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Research, Development and Application of Hybrid Model of Back-to-Back HVDC Link

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ABSTRACT Recent hybrid simulators (or co-simulators) of the electric power system are focused on scientific and research features to propose and develop novel and more accurate simulators. The present paper demonstrates one more hybrid modelling approach based on application and combination of three modeling approaches all together: physical, analog and digital. The primary focus of the proposed approach is to develop the simulation tool ensuring such vital characteristics as three-phase simulation and modeling of a single spectrum of processes in electric power system, without separation of the electromagnetic and electromechanical transient stages. Moreover, unlimited scalability of the electric power system model and real-time simulation to ensure the opportunity of data exchange with external devices have been considered. The description of the development of the hybrid model of back-to-back HVDC link based on the proposed approach is discussed and analyzed. To confirm properties of the mentioned hybrid simulation approach and hybrid model of back-to-back HVDC link, the simulation results of the interconnection of non-synchronously operating parts of the electric power system; power flow regulation; dynamic response to external fault and damping of power oscillation in electric power system are presented and examined. Moreover, to confirm the adequacy of the obtained results, the comparison with a detailed voltage source converter HVDC model (Simulink Matlab) and Eurostag software are introduced.

INDEX TERMS Power system, hybrid type of simulation, back-to-back HVDC link, research and development, asynchronous interconnection, power flow regulation, dynamic response, damping.

I. INTRODUCTION

Currently, several works have been devoted to the development of hybrid simulators (or co-simulators) of the electric power system (EPS) to ensure such key characteristics as [1]–[4]: 1) Three phase simulation; 2) Modeling of a single spectrum of processes in EPS, without separation to electromagnetic and electromechanical stages of a transient; 3) Unlimited scalability of EPS model; and 4) Real-time simulation to ensure the opportunity of a data exchange with external devices (in particular, closed-loop testing).

Mainly such hybrid simulators are based on a combination of different simulation approaches [3], [5]–[10]. For instance,

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in [3], [5], [7], the authors have proposed both applications of Electro-Magnetic Transient (EMT) and Phasor-Domain simulation methods. In such cases, the EMT is used to simulate a detailed three-phase mathematical model of EPS and the typical calculation of the time-step is found to be less than 10μs, but only for small and the most interesting part of EPS due to the limited computational resource of a processor.

The calculation of pre-emergency mode, mainly characterized by the fundamental harmonic (50Hz), can be realized with a time-step of 50μs. It allows to use simple algebraic equations with complex coefficients in the Phasor-Domain simulation instead of solving differential equations in the time domain for modeling processes in EPS. Thus, it is assumed that the electromagnetic stage of the transient processes (for instance, from the moment of appearance and elimination of short-circuit) decays within a short period of time; therefore this process can be reproduced in detail; and also that the rest of the EPS does not have any significant impact on the analyzed part of EPS.

There are several disadvantages of using such an approach as follows [11]–[13]: 1) Small part of EPS can be solved by EMT, as a matter of the substantial simulation calculation burden limiting the size of the simulation; 2) Data exchange between parts of EPS, solved by EMT and Phasor-Domain simulation, is carried out considering a large time-steps, and thus, preventing spreading the disturbances with a small-time constant among these parts and resulting in distortion on the EPS in general. This conclusion is confirmed by comparison of simulation results obtained by different simulators [14], in particular, loosing the information when exchanging the data among the simulated parts besides the delay when exchanging the information (due to the use of different time steps) results in an error in case of electromagnetic transients, and 3) An assumption is made to that part of EPS calculated in Phasor-Domain simulation as no fluctuations exist up to 200Hz (usually these are low-voltage networks without long transmission lines and reactive power compensation equipment). Accordingly, for the simulation of EPS with long transmission lines and reactive power compensation equipment, this approach is not applicable. Considering this remark, it is not possible to set the automatic control systems of flexible alternating current transmission system devices, high-voltage direct current (HVDC) transmission system, etc. accounting for the effect of low-frequency oscillations; that can result in an inappropriate response.

To provide real-time simulation in [6], [13], the authors proposed to separate the solution of the mathematical model of EPS between several computing cores – Simulator_1 and Simulator_2 (see Figure 1). In this case, simulation results of the Simulator_1 at a previous calculation step are used as initial data for Simulator_2 [6].

Determination of the decoupling point of EPS model is one of the requirements for applying this approach. Transmission line (TL), or other components alike, are usually used as a

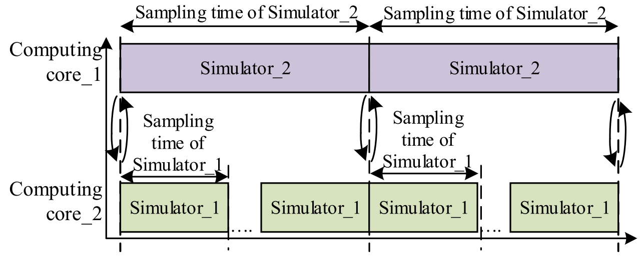

FIGURE 1. Hybrid simulation approach using multi-core tools.

decoupling point. However, several limitations have to be considered. The TL length should be considered because the wave propagation time along the communication line should not be less than the integration step, and that is not all the time attainable with a short line length or through the use of equivalence of multi-parallel lines [15]. In addition, according to [6], the mentioned method can be applied to a small part of EPS; otherwise, the calculation would require a significant computational and time resource and can lead to the accumulation of integration errors, which is determined by using a numerical method for solving the mathematical models.

There are many studies [3], [16], [17] proposing simulation tools using Field Programmable Gate Array (FPGA). The FPGA permits, through the distribution of mathematical models' parts of EPS among the corresponding numbers of FPGAs, to increase the modeled EPS size in detail and to use minor time step (100ns) [3], [16], [17]. However, a demand exists for using simplified mathematical models of rest power equipment of EPS. For instance, the description of network components is through linear algebraic equations, and models of the primary generator engine and excitation systems are extremely simplified, and thus, reducing entirety and how reliable of simulation results are.

In this work, the results of the application of another type of hybrid simulator are presented. The work targets the application and combination of three modeling approaches all together: physical, analog and digital – hybrid simulation approach.

The rest of the paper is structured as follows. The detailed description of the hybrid simulation approach is given in Section II. In Section III, the case studies and simulation outcomes prove how adequate the model is. Finally, brief conclusions are made in Section IV.

It should be noted that the results presented in this article are a continuation of earlier work [18], [19], in relevance with the application of this hybrid simulation approach for creating comprehensive simulation tools of EPS, in particular back-to-back HVDC link (B2B HVDC).

II. DESCRIPTION OF THE PROPOSED HYBRID SIMULATION APPROACH

It was mentioned that the proposed hybrid simulation approach combines physical, analog and digital simulation levels:

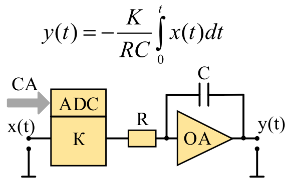

FIGURE 2. The realization of continuous implicit integration method. In Fig. 2 the ADC – analog-to-digital conversion, OA – operational amplifier, CA – control action.

A. ANALOG SIMULATION LEVEL IS USED TO ELIMINATE SYSTEMATIC ERROR OF INTEGRATION

The whole range of significant processes in power equipment is fully and accurately described by theoretically assured differential equations systems. Solution of these differential equations systems are carried out by a continuous (analogue) implicit methodically accurate integration method, i.e. using an analogue method in real time and at unlimited intervals. So, an integrator based on an operational amplifier is used to realize an operation of integration of differential equations systems (see Figure 2). It helps to eliminate the need for simplifications of mathematical models and a methodological calculation error [20], [21].

The speed of integration (or time scale) is found by the integrator time constant ($M_t = RC/K$). So, for real time integration the time scale in the analog method is proposed to equal to 1 ($M_t = 1$), while the value of R and C are selected based on the conditions of the smallest voltage drop at this resistor (R) and the smallest capacitor size. In this case, during one second the output voltage of the integrator with a unity gain ($M_t = RC/K = 1$) would change by one unit (pu) when the input voltage of the integrator will be equal to one unit (pu).

Based on analysis of the equivalent scheme of modeled power equipment a solution scheme (called parallel digital-to-analog structure of continuous methodically accurate real-time solution of systems of differential equations) of this mathematical model is developed (see Figure 3). In Figure 3, the continuous mathematical variables of input/output currents are to undergo a conversion through a voltage-current converter. The result of such a conversion is the relevant model physical currents, then the formed voltage at the node connecting the physical models is set back to the mathematical model via voltage follower (+1).

B. PHYSICAL MODELING LEVEL FOR ENSURING THE ADEQUACY OF THE WHOLE SPECTRUM OF SWITCHING PROCESSES SIMULATION

As a matter of lacking a consistent theoretical base to develop suitable mathematical models, fully and accurately described the range of switching processes, the physical modeling level is the best solution for simulation of different switching processes in power semiconductors, numerous switching of circuit breakers and short circuits. Continuous mathematical variables of the input/output currents of the mathematical models are converted by the voltage-current converter (u/i).

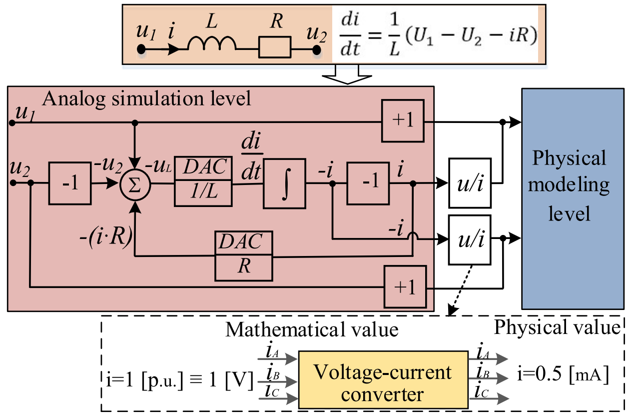

FIGURE 3. Development of the parallel digital-to-analog structure of continuous methodically accurate real-time solution of systems of differential equations of RL-element.

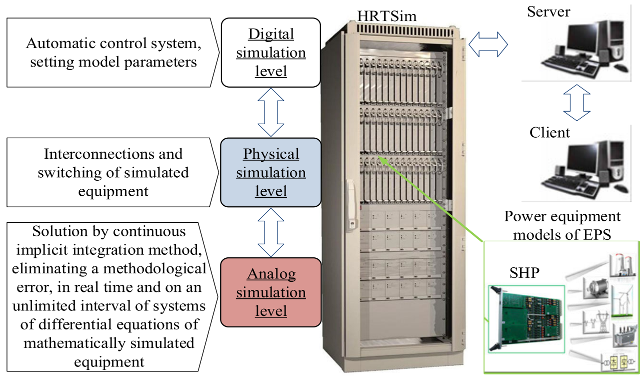

FIGURE 4. The basic concept of the proposed hybrid simulation approach.

The conversion of the mathematical models into the relevant model of physical currents is made to connect the analog and physical modeling levels, thereby providing a normal communication between the simulated equipment (see Figure 3).

C. DIGITAL MODELING LEVEL

The implementation of digital to analogue and analogue to digital conversions and the deployment of IT-technologies are to provide all information and control functions, as well as conversion and visualization of the obtained information. Such considerations results in the developed hybrid real-time power system simulator (HRTSim) as demonstrated in Figure 4.

According to Figure 4, each element of EPS: synchronous and asynchronous machines, transformers, transmission lines *et al.* is realized by the special hybrid processor (SHP) – the main element of HRTSim [22], [23].

In Figure 5, the presented hierarchy of the HRTSim environment consists of several levels responsible for simulation and characterized by the minimum allowed time delays that guarantee the real-time of simulation. The Central processing unit (CPU) is used to provide all interaction functions of the server with peripheral processors such as; (analog to digital conversion processors (PADC) and switching processors (SwP)). Moreover, the functions of converting from analog

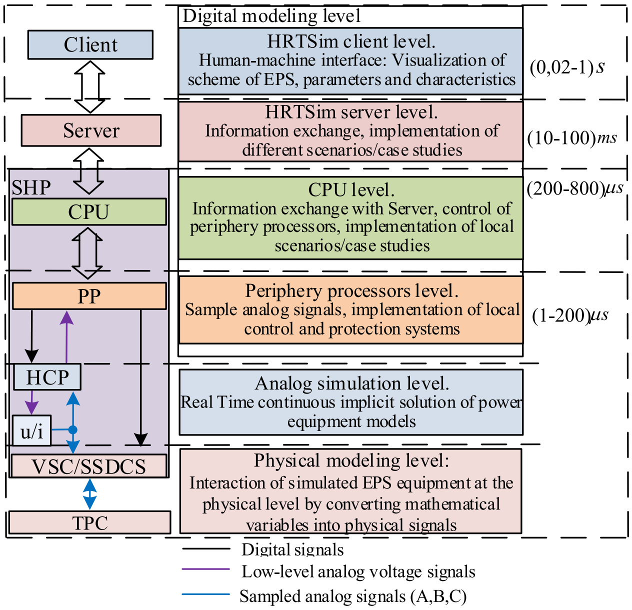

FIGURE 5. The hierarchy of the HRTSim.

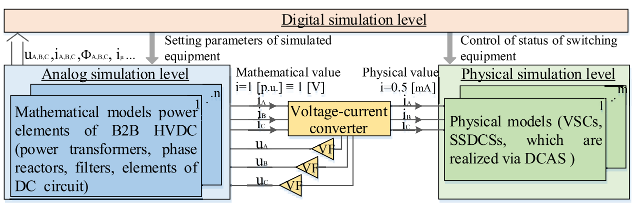

FIGURE 6. The basic principle realization of SHP of B2B HVDC model.

to digital besides the read and process of the simulation data from the parallel digital-to-analog structure, realized in the hybrid coprocessor (HCP), are carried out by the PADC. The SwP controls the status of series and shunt digitally controlled three-phase switches (SSDCS). The SSDCS are utilized to implement all sorts of commutations. The functional three-phase inputs and the functional three-phase outputs of phase A, phase B and phase C of SHP are connected as per the topology of the modelled power system through the use of 3-phase commutator. It enables to scale the simulated 3-phase EPS, realize a natural communication of the simulated equipment and numerous commutation processes in EPS model, besides the provision of communication with external software/hardware tools such as SCADA system, automatic control systems and etc.

Below, a brief description of SHP of B2B HVDC development is presented while detail information was shown earlier in [18], [19].

D. DEVELOPMENT OF SPECIAL HYBRID PROCESSOR OF B2B HVDC

According to the analysis of B2B HVDC scheme and operation principle, the SHP of B2B HVDC model consists of (see Figure 6):

1) Mathematical models (to simulate the whole range of significant processes in the equipment that does not contain switching elements – power transformers, phase reactors, filters, elements of direct current (DC) circuit) [19].
2) Physical models (to simulate the model of voltage source convertors (VSC) and SSDCS, which are realized via digital-controlled analog-switches (DCAS) [18]).

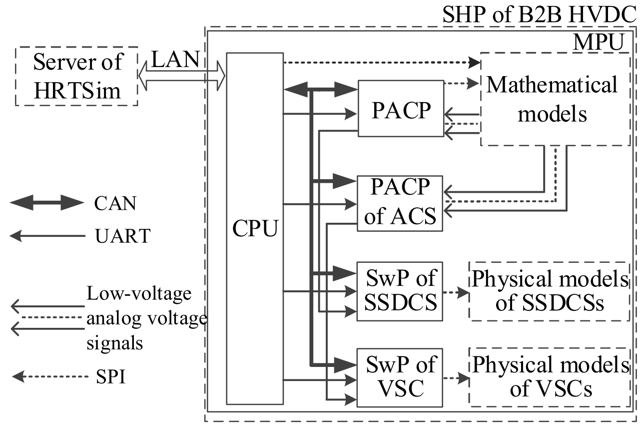

FIGURE 7. The structural scheme of the microprocessor unit (MPU).

A detailed description of the development of mathematical and physical models was presented in [18], [19], [22], [23]. Additionally, the realization of the digital part of the SHP of B2B HVDC is analyzed below.

The digital level is used for the following functions (data exchange function; automatic control of parameters and settings of the modeled equipment; conversion and visualization of the obtained information) and is carried out through digital to analog and analog to digital conversion of information using the essential software/hardware.

The structural scheme of the microprocessor unit (MPU) of the SHP of B2B HVDC consists of (see Figure 7):

1) Central processing unit (CPU): it is used to provide all interaction functions of the server of the HRTSim with PADC and SwP (receiving the parameters' values of the mathematical models of power transformers, phase reactors, filters and elements of DC circuit from the server, transmitting the simulation data to the server machine; synchronization and reprogramming of all PADCs and SwPs).
2) The functions of converting from analog to digital (ADC), read and process of the simulation data from mathematical models, besides the functional processing of the obtained information for implementation of automatic control system (ACS) of B2B HVDC (ABC-to-dq transformation, forming the control activities for pulse-width modulation (PWM), etc.). These are carried out by the PADC.
3) The SwP controls the status of DCASs of physical models of VSC and SSDCS.

In Figure 7, the Controller Area Network (CAN) bus protocol is used for broadcasting interactions between

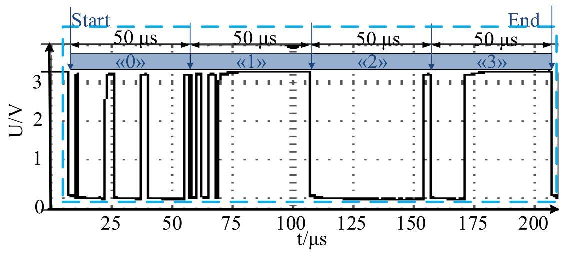

FIGURE 8. The time diagram of main cycle of the PADC of ACS program.

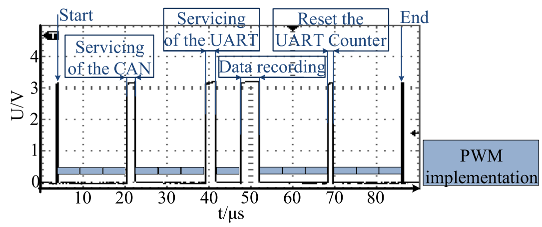

FIGURE 9. The time diagram of main cycle of the SwP of VSC program.

processors of MPU. The UART (Universal Asynchronous Receiver/Transmitter) bus protocol is used to carry out individual interactions between processors of MPU. The SPI (Serial Peripheral Interface) bus protocol is used to organize the control of parameters of the modeled power; through the LAN (local area network) and all information as well as to control interactions between the CPU and the server machine of HRTSim.

In accordance with the structure scheme of the MPU and of the modern ACS of B2B HVDC, the corresponding PADC of ACS, SwP of VSC and SwP of SSDCS programs based on the at91sam7 $\times$ 256 microcontroller were developed and implemented.

The main cycle of the PADC of ACS program includes the following commands: checking and reading of ADC, processing of data arrays, servicing of the UART (transferring data to SwPs, receiving from the CPU the settings of controllers of ACS) and the CAN (synchronizing the operation time of the CPU and the PADCs), and amounts to around 200 μs (four quanta of 50μs each).

The main cycle of the SwP of VSC program includes the following commands: servicing of the UART (receiving and checking data from the PADC of ACS or CPU) and the CAN (interrogating the switching status of DCASs, implementation of the PWM procedure, via. comparison of reference and carrier signals and the formation of control pulses for DCASs).

For assuring an adequate model of ACS of B2B HVDC (viz. MPU of the SHP of B2B HVDC), time diagrams of the PADC of ACS program and SwP of VSC program are shown in Figures 8 and 9 and Table 1. For instance, the total time spent by SwP of VSC program for PWM implementation is around 5.7μs, which guarantees its simulation in real time.

Because of the implementation of the hybrid simulation method, the SHP of B2B HVDC was developed. The next

TABLE 1. The time diagram of main cycle of the PADC of ACS program.

Operation	Time, µs
Reading and processing of ADC	13
Digital filtering of measured data	4
ABC-to-dq transformation	15
Calculation of p(t), q(t), s(t)	3
Initialization of controllers of ACS	1
Calculation a reference value of voltage controller	2.4
Calculation a reference value of active power controller	2.7
Calculation a reference value of reactive power controller	2.7
dq-to-ABC transformation	2.5
Transferring data to SwP of VSC via the UART	2

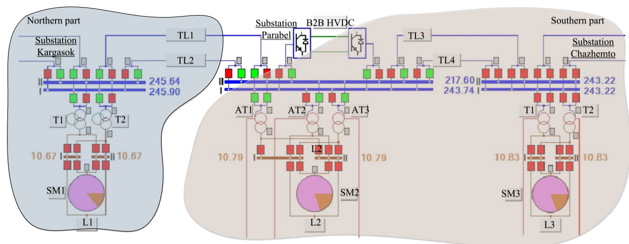

FIGURE 10. The fragment of the scheme of Tomsk EPS implemented in HRTSim. In Fig. 10 SM – synchronous machine, T – transformer, AT – auto transformer, L – load, TL – transmission line.

section presents the results of studies and analysis of the SHP of B2B HVDC to confirm its properties. In particular, three-phase modeling of single-continuous spectrum processes (without separation into steady-state and electromagnetic and electromechanical stages of transient processes) in real time and on an infinite interval is introduced.

III. REASERCH STUDIES OF THE DEVELOPED SHP OF B2B HVDC

To confirm the mentioned properties and adequacy of the simulation, the developed SHP of B2B HVDC was installed into the HRTSim, and the subsequent studies were carried out [24]–[27]:

1) Interconnection of non-synchronously operating parts of EPS.
2) Power flow regulation and reversal (dynamic response to step changes of active power regulator).
3) Dynamic response to external faults.
4) Damping of power oscillation in EPS.

These studies were carried out on the Tomsk EPS model, because there is a long (about 800km) 220kV transit between the northern part, which mainly supplies oil and gas companies, and the southern part (see Figure 10). Nowadays, this transit has a point of operating section at Parabel substation, so these parts are operating non-synchronously.

In this regard, it is relevant to solve this problem and to increase the level of operational reliability and energy supply efficiency for consumers (e.g. oil/gas sector), especially for

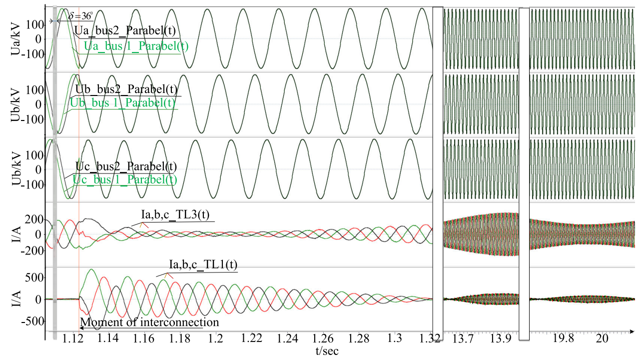

FIGURE 11. Oscillograms of currents and voltages in case of iinterconnection of non-synchronously operating parts of Tomsk EPS at $\delta \approx 36°$.

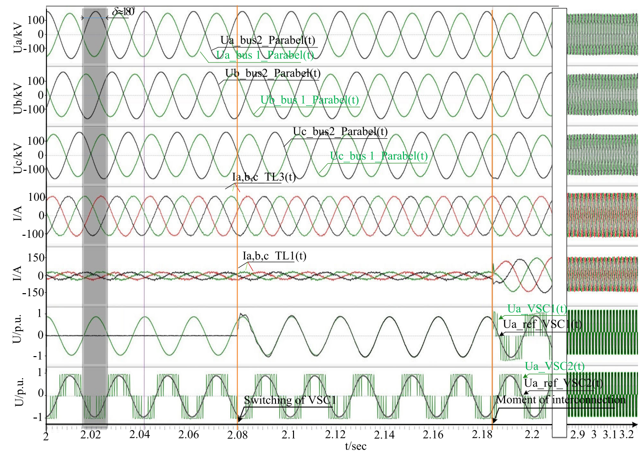

FIGURE 12. Oscillograms of currents and voltages in case of asynchronous iinterconnection of non-synchronously operating parts of Tomsk EPS at $\delta \approx 180°$ via B2B HVDC.

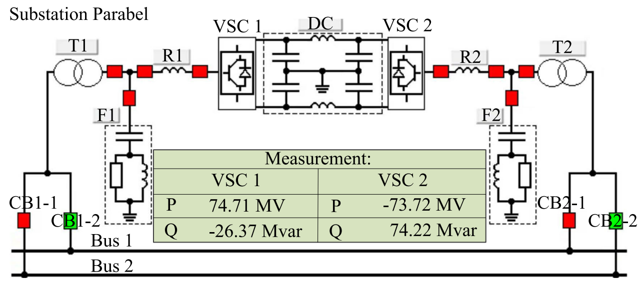

FIGURE 13. DMCP of the SHP of B2B HVDC, showing the current mode status and the amount of power flow through the B2B. In Fig. 13 T – power transformer, R – phase reactors, F – filters, DC – direct current circuit, CB – circuit breaker.

the time of routine switching of operations, besides improving how flexible and sustainable Tomsk EPS operation is.

A. CASE 1

The analysis of feasibility study [28], [29] reports the phase-shifting device with an angle range that is around $\delta = \pm 40°$. However, as noted in [30]–[32], it will not solve the discussed problem in general and especially under the growing energy consumption. Moreover a parallel operation of the North and South parts of the Tomsk EPS is possible, but in a limited angle range between the voltages of Parabel substation.

The obtained simulation results of the interconnection through synchronization tools and busbar circuit breakers of Parabel substation are shown in Figure 11. The critical value of angle at which the interconnection is possible have to be less than $\delta_{crit} = 36°$. This condition does not lead to significant power surges and instability of EPS. According to the presented oscillograms, it can be seen that such interconnection leads to significant power surges (about 120 MW), i.e. the approximate value of the power flow is about 4 MW/deg. This value roughly coincides with the measured value of power surges obtained during the field experiment and calculation in the Tomsk EPS [32].

On the other hand, the B2B HVDC link can be used as an effective solution to this problem. The B2B HVDC link is providing the asynchronous interconnection at whatever angle value between the voltages (even with $\delta = 180°$), angular frequencies and magnitude of the voltages, and does not lead to power surges, the appearance of non-damping oscillations and disruption of the normal EPS operation (see Figure 12).

B. CASE 2

In Figure 13, the fragment of the developed dynamic monitoring and control panel (DMCP) of the SHP of B2B HVDC software is presented, which displays the monitored parameters (power flow, voltage levels) during operation of the B2B HVDC model.

As per the scenario, the active power reference of VSC 1 is changed from 0.2p.u. up to 1p.u. with 7 steps in a time-step of 0.5 sec, then the power flow changes the direction. The obtained simulation result of the power flow regulation and the reverse are presented in Figure 14. It has been observed that the voltage fluctuations accompany the change in power flow on the capacitor battery of the DC circuit, whose level is under control of the control system. Besides that, the power reverse is run in a time of 0.1-0.5sec, and this is relevant to the time shown in [33], [34].

The same scenario (but for small two-machine EPS) was carried out in Simulink Matlab with a detailed model of VSC HVDC. The simulation results got through the SHP of B2B HVDC and Simulink are almost the same (see Figure 14).

C. CASE 3

Within the framework of these studies, the impact of B2B HVDC on emergency processes in EPS, in particular the most severe form of emergency disturbance – three-phase short circuit (SC), is considered [24], [25], [35]. According to the scenario, a short circuit occurs at the transmission line (TL1). As a result, the phase currents increase up to 3kA, which blocks the commutations of the power semiconductor switches and thus, operating the protection system (circuit breakers (CB) of TL1 of switched off). In this case, the power flow via B2B HVDC stops, and the voltage level on the

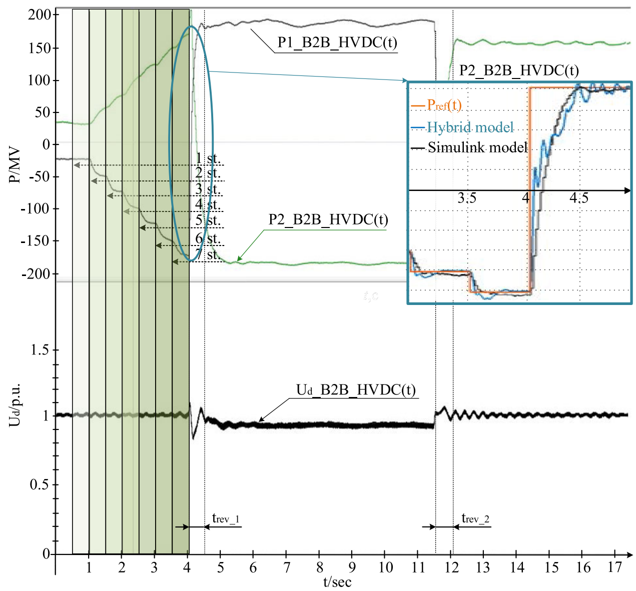

FIGURE 14. Oscillograms of power flow (P1_B2B_HVDC(t) and P2_B2B_HVDC(t)) and DC voltage (Ud_B2B_HVDC(t)) of B2B HVDC model under power flow regulation and reversal. In the blue box the comparison of simulation results obtained by the hybrid model (SHP of B2B HVDC) and Simulink VSC HVDC model are presented.

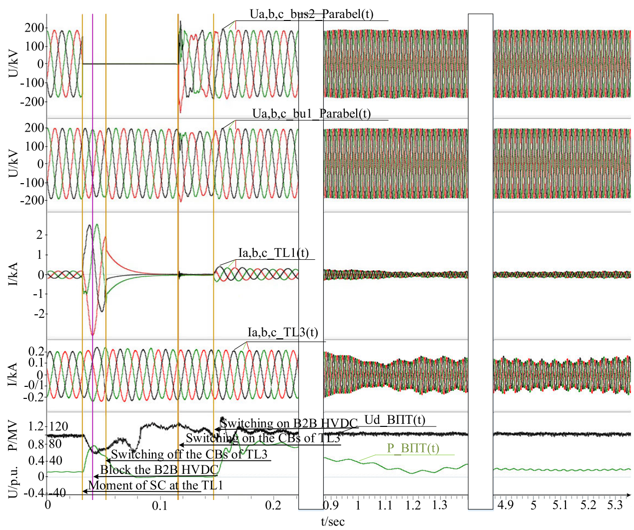

FIGURE 15. DPNU of the SHP of B2B HVDC, showing the current mode status and the amount of power flow through the B2B. In Fig. 15 T – power transformer, R – phase reactor, F – filter, DC – direct current circuit, CB – circuit breaker.

capacitor battery of the DC circuit is limited and controlled by the control system (see Figure 15).

Simultaneously, the installation of B2B HVDC decreases the level of SC current in EPS. As for TL1, the level of SC current has been limited from 1240A to 880A. Also, the level of SC current for TL3 decreases from 1300A to 910A. Consequently, it decreases the current demand of the equipment and raises its life. Moreover, B2B HVDC allows damping oscillations in the EPS during SC and reduces the mutual influence of SC in the EPS.

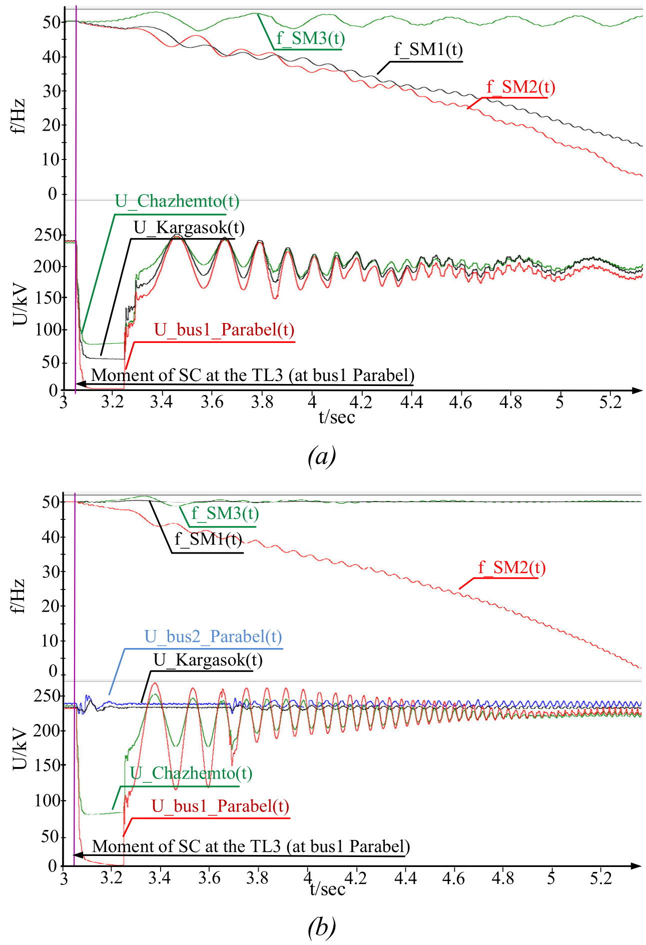

FIGURE 16. Oscillograms of SMs frequency and voltage of substations under SC at TL3 without (a) and with (b) B2B_HVDC.

In addition, B2B HVDC allows to damp oscillations in the transient process and to support the voltage level to increase the stability operation of loads, especially the machine loads. For instance, during the SC at Parabel substation, the significant voltage drop causes the synchronous machines stop at Kargasok substation (SM1) and Parabel substation (SM2), while the operation of B2B HVDC allows supporting the voltage at these substations, so SM2 remains in operation (see Figure 16).

To confirm the competence of the obtained results considering the SHP of B2B HVDC model, the same scheme of Tomsk EPS and a scenario of external faults were realized in Eurostag software [36]. It should be noted that the reason for comparison with the Eurostag is that it is the most used (in particular, Russian company ≪ System Operator of the United Power System ≫) simulator and its properties allow modelling the large scale EPS.

In Figure 17, osillograms of SMs frequency, obtained by HRTSim and Eurostag, are presented. It is shown that the curves coincide qualitatively. However, the quantitative difference is related with the utilization of different approaches for setting the parameters of power equipment models and their implementation as a whole. In particular, the model of

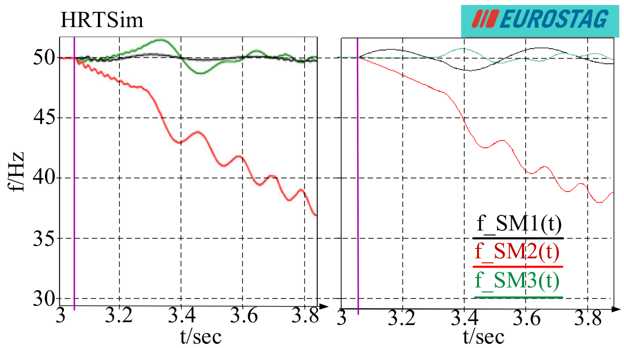

FIGURE 17. Oscillograms of SMs frequency under SC at TL3.

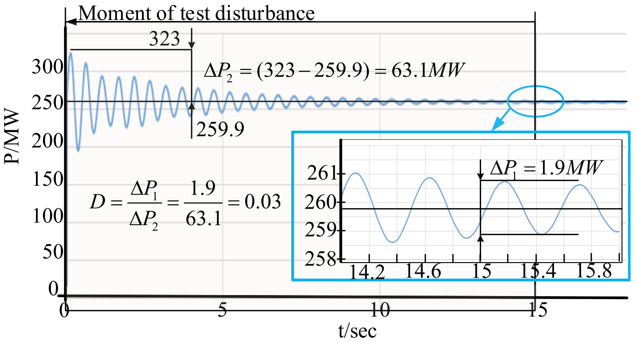

FIGURE 18. Oscillograms power flow and calculation of level of power oscillation.

B2B HVDC is realized according to two dynamic controlled injectors delivering the power consumption/production to the node, while some of automatic control components and DC circuit are simulated by macroblocks for other applications [36].

D. CASE 4

Currently, the automatic excitation control (AEC) of the generators is the main regulator used for damping power oscillations in EPS. According to the requirement [37] the evaluation of damping properties are carried out by level of power oscillation after 15 sec from the moment of test disturbance (it is usually three phase SC during 0.02 sec at bus of power station).

The following equation is used to calculate the level of power oscillation:

$$D = \frac{\Delta P_1}{\Delta P_2} \tag{1}$$

where ΔP_1 is value of power oscillation after 15 sec from the short circuit; ΔP_2 is maximum value of power oscillation, which is determinated as difference between a peak value of active power at the transient process and its steady-state value.

An example of calculating the value of D for one of the power station of Tomsk EPS is presented in Figure 18.

If value of D is less than 0.01, the AEC settings are effective and considered satisfactory [34]. The obtained value is not satisfied to the requirement, this indicates that the AEC settings should be reviewed and configured correctly.

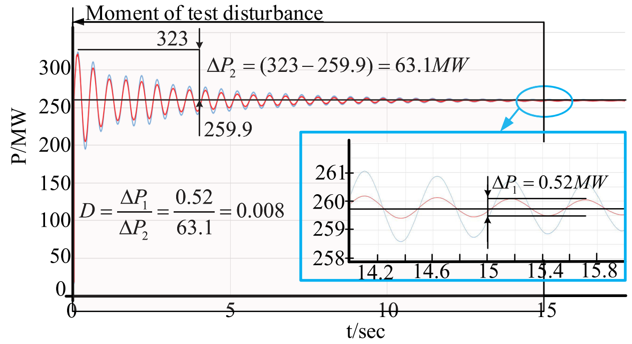

FIGURE 19. Oscillograms power flow and calculation of level of power oscillation in EPS with B2B HVDC.

TABLE 2. Calculation of dominant modes parameters by Prony analysis.

	Amplitude, MV	Frequency, Hz	Attenuation factor, 1/sec
Without B2B HVDC	24.68	0.6	-10.8
	65.13	1.56	-17.14
	67.48	1.98	-13.47
With B2B HVDC	39.18	0.75	-24.23
	1.53	1.72	-5.19

However, properties of B2B HVDC, in particular DC circuit, application of VSCs providing independent active and reactive power control, and supplementary controller using for power-oscillation damping [26], [27], allows to increase the damping properties of EPS. So, to assess the damping contribution of the B2B HVDC, the value of D was recalculated (see Figure 19).

Additionally, the calculation results of dominant modes parameters by Prony analysis [38], [39] are shown (see Table 2).

It can be noticed that the application of B2B HVDC leads to a decrease in the value of D and the frequencies of dominant modes would increase, while the amplitude of the higher-frequency components of the oscillations is significantly reduced, which indicates a better power oscillation damping.

IV. CONCLUSION

This paper presents one more hybrid modeling approach based on application and combination of three modeling approaches at once: physical, analog and digital.

The proposed approach allows the development of simulation tools, which provide three-phase simulation; modeling of a single spectrum of processes in EPS, without separation to electromagnetic and electromechanical stages of transients; unlimited scalability of EPS model; and real-time simulation.

The description of development of hybrid model of B2B HVDC according to the proposed approach was shown, for instance the realization principle of mathematical and physical models of power equipment of B2B HVDC, as well as the realization of its ACS. The presented time diagrams of the PADC of ACS program and SwP of VSC program guarantee its simulation in real time.

To confirm the mentioned properties of hybrid model of B2B HVDC, in particular three-phase modeling of a single (without separation into steady state and electromagnetic and electromechanical stages of transient processes) continuous spectrum processes in real time and on an unlimited interval, the simulation results of interconnection of non-synchronously operating parts of EPS; power flow regulation; dynamic response to external fault and damping of power oscillation in EPS was presented. It can be noted that the hybrid model correctly adequately reflect simulated processes and behavior of B2B HVDC.

The description of the developed hybrid model of B2B HVDC based on the proposed approach was introduced and discussed. For instance, the realization principle of mathematical and physical models of power equipment of B2B HVDC, as well as the realization of its ACS have been considered. The presented time diagrams of the PADC of ACS program and SwP of VSC program guarantee its simulation in real-time.

The results confirmed the mentioned properties of hybrid model of B2B HVDsC, in particular, three-phase modeling of a single (without separation into steady-state and electromagnetic and electromechanical stages of transient processes) continuous spectrum processes in real-time and on an unlimited interval. Moreover, the simulation results of the interconnection of non-synchronously operating parts of EPS; power flow regulation; dynamic response to external fault and damping of power oscillation in EPS have been presented. It can be noted that the hybrid model correctly and adequately reflect the simulated processes and the behavior of B2B HVDC.

Also, the paper compares the simulation results found considering the detailed VSC HVDC model (Simulink Matlab), as widely used software for simulation of electromagnetic transients), and Eurostag software (where large scale EPS can be realized) shows the adequacy of the developed SHP of B2B HVDC.

In spite of this, the proposed hybrid approach and the developed HRTSim and SHP of B2B HVDC are very complex with specific issues arising with each simulator. In summary, they are inflexible and take time to develop a model; however, this makes it possible to use only one complex system to solve most research problems. Therefore, further work will target improving the HRTSim and SHP of B2B HVDC, and studying the mutual influence of B2B HVDC and EPS.

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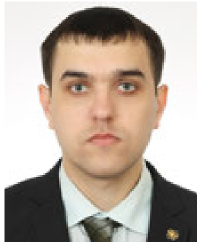

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