This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

A Hybrid Simulation Model for VSC HVDC

Yury S. Borovikov, Alexandr S. Gusev, Almaz O. Sulaymanov, Ruslan A. Ufa, Aleksey S. Vasilev, Mikhail V. Andreev, Nikolay Yu. Ruban, and Aleksey A. Suvorov

***Abstract*—The motivation for the presented research is based on the needs to develop new methods and tools for obtaining the information required to evaluate the mutual influence of HVDC and HVAC systems. This paper presents the specialized concept of a hybrid simulation for advanced modeling of VSC HVDC. The results obtained by the prototype of specialized hybrid processor of VSC HVDC model confirm the effectiveness of the proposed approach with respect to the detailed representation of commutation process of real power semiconductors and possibility of real-time simulation of all the processes in VSC and EPS as a whole without any decomposition and limitation on their duration.**

***Index Terms*—Power system simulation, real-time systems, hybrid simulation technology, VSC HVDC.**

I. Introduction

THE GROWING complexity of EPS (electric power system) poses new challenges to ensure its reliability and stability. At the same time, the progress achieved in power electronics has demonstrated the HVDC (High-voltage direct current) technologies effectiveness in solution of conventional tasks such as asynchronous interconnection, long distance transmission, increasing the local and systemic controllability of EPS, as well as the relatively new challenges related with integration of the distributed renewable energy sources into HVAC (High-voltage alternating current) system [1]–[3].

Converter based on power semiconductors is the main element of these technologies. Currently, the scheme of HVDC based on two types of converters - line commutated converter (LCC) and voltage-source converter (VSC) - is used in EPS. It should be noted that VSC based on fully controlled high-speed power switches (IGBT, GTO) has several advantages compared to LCC [2], [4], [5], such as:

- the independent control of active and reactive power;
- the provision of reverse of power flow without changing the polarity of the voltage.

Manuscript received December 17, 2014; revised April 25, 2015 and September 12, 2015; accepted November 23, 2015. This work was supported in part by the Framework of Realisation of Strategic Programme on National Research Tomsk Polytechnic University Competitiveness Enhancement in the Group of Top Level World Research and Academic Institutions, and in part by the Competitiveness Enhancement Program of Tomsk Polytechnic University (Project_Leading Research University_Institute of Power Engineering_138_2014). Paper no. TSG-01233-2014.

The authors are with the Department of Electrical Power System, Institute of Power Engineering, Tomsk Polytechnic University, Tomsk 634050, Russia (e-mail: borovikov@tpu.ru; gusev_as@tpu.ru; sao@tpu.ru; hecn@tpu.ru; vasilevas@tpu.ru; andreevmv@tpu.ru; rubanny@tpu.ru; suvorovaa@tpu.ru).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSG.2015.2510747

At the same time, the possibility of parallel-series connections and a high speed commutation of power semiconductors (switching time of the IGBT (Insulated-gate bipolar transistor) is 5 μs) allow the formation of a more sinusoidal wave of voltage, which consequently reduces the Total harmonic distortion, and as a result, the optimization of parameters of the HVDC filter on the AC (alternating current) side.

The flexibility and high speed controllability of VSC HVDC enable to use them as additional voltage regulation and damping of low frequency oscillations in the EPS, caused by a short circuit, disconnection of generators and etc. [1], [6].

Nevertheless, the practical necessity of relevant research and analysis to ensure safe and reliable operation of these technologies and EPS in general are emphasized by many research groups and engineers [7]–[9].

The most complex and urgent tasks include [10], [11]:

- the analysis of the mutual influence of HVDC and HVAC systems, including their control and protection upon each other and the EPS as the whole, especially in transient conditions;
- the development, testing and adjustment of the local and systemic automatic control and protection systems.

A solution of these tasks requires full-scale experiments in real EPS, which cannot be conducted. Therefore, the control and monitoring system (like a Wide Area Control System) and hard- and software simulation tools are the main sources used to obtain the information required for analysis of the EPS operation [8]. Study of experience of their application in practice allows us to define advantages and disadvantages of these approaches and identify promising directions of the development of methods and tools of EPS analysis. One of the most striking examples of the application of the control and monitoring system for the EPS analysis containing HVDC technologies can be viewed in the EPS of South China [8]. According to [8], the received for several years emergency shutdown data of HVDC, that led to cascading failures and separation of EPS, ensured the development of effective configuration of automatic control system (ACS) of hybrid HVAC and HVDC systems and the prevention of similar accidents in the future.

There are some weaknesses in this approach:

- the high complexity associated with the analysis of disturbance processes in case of low observability of the EPS;
- the limited applicability of the measurement results to set up the ACS of hybrid HVAC and HVDC systems;
- the occurrence of previously unobserved disturbances;

- the existence of a wide range of all possible pre-emergency modes of EPS;
- the significant time resources required for the various experiments in a real EPS and further analysis of obtained results.

That is why the control and monitoring system can not be regarded as a primary source of information for the analysis of the mutual influence of HVDC and HVAC systems. However, it can be used to verify the results of EPS simulation [8], [9]. At the same time, the reliability and adequacy of the simulation results will depend on the chosen simulation methods and tools.

The rest of this paper is organized as follows. Section II introduces the HVDC simulation challenges and proposes alternative tools based on hybrid real time simulation concept. Section III presents the VSC HVDC simulation including adequate representation of commutation process of real IGBT and experimental research of the 2-level VSC HVDC model in EPS. Conclusions are stated in Section IV.

II. The Simulation Challenges

To solve the problem of the reliability and adequacy of the simulation processes in a real VSC HVDC the modeling system should take into account the specifics of the operation of these devices, in particular:

- the phase-phase operation of VSC;
- the use of high-speed fully controlled power semiconductors;
- the continuous high-speed operation in all possible normal, emergency and post-emergency operating conditions of EPS.

Furthermore, to solve the above mentioned problems, the simulation systems should meet the following requirements [10], [12], [13]:

- the models of EPS elements must be three-phase (or more) to account properly for all the unbalanced conditions;
- the simulator must be capable (scalable) to implement an EPS model of any size;
- the simulation of EPS must exclude the decomposition of processes and limitations on their duration (without separation of electromagnetic and electromechanical transient processes modeling in power equipment and EPS as a whole);
- the real-time simulation and the possibility of interconnection with external devices and systems.

Currently, digital modeling complexes are widely used for analysis of the EPS (RTDS, HYPERSIM [9], [14] and others). These complexes have shown to be successful in the simulation of electromagnetic transients and closed loop testing of ACS, but the numerical integration methods used in digital simulation tools do not enable to perform real time simulations of EPS without processes of decomposition over an unlimited period of time because of the integration time step issue.

Additionally, the digital simulation of large EPS is affected by problems associated with the limitations on the size of a model solved by a single processor. Thus, the model partitioning and application of the travelling wave transmission line models to connect the parts of a power system model distributed between several processors is required. A trick of the application of the travelling wave model is that a traveling time of a transmission line has to be greater or equal to an integration time step which is not always accessible and thus may require forced correction of inductance and capacitance values of a transmission line model.

The distribution of EPS model limits the number of processors, that can be connected to one node, and leads to forced simplifications and equivalent representations of power equipment and EPS models. These limitations of digital modeling complexes are shown in simulation of short transmission line (in back-to-back HVDC system), or simulation of Multi-terminal HVDC projects with a short DC (direct current) link [15].

At the same time the issue of simulating in real time large EPS without separation of electromagnetic and electromechanical transient processes is not solved in full [16], [17]. This statement is confirmed by observed trends in research and development of hybrid simulation tools, based on application of different numerical simulation methods [7], [15]–[17].

However, after the detailed analysis of some of mentioned in [16] and [17] hybrid complexes obviously that required detailed and comprehensive modeling of EPS is not fully achieved. Thus, in [17] to analyze the processes caused by faults in HVDC convertors authors used simulation time step around 50 μs, whereas the switching time of Gate turn-off thyristor is about 30 μs, for IGBT 5 μs. Besides the data exchange between the used complexes is carried out with bigger simulation time step than the simulation time step of electromagnetic transients modeling.

To solve mentioned issue of real time simulation of HVDC systems and EPS as a whole, the hybrid simulation technology based on the application of analog, digital and physical modeling approaches and realized in Hybrid Real-time Simulator of EPS (HRTSim), developed in Tomsk Polytechnic University, is proposed.

The results of the development and research of the VSC model, realized in HRTSim, are shown in this article.

A. The Concepts of Hybrid Simulation of EPS

The concept of hybrid simulation is based on the use of three modeling approaches: analog, digital and physical, each of which achieves maximum efficiency in solving individual subtasks. A detailed description of the concepts and tools is presented in [18] and [19].

The basic points of the concepts are:

- the power equipment of EPS is described via complete systems of differential equations adequately representing the whole significant range of quasi-steady and transient processes in this equipment and forming comprehensive mathematical models of corresponding types of the simulated equipment;
- the methodologically accurate with guaranteed instrumental error solution of differential equation systems in real

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

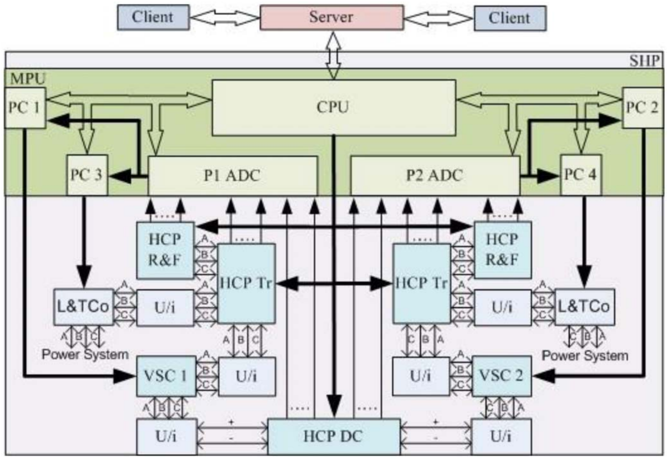

Fig. 1. The structural diagram of the SHP of the VSC HVDC model: MPU - microprocessor unit; CPU - central processing unit; P1 ADC and P2 ADC - processors of analog-to-digital converters; PC 1-4 - commutation processors; HCP R&F - reactor and filter hybrid coprocessors; HCP Tr - transformer hybrid coprocessors; HCP DC - hybrid coprocessor of the direct current circuit; U/i - integrated microelectronic voltage-current converters; L&TCo - longitudinal-transverse commutators, VSC 1 and VSC 2 - physical models of the power semiconductors of VSC topology simulated at the physical model level via integrated microelectronic digitally controlled analog switches (DCAS).

time and over an unlimited period of time are carried out by means of the continuous implicit integration method;

- all types of commutation of power equipment, including the power semiconductors, are carried out on a model physical level;
- the interconnection between a physical model and mathematical simulation levels is provided by means of appropriate voltage-current converters;
- a mutual conversion of mathematical and model physical variables in conjunction with simulation on the physical model level of the commutation of power equipment provides the ability of unlimited scalability of the simulated EPS;
- all informational and control functions, as well as modeling control and protection systems are implemented on a digital level using a digital-to-analog, analog-to-digital conversion and specialized local and server software.

The given concept is realized in the specialized software and hardware hybrid complex - Hybrid Real-Time Simulator (HRTSim) of EPS.

Specialized hybrid processor (SHP) is the basic element of the modular structure of the HRTSim and provides an adequate comprehensive simulation in the real-time of power equipment models, as well as control and protection systems.

In Figure 1 and 2 the structure and appearance of the developed experimental SHP of the 2-level VSC HVDC model are shown.

According to the above concept, the solution of comprehensive mathematical models of the simulated equipment is carried out via the hybrid coprocessors (HCP). The result of solution is transmitted to the MPU (microprocessor unit) via the PADC (processors of analog-to-digital converter). The whole range of data transformations required to oversee the process of simulation, as well as real-time control of parameters of the modeled power equipment, depending on the desired solution speed of a control algorithm, are implemented in the MPU.

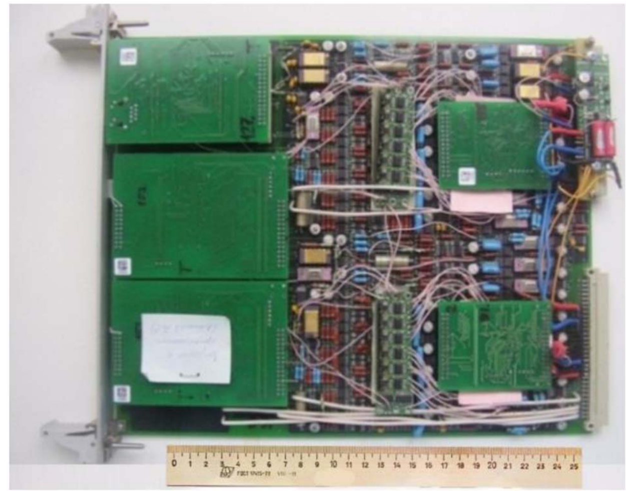

Fig. 2. Appearance of the experimental SHP of the VSC HVDC model.

The universality of the concept and modular structure of the HTRSim allow the development of a model of any element of EPS, including devices and HVDC, and to integrate them into the HTRSim, as well as to provide interconnection with various external software and hardware tools: operational information systems, SCADA system etc. [20].

III. VSC Simulation

To create an adequate model of HVDC it is necessary to provide completeness and accuracy of the process description in the steady-state and transient operating conditions, determined by modeling implementation errors at all the mentioned digital, analog, and physical levels of simulation. Digital simulation is carried out only for the control system of HVDC.

Modeling errors at the physical model level lead to a deviation of loss level, distortion of voltage and current waveforms on both the DC and AC side in the significant frequency spectrum of the EPS. Based on this, the simulation of process at the physical model level is critical to the modeling results, especially for the pulse mode of VSC. Errors at this level can be caused by incorrect characteristics of power semiconductors or parameters of the DC circuit. The latter problem is successfully solved by the selection of components. The characteristics of the physical models of power semiconductors require additional analysis and will be addressed in future works.

A. Simulation of Commutation Process

As mentioned above, the physical model level is particularly important, because at this level an operation of power switches is modeled via integrated microelectronic digitally controlled analog switches (DCAS).

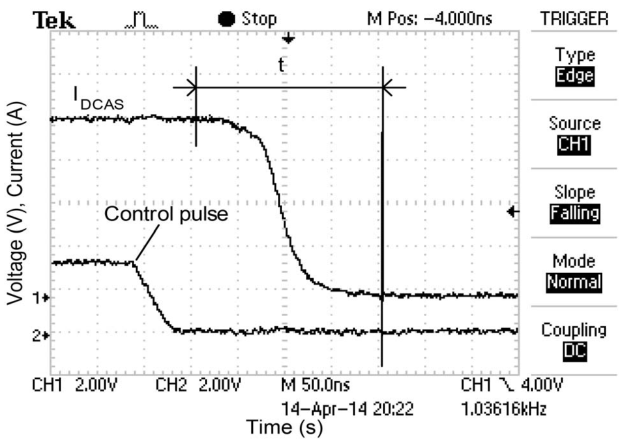

Fig. 3. The current waveform of the DCAS commutation.

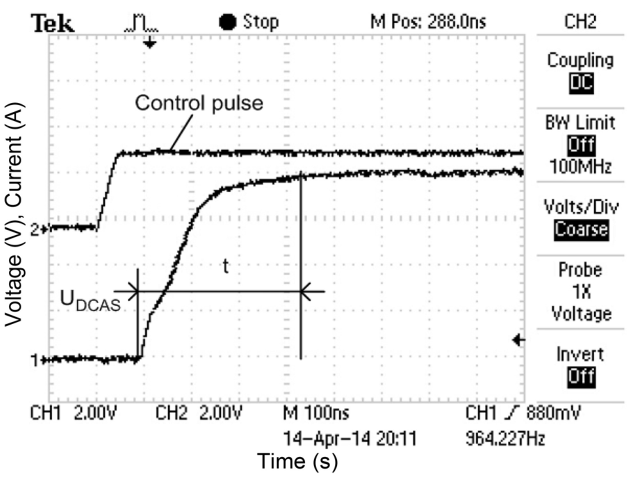

Fig. 4. The the voltage waveform of the DCAS commutation.

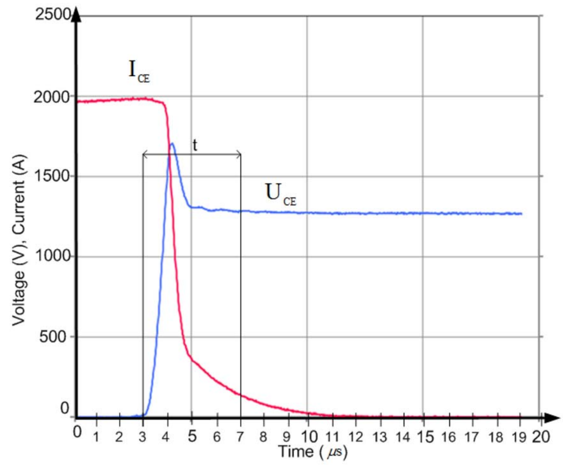

Fig. 5. The current and voltage waveforms of real IGBT (type № 5SNR).

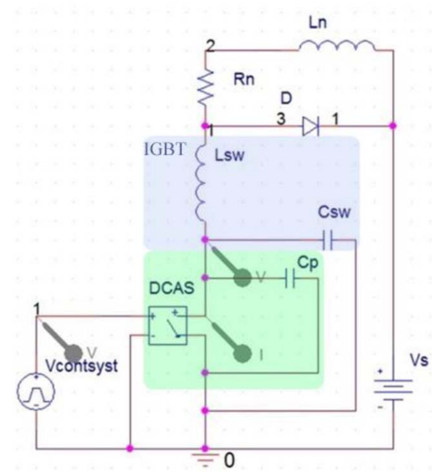

Fig. 6. The scheme of IGBT commutation process without the snubber circuit: Csw, Lsw - equivalent capacity and inductance of IGBT, Cp - coupling capacitance of DCAS, Rn, Ln- equivalent load, D – bypass diode.

Furthermore, to ensure the similarity of the model to real power switches and to simulate any type of power semiconductors, the corresponding commutation algorithms have been developed and implemented in MPU of SHP. According to the obtained DCAS characteristics (Fig. 3-4) the switching time (t) is about 300 ns, while a switching time of IGBT is more than 3 μs (Fig. 5). As a result, the DCAS can be considered an Ideal Switch.

Consequently, the equivalent circuit of DCAS can be adapted to simulate real power switches. Analysis of equivalent circuits of DCAS and real IGBT (type № 5SNR), a comparison of their parameters, taking into account modal and technical scaling coefficients were carried out to verify the adequacy of this simulation.

It should be noted that the character of the transition process can be adapted by appropriate selection of parameters and variation of the equivalent circuit depending on the type of simulated power semiconductors. Moreover, transition process of voltage is of more particular importance, because the voltage signal is used for calculation processes in the rest of control system of VSC.

A fragment of the results of this research and modeling in the software environment OrCAD is presented in the format of this work.

The scheme of IGBT commutation process (type № 5SNR) without the snubber circuit is shown in Figure 6. This scheme combines the equivalent circuit of DCAS and IGBT, which in aggregate allow us to form the parameters of a circuit to simulate the commutation of real switch.

The value of the IGBT direct and reverse resistance is set in the DCAS.

The current and voltage oscillograms of the IGBT in different operation modes without the snubber circuit are shown in Fig. 7-8.

The scheme of IGBT commutation process (type № 5SNR) with the snubber circuit presented in [21] and [22] is shown in Figure 9.

The current and voltage oscillograms of the IGBT in different operation modes with the snubber circuit are shown in Fig. 10-11.

According to the presented commutation process the switching time (t) is about 6 μs, while the switching time of real

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

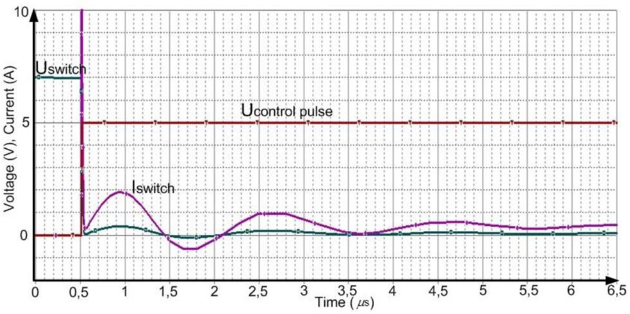

Fig. 7. Turning on process without the snubber circuit.

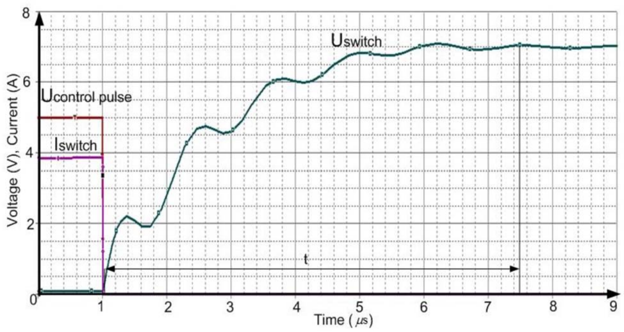

Fig. 8. Turning off process without the snubber circuit.

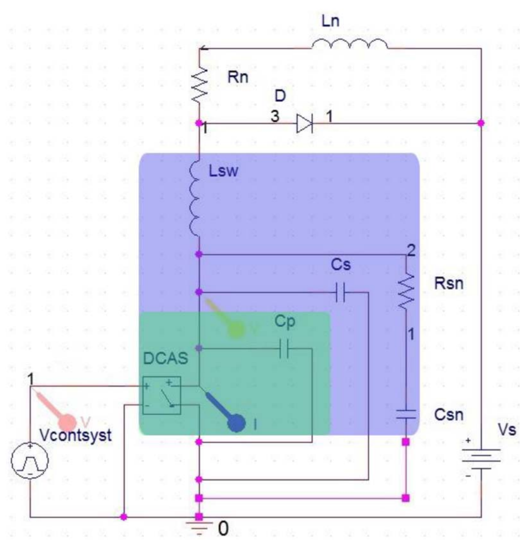

Fig. 9. The scheme of IGBT commutation process with the snubber circuit. Csn, Rsn – snubber circuit.

5SNR IGBT is about 5 μs (see Fig. 5). The difference may be caused by errors in the recalculation of the parameters of the 5SNR IGBT or parameters of the DC circuit that are successfully solved by selection of elemental base and components. For example, precision resistors (with more accurate nominal value) or accurate operational amplifiers can be used to improve the accuracy of representation of commutation process. The characteristics of physical models of switches require additional analysis will be addressed in future works.

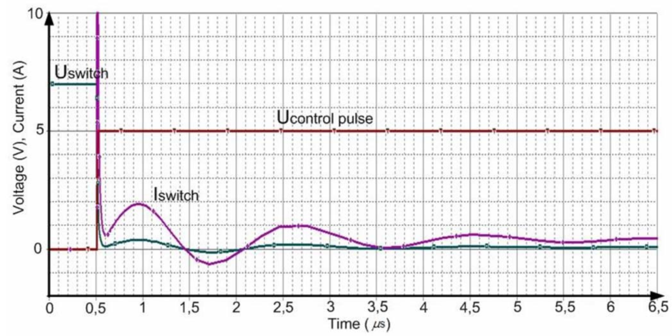

Fig. 10. Turning on process with the snubber circuit.

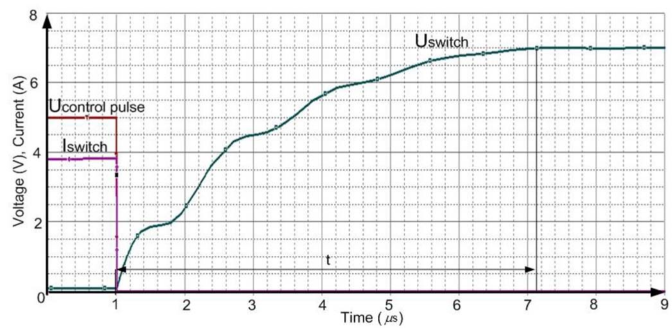

Fig. 11. Turning off process with the snubber circuit.

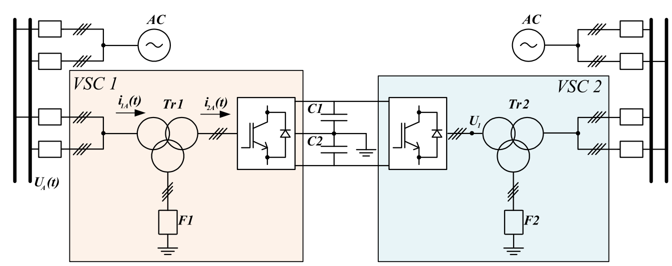

Fig. 12. The scheme of experimental research of the VSC HVDC model: Tr - transformer, F - filter, C – capacitor bank.

B. Simulation of VSC HVDC

In [23] and [24] the simulation of VSC HVDC, including the frequency characteristics of HCP of the basic equipment of HVDC, and static modes at different levels of power consumption/generation and voltage of VSC HVDC were considered.

To confirm the adequacy of the simulation process, the analysis of developed 2-level VSC HVDC model characteristics in the static modes on a model of two-machine has been provided.

The scheme of experimental research of the SHP of VSC HVDC in EPS is shown in Figure 12.

The parameters of the study system scheme are resented in Table I.

The obtained waveform of voltage ($U_A(t)$), current ($i_A(t)$), as well as the calculated values of apparent ($S(t)$), active ($P(t)$) and reactive ($Q(t)$) powers are shown in Figures 13-14.

TABLE I
PARAMETERS OF THE STUDY SYSTEM OF FIG.12

Quantity	Value
Basic voltage, kV	110
Basic power, MVA	200
Basic frequency, Hz	50
Switching frequency, Hz	1050
AC nominal voltage, relative units (r.u.)	1
AC active resistance, (r.u.)	0,02
AC inductive resistance, (r.u.)	0,155
Transformer voltage rating	110/28,6/10
Resistance of high voltage winding of the transformer:	
active resistance, (r.u.)	0,0114
inductive resistance, (r.u.)	0,2625
Resistance of medium voltage winding of the transformer:	
active resistance, (r.u.)	0,01
inductive resistance, (r.u.)	0,6597
Resistance of low voltage winding of the transformer:	
active resistance, (r.u.)	0,007
inductive resistance, (r.u.)	0,0734
Magnetizing branch, (r.u.)	300
Value of capacity of Filter, (r.u.)	0,03091
Active resistance of Filter, (r.u.)	11,44

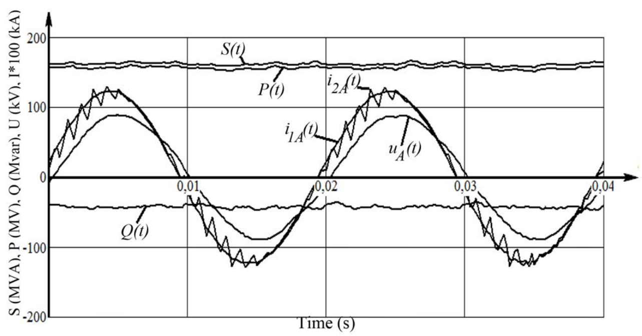

Fig. 13. The mode of consumption of $P(t)$ and generation of $Q(t)$.

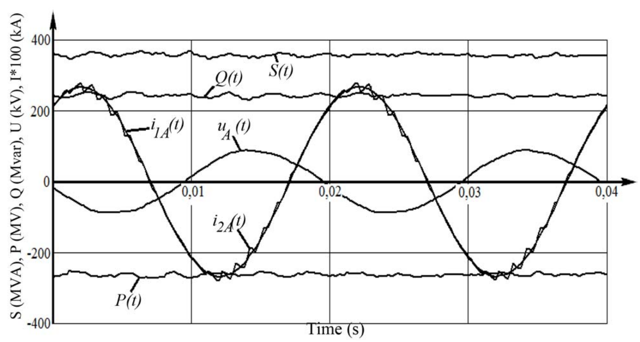

Fig. 14. The mode of generation of $P(t)$ and consumption of $Q(t)$.

The oscillograms of the voltage $U_1(t)$ (see Fig. 12) on the AC side of the VSC obtained by a digital oscilloscope are shown in Figures 15-16.

In Figure 17 the spectral analysis obtained via SHP of VSC HVDC and model of VSC in MatLAB Simulink in significant frequency range up to 5 kHz is presented.

According to spectral analysis the voltages formed by SHP of VSC HVDC and the model of VSC in MatLAB Simulink are almost identical. Deviations at high frequencies are caused

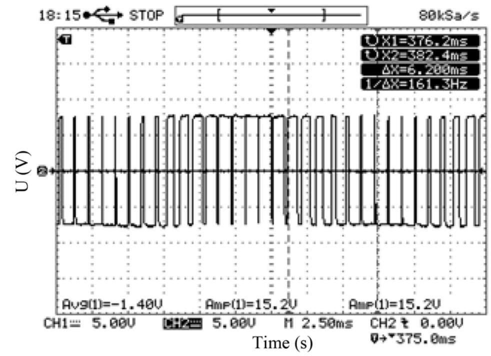

Fig. 15. The oscillogram of the phase voltage of VSC HVDC model.

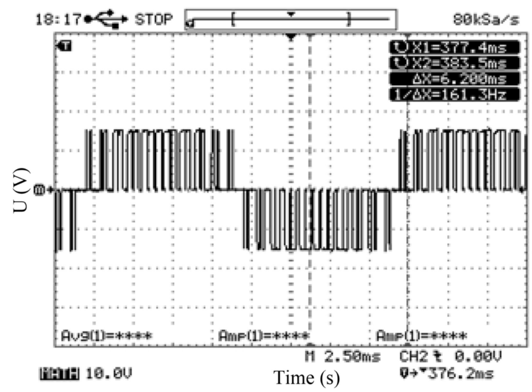

Fig. 16. The oscillogram of the phase-to-phase voltage of VSC HVDC model.

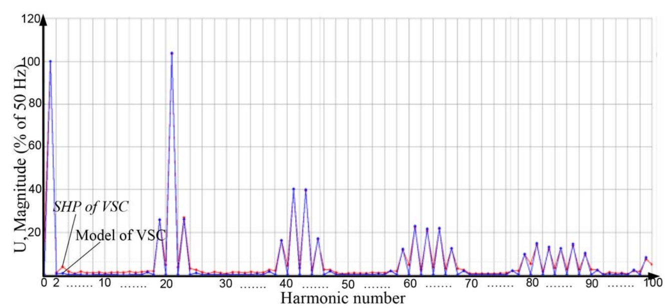

Fig. 17. The spectral analysis of VSC HVDC model.

by noises in the channel of the oscilloscope and the influence of other models as part of a pilot scheme of SHP of VSC HVDC. These deviations are within the allowable margin of error.

The obtained waveform and frequency properties of the voltage, as well as the simulation result given in [23] and [24] completely determine the adequacy of the simulation of HVDC based on VSC at steady-state operating conditions of EPS.

IV. CONCLUSION

The specialized concept of a hybrid simulation and the results of its experimental realization show the possibility and efficiency of the proposed approach to the development of the models of power semiconductors and VSC implemented on them.

The obtained results allow us to carry out a detailed representation of commutation process of IGBT and adequate modeling of spectral analysis of VSC, as well as comprehensive real-time simulation of all the processes in HVDC and EPS as a whole without any decomposition and limitation on their duration.

REFERENCES

[1] P. Thepparat, D. Retzmann, E. Ogée, and M. Wiesinger, "Smart transmission system by HVDC and FACTS," in *Proc. IEEE Towards Carbon Free Soc. Through Smarter Grids*, Grenoble, France, Jun. 2013, pp. 1–6.

[2] A. L'Abbate *et al.*, "The role of facts and HVDC in the future paneuropean transmission system development," in *Proc. IEEE 9th IET Int. Conf. AC DC Power Transm.*, London, U.K., 2010, pp. 1–8.

[3] D. Povh, "Use of HVDC and FACTS," *Proc. IEEE*, vol. 88, no. 2, pp. 235–245, Feb. 2000.

[4] J. Zhu and C. Booth, "Future multi-terminal HVDC transmission systems using voltage source converters," in *Proc. 45th Int. Univ. Power Eng. Conf.*, Cardiff, Wales, 2010, pp. 1–6.

[5] L. Bertling and J. Setreus, "Introduction to HVDC technology for reliable electrical power systems," in *Proc. 10th Int. Conf. Probabilist. Methods Appl. Power Syst.*, Rincón, Puerto Rico, 2008, pp. 1–8.

[6] N. M. Tabatabaei, N. Taheri, and N. S. Boushehri, "Damping function of back to back HVDC based voltage source converter," *Int. J. Tech. Phys. Probl. Eng.*, vol. 2, no. 3, pp. 82–87, Sep. 2010.

[7] L. Chen, K.-J. Zhang, Y.-J. Xia, and G. Hu, "Hybrid simulation of ±500kV HVDC power transmission project based on advanced digital power system simulator," *J. Electron. Sci. Technol.*, vol. 11, no. 1, pp. 66–71, Mar. 2013.

[8] D. Qi, "Defense schema against large disturbances in China Southern PowerGrid," *Electra*, vol. 257, pp. 4–16, Aug. 2011.

[9] B. M. Yang, C.-K. Kim, G. J. Jung, and Y. H. Moon, "Verification of hybrid real time HVDC simulator in Cheju-Haenam HVDC system," *J. Elect. Eng. Technol.*, vol. 1, no. 1, pp. 23–27, 2006.

[10] L. Zhi-Hui *et al.*, "Modeling and simulation research of large-scale AC/DC hybrid power grid based on ADPSS," in *Proc. IEEE PES Asia-Pac. Power Energy Eng. Conf. (APPEEC)*, Hong Kong, Dec. 2014, pp. 1–6.

[11] K. Ou *et al.*, "MMC-HVDC simulation and testing based on real-time digital simulator and physical control system," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 2, no. 4, pp. 1109–1116, Dec. 2014.

[12] L. Xu, Y. H. Tang, W. Pu, and Y. Han, "Hybrid electromechanical-electromagnetic simulation to SVC controller based on ADPSS platform," *J. Energy South Africa*, vol. 25, no. 4, pp. 112–122, Nov. 2014.

[13] O. Nayak, S. Santoso, and P. Buchanan, "Power electronics spark new simulation challenges," *IEEE Comput. Appl. Power*, vol. 15, no. 4, pp. 37–44, Oct. 2002.

[14] L. Snider, J. Bélanger, and G. Nanjundaiah, "Today's power system simulation challenge: High-performance, scalable, upgradable and affordable COTS-based real-time digital simulators," in *Proc. Joint Int. Conf. Power Electron. Drives Energy Syst. (PEDES)* Power India, New Delhi, India, Dec. 2010, pp. 1–10.

[15] P. A. Forsyth, T. L. Maguire, D. Shearer, and D. Rydmell, "Testing firing pulse controls for a VSC based HVDC scheme with a real time timestep $< 3\ \mu s$," in *Proc. Int. Conf. Power Syst. Transients*, Kyoto, Japan, Jun. 2009, pp. 1–5.

[16] Y. Zhang, A. M. Gole, W. Wu, B. Zhang, and H. Sun, "Development and analysis of applicability of a hybrid transient simulation platform combining TSA and EMT elements," *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 357–366, Feb. 2013.

[17] Z. Xiao-Xin *et al.*, "Concept and mechanism on full-process dynamic real-time simulation of power system with parallel-in-time-space," in *Proc. Int. Conf. Power Syst. Technol. (POWERCON)*, Hangzhou, China, Oct. 2010, pp. 1–7.

[18] A. Prokhorov, Yu. Borovikov, and A. Gusev, "Real time hybrid simulation of electrical power systems: Concept, tools, field experience and smart grid challenges," *Int. J. Smart Grid Clean Energy*, vol. 1, no. 1, pp. 67–68, Sep. 2012.

[19] M. Andreev and A. Sulaymanov, "Platform based on hybrid real-time power system simulator for development and research of intelligent power systems with active-adaptive networks," in *Proc. IEEE Eindhoven PowerTech*, Eindhoven, The Netherlands, 2015, pp. 1–6.

[20] A. Prokhorov, Y. S. Borovikov, and A. S. Gusev, "Hardware-in-the-loop testbed based on hybrid real time simulator," in *Proc. IEEE Innov. Smart Grid Technol. Europe*, Lyngby, Denmark, 2013, pp. 1–5.

[21] A. A. Andreas, "A novel test method for minimising energy costs in IGBT power cycling studies," Ph.D. dissertation, Dept. Fac. Eng. Built Environ., Univ. Witwatersrand, Johannesburg, South Africa, 2006, pp. 1–207.

[22] L. Max, "Energy evaluation for DC/DC converters in DC-Based wind farms," M.S. thesis, Dept. Energy Environ., Chalmers Univ. Technol., Gothenburg, Sweden, 2007, pp. 1–151.

[23] A. Prokhorov, R. Ufa, and A. Vasilev, "Synthesis of hybrid models for advanced simulation of HVDC systems," *Int. J. Smart Grid Clean Energy*, vol. 3, no. 2, pp. 207–213, Apr. 2014.

[24] R. Ufa, V. Sulaymanova, and A. Gusev, "Hard- and software of real time simulation tools of electric power system for adequate modeling power semiconductors in voltage source convertor based HVDC and FACTS," in *Proc. MATEC Web of Conf.,* vol. 19. Les Ulis, France, 2014, Art. ID. 01029.

Yury S. Borovikov was born in Ust-Kamenogorsk, Kazakhstan, in 1978. He received the D.Sc. (Tech.) degree in electrical engineering from Tomsk Polytechnic University, Tomsk, Russia, in 2014.

He is currently an Associate Professor of Electrical Power System Department, Institute of Power Engineering, Tomsk Polytechnic University. His research interests include simulation of power systems based on FACTS controllers and active-adaptive networks.

Alexandr S. Gusev was born in Dushanbe, Tajikistan, in 1947. He received the D.Sc. (Tech.) degree in electrical engineering from Tomsk Polytechnic University, Tomsk, Russia, in 2000.

He is an Associate Professor of Electrical Power System Department, Institute of Power Engineering, Tomsk Polytechnic University. His main fields of interest are hybrid simulation technology of power system and smart grids.

Almaz O. Sulaymanov was born in Frunze, Kyrgyzstan, in 1967. He received the Engineering and Ph.D. degrees from Tomsk Polytechnic University, in 1991 and 2009, respectively.

He is an Associate Professor and the Head of Research Laboratory Electrical Power System Simulation of Electrical Power System Department, Institute of Power Engineering, Tomsk Polytechnic University. His main fields of interest are power system simulation, protection, automation, and control system.

Ruslan A. Ufa was born in Nikitinka, Kazakhstan, in 1988. He received the M.Sc. degree from Tomsk Polytechnic University, in 2012.

He is currently an Assistant of Electrical Power System Department and an Engineer of Research Laboratory Electrical Power System Simulation, Tomsk Polytechnic University. His research interests include simulation of power systems based on HVDC system and smart grids.

Aleksey S. Vasilev was born in Tomsk, Russia, in 1986. He received the M.Sc. and Ph.D. degrees from Tomsk Polytechnic University, in 2009 and 2013, respectively.

He is currently a Lecturer of Electrical Power System Department, Institute of Power Engineering, Tomsk Polytechnic University. His research interests include simulation of power systems based on FACTS controllers and active-adaptive networks.

Mikhail V. Andreev was born in Sorsk, Russia, in 1987. He received the Engineering and Ph.D. degrees from Tomsk Polytechnic University, in 2010 and 2013, respectively. He is currently an Associate Professor of Electrical Power System Department and an Engineer of Research Laboratory Electrical Power System Simulation, Institute of Power Engineering, Tomsk Polytechnic University. His research interests include simulation of smart grids, control systems, relay protection, and automation.

Nikolay Yu. Ruban was born in Ust-Kamchatsk, Russia, in 1988. He received the Engineering and Ph.D. degrees from Tomsk Polytechnic University, in 2010 and 2014, respectively. He is currently a Senior Lecturer of Electrical Power System Department and an Engineer of Research Laboratory Electrical Power System Simulation, Institute of Power Engineering, Tomsk Polytechnic University. His research interests include simulation of smart grids, control systems, relay protection, and automation.

Aleksey A. Suvorov was born in Tomsk, Russia, in 1990. He received the Diploma degree in engineering from Tomsk Polytechnic University, in 2014. He is currently an Assistant of Electrical Power System Department and a Postgraduate Student of Tomsk Polytechnic University. His research interests include simulation electric power systems and validation of electric power system simulation tools.