IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 2, 2020, accepted July 13, 2020, date of publication July 22, 2020, date of current version August 5, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3011207

Comprehensive Validation of Transient Stability Calculations in Electric Power Systems and Hardware-Software Tool for Its Implementation

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The validation strategy development and carried out research was supported in part by the Russian Science Foundation under the Governmental Grant (Investigation the problem of processes calculations reliability in electric power systems with active-adaptive networks and distributed generation and development the methodology of their comprehensive validation) under Grant 18-79-10006. The development of the test mathematical model of electric power system was supported in part by Khalifa University, Abu Dhabi, United Arab Emirates, under Award FSU-2018-25.

ABSTRACT Reliability and survivability of electric power systems (EPS) depend on transient stability assessment (TSA). One of the most effective way to TSA is time-domain simulation. However, large-scale EPS mathematical model contains a stiff nonlinear system of high-order differential equations. Such system cannot be solved analytically. At the same time, numerical methods are imperfectly applied for such system due to limitation conditions. To make it appropriate, the EPS mathematical model is simplified and additional limitations are used. These simplifications and limitations reduce reliability of simulation results. Consequently, their validation is needed. The most reliable approach to provide it is to compare the simulation results with the field data. However, in practice, there are not enough data for such validation. This paper proposes an alternative approach for validation – the application of a reference model instead of field data. A hardware-software system HRTSim was used as a reference model. This power system simulator has all the necessary properties and capabilities to obtain reliable information required for comprehensive validation of transient stability calculations in EPSs. Main disturbances leading to instability in EPSs are investigated to conduct the validation (processes in cases of faults, single-phase auto-reclosing operation and power system interconnection). Fragments of corresponding experimental studies illustrate the efficiency of the proposed approach. Obtained results confirmed the possibility of the developed approach to identify the causes of numerical calculation errors and to determine disturbances calculated with the significant error. In addition, experimental studies have revealed that numerical calculations error depends on disturbances intensity.

INDEX TERMS HRTSim, hybrid simulation, numerical simulation, power system dynamics, power system simulation, power system stability, smart grids, transient stability, validation.

NOMENCLATURE AND ABBREVIATIONS

NOMENCLATURE

C	Capacitance
C_ξ	Capacitance of phase ξ
$d\Psi_d/dt$	Transformer voltage term
$d\Psi_q/dt$	Slip voltage term
f	Frequency
$F_{\mu\xi}$	Magnetomotive force of phase ξ
f_u	Fundamental frequency of signal
i	Instantaneous current in tested RL-circuit
I	RMS current
i_A	Mathematical variable of current
$i_{a,b,c}$	Instantaneous currents of A, B and C phases

The associate editor coordinating the review of this manuscript and approving it for publication was Lei Chen.

i_{DCAS}	Current of digitally controlled analog switches
I_f	Excitation current
I_{out}	Output current in physical level
I_{phase}	RMS value of phase current
i_ξ	Instantaneous current of phase ξ
j	Number of parallel power lines
K	Gain
K_{DAC}	Gain of digital-to-analog converter
L_0	Inductance of zero sequence
L_{0j}	Mutual inductance of parallel power lines
L_{BP}	Mutual inductance between phases
L_ξ	Inductance of phase ξ
M_t	Time scale
n	Number of transformer windings
p	Coefficient of magnetic flux
P	Active power
Q	Reactive power
R	Value of resistance
r_0	Resistances of zero sequence
r_{0j}	Resistances of zero sequence with parallel lines
R_S	Current limiting resistance
$R_{SH/S}$	Shunt and series resistance
r_ξ	Resistance of phase ξ
S	Apparent power
s	Slip
t	Time
T_e	Electrical torque
T_m	Mechanical torque
u	Instantaneous voltage in tested RL-circuit
U	RMS voltage
$u_{a,b,c}$	Instantaneous voltages of A, B and C phases
U_f	Excitation voltage
$U_{in/out}$(t)	Input/Output voltage
U_{phase}	RMS value of phase voltage
u_ξ	Instantaneous voltage of phase ξ
W_ξ	Number of turns of phase ξ
δ	Mutual angle
ξ	A, B and C phases
φ	Phase angle
Φ_ξ	Magnetic flux of phase ξ

ABBREVIATIONS

ADC	Analog-to-digital converter
AT	Autotransformer
AVR	Automatic voltage regulator
BFP	Breaker failure protection
CB	Capacitor bank
CPS	Central power station
CPU	Central processing unit
DAC	Digital-to-analog converter
DCS	Digital control signal
DCAS	Digitally controlled analog switch
DG	Distributed generation
EEAC	Extended equal-area criterion
EPS	Electric power system
FACTS	Flexible alternative current transmission systems
G	Generator
HCP	Hybrid co-processor
HRTSim	Hybrid Real-Time Power System Simulator
HSS	Hardware and software simulator
HVDC	High-voltage direct current systems
IM	Induction motor
L	Static load
MPU	Microprocessor unit
OA	Operational amplifier
PADC	Analog-to-digital conversion processor
PL	Power transmission line
PMU	Phasor measurement unit
PP	Peripheral processor
PRTSA	Pattern recognition-based transient stability assessment
PSS	Power system stabilizer
R	Shunt reactor
RES	Renewable energy sources
RTDS	Real-Time Digital Simulator
SC	Short-circuit
SCADA	Supervisory control and data acquisition
SM	Synchronous motor
SP	Specialized processor
SPAR	Single-phase auto-reclosing
SPI	Serial peripheral interface
SS	Substation
SSDCS	Series and shunt digitally controlled three-phase switch
ST	Software tool
SwP	Switching processor
T	Transformer
TPC	Three-phase commutator
TPP	Thermal power plant
TSA	Transient stability assessment
UPS	United power system

I. INTRODUCTION

Electric power systems (EPS) are the fundamental infrastructure of any modern state and unite its territory in a unified, complex and branched grid. There are inevitable emergency disturbances in such grids (overloads, faults, etc.). In this regard, any EPS must have a high level of stability, which is currently divided into two main categories depending on the disturbance: steady-state stability and transient stability. Each category includes some stability subcategories depending on the system's main variable in which instability can be observed, the severity of the disturbance, transients' duration and other key factors [1]. The transient stability is discussed in this paper. The transient stability problems have been investigated in the literature for a long time [2], a lot of recommendations, approaches, methods for its assessment and improvement have been made which form the basis of international standards. The greater attention to this problem is understandable as it is primarily associated with severe instability effects in EPS [3]. Blackouts analysis confirms that many of them are associated with a loss of transient stability [4]–[6]. Solving transient stability problems remained at a high level in modern EPSs. Since the penetration of renewables and distributed generation significantly changes the dynamics of EPS, the transient processes become faster [7] and in some cases unpredictable [8].

Transient stability assessment (TSA) is an extremely difficult task due to its nonlinear nature and the high speed of transient processes. Currently, there are some groups of methods for TSA. One of the rapidly developing area is the development of methods for online TSA: extended equal-area criterion (EEAC) [9], Lyapunov exponents methods [10] and pattern recognition-based TSA methods (PRTSA) [11]. Since the main purpose of these methods is an assessment stability in online mode, they have some limitations that are made consciously in order to speed up the calculation time. The calculation time is the most important in this case. Simplified models of electrical machines and their control systems, network elements are generally used for these methods. It is extremely difficult task to form the optimal equivalent of generators with various inertia constants and control systems for the EEAC methods, as a consequence, the impact of various generators can be lost with high probability. The recorded data is used by PRTSA methods for model learning. It makes impossible to use such methods for a design of power systems. In addition, the trained model is sensitive to any changes in the topology of EPS and additional learning will be required constantly. It is practically impossible to take into account all states and disturbances in the EPS due to their variety for model learning. Another large group of TSA methods requires significant computational resources and they are intended for use in offline mode, but at the same time such methods have higher reliability. One of them are methods used stability criteria for TSA (algebraic stability criterion as Routh-Hurwitz or frequency stability criterion as Nyquist-Mikhailov). The determination of stability criteria for nonlinear systems of high-order differential equations describing large-scale EPS is extremely difficult and practically unsolvable task. Therefore, the scope of its using is very limited. Another direction is the direct methods based on using the Lyapunov function [12], [13]. The direct methods have found much wider application for TSA. There are many modern variations and renovations [14]–[16]. The main disadvantages of these methods are the size limitation of the considered system of differential equations, the unreliability of computation techniques [2] and the complexity of choosing the Lyapunov function that significantly affects the adequacy of obtained results [3]. Moreover, there are recommendations to perform the validation by time-domain simulation for EPS' critical states in which instability can occur after using the direct methods for stability assessment [17]. As a result, the applicability of these methods for large-scale EPS is also limited. The feature of all reviewed methods is the ability to answer only one question – is the power system stable or not? Such methods cannot obtain the information about the dynamic of transient processes, magnitude deviation of the system state variables, period and decay time of these deviations. All these characteristics are assessed separately. In this regard, the time-domain simulation for TSA is the most straightforward approach with high-accuracy calculation results and it is used for the design and operation of real power systems. However, EPS is a complex technical dynamic system where all types of equipment are continuously interconnected by a single continuous spectrum of quasi-steady and transient processes. The overall mathematical model of any large-scale EPS, even with acceptable partial equivalence, continuously comprises a stiff, non-linear system of differential equations of extremely high order. Such a system cannot be resolved analytically. At the same time, the application of numerical methods is limited by Lipschitz condition, Dalquist theorem, etc. [18], [19]. As a result, poor conditionality of the overall mathematical model due to the restrictive surroundings of the numerical approaches leads to unsatisfactory solution results. The only way to improve conditionality is to decrease stiffness, differential order and to bound the solution interval. This can be applied only over simplifications, for instance: (1) decomposition of continuous spectrum for developments in EPS on quasi-steady and transient processes, (2) single-phase structures scheming rather than three-phase, (3) facilitation of the equipment mathematical representations, essentially of the power network elements, which are frequently existing in the form of the equivalent algebraic equations, (4) restriction of the solution time-interval, (5) increasing simulation time-step, etc. Furthermore, irrespective the facilitations and restrictions, the global error of the numerical solution is permanently unidentified [18], [19]. A more detailed analytical analysis of this problem was carried out in [20]–[22]. Obviously, all of these disadvantages are inherited through the tools implementing numerical integration and governs the restricted properties and competences of the several software tools (ST) used for transient stability calculations in the electric power industry. The situation is different with hardware and software simulator (HSS) allowing the use of detailed three-phase EPS mathematical models and reproduction of the electromagnetic and electromechanical transient processes and its stages [23]. However, the digital HSSs have their own problems and their various solutions for large-scale EPS simulation [24]. Nevertheless, there are serious limitations in such modelling [25]. In this regard, most of the calculations for transient stability analysis are currently performed using STs discussed in this paper. Thus, the use of information about state and processes in EPS obtained via the one-sided numerical approach with unknown reliability can lead to the incorrect design and operational solutions related to the transient stability assessment and the development of means for its improvement. In this regard, there is a need to validate such information [4], moreover comprehensively. The comprehensive validation is an assessment of the completeness and the reliability of states and processes calculation results obtained via STs for various types of disturbances with various intensities and locations, which are used for the transient stability analysis. This paper addresses this problem and is organized as follows. Section III is devoted to the analysis of existing EPS validation approaches. Section IV describes the proposed approach to the comprehensive validation of transient stability calculations. A specific sequence of steps for its implementation is presented in Section V. The results of experimental studies confirm the effectiveness of the proposed approach, as presented in Section VI.

II. VARIOUS VALIDATION APPROACHES IN EPS

Currently, there are several types of validation for EPS simulation [26]: internal validation and sensitivity analysis (impact of the applied simplifications, limitations and input parameters of the mathematical model on the reliability of the simulation results); comparison of simulation results with field (real) data; cross-validation (comparison of the performance of one tool with another). Approaches for validation of different devices, the modeling of which is difficult for various reasons, are also known [27]. The most significant validation approach is the second one according to studies carried out in Europe [28] and USA [29]. The published validation results [30]–[32] demonstrate the differences between data obtained by simulation processes and recorded data in EPS. This is mainly associated with the mismatch between the mathematical model parameters and real data. In such work, an adaptation of simulation results to recorded data is used. It consists of varying models' parameters, mainly the static load characteristics and regulators' settings. This allows reproducing the overall trend of the real transient processes. However, the desired transient processes trend can be obtained by varying different parameters and their combinations given many EPS mathematical model parameters. Moreover, it is extremely difficult to choose an adequate combination to real data [33]. At the same time, there are no guarantees that the EPS model adapted in this way will reliably reproduce other states and disturbances that are different from the recorded data used to adapt the EPS model.

Since the adaptation for large-scale EPS model has a private nature, as the main way to increase the simulation reliability is the adaptation of an individual mathematical models of equipment or groups of the same equipment [34]. It is realized by assessing the response of the mathematical model to a specific disturbance recorded by the phasor measurement unit (PMU) and the related fine-tuning of the model parameters (fast-responding generator technique is applied to adjust the mathematical models of turbo and hydro generators [33], wind generators [35], solar power plants [36], etc.). In some studies, it is proposed to use the results of a detailed modelling of the studied equipment in a test scheme, instead of PMU [37]. The indicated way allows to adapt the equipment or several equipment models to a specific disturbance, but this approach does not solve the problem of transients calculations validation for the overall mathematical model of large-scale EPS. It could be concluded that it is not possible to determine reliably the parameters of which equipment and how much they need to be changed for the total large-scale EPS mathematical model [33]. Moreover, if it is assumed that all equipment models would be adapted, the indicated approaches do not take into account properties and capabilities of ST used to calculate the overall EPS mathematical model. The simplifications, limitations and unknown global error are inevitable for ST. It makes the validation results for individual process inapplicable for other processes. Moreover, this result is inapplicable for the entire spectrum of various quasi-steady and transient processes (even for a very limited part of this spectrum). Validation and adaptation for each simulation result are necessary. However, it is not feasible due to the lack of necessary recorded data now and in the near future, regardless of devices' development level for measuring and recording processes in EPS. It is related to the fact that the spectrum of possible states and disturbances in EPS is very wide, and the probability of their combination and occurrence is unpredictable and uncertain. This is particularly relevant for modern EPSs with distributed generation (DG), renewable energy sources (RES), flexible alternative current transmission systems (FACTS) and high-voltage direct current systems (HVDC). In addition, the justification of the used adaptation is also open to question. From the foregoing follows that the existing approach for validation based on using the recorded data is fundamentally and, in some cases, unacceptably limited. The comprehensive validation problem of transient stability calculations for large-scale EPS in the framework of such an approach is unsolvable at all.

III. THE DEVELOPED WAY OF TRANSIENT PROCESS CALCULATIONS VALIDATION REQUIRED FOR RELIABLE STABILITY ASSESSMENT OF EPS

A. ALTERNATIVE APPROACH TO COMPREHENSIVE VALIDATION

The indicated insolubility of the comprehensive validation problem based only on the field data predetermines an alternative way for this problem solution. The main idea of the developed approach is the use of information about states and processes in EPS obtained via a reference model. The reference model must have the properties necessary for a reliable simulation of a continuous significant spectrum of quasi-steady and transient processes in equipment and EPS without decomposition and on unlimited time interval. Considering the above problems, STs do not allow this. Therefore, the authors of this paper developed the concept of EPS hybrid simulation to create a specialized hardware-software tool as the reference model. The hybrid approach to EPS simulation consists of aggregating and co-using several modelling approaches (analog, physical and digital) to achieve the indicated properties. Thus, the proposed way expands the range of tasks to be solved during the validation and makes it comprehensive. In addition to adapting the EPS mathematical model, the proposed approach allows to assess the impact of the applied simplifications and limitations in the numerical simulation on the completeness and reliability of transient stability calculations for various disturbances. The developed approach also makes it possible to identify disturbances and processes occurring in the EPS that are simulated with a significant error.

The widespread use of hybrid tools would radically solve the problem of obtaining comprehensive and reliable information about normal and emergency quasi-steady and transient processes in equipment and EPS in general. However, the hybrid tools inevitably form a complex hardware-software system. The commercial manufacture and widespread using of such tools are a very expensive and long-term project. This can be considered now as some possible prospect. At the same time, the created experimental sample of such tool – the Hybrid Real-Time Power System Simulator (HRTSim) developed by the authors – allows to implement of the indicated approach for validation and has all the above properties and capabilities. This makes it possible to use the HRTSim as the reference model for obtaining reliable information about the entire spectrum of processes in a large-scale EPS, necessary for the comprehensive validation of EPS transient stability calculations.

B. MAIN FEATURES AND CAPABILITIES OF THE HRTSIM

The experimental sample of HRTSim is a parallel multiprocessor software and real-time hardware system of a hybrid type [20]. The HRTSim consists of specialized processors (SP) and an informational-controlling system (Fig. 1).

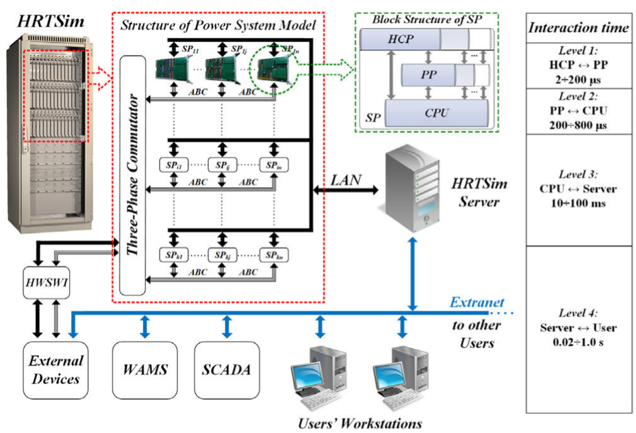

FIGURE 1. **HRTSim structural scheme and its informational-controlling system: HWSWI – hardware and software interface; WAMS – wide-area measurement systems; SCADA – supervisory control and data acquisition.**

The methodologically accurate solution of the power equipment mathematical models is performed by developing SPs standardized for all types of EPS' elements and are universal for each of them [38]. Each SP involve a microprocessor unit (MPU) containing of a central processing unit (CPU) and functionally oriented peripheral processors (PP). The mathematical models of the main power equipment have been appreciated in hybrid co-processors (HCP). The three-phase physical inputs-outputs of all SPs have been prepared with series and shunt digitally controlled three-phase switches (SSDCS).

The key features of the hybrid approach and its implementation proved the HRTSim properties and the possibility of using HRTSim as a reference model, are given below.

1) ANALOG LEVEL

The main spectrum of quasi-steady and transient processes in EPS equipment with no switching elements are described by theoretically strictly justified and checked systems of differential equations. Each detailed three-phase mathematical model consists of stiff-nonlinear high-order system of differential equations.

The continuous implicit integration method is used in HRTSim for methodically accurate, parallel and continuous real-time solutions of such systems on unlimited time interval (Fig. 2) [39]. In this case, the simulation accuracy depends on the instrumental error of the integrated microelectronic components strongminded by their frequency and phase responses. Error is not more than 1% in the currently used HRTSim' configuration for simulating processes in EPSs (up to 1 kHz). The error can be reduced by using precision components.

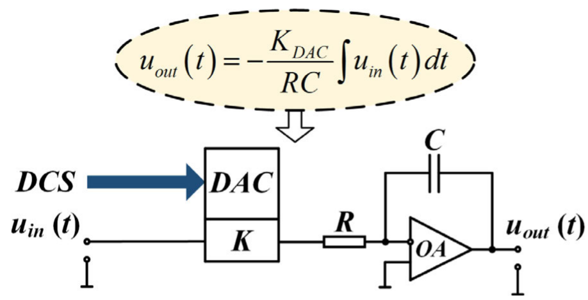

FIGURE 2. **Description of a continuous implicit integration method: DCS – digital control signal; DAC – digital-to-analog converter; OA – operational amplifier; $u_{in}(t)$ and $u_{out}(t)$ – input and output voltage, K_{DAC} – gain of DAC.**

The integration operation is implemented using an integrator based on an operational amplifier (OA) to exclude the need for matching and mutual influence of input/output voltage levels. The integration time or in other words the time scale is determined by the integrator time constant ($M_t = K/RC$). M_t is taken equal to one, and the resistor and capacitor values have been selected conferring to the circumstances of the lowest voltage drop across the resistor and the smallest size of the capacitor to instrument a real-time solution. In this case, the integrator output voltage will change by one unit in one second when a voltage equal to one unit is applied to the integrator input and the integrator gain factor is equal to one ($M_t = 1$). When the input signal frequency changes by two times, the integrator output signal also changes proportionally (1)–(2). Experimental confirmation was performed on the example of the used in HRTSim integrator based on OP2177 OA, $R = 100$ kOhm,

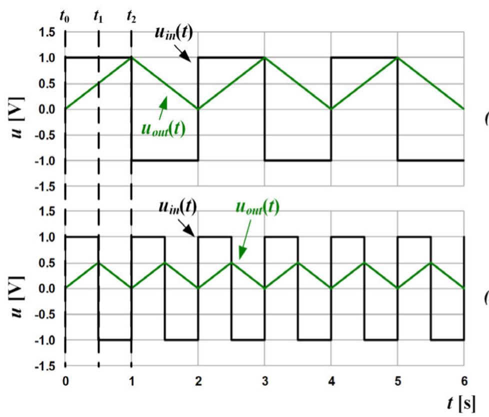

FIGURE 3. Oscillograms of the $u_{in}(t)$ and $u_{out}(t)$ in case of different fundamental frequencies: (a) $f_u = 0.5$ Hz; (b) $f_u = 1$ Hz.

$C = 10\ \mu$F (Fig. 3).

$$u_{out}(t_1) = u_{out}(t_0) + \int_{t_0}^{t_1} u_{in} dt = u_{out}(t_0) + u_{in}(t_1 - t_0) = 0.5\text{V} \quad (1)$$

$$u_{out}(t_2) = u_{out}(t_0) + \int_{t_0}^{t_2} u_{in} dt = u_{out}(t_0) + u_{in}(t_2 - t_0) = 1\text{V} \quad (2)$$

HCPs are developed for the HRTSim to implement the analog approach for integration. Each HCP is specialized parallel digital-to-analog structures for continuous and methodically accurate solution of nonlinear differential equations describing the simulated equipment in real-time and on an unlimited interval. The developed HCPs have the ability to digitally control the parameters of the mathematical models which is carried out via DACs. All developed HCPs are tested by comparing oscillogram of input and output voltages and currents, frequency characteristics obtained theoretically (analytically) and experimentally. As an example, the developed HCP of *RL*-circuit for HRTSim is shown in the Fig. 4.

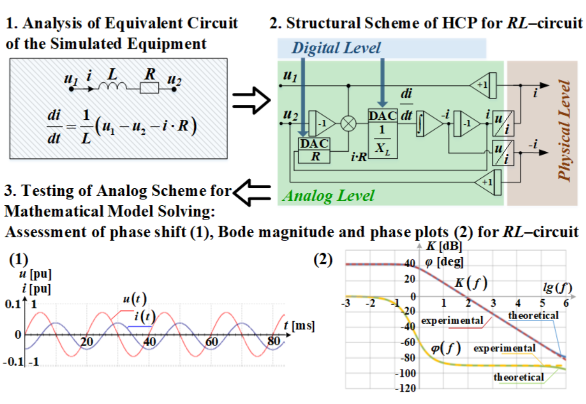

FIGURE 4. HCP of *RL*-circuit: "−1", "+1" – inverting and non-inverting OA voltage followers, *u/i* – voltage-to-current converters, $R = 0.001639$ [pu], $X_L = 0.1335$ [pu].

The processes in the main EPS' equipment (electric machines, power transformers, autotransformers, power transmission lines, loads, etc.) are directly interrelated and determinant. The mathematical models describing them are very conservative and differ mainly in parameters values. This justifies the expediency and necessity of modelling them as HCPs. Taking into account that the equations of the main equipment models are solved in an analog way and cannot be taken from the model library by analogy with digital simulators, but can only be reconfigured by changing numerous coefficients, following universal models had been established and applied in HRTSim: (1) universal mathematical model of synchronous and induction electric machines, (2) universal mathematical model of power transformer with five windings (five windings cover all possible cases of implementation of power transformers), (3) universal mathematical model of power transmission line, etc. The description of main equipment' mathematical models is presented below.

1. The universal mathematical model of synchronous and induction electrical machines consist of high-accuracy equivalent circuit using Park's transformation and mutual conversion systems of *dq* and *ABC* variables ($dq \leftrightarrow ABC$). The high accuracy has been realized by increasing the number of simulated damping circuits and seeing the frequency dependence of their parameters. The consideration of three d-axis and four q-axis damping circuits offers acceptable accuracy of the simulation for just about all cases.

The system of equations has been complemented by the mechanical swing equation, the differential equations relating processes in an excitation system and voltage regulator, in addition to the differential equations that regenerate processes in the primary mover: steam, gas or hydro turbine, boiler for steam turbines and its control systems, wind turbine, etc. Furthermore, the model of electrical machines regenerates nonlinearity of rotor steel saturation and dependence of rotor circuits' resistances from frequency. The description of these models is not included into the paper due to the large volume of information. This description are presented in detail in [40]–[42].

The main distinction among the mathematical models of an electrical motor and a generator is in the reverse direction of electromagnetic and mechanical torques. In addition, the mechanical torque is the resisting torque of the driven mechanism, mathematical model of which is too applied in the universal mathematical model of synchronous and induction electric machines.

2. The universal mathematical model of transformer should compound the structure of equations of a three-phase transformer with five windings, which realized through equation (3):

$$W_{\xi n}\frac{d\Phi_{\xi}}{dt} \pm L_{\xi n}\frac{di_{\xi n}}{dt} + r_{\xi n} i_{\xi n} - u_{\xi n} = 0, \quad (3)$$

where $W_{\xi n}$ is a number of turns of the n winding of the phase $\xi = A, B, C$, Φ_{ξ} is a magnetic flux of the phase ξ, $L_{\xi n}$ is a transformer leakage inductance of the n winding of the phase ξ, $i_{\xi n}$ is a current in the n winding of the phase ξ, $r_{\xi n}$ is an active resistance of n winding of phase ξ, $u_{\xi n}$ is a voltage of the n winding of the phase ξ.

The model is complemented through the balance equation of magnetomotive force for each phase and the equation of voltage creating in agreement with a winding connection outline. Simulation of the saturation curve $F_{\mu\xi} = f\ (\Phi_\xi)$ is done with equation (4):

$$F_{\mu n} = \Phi_\xi^2 - \alpha\Phi_\xi\left(\Phi_\xi - F_{\mu n}\right) \approx \Phi_\xi^p, \tag{4}$$

where $F_{\mu\xi}$ is a magnetomotive force of the phase ξ, Φ_ξ is a magnetic flux of the phase ξ, p is a coefficient, which is usually equal to 3 or 5 (considering the practical experience).

This model provides a more flexible and efficient approximation, with the ability to obtain functions with non-integer degrees. Coefficient α in the equation (4) allows making the characteristic $F_{\mu\xi} = f\ (\Phi_\xi)$ near to exact core-steel saturation curve.

3. The universal mathematical model of power transmission line (PL) has been expressed in correspondence with equivalent circuit (Fig. 5) for each phase ξ.

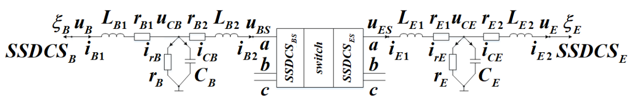

FIGURE 5. Equivalent circuit of phase A for three-phase PL with variable location of fault: subscript *B* is the beginning of the line, subscript *E* is the end of the line.

Matching to this structure and taking into consideration the mutual induction among phases and parallel lines mathematical models of each phase ξ can be molded by (5)–(9):

$$\frac{di_{B1\xi}}{dt} = \frac{1}{L_{B1\xi}} \times \left[\left(u_{B\xi} - u_{cB\xi} - 3L_{0B}\frac{di_{0B}}{dt} - 3r_{0B}i_{0B} - r_{B1\xi}i_{B1\xi}\right) - \sum_{j=1}^{m}\left(3r_{0Bj}i_{0Bj} + 3L_{0Bj}\frac{di_{0Bj}}{dt}\right)\right] \tag{5}$$

$$\frac{di_{B2\xi}}{dt} = \frac{1}{L_{B2\xi}} \times \left[\left(u_{cB\xi} - u_{BS\xi} - 3L_{0B}\frac{di_{0B}}{dt} - 3r_{0B}i_{0B} - r_{B2\xi}i_{B2\xi}\right) - \sum_{j=1}^{m}\left(3r_{0Bj}i_{0Bj} + 3L_{0Bj}\frac{di_{0Bj}}{dt}\right)\right] \tag{6}$$

$$\frac{du_{cB\xi}}{dt} = \frac{1}{C_{B\xi}}\left(i_{B1\xi} - i_{B2\xi} - i_{rB\xi}\right), \quad i_{rB\xi} = \frac{u_{cB\xi}}{r_{B\xi}} \tag{7}$$

$$3\frac{di_{0B}}{dt} = 0.5\left(\frac{di_{B1A}}{dt} + \frac{di_{B2A}}{dt} + \frac{di_{B1B}}{dt} + \frac{di_{B2B}}{dt} + \frac{di_{B1C}}{dt} + \frac{di_{B2C}}{dt}\right) \tag{8}$$

$$3i_{0B} = 0.5\left(i_{B1A} + i_{B2A} + i_{B1B} + i_{B2B} + i_{B1C} + i_{B2C}\right) \tag{9}$$

where $L_{0B} = (L_{B1\xi} + L_{B2\xi} + L_{BBP})$ is an inductance of T-type equivalent circuit of the simulated PL for zero sequence, L_{BBP} is a mutual inductance between phases, L_{0Bj} is a mutual inductance for $j = i \div m$ parallel PLs, r_{0B} and r_{0Bj} is a resistances for zero sequence currents i_{0B} and parallel PLs with mutual inductances i_{0Bj}.

The equations will be the same for the end of the line. The element 'switch' in Fig. 5 is used for separation of the single line on two T-lines for modeling short PLs.

4. The universal mathematical models of short and equivalent PL, equivalent static load, shunt reactor and capacitor bank are formed by (10) – (12) because of identity of their equivalent circuits:

$$\frac{di_{\xi L}}{dt} = \frac{1}{L_\xi}\left(u_{\xi B} - u_{\xi E} - r_{\xi L}i_{\xi L} - 3L_0\frac{di_0}{dt} - 3r_0 i_0\right) \tag{10}$$

$$i_\xi = \frac{1}{r_\xi}\left(u_{\xi B} - u_{\xi E}\right) \tag{11}$$

$$\frac{du_{\xi C}}{dt} = \frac{1}{C_\xi}i_{\xi C}, \quad i_{\xi C} = \frac{1}{r_{\xi C}}\left(u_{\xi B} - u_{\xi E}\right) \tag{12}$$

where subscript E for loads and reactors means side of model connected to neutral (i.e. $u_{\xi E} = 0$).

Thus, each universal model can be a combination of possible mathematical models of a specific equipment (e.g., electric machines) and if essential universal models is tuned to the specific case by changing the coefficients (e.g., turbo generators, hydro generators, synchronous and induction motors have been simulated by the universal model of electric machines). The descriptions of other implemented models, e.g. models of FACTS devices, are presented in detail in [38], [43].

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 to the voltage-to-current converters (u/i in Fig. 4). These mathematical variables of the currents are converted by voltage-to-current converters into the corresponding physical currents. This operation is carried out via the signal multiplier, based on the AD534 scheme (Fig. 6).

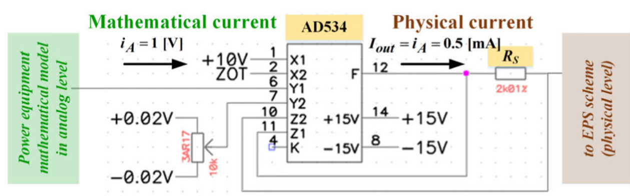

FIGURE 6. Scheme of voltage-to-current conversion based on AD534.

The voltage, formed at the outputs Z_1 and Z_2, determines the output current I_{out} (13), proportional to the resistance R_S:

$$I_{out} = \frac{(X_1 - X_2)\cdot(Y_1 - Y_2)}{10[\mathrm{V}]}\cdot\frac{1}{R_S} = \frac{(10[\mathrm{V}] - 0)\cdot(1[\mathrm{V}] - 0)}{10[\mathrm{V}]}\cdot\frac{1}{2[\mathrm{k}\Omega]} = 0.5[\mathrm{mA}] \tag{13}$$

To ensure the 1% error in the formation of I_{out}, as well as taking into account the instrumental limitation of $I_{out} = \pm 10$ mA, the R_S value typically should be less than 2.5 kΩ, but more than 1 kΩ.

2) PHYSICAL LEVEL

One of the important problems of digital simulation remains the complexity of adequate switching processes modelling, in particular, the operation of power semiconductor switches, circuit breakers switching and various short-circuits (SC). Currently, there is no theoretical basis for the development of adequate mathematical models describing the entire spectrum of switching processes in detail. Thus, to confirm satisfactory simulation of the whole spectrum of various switching processes the physical method of simulation is used. The physical level is realized by converting continuous mathematical variable of currents into their corresponding physical currents and voltages (Fig. 6). The interaction of physical currents relative to the simulated mathematical variables guarantees the maximum compliance to the real power system, eliminates problems of digital data exchange between simulated equipment, and contribute the possibility of theoretically unlimited rise in the scale of the EPS mathematical model.

Switching elements are reproduced via digitally controlled analog switches (DCAS) [44]. Due to the obtained experimental oscillograms (Fig. 7) and the technical characteristics of modern DCAS, their switching characteristics can be considered as an ideal in comparison with circuit breaker or power semiconductor switch.

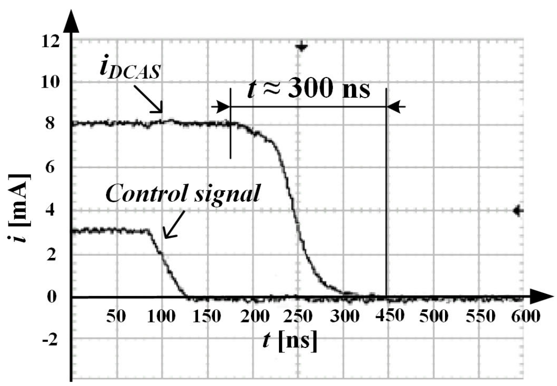

FIGURE 7. Oscillograms of DCAS' switching process.

The DCAS are equipped with digital-controlled resistances modelling the shunts of linear switches in accordance with their technical characteristics to ensure adequate simulation of switching processes in circuit breakers. The digital-controlled resistances for reproducing arc resistance are used for reliable simulation of SCs. Consequently, the physical model of SSDCS that was developed performs all types of commutations (Fig. 8).

The interaction of the all simulated equipment of EPS is carried out using a cross-board of three-phase commutator (TPC) (Fig. 9), whereby the models of EPS are connected

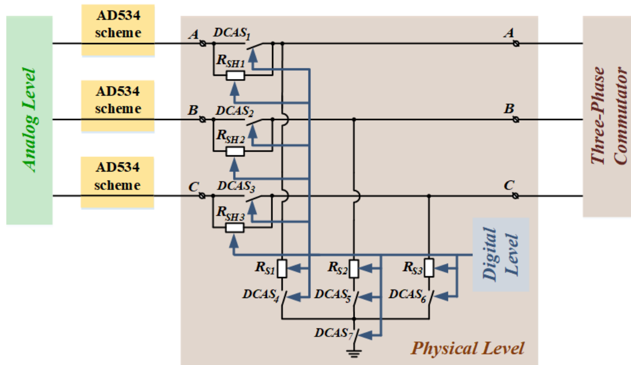

FIGURE 8. Structural scheme of digitally controlled physical model of SSDCS: R_{SH} and R_S – shunt and series resistances.

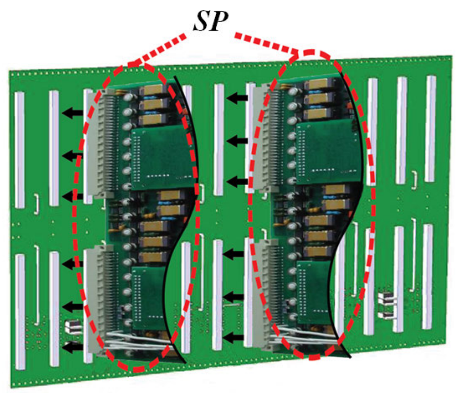

FIGURE 9. External view of a cross-board of TPC.

according to the topology of simulated EPS. As a result, the physical connections between the simulated equipment is implemented via TPC. In addition, a power supply of SPs are carried out via TPC.

3) DIGITAL LEVEL

The digital approach has been applied for: (1) providing ý all informational and controlling functions, (2) automated and automatic control of the parameters and settings of the simulated equipment, switching elements, and simulation in general, (3) showing the simulation results and their recording. This approach has been executed through earnings of the digital-to-analog and analog-to-digital conversion of information over the necessary software and hardware (Fig. 10).

For processing a large amount of received/sent data, a multi-level informational-controlling system of the HRTSim was developed. Such system includes four main parts:

1. *Server*: The HRTSim Server performs many different processes in parallel – it interacts with Users (a separate parallel process is created for each User), interacts with SPs, implements statics' and dynamics' scripts. The general structure of Server processes is shown in Fig. 11.

An important part for simulation is statics' and dynamics' scripts. The statics' script usually sets the required steady state (it is also can be done via SCADA data) and includes

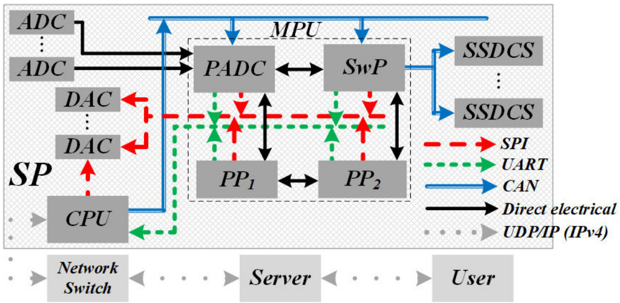

FIGURE 10. Scheme of SP' information exchange.

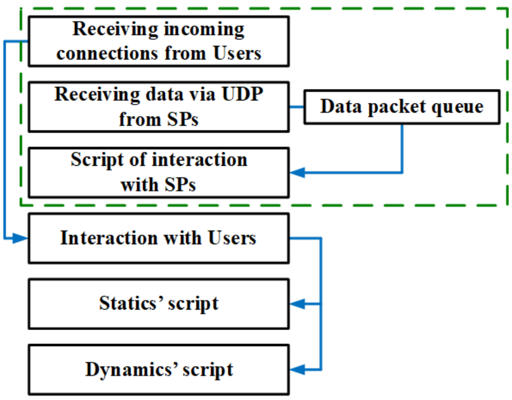

FIGURE 11. Block diagram of Server parallel processes interaction.

switching devices states, as well as power equipment parameters. The dynamics' script is mainly used to simulate transients that occur during disturbances in EPS, such as SCs, disconnection/connection of loads or generators, etc. The dynamics' script is transmitted for execution via Server to the corresponding SPs. Such script is usually including small amount of parameters to be set up, unlike statics' script. All scripts are adaptable and User can create, edit and run them in real time.

2. *CPU*: CPU is responsible part for the software communication with the HRTSim Server via Ethernet interface and UDP/IP protocol. This protocol allows speeding up information exchange comparing with more widely used TCP/IP due to no necessity to initialize special transmission channels or data paths. The interaction with PPs of SP is performed with two protocols: CAN and UART. CAN protocol is highly reliable. However, it is impossible to achieve a high speed of transmission. Due to these properties, it is excellent for sending control commands from a User to PPs of SP. Two types of signals can be sent via CAN: broadcast (e.g., a synchronization command) and individual (e.g., setting of a specific parameter for mathematical model implemented in a PP). UART protocol has opposite properties. It should be noted that it is used only to transfer the simulation results from PPs to CPU and then via Server to User. In this context, high reliability is not required, but speed is needed, because a huge amount of information is required to be transmitted in a short time. The interaction of CPU using UART is carried out only individually, i.e. each processor, independently to the others, transmit only certain information, e.g., specified in the dynamics' script. Transmission is started after CPU sending one-byte command. Then specific PP returns a packet of data corresponding to this command. Besides PPs interaction, CPU also controls DACs that implement coefficients of differential equations solved in analog way in HCP. The interaction is implemented using Serial Peripheral Interface (SPI), designed to provide simple and high-speed pairing of microcontrollers and peripherals. The structure of CPU information interaction is shown in Fig. 12.

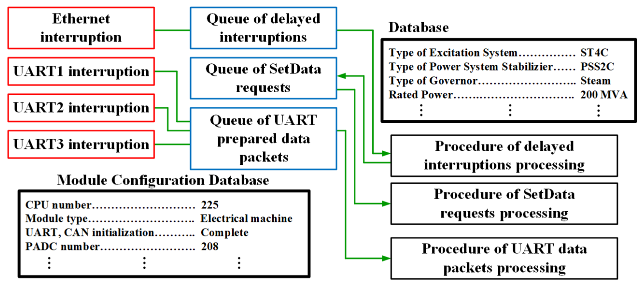

FIGURE 12. Block diagram of CPU parallel processes interaction.

3. *MPU*: MPU contains of analog-to-digital conversion processors (PADC), switching processors (SwP) and other PPs. PADC reads instantaneous values of state variables of the simulated EPS equipment (e.g., phase currents and voltages), calculates both vector values and effective values of three-phase powers (P, Q, S). SwP is used to control states of SSDCS. The number of PPs can vary from 2 to 3, depending on the type of SP [20]. Their purpose is implementation of the $dq \leftrightarrow abc$ transformation, as well as formation of mathematical models library for control, protection and automation systems. In each PP, algorithms for controlling specific parameters (nonlinearity of the magnetizing circuit of transformer and rotating machines, static load characteristic, etc.) of mathematical models solved in analog way can be implemented. Therefore, these processors are also connected via SPI with corresponding DACs.

In addition to these interaction methods, there is a direct (called electrical) interaction between processors by setting/releasing the voltage on the corresponding pins of the input/output controller. At each PP, AT91SAM7X256 microcontroller is installed having two 32-bit input/output controllers.

The simulation of EPS auxiliary equipment (automatic control systems, primary movers, excitation systems, etc.) is carried out by digital level due to the significant variety of such devices which are currently microprocessor-based. The simulation of these models is distributed between PP depending on the computing resources necessary for the implementation of each model. The main cycle (analog-to-digital converter (ADC) reading, digital filtering, calculations of auxiliary equipment mathematical models, writing data to the buffer, etc.) is 200 μs by using AT91SAM7X256 microcontrollers at 80 MHz clock speed with the number of samples per period for the ADC equal to 100. Moreover, the main cycle is divided into several time quantum for faster execution of certain procedures. Using microcontrollers with a higher clock speed or parallelizing calculation process by increasing microcontrollers number, the specified time range can be reduced. The time of interaction between CPU and Server, as well as Server and User is calculated in tens and hundreds of milliseconds. This speed is determined by communication protocol and features of the basic (for Server software) operating system (Windows OS). However, this fact is not decisive, because even with such time of data exchange, the User does not have time to perceive and analyze every change of data from the EPS model.

4. *User*: Any program that interacts with Server is considered as a client (User). The offsite clients can have their own interface and operate on either local or remote workstations (computers). The main requirement is that they must interact on the protocol supported by HRTSim Server. The User can work with HRTSim using specialized software developed for this purpose. It consists of four subsystems: subsystem of monitoring and control panels; subsystem of quasi-steady and transient processes recording (as oscillograms); subsystem of statics' scripts; subsystem of dynamics' scripts. Users' software directly communicates with HRTSim Server via UDP/IP protocol using XML-requests (messages).

Thus, the implementation of HRTSim on the basis of a hybrid approach allows to achieve the main advantages in Table 1.

TABLE 1. Challenges and our solutions.

№	Challenge	Solutions
1	- putrefaction of processes and states in EPS; - simplification of mathematical models of equipment and EPS in general; - limitation of the simulation time-interval; - variable global error of numerical integration of differential equations	analog level: application of continuous methodically precise implicit integration method for differential equations solution
2	- inadequate reproduction of switching processes; - limitation of scale of modeled EPS	physical level: interaction of simulated EPS equipment at the physical level through altering mathematical variables into physical signals
3	- constraint of operability of informational and regulating characteristic and capabilities	digital level: application of digital-to-analog and analog-to-digital conversion of information based on modern IT machineries

C. VALIDATION HRTSIM VIA COMPARISON WITH RTDS

The comparison of the developed HRTSim with widely applied and reliable tool for EPS simulation – Real-Time Digital Simulator (RTDS) – was executed. Moreover, the aim of these two simulators' comparison remains to demonstrate the competence of HRTSim, but not to display its lead over RTDS. The simulation results were compared in the test 18-bus EPS scheme to demonstrate the possibility of obtaining quasi-steady and transient processes via HRTSim for various disturbances necessary for the comprehensive validation of EPS transient stability calculations. The considered three-phase test system (Fig. 13) contains the main EPS equipment with identical mathematical models and their parameters in both simulators: generators (G) with prime movers and governors, automatic voltage regulators (AVR) with power system stabilizers (PSS); synchronous (SM) and induction (IM) motors with prime movers and additional automatic regulation and control systems; transformers (T) and autotransformers (AT); power transmission lines (PL); static loads (L), reactors (R), capacitor banks (CB) and equivalent generator (G-1) with constant frequency and unlimited power.

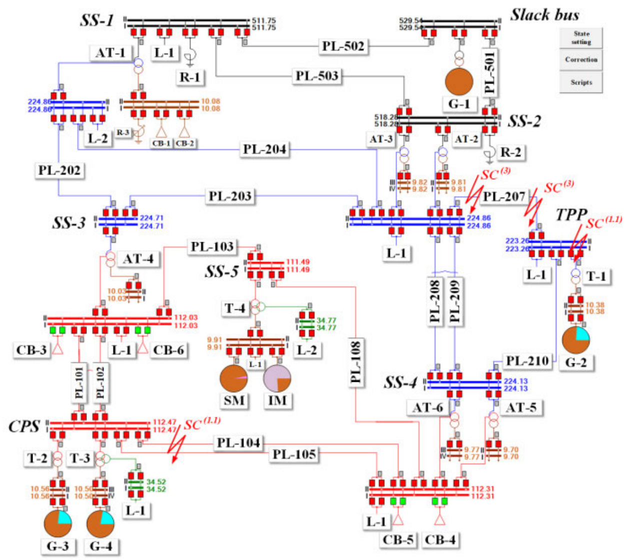

FIGURE 13. The single-phase view of the simulated test 18-bus scheme in HRTSim: SS – substation.

The validation of the adequacy of transient stability calculations was approved through simulating processes in case of a three-phase SC on the 220 kV transmission line PL-207 close to the SS-2. Moreover, the simulation results have been visualized in Fig. 14 are the same.

There was also made a comparison of the AVR&PSS functioning, which have a strong impact on transients used to assess the EPS transient stability. The article introduces a assessment of the AVR&PSS operation in the case of the next disturbances:

1) *Case 1*: sequence of two two-phase-to-ground SCs close to 220 kV TPP buses (Fig. 15a) – the time between two faults is 0.3 s, the duration of the first SC is 0.2 s, and the second is 0.5 s;
2) *Case 2*: two-phase-to-ground SC (with a duration of 0.15 s) at the side of PL-104 close to the CPS 110 kV

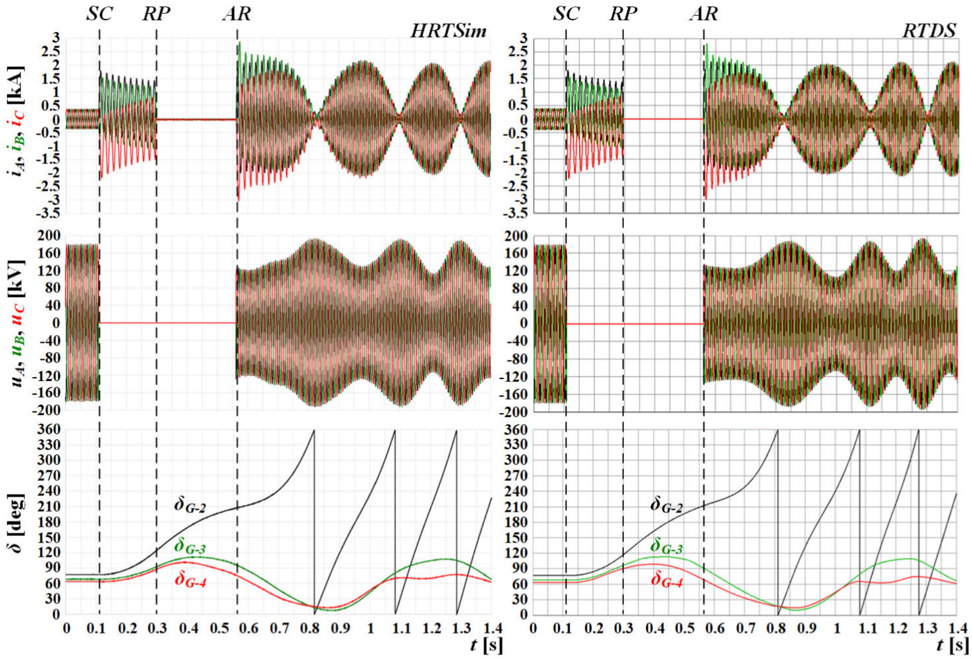

FIGURE 14. The oscillograms of the PL-207 instantaneous currents and voltages, generators' mutual angles for the case of three-phase-to-ground SC at the SS-2: RP – relay protection operation, AR – auto-reclosing.

buses with PL-104 tripping (Fig. 15b) – in this experiment the G-3 at CPS is disconnected by emergency automation after 0.35 s from the moment of fault occurrence to maintain transient stability;

3) *Case 3*: three-phase-to-ground SC (with a duration of 0.18 s) at the side of PL-207 close to the TPP 220 kV buses with the PL-207 tripping without loss of transient stability (Fig. 15c).

The analysis of obtained oscillograms displays the identical operation behavior of AVR&PSS mathematical models in all cases.

Thus, all obtained results show the similar transient processes. This confirms the possibility of obtaining sufficiently adequate information necessary for a comprehensive validation of transient stability calculations via HRTSim. Also, this confirms the adequacy of the hybrid approach and developed HRTSim as a whole, because the results obtained via digital simulators for the small test schemes can be considered reliable and the problems of numerical simulation noted above are not manifested in this case.

IV. THE STRATEGY FOR COMPREHENSIVE VALIDATION OF TRANSIENT STABILITY CALCULATIONS

The strategy defines the sequence and content of the actions for comprehensive validation of transient stability calculations, which are different for each particular EPS only by the set of initial state of this EPS in the HRTSim and the ST that should be validated (studied ST). The strategy consists of the following actions:

1. The initial state of the modeled large-scale EPS is set both in the HRTSim and ST on the basis of schematic diagram of EPS in normal operating state, database of equipment parameters and control devices settings.

2. If SCADA data are available, the initial state setting can be performed using this information. For this purpose, the special software procedures have been developed in the HRTSim that importing the SCADA database of the simulated EPS into the HRTSim database via TCP/IP protocol via extranet. The possible false or missing SCADA telemetry data are checked and automatically corrected by developed software procedures of HRTSim.

3. The single detailed three-phase mathematical model of large-scale EPS and methodologically accurate implicit integration method are used in the HRTSim for the entire continuous spectrum of quasi-steady and transient processes. Therefore, the HRTSim initial validation is possible only by any state or process, such as a quasi-steady state of the simulated EPS obtained from SCADA. The obtained in this manner validation results can be disseminated to the entire spectrum of quasi-steady and transient processes including switching overvoltages (0–1000 Hz) due to HRTSim properties. In this regard, the comparison of a quasi-steady state of the simulated EPS by HRTSim with SCADA data is carried out. The obtained comparison results are guaranteed to validate the HRTSim.

4. The validation spectrum is being formed. The basis of the spectrum is processes, including the extreme contingencies [2], information about which is necessary for reliable and effective transient stability assessment.

5. Simulation scenarios of validation spectrum are being developed. The validation scenarios take into account the properties and capabilities of ST, as well as the processes which are calculated with a significant error:

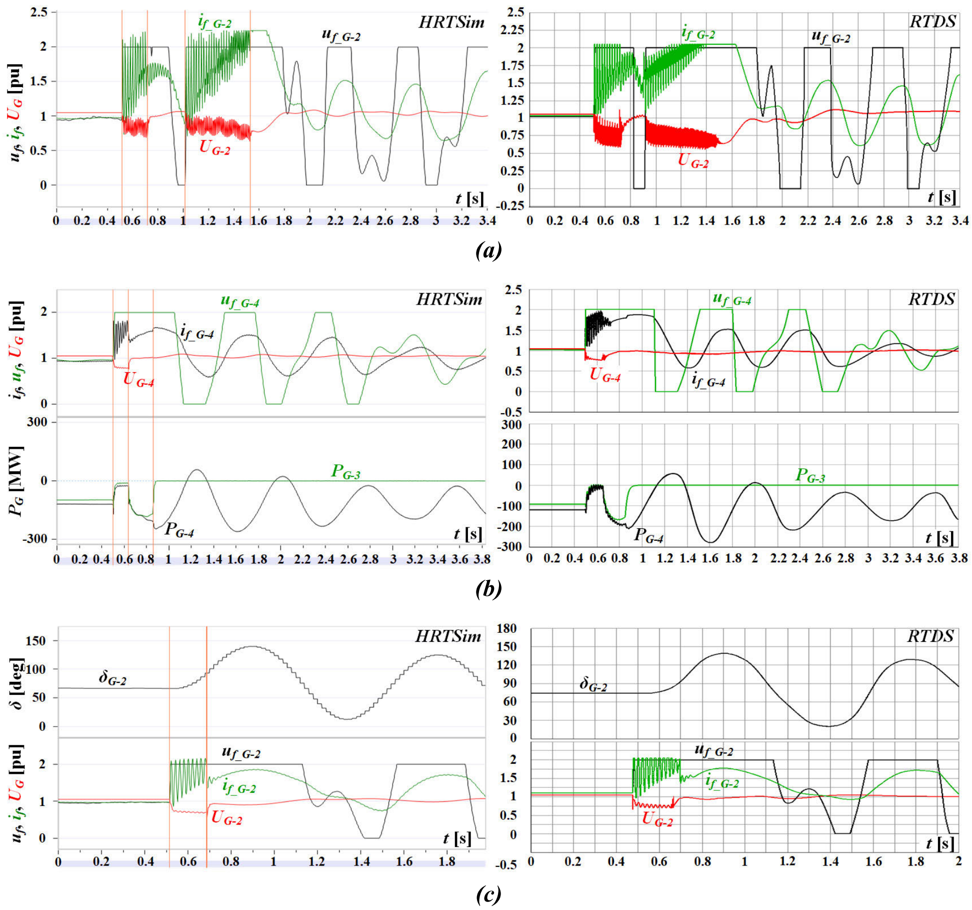

FIGURE 15. The oscillograms of the AVR&PSS models operation and some generators– variables for the Case 1 (a), Case 2 (b) and Case 3 (c): u_f, i_f – excitation voltage and current respectively, U_G – RMS voltage at generator's terminals.

5.1. Among the various extreme contingencies, used for the transient stability assessment, the most relevant processes for validation are the processes that most likely lead to transient instability. Such processes are usually associated with disturbances resulting from the imposition or sequence of faults that most frequently occur in case of a bolted three-phase SC at near-to-generator buses with high loaded sending PLs, a circuit breaker failure and, consequently, a fault clearing by breaker failure protection (BFP) operation. When this happens, there is a significant decrease in generating power because of a voltage drop. The probability of transient instability sharply increases due to the increased fault clearing time caused by the breaker failure, and due to the additional kinetic energy of the generators rotors and the corresponding increase in the generators' mutual angle.

5.2. The high probability of temporary line-to-ground SC on high-voltage PLs [2] predetermined the expediency and prevalence of using a single-phase auto-reclosing (SPAR). The SPAR allows to continue power supply of consumers in case of admissibility open-phase mode and to save electrical communication between EPS' parts via non-damaged phases thereby enhancing power system stability. However, there are difficulties in reliable assessment of such dynamic transition due to increased fault clearing time and duration of a dead time in the auto-reclose cycle. In this connection, the validation scenario for assessing the reliability of transients' calculations taking into account the SPAR operation is relevant. In this case, the operating state with high loaded PL is initially formed, and then a single-phase SC on this PL is simulated with a duration determined by the critical clearing time and SPAR operation. The transient stability assessment is carried out by the oscillograms of mutual angles' changing.

5.3. The reliability and efficiency of power system parts interconnection depends on the angle between the voltages at the points of interconnection and occurring processes. The adequacy of such transients' simulation taking into account possible emergency consequences is particularly important. Therefore, the appropriate validation scenario should be developed that allows determining the acceptable conditions for EPS interconnection by the oscillograms of currents, voltages and voltage angle difference between points of interconnection.

6. The developed validation scenarios are implemented in both the studied ST and the HRTSim. The obtained

simulation results are being compared. The revealed and analyzed differences make it possible to determine the adequacy of transient stability calculations in case of various disturbances, as well as to assess the consequences of the simplifications and limitations applied in studied ST. Besides, according to the results, the disturbances and occurring processes in EPS are being identified, which are calculated via studied ST with a significant error.

The block diagram of the proposed approach is demonstrated in Fig. 16. Thus, the results of such validation provide an opportunity to assess the reliability and efficiency of transient stability tasks solution, which is carried out using the information obtained via various STs for large-scale power systems analysis and simulation.

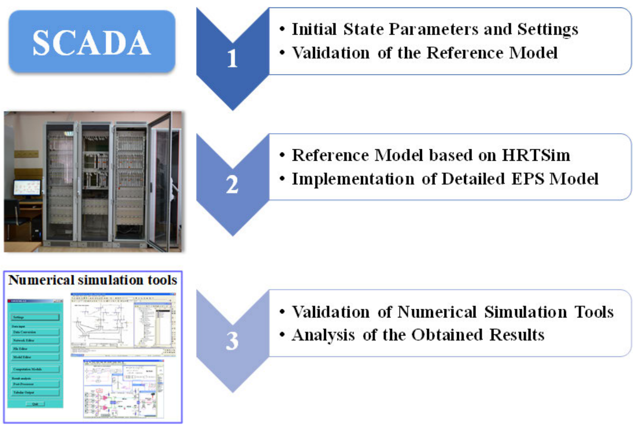

FIGURE 16. The block diagram of the proposed approach for STs' validation via HRTSim.

V. EXPERIMENTAL RESULTS

The mathematical model of large-scale EPS for experimental studies was developed according to the first point of strategy. The spectrum of quasi-steady and transient processes under normal and emergency EPS states necessary for the transient stability analysis were reproduced via the developed model. This EPS model was simulated in both HRTSim and studied ST. The ST selected for the validation allows to simulate electromechanical transients, contains sufficiently detailed mathematical models of equipment, has a reliable numerical integration method and a widely used in the world for transient stability assessment. However, despite the high development level of such tool, it has all the above-mentioned inevitable simplifications and limitations.

The three-phase electrical grid of Tomsk region (Siberia, Russia) was used as an EPS model (Fig. 18). This EPS has been chosen because the authors have the full database of equipment parameters and its characteristics (parameters of synchronous generators, power transformers, power transmission lines, shunt reactors, algorithms and settings of the automatic control systems, automatic voltage regulators, excitation systems, power system stabilizers, etc.), and also the SCADA data. The EPS model consists of: an electric grid of different voltage level (500, 220, 110 and 35 kV) with transformers and autotransformers of various power ratings, the main power plants of Tomsk EPS (TPP-3, SHK and CPS-2), distributed generation facilities (gas turbine power plants at SS Igolskaya and SS Lugineckaya), dynamic loads in the form of detailed mathematical models of synchronous and induction motors with their control systems, controlled shunt reactors, etc. The connections with neighboring power systems are modeled by equivalents that provide adequacy of the EPS model. The slack bus is simulated as an equivalent generator (Siberian PS) with constant frequency and unlimited power that has the characteristics, parameters and automatic control systems of an ordinary synchronous generator. This allows reproducing the response of neighboring power system when different disturbances occur. Thus, the total model consists of the following three-phase elements: 200 buses, 42 electric machines with transformers, 97 power transmission lines, 42 power transformers and autotransformers, 63 static loads. The EPS model with the identical topology and equipment parameters was simulated in the studied ST.

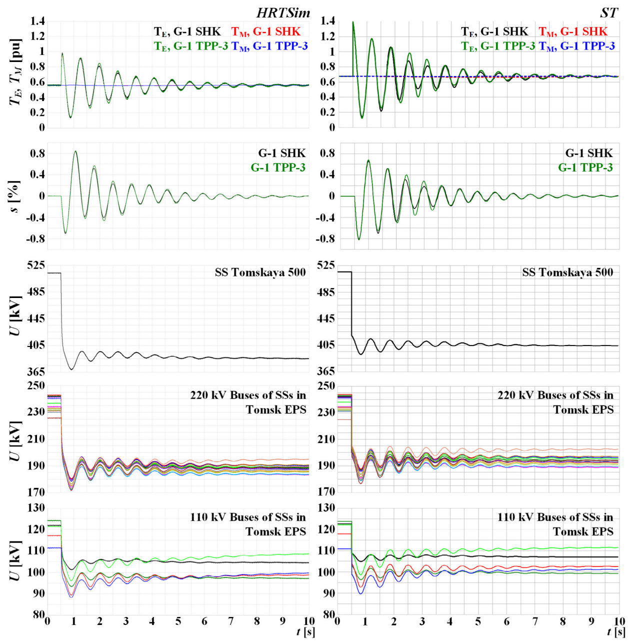

FIGURE 17. Oscillograms of processes obtained via HRTSim and ST in case of a tie line tripping (VL-526 500 kV SS Itatskaya – 500 kV SS Tomskaya).

A qualitative comparison of transients' simulation results via both HRTSim and studied ST was carried out at the final stage of the EPS model development. The tie line tripping without faults is shown in Fig. 17. Quantitative indicators was not assessed at this preliminary stage. The oscillograms obtained in all experiments, including presented in the paper (for Section VI), demonstrate a similar trend of the transients.

The HRTSim comprehensive validation was performed by comparison of the simulation results of normal operating state with SCADA data according to the second point of strategy. The results of comparison are within the average

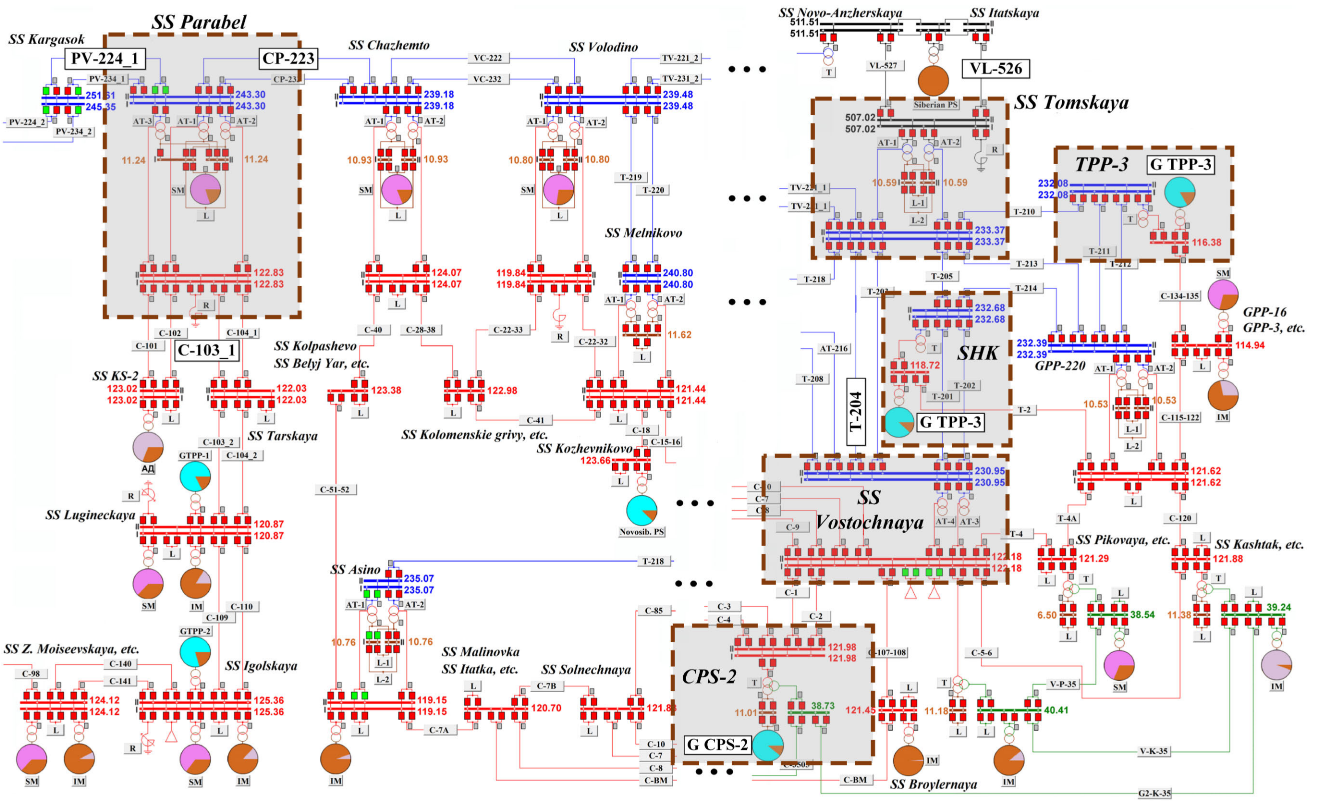

FIGURE 18. The single-phase view of the fragment of simulated Tomsk EPS in HRTSim.

statistical error of the SCADA system used in Tomsk EPS – do not exceed 5%. In addition, the HRTSim simulation results were compared with the recorded data of various disturbances occurred in Tomsk EPS. The obtained results also confirmed the adequacy of the HRTSim simulation [20]. After that, the simulation of various states and disturbances used for the transient stability assessment was carried out according to the scenarios developed in the fifth point of strategy.

A. VALIDATION OF TRANSIENT STABILITY CALCULATIONS IN CASE OF THE MOST SEVERE DISTURBANCE

The validation of transient stability calculations in accordance with the scenario (point 5.1) was carried out by transients' modelling under the most severe disturbance: a three-phase-to-ground SC at the 220 kV PL T-204 close to SS Vostochnaya with the longest fault clearing time due to the circuit breaker failure and BFP operation. The simulation results shown in Fig. 19 are different.

Aperiodic currents arising in the rotor and stator of synchronous machines during a fault create magnetic fields leaded to the rotor braking at the initial stage, as an example, this can be seen for a generator at CPS-2 that is electrically closer to the fault location (Fig. 20a). Three periods of the oscillograms in Fig. 20a contains moments where the electromagnetic torque exceeds the mechanical torque that causes short-term decreases in the rotational speed. In contrast, aperiodic currents of the rotor and stator calculated without taking into account transformer voltage term form an electromagnetic torque leading to a continuous increase in the rotational speed over the whole interval before fault clearing (Fig. 20b). Also, the impact of harmonic spectrum on the electromagnetic torque is excluded for single frequency calculations.

The simplified electric machine models (excluding the transformer voltage term) and grid elements (use of algebraic models excluding the impact of aperiodic components) in the studied ST lead to the fact that the magnitude and form of currents and voltages differ from the similar simulation without simplifications. Consequently, this leads to a difference in the electromagnetic torque that determines the transients' dynamics, because it depends on the aperiodic components decay in the electric machines and grid elements. In particular, the speed decrease and the stator voltage value are different (Fig. 20).

Aperiodic currents with reverse signs arising in the stator and rotor after fault clearing by BFP lead to a decrease in the electromagnetic torque and an increase in the rotor speed. The surge of transformer voltage term shown in Fig. 20a is corresponded to these currents. The electromagnetic torque magnitude after fault clearing is about 1.15 pu in the HRTSim (Fig. 20a) and 1.62 pu in the ST (Fig. 20b). This is determined by the increase in electromagnetic torque due to the impact of slip voltage term and the exclusion of oppositely directed transformer voltage term. All these facts together with the

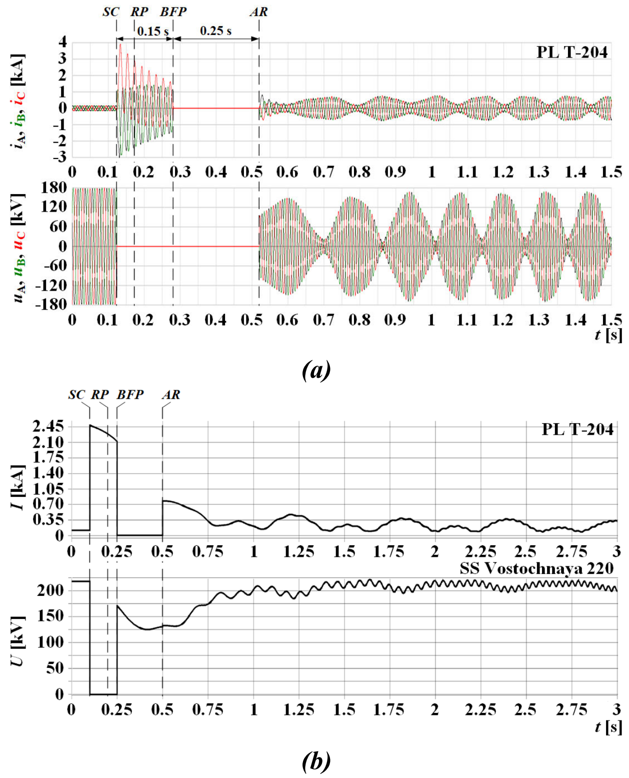

FIGURE 19. Oscillograms of processes obtained via HRTSim (a) and ST (b) in case of a three-phase-to-ground SC at the PL T-204 close to SS Vostochnaya.

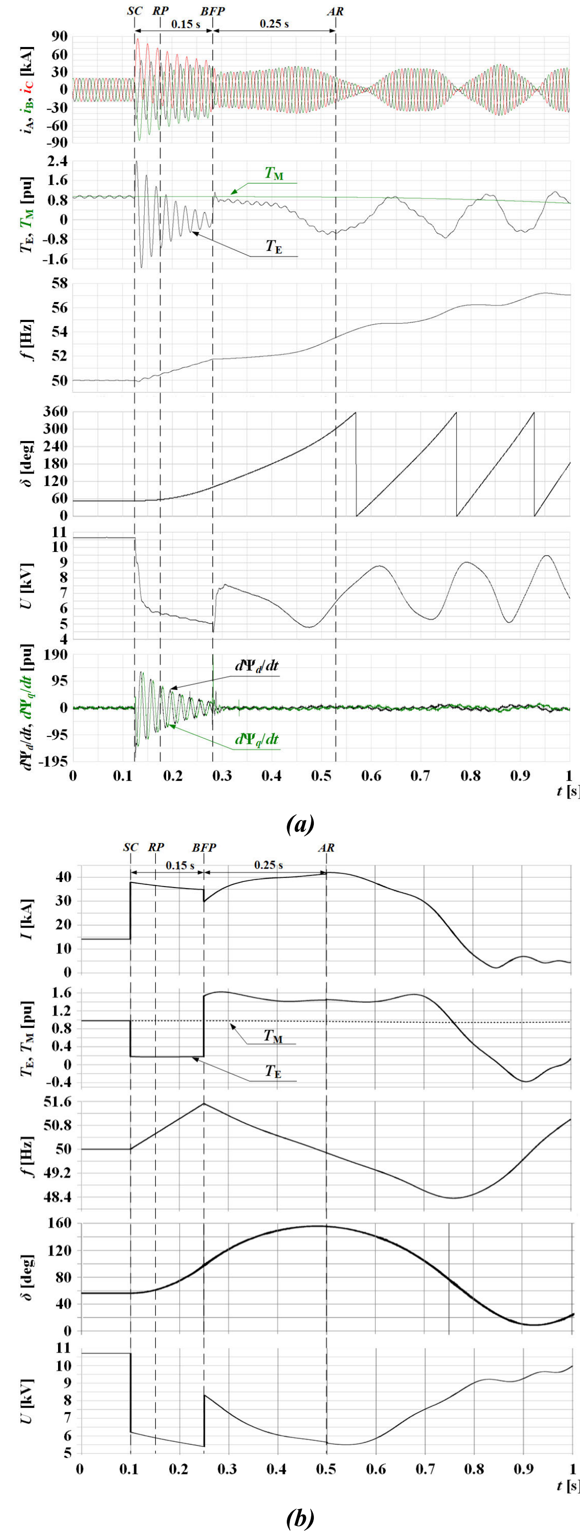

FIGURE 20. Oscillograms of processes in generator at CPS-2 obtained via HRTSim (a) and ST (b) in case of a three-phase-to-ground SC at the PL T-204 close to SS Vostochnaya.

error in the electromagnetic torque formed at this stage of transient process leads to a subsequent rotor braking in the simulation results obtained via ST. An additional error arises due to the exclusion of the impact of the frequency-dependent inductive reactance on the formation of reactive power flows and voltage levels.

Thus, since certain phenomena are predominant at each stage of the transient processes (damping of aperiodic components, change in frequency, etc.), the reliability of the next stage calculation depends on the previous one. At the same time, the simplified transients' simulation leads to distorted formation of currents and voltages during the transients. This reduces the possibility of a reliable transient stability assessment. As can be seen, the appropriate comprehensive simulation is significant throughout the entire process of fault occurring, its clearing, subsequent events and their mutual influence. In addition, the calculation of fast transients is associated with the need to use the minimum simulation step. This can lead to an increase in the number of step-by-step calculations and usually to an accumulation of the global numerical solution error.

B. VALIDATION OF TRANSIENT STABILITY CALCULATIONS IN CASE OF SPAR OPERATION

The following events were simulated for the validation of transient stability calculations in case of the successful SPAR operation according to the point 5.2 of strategy: a line-to-ground SC at the 500 kV PL VL-526 close to SS Tomskaya, high-frequency phase comparison line

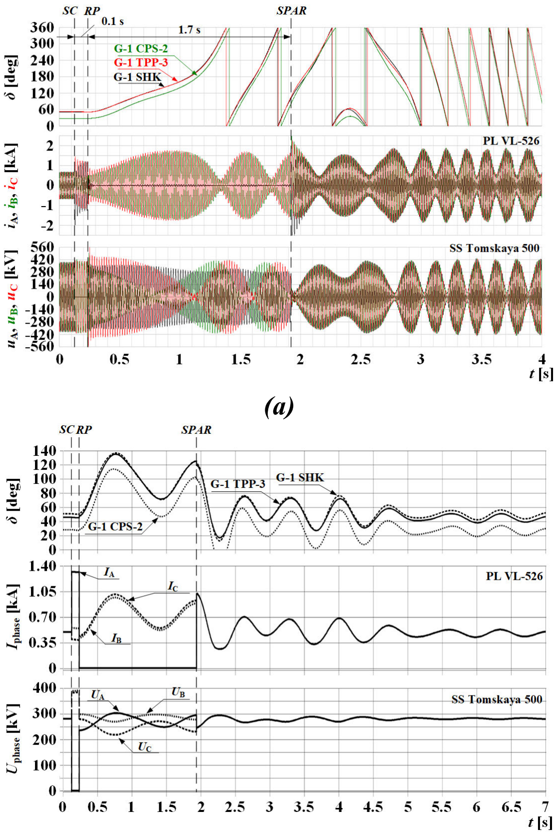

FIGURE 21. Oscillograms of processes in generators at CPS-2, TPP-3, SHK and PL VL-526 obtained via HRTSim (a) and ST (b) in case of a line-to-ground SC at the PL VL-526 close to SS Tomskaya and successful SPAR.

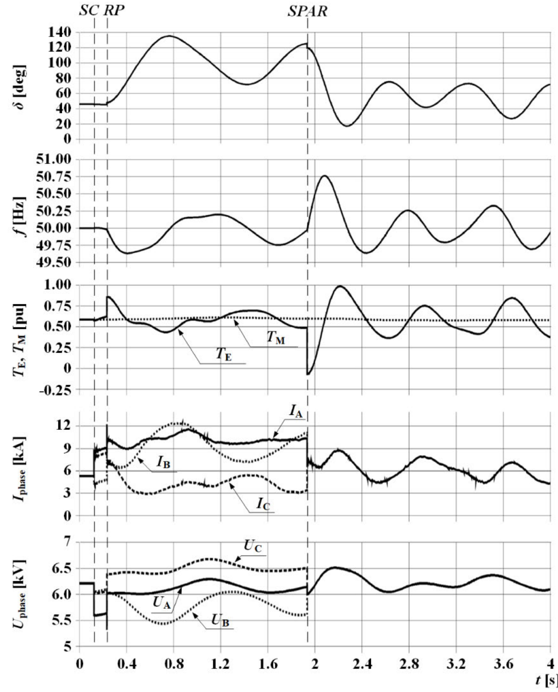

FIGURE 22. Oscillograms of processes in generator at TPP-3 obtained via ST in case of a line-to-ground SC at the PL VL-526 close to SS Tomskaya and successful SPAR.

protection operation (40 ms) and successful SPAR taking into account the response time of the SF6 circuit breaker of the PL (60 ms), deionization time at 500 kV PL with shunt reactors (1.2 s) and average reserve time (0.5 s). The obtained oscillograms demonstrate the different transients: loss of stability in HRTSim (Fig. 21a) and restoration of normal operating state in ST (Fig. 21b). In addition, the oscillogram of the faulted phase current does not reflect the electrostatic effect of the non-faulted phases due to the algebraic single-line simulation of the grid elements. Therefore, it is impossible to assess the decrease in the SPAR cycle time.

The indicated differences are also confirmed by the analysis of processes in each of the generators, in particular, in a generator at TPP-3 that is electrically closer to the fault location (Figs. 22-23). The algebraic simulation of grid equipment, the method of symmetrical components for a single frequency value, the exclusion of transformer voltage term and interphase interactions are used in the studied ST. These features do not allow to reproduce the aperiodic and harmonic components of currents arising in the electric machines and grid in case of unsymmetrical faults. Additionally, there is no their impact leading to an increase in the electromagnetic torque and its distortion in the unsymmetrical operation (Figs. 22-23). In particular, the difference in the maximum value of the negative-sequence currents causing additional rotor braking is 25%. Moreover, the oscillograms of currents, voltages, and electromagnetic torque changing simulated in ST significantly differ from the similar values obtained via the HRTSim due to the indicated applied simplifications and limitations. For example, the processes obtained via HRTSim (Fig. 23) compared to ST (Fig. 22) reflect the rotor braking and loss of stability in the cycle of unsymmetrical EPS operation. The successful SPAR and, consequently, restoration of the system symmetry do not restore synchronism and prevent the beginning of an asynchronous operation. The most part of motor load stopped at time $t \approx 2.24$ s leading to an increase in the rotor speed, but this process is also absent in the simulation results obtained via studied ST.

C. VALIDATION OF TRANSIENT STABILITY CALCULATIONS IN CASE OF POWER SYSTEM INTERCONNECTION

Today EPS of the Tomsk region consists of asynchronously operating northern and southern parts, the operational section between which passes through the transit of 220 kV with length of 797.3 km (including the territory of the united power system (UPS) of Siberia – 785.7 km) between SS Tomskaya (UPS of Siberia) – SS Volodino – SS Parabel – SS Sovetsko-Sosninskaya – Nizhnevartovskaya GRES (UPS of Ural) [45]. In normal operating state, the operational section is located on the area between SS Vertikos – SS Parabel. A possible solution to improve the reliability of power supply for responsible consumers located in the power-deficient

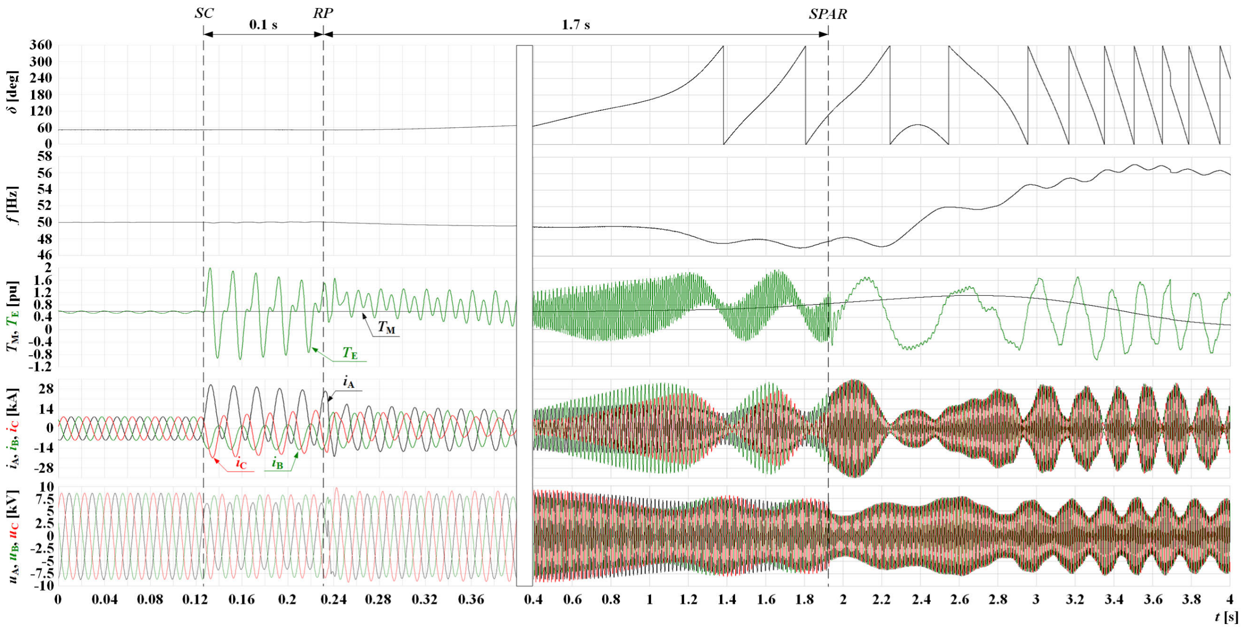

FIGURE 23. Oscillograms of processes in generator at TPP-3 obtained via HRTSim at different scales in case of a line-to-ground SC at the PL VL-526 close to SS Tomskaya and successful SPAR.

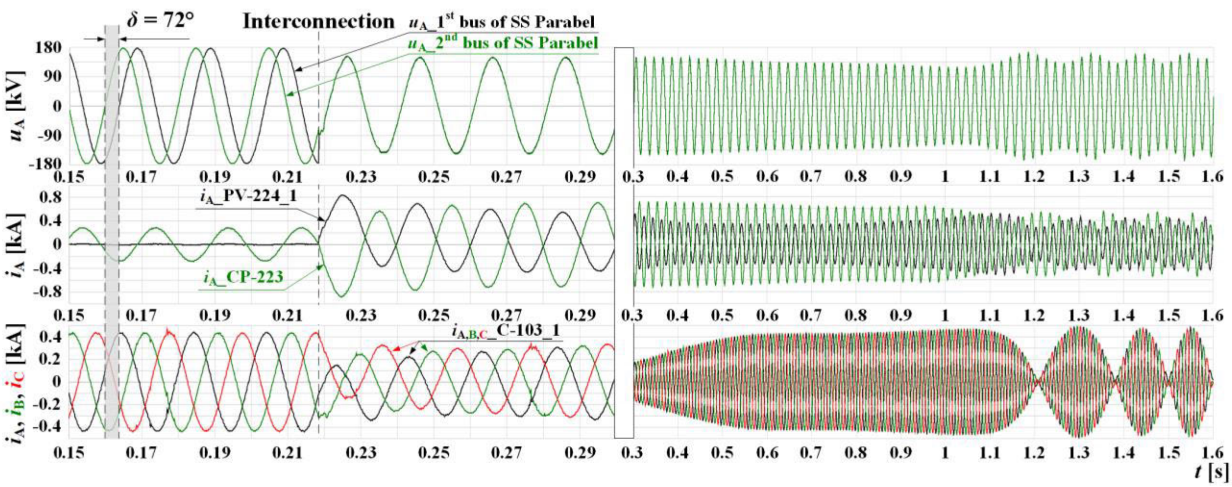

FIGURE 24. Oscillograms of processes obtained via HRTSim at different scales in case of an interconnection ($\delta = 72°$) of Tomsk EPS' northern and southern parts.

northern part is the parallel operation of Tomsk EPS' northern and southern parts. However, the information about the limiting angle difference between the voltages at the substation of interconnection (δ) in which transient stability will not be lost is required to assess the possibility of such interconnection. In this regard, the simulation was carried out for different angles δ between the voltages at 1st bus and 2nd bus of SS Parabel in order to assess the reliability of processes' calculations arising in case of the interconnection (point 5.3 of strategy). The results obtained via ST demonstrate the simulation error growth with increase in δ and, accordingly, voltage oscillations. In particular, the changes in the error for values of the PL C-103_1 currents after interconnection are as follows: (1) at $\delta = 12°$ is about 4.6% and 0.1% after 4 s of the interconnection, (2) at $\delta = 47°$ – 28.4% and 9,9% after 4 s, (3) at $\delta = 72°$ or more the processes differ radically – the loss of transient stability in HRTSim (Fig. 24) and the normal operating state in ST (Fig. 25). These differences of the simulation results are associated with the applied simplifications and limitations, especially with the use of algebraic models of grid elements that distort the propagation of currents' and voltages' oscillations through the power network and caused by them processes in generators and other electric machines.

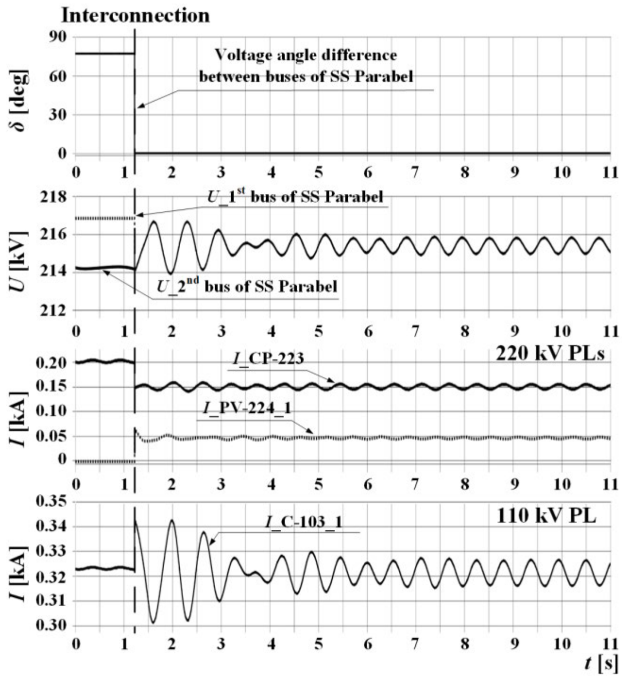

FIGURE 25. Oscillograms of processes obtained via ST in case of an interconnection ($\delta = 72°$) of Tomsk EPS' northern and southern parts.

VI. CONCLUSION

The developed approach allows providing the comprehensive validation of transient stability calculations for EPS of any size and configuration based on information received from the reference model with guaranteed acceptable accuracy. An experimental sample of HRTSim was used as the reference model. The HRTSim can initially be validated via comparison with only SCADA data and there are no need in transients' data, which is difficult to obtain. That is possible since the single detailed three-phase mathematical model of large-scale EPS and methodologically accurate implicit integration method are used in the HRTSim for the entire continuous spectrum of quasi-steady and transient processes. The obtained in this manner validation results can be disseminated to the entire spectrum of processes and they are guaranteed to validate the HRTSim. The developed strategy for comprehensive validation and tools for its implementation form the theoretical contribution of this paper. The using of a reference model – HRTSim, which can be validated by only one state or process in EPS, instead of the transients' data used in the existing validation methods is the main novelty of the developed approach. The main limitation of proposed approach consists in the possibility of HRTSim to simulate the necessary scale of EPS, but due to interconnection of simulated equipment at a physical level, this limitation is only connected with total cost of HRTSim. The HRTSim' simulation results adequacy is also confirmed theoretically and experimentally by comparing its results with widely applicable EPS simulator – RTDS (for a small EPS scheme).

The proposed approach for validation eliminates the need to have a huge amount of field data compared to existing validation methods. It is impossible to collect full data that is necessary for these methods, now and in the near future, regardless of development level of devices for measuring and processes recording in EPS. It is related to the fact that the spectrum of possible states and disturbances in EPS is very wide, and the probability of their combination and occurrence is unpredictable and uncertain. This is particularly relevant for future EPSs with DG, RES and FACTS. Exactly this problem determines the need of using the developed approach for comprehensive validation of large-scale (real) EPS models. The proposed approach makes possible the assessment of the results' reliability obtained via various applied STs for power system analysis and simulation in case of various disturbances (and their sequence), particularly, in modern EPSs with a significant share of DG, RES and FACTS. In the near future, it is planned to test the developed approach at real power system with a deep penetration of RES and DG. The main informational cycle of HRTSim will be accelerated by using microcontrollers with a higher clock speed (now testing STM32F429) for such research. The created hybrid tool allows identifying the causes of calculation errors, which can be used to formulate a strategy for varying the parameters of EPS mathematical model in order to increase adequacy of the results. It is authors' future research. The adequacy of the results obtained using the adapted EPS mathematical model can be validated for various scheme topology, disturbances and following processes in a similar way by comparison with the results from the reference model. In addition, the developed approach allows determining disturbances and following processes calculated with the significant error, which are required to be analyze in detail before it practical application. Exactly such results are presented in the paper. Experimental studies have revealed that in the case of less severe disturbances a lower level of error is observed in the simulation results obtained via studied ST, and vice versa.

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