it can be considered as an ideal switch in comparison with circuit breaker or power semiconductor device.

The interaction of the all simulated EPS equipment is carried out using a cross-board, whereby mathematical models of electrical machines, transformers, etc. are connected according to the topology of simulated EPS.

C. Digital Control

The digital approach is used for the following functions: (1) providing informational-controlling functions, (2) automated and automatic control of parameters and settings of the simulated equipment, (3) displaying the simulation results and their recording. This approach is carried out by digital-analog and analog-digital conversion of information using a necessary software and hardware tools. For processing a large amount of received/sent data, a multi-level informational-controlling system (ICS) of the HRTSim is developed.

Aggregation of all mentioned levels (analog, physical and digital) forms a single algorithm for hybrid mathematical models development implemented as specialized processors (SPs). The developed SP is the main part of HRTSim. Each SP contains a MPU consisting of a CPU and functionally oriented PP. The mathematical models of the main power equipment are realized in hybrid co-processors (HCP). HCPs are developed to implement the analog approach for integration. Digitally control the parameters of the mathematical models is carried out via DACs. All types of commutations in SP are realized by SSDCS. A detailed description of all levels is presented in [28].

Thus, the implementation of DSS on the basis of a hybrid approach allows to achieve the following main advantages:

- non-decomposition of modes and processes in EPS;
- lack of simplification of mathematical models of equipment and EPS in general;
- lack of limitation of the simulation time-interval;
- lack of variable methodological error of numerical integration of differential equations;
- opportunity for the modeling faster than real time without simplification of the applied mathematical models;
- adequate reproduction of switching processes;
- the scale of modeled EPS can be large (theoretically unlimited).

The developed system is based on HRTSim, which is used to simulate EPS in real time, i.e., it is a model analogue of a real EPS, on which the operator can test his actions before using them in a reality. To implement operator’s decision support functions themselves, the specialized software was developed that consists of separate software modules with specific functionality. This software is installed on the DSS Server. The operation of these modules is described in the next section. The DSS structure has a form shown in the Fig. 4. The block diagram of interaction of DSS software modules is shown in the Fig. 5.

IV. SYSTEM OPERATOR DECISION MAKING VIA DSS

The tasks (planning and operating control) that should be solved by operator in each of EPS states are defined and regulated by instructions and regulatory documents, which do not always take into account the particular EPS features. The properties of the developed DSS allow to solve the entire list of mentioned tasks in detail and more effectively, as well as to expand it through the possibility of testing potential solutions on the same EPS model. The generalized algorithm of operator actions to make various decisions using the developed system is shown in Fig. 6.

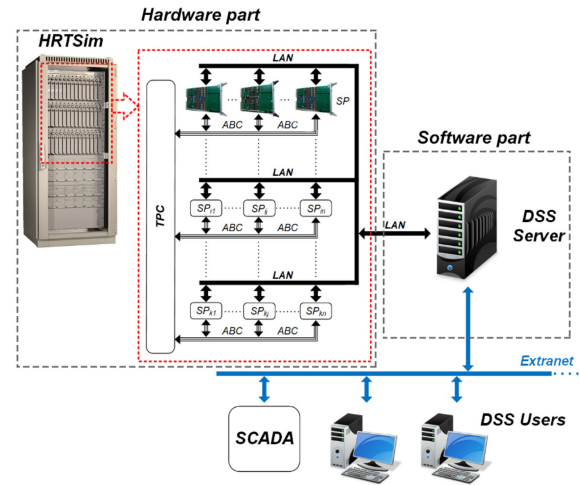


Fig. 4. The DSS structure.

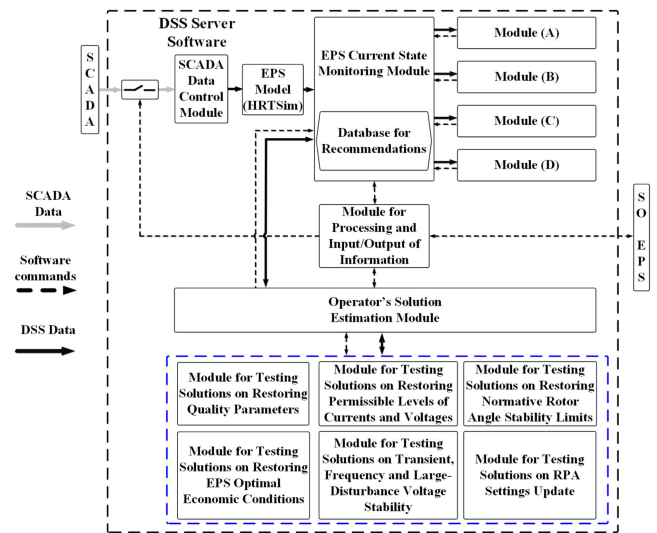


Fig. 5. The block diagram of the interaction of the DSS software modules.

The DSS operates in monitoring mode by default. The Data Control Module of DSS implements SCADA data import via Extranet by TCP/IP to the Server database for data conversion and playback of the current operating state of the simulated EPS. The used SCADA data has the following structure: telemetry (TM) and telealarm (TA). TMs are divided into the following groups: 1) voltages in nodes; 2) active and reactive power; 3) frequency on the power stations buses; 4) the position number of the transformer load tap changer; 5) currents. In the absence of some SCADA data, an automatic calculation of the missing data is carried out. The possible false SCADA data is corrected automatically by the developed software procedure, based on the balance equations. The SCADA data validation and post-calculation procedure is very important, because on the basis of these data the current mode in the EPS model is established and corrected (load capacities are changed, commutations are made in the model, etc.).

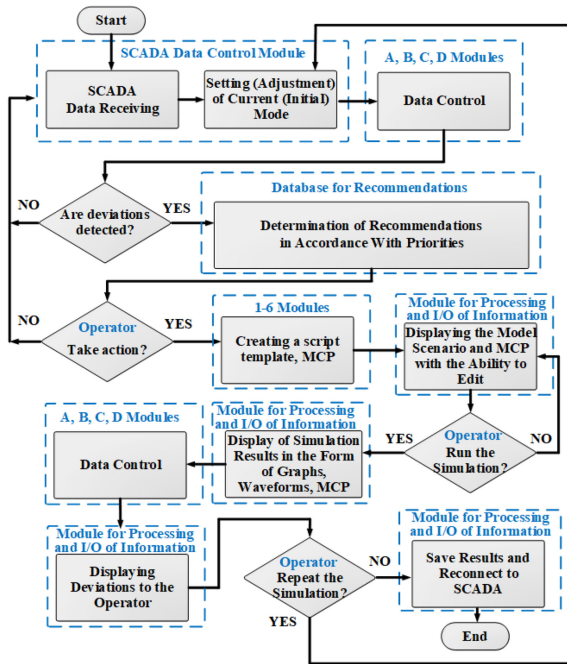


Fig. 6. The generalized algorithm of the operations of dispatching personnel by using DSS.

Based on SCADA telemetry, the developed DSS continuously reproduces in real time the current mode of the EPS, which is monitored by the EPS Current State Monitoring Module of the equipment and EPS. This module sorts the data, makes necessary selections and transfers them to appropriate controlling software modules A, B, C and D. Modules A, B, C and D contain equations, inequations, and other functions that compare mode parameters (current, voltage, frequency, etc.) and their deviations from permissible values. All the functions laid down are implemented in accordance with the dispatching regulatory and technical documents of a specific EPS. The presented system was developed for the Tomsk EPS, the formulas used were agreed with the dispatching personnel of this power system.

- Module for Power Quality Control – assesses voltage deviation, magnitude of voltage change, voltage fluctuations, total harmonic distortion, voltage harmonic components, voltage unbalance factor, and frequency deviation.
- Module for Control of Current and Voltage Level Limits – assesses thermal limits of power equipment and voltage levels allowed for insulation.
- Module for Assessment of Small-Disturbance Angle and Voltage Stability – assesses mentioned categories of stability at the current operating state. In addition, this software module: (1) monitors current values of active power that must not exceed maximum permissible and emergency permissible active power flows, which are set by the EPS operator, (2) implements control test of the EPS parameters values in operating state:

- current load of the transmission lines and electrical equipment must not exceed the permissible values (taking into account value and duration of the overload);

- bus voltages must be in the range of permissible values (amplitude and duration of the voltage increase/decrease).

- Module for Assessment of EPS Economic Conditions – controls active and reactive power flows to assess the power losses and the optimal electrical load of the equipment.

These software modules generate signals in case of control parameters deviation. In that case, the appropriate recommendations are formed by Module for EPS Current State Monitoring. For example, in the case of a frequency deviation from the nominal value, the recommendation will contain information about the node in which the frequency deviation occurred by a certain value, and recommended procedures for the operator associated with the power reserve, with the frequency control using individual generating units or power plants, etc.

The operator has opportunity to check possible actions in such system. Thus, Operator's Solution Estimation Module starts to operate and the DSS switches to testing mode. SCADA data are ignored in decision making process. The simulation is performed in K-times faster than real time. Depending on the formed recommendations, Operator's Solution Estimation Module transfers data to the appropriate software modules for additional testing of operator's actions aimed at restoring the necessary EPS parameters. These software modules form templates of different scripts and display it to the operator. Script templates contain typical procedures that should be performed by the operator to restore the EPS normal operating state, depending on the type of disturbance (increase/decrease power generation at power plants, transformer tap changing, connection/disconnection or parameters changing of the reactive power compensation devices, etc.). The EPS operator should only select the elements on which these actions will be realized. If necessary, it is possible to edit the script. Thus, the main purpose of the templates is the maximum simplification of the preparatory actions that the operator has to be done.

In addition to the four software modules corresponding to similar software modules for EPS Current State Monitoring, Operator's Solution Estimation Module includes a Module for Testing Solutions on Transient, Frequency and Large-Disturbance Voltage Stability and a Module for Testing Solutions on RPA Settings Update (for example, turbine governors, excitation systems, etc.). The first of them contains script templates, which include normative disturbances, to test the mentioned classes of the EPS stability. The second contains the script templates, which allow testing automation systems settings.

The EPS Current State Monitoring Module never stops to control current model operating state. If the operations taken by the EPS operator did not lead to the desired result, it is possible to return the initial state of the simulated EPS, which was at the moment of SCADA disconnection, and try another actions. Based on the simulation results and the message from the EPS current state monitoring module, the operator makes a decision on the admissibility of his actions, and selects the most optimal of them, after which he already implements it in a real EPS. The switching back to monitoring mode is made by the operator.

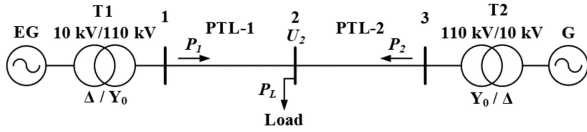


Fig. 7. The modelled test scheme, *EG* is an equivalent generator with constant frequency and unlimited power.

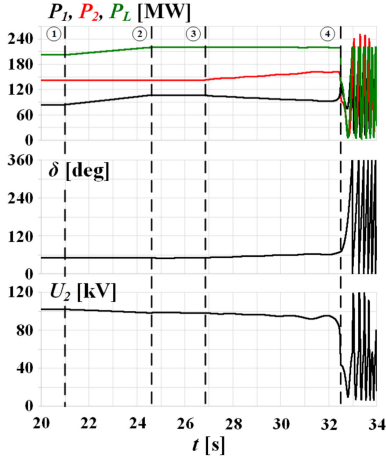


Fig. 8. Power system variables waveforms from DSS in the first case study.

V. CASE STUDY

The DSS algorithm does not change depending on the scale of the EPS, but is only supplemented by the necessary criteria and conditions depending on the specifics of the particular modelled EPS and the requirements for operators. To demonstrate the internal relationships and the algorithm of the DSS as a whole, two cases were studied: on a test EPS and on a real EPS model.

A. Case 1

The studies three-phase test scheme is presented in Fig. 7. The program emulator was developed to simulate SCADA, that stores a database of telemetry of the test EPS. The test scenario is to verify the DSS operation in one of the most common perturbation in EPS, associated with a transmission line overload and the corresponding violation of the coefficient of active power transfer stability margin ($K_{P,\min}$), which should not be less than 20% in normal state:

$$K_{P,\min} = \frac{P_{\max} - P}{P_{\max}}, \quad (6)$$

where P_{\max} is a maximum active power flow in a controlled transmission in accordance with power system stability, P is a current active power flow in a controlled transmission.

For this purpose, using the SCADA emulator, the load at node 2 is increased. DSS operates in real time and receives data from SCADA (part 1 – 2 at Fig. 8). When P_1 is reached 106.8 MW (point 2 at Fig. 8), there is a violation of the coefficient of active power transfer stability margin ($K_{P,\min} = 5.3\%$). The value of maximum active power flow for *PTL-1* is 112.8 MW. Since this case is a simplified test study, the value of irregular

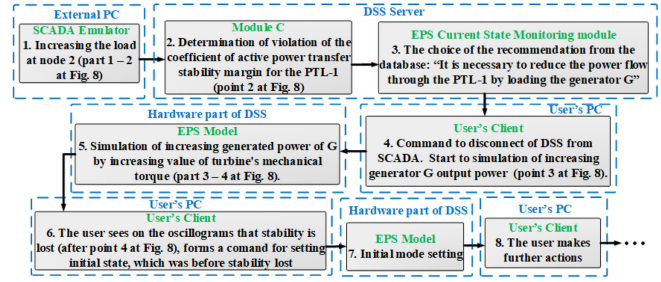


Fig. 9. Typical software and hardware operations and user actions by using DSS in the first case study.

power oscillations is assumed to zero. In this operating state of EPS, the Module C triggers and displays a warning message to the operator. If the operator decides to eliminate this deviation from the permissible values for normal operating state of the EPS, he performs DSS disconnection from SCADA, selects the integration speed and starts to simulate.

After that, the modules for testing solutions on restoring stability margins display an appropriate recommendation, which consists in this case of the need to decrease the active power flow in *PTL-1* by the increasing of generator *G* output power (in the initial state the mechanical torque was 0.71 pu). With the help of recommendation proposed by DSS, operator simulates an increasing of generator's output power by DSS (part 3 – 4 at Fig. 8). Power flow of *PTL-2* exceeds the transfer limit at point 4 (Fig. 8). Generator's operating point moves to unstable area of his power-angle curve and generator *G* loss of equilibrium (between electromagnetic and mechanical torques). The power system instability is clearly observed after 32 sec at Fig. 8. Thus by performing simulation using DSS the operator determines the permissible *PTL-2* power flow in the current state which will not lead to loss of stability.

At the same time, the coefficient $K_{P,\min}$ was restored only to 16% with the help of this measure, which is insufficient. Control Modules (in this case Module A and C) again display a warning and generate recommendations. The operator continue to simulate by DSS different action for restoration of normal state. After completing all simulation steps, the operator switches DSS back to receiving data from SCADA and performs tested actions on the real EPS. Main software and hardware operations and user actions by using DSS according to the generalized algorithm of the dispatching personnel operations (Fig. 6) are shown in Fig. 9.

B. Case 2

To confirm the properties and capabilities of the developed DSS, it was tested in one of the most complex emergency state for the power system of the Tomsk region (Siberia, Russia). The power system of the Tomsk region consists of asynchronously operating northern and southern parts, the controlled area between which passes through the transit of 220 kV with length of 797.3 km between Tomskaya substation (SS) (Siberia UPS) – Volodino SS – Parabel SS – Sovetsko-Sosninskaya SS – Nizhnevartovskaya GRES (Ural UPS). In normal operation,

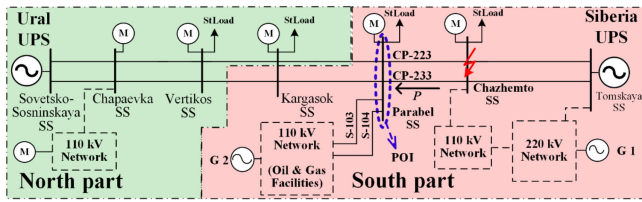


Fig. 10. The scheme of the power system of the Tomsk region, where G1–6 – power plants, M – synchronous and induction motors, StLoad – static loads.

the cross-section is located on the area between Vertikos SS – Parabel SS (Fig. 10).

Large part of the load are concentrated in the northern part – oil and gas facilities (some of them are supplied from the southern part via SS Parabel). Due to the lack of double-sided power supply, the reliability of consumers power supply is low, while own generation in the northern regions is not enough. Therefore, operational switching at transit substations with full removal of voltage, even for a short time, always leads to temporary shutdown of some consumers, and since the share of synchronous motors is large, asynchronous switching is impossible. A possible solution is the implementation of parallel operation of the northern and southern parts of the EPS. However, to assess the possibility of such interconnection, information about critical angle δ (phase angle difference between bus voltages) is needed at which power system stability will not be lost (stable operation of the motors will remain, the power surge formed after switching on will not lead to unacceptable thermal effects). The solution of this task by the operator using the DSS is demonstrated below.

At one of the power transmission lines CP-223 (Fig. 10), which is used for power supply of oil and gas facilities, a single-phase fault (AG) occurs with an unsuccessful three-phase autoreclosing. As a result, the line remaining in operation (CP-233) is overloaded, the stability limits are reduced, but the limit of the transmitted power is still not exceeded. If the load increases and, accordingly, the power flow through this power transmission line increases, there will be a loss of stability or the automatic overload limiter of the equipment will start to act. It will lead to partial load disconnection. In this situation, the operator, in accordance with regulatory instructions, has no more than 20 minutes to make decisions. There is only one way to prevent an accident – interconnection of northern and southern parts.

The sequence of DSS actions in the current operating state consists in the following. Data Control Module converts and validates the received from SCADA data, it enters to the Module for EPS Current State Monitoring, which sorts and transfers data to Modules A, B, C and D. Each Modules captures invalid values of controlled variables and displays a warning message. Corresponding warnings, recommendations and scripts, which are suggested to the operator by DSS, are presented in Fig. 11.

The operator performs disconnection of DSS from SCADA and selects the generated recommendation with the highest priority associated with violation of coefficient of active power transfer stability margin and exceedance of maximum permissible active power flow on transmission between 220 kV

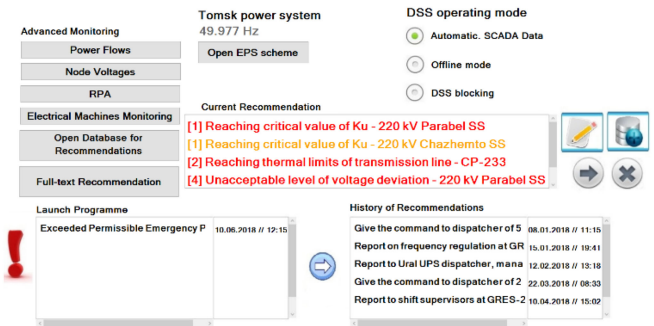


Fig. 11. The main monitoring and control panel.

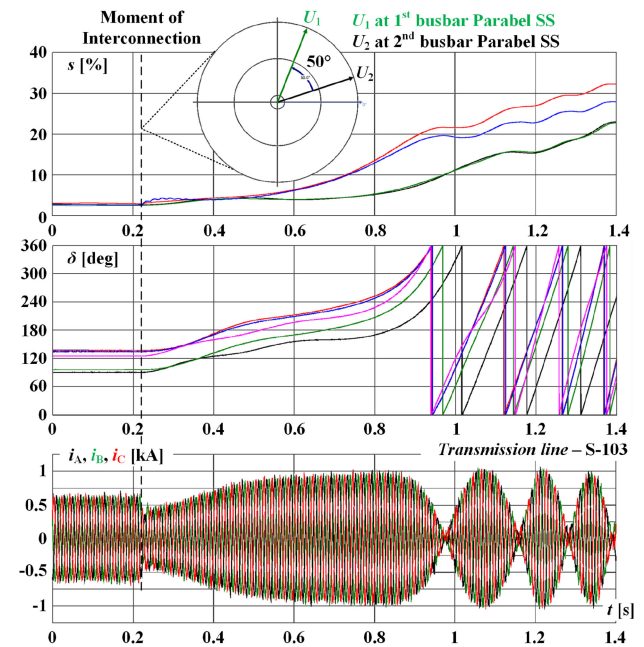


Fig. 12. Oscillograms of the processes in the case of interconnection at $\delta = 50^\circ$, where s [%] and δ [deg] show slip of induction motors and power angle of generators at oil and gas facilities.

Chazhemto SS and 220 kV Parabel SS. The main solution to this problem is the interconnection of asynchronously operating parts, thereby a template for this modeling scenario is formed for the operator in the Module for Testing Solutions on Restoring Stability Margins. The possibility of interconnection is estimated by the angle δ between voltages on the 1st and 2nd busbars of Parabel SS. In current EPS state, the angle is $\delta = 50^\circ$, which is permissible in theory, and the operator starts simulation. However, after interconnection there is a loss of stability and the stall of the entire motors, which are supplied by the 110 kV lines S-103 and S-104, on which the electric swing center was formed (Fig. 12).

Since the simulation results (Fig. 12) demonstrated an unsuccessful connection, the operator returns to the initial EPS state in DSS. Then operator changes generation of reactive power by generators in EPS southern part and try again to interconnect. In this case, it is successful (Fig. 13). After all tests were finished, operator switches DSS monitoring mode and performs these actions in real EPS.

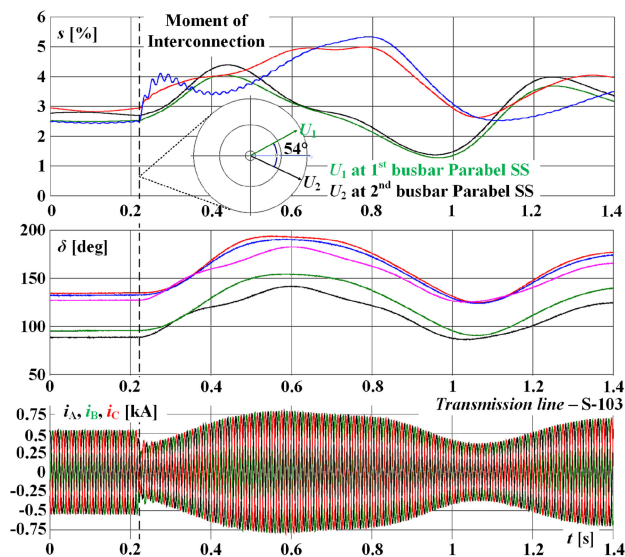


Fig. 13. Oscillograms of the processes in the case of interconnection at $\delta = 54^\circ$.

Thus, the success of interconnection in each case depends on the current EPS operating state as a whole, and the orientation only towards a limited set of data and generalized theoretical calculations lead to incorrect operator's decisions, which can be avoided by preliminary testing of these actions on DSS. Studies on DSS allow to promptly form measures to change the state of the EPS, which can be inappropriate for interconnection.

VI. CONCLUSION

The developed DSS allows operators to verify their actions to restore the normal operating state by means of quick, complete and reliable simulation, assess their consequences and choose the most optimal one, after which they can already be taken in a real EPS. This was achieved through the application of a hybrid approach to EPS simulation developed by the authors. The developed DSS has the following key characteristics that allow it to provide the necessary support to the operator with high precision in critical situations that are not regulated by instructions and the operator is forced to act at random, based on his intuition and experience:

- The created DSS consists of two main parts: a software and hardware tool that simulates EPS in real time (HRT-Sim), and specialized software for implementing decision support functions.
- The possibility of parallel operation of a simulated EPS with SCADA is realised for obtaining initial or current operating states of EPS model.
- Considering the need for the functional processing of a large amount of data, the DSS is generally implemented as a multi-level and multiprocessor system to perform specific tasks. Due to this DSS is a model analogue of a real EPS.
- The DSS automatically changes the current operating state of the EPS model according to the SCADA data without the intervention of an operator.

- To ensure reliable and effective decision-making process, as well as ability to promptly test operator's actions, EPS simulation in DSS can be done faster than real time. On the current element base, it was possible to speed up in five times.

The ability for operator to test actions on the detailed EPS model, especially with the simulation speed faster than real time, allows testing several different situations, choosing most effective ones and, as a result, reducing possible negative effect.

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