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Synthesis of hybrid models for advanced simulation of HVDC systems

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Abstract

The large-scale introduction of high voltage direct current (HVDC) systems requires solving a number of complex tasks aimed at ensuring the reliability and stability of new combined HVDC/AC systems, as well as the development of their control and protection, and analysis of the mutual influence of HVDC and HVAC components. However the analysis of research results obtained from a worldwide shows that more comprehensive simulation tools are necessary to allow this. This paper presents the hybrid simulation technology and approach allowing synthesizing hybrid models of power equipment, including the elements of HVDC systems, which aim is to maximally meet modern requirements for modeling and simulation tools. The results of the application of the hybrid approach for development of the models of HVDC systems based on different types of converters, as well as the results of experimental research intended to prove models' capabilities are given in the paper.

Keywords: Hybrid simulation technology, HVDC system, real time, power electronics.

1. Introduction

The growing complexity of power systems addresses to new challenges for ensuring their reliability and sustainability. At the same time, achieved progress in power electronics promises new prospects of using HVDC systems that have already proven their effectiveness in solution of conventional tasks such as asynchronous interconnection and long distance transmission, as well as of the relatively new challenges related to the integration of the distributed renewable energy sources into AC grids [1], [2].

But emergence and large-scale installation of new HVDC equipment and schemes such as voltage source converter (VSC) based systems and multi-terminal links both open new opportunities to improve controllability of power systems and increase the number of operational and research tasks [3].

The most complex and urgent of those tasks include [4]:

- Analysis of the mutual influence of HVDC and HVAC systems, including their control and protection upon each other and the power system on the whole, especially in transient conditions;
- Development, testing and adjustment of the local and generalized control and protection systems.

A solution of these tasks requires full-scale experiments in a real power system, which cannot be conducted. Therefore, the simulation remains the main tool for analyzing HVDC systems in the structure of large power systems [5].

But the high requirements to power system simulators are dictated by the complexity of the tasks contributing to a comprehensive study of the processes occurring in power systems, as well as by convertors characteristics. These requirements, explained in more details in the next chapter, cannot be completely satisfied by the existing simulators.

Currently, digital simulators are widely used for power system analysis. The limitations of the digital simulators are well known and are mainly determined by the utilized numerical integration methods, which impose some significant simplifications and assumptions on power equipment models. This leads

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to the decomposition of power system tasks, application of various numerical methods and lack of the model's details [6]. A hybrid simulation technology can serve as an alternative for purely digital simulation. This technology is based on the synthesis of simulation tools and models of power system elements according to the requirements of the research tasks. The example of such a kind of simulators is a hybrid real-time simulator (HRTSim), which architecture is discussed in more detail in [7]. However, the use of the mentioned hybrid simulation technology complicates the development of the models and applies some additional requirements to them. This paper proposes an approach and demonstrates results of the development of a hybrid model of HVDC system that completely meet the requirements to the advanced power system simulation.

2. Requirements for Power System Simulators and Models

2.1. General requirements

The most keenly discussed requirements for the simulators intended for research and development of power systems are determined by the design and operation of modeled power equipment. And this becomes especially vital in the presence of HVDC systems. In the most cases, researchers are agreed on the necessity to use detailed power equipment models, including power electronic converters' models accounting topologies and control algorithms of real devices, and name a simulation without decomposition of the processes as the key requirement.

The decomposition can be avoided in case of solution of detailed power equipment models on the unlimited period of time covering the processes and phenomena of any possible duration and frequency. However these requirements are mostly mutually exclusive for digital simulators, since the integration time step that should be minimized for simulation of fast electromagnetic transient processes and electronic converters should be significantly extended for simulation of very long duration processes. It is possible to fulfill both requirements only in case of simulation of small size power systems and absence of additional requirements to the computational speed.

However, since HVDC systems are usually used for interconnection of large HVAC systems, the simulator must be capable (scalable) to implement a power system model of any size.

Besides, it is often necessary to provide a real-time simulation and interconnection with external devices and systems. This requirement is associated with the tasks of developing, closed- loop testing and adjustment of control and protection of HVDC [4], [9]. Moreover, the real-time simulation can significantly improve the research productivity and save time of the large power systems simulation [6].

The existing digital real-time simulators are effective tools for testing control and protection devices, but, as it has been mentioned earlier, the numerical integration methods used in digital simulation tools do not allow performing power systems real time simulation without processes decomposition at the unlimited period of time because of the integration time step issue.

Besides, the digital simulation of large power systems 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.

Simultaneous implementation of all stated requirements to a simulator and models is essential to carry out a comprehensive analysis of the HVDC and HVAC systems interaction, accounting their control and protection devices, particularly while researching cascading failures [5], [8]. Nevertheless, despite numerous publications stating the mentioned tasks, there are no examples of their comprehensive solution. The digital simulators that are used in the most of the cases of HVDC system studying remain to be narrowly specialized and this is confirmed by the contradictory reports of their users [8], [10], [11], and by necessity to use field statistical data [5] instead of thorough simulation.

To meet all the stated requirements a new simulation approach providing necessary capabilities should be developed. The research results from different authors show that the most optimal solution can be provided by hybridization of several approaches [12]. However, it will be demonstrated further in the paper that the change of the simulation technique obliges to significantly change a method of power equipment models synthesis.

2.2. Requirements of hybrid simulation environment for power equipment models

To achieve all above mentioned requirements for simulators and models, the hybrid simulation technology has been developed. It is based on the application of three modeling approaches: analog, digital, and physical, each of which achieves the maximum capabilities in solving individual subtasks. The detailed description of the hybrid simulation technology and tools is given in [7].

However it should be mentioned that additional requirements and specifics of hybrid models development come along with the advanced capabilities that hybrid simulation provides. These particularities can be explained on the basis of the block diagram of hybrid software and hardware simulation environment, see Fig. 1.

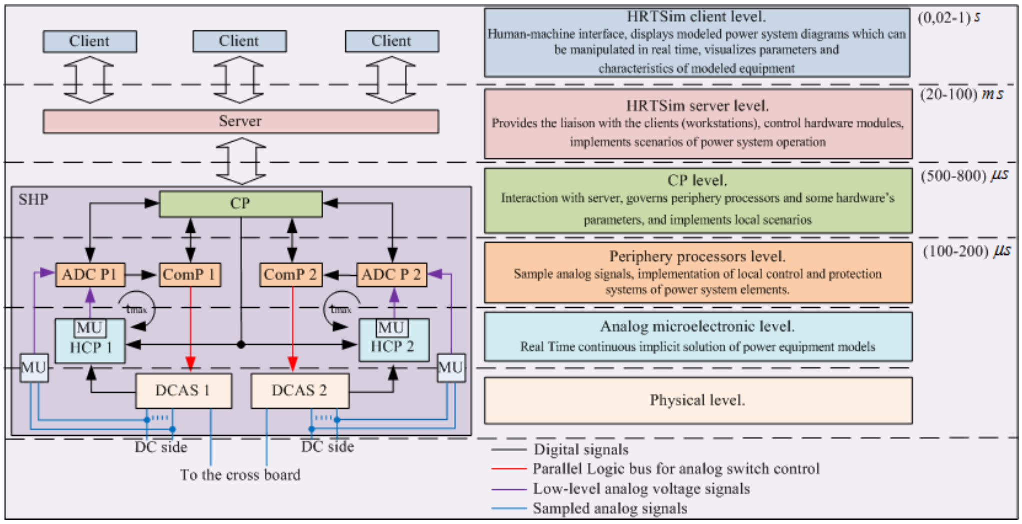


Fig. 1. The block diagram of hybrid software and hardware simulation environment: CP – central processor; ADCP1 and ADCP2 – analog-to-digital converters' processors; ComP1 and ComP2 – commutation processors; HCP1 and HCP2 – hybrid co-processors; DCAS1 and DCAS2 – digitally-controlled analog switches; MU - measuring unit; $t_{\max}$ – time delays of the digital channel.

Fig. 1 shows the hierarchy of the HRTSim environment consisting of several levels responsible for simulation of a certain element of HVDC system and characterized by the minimum allowed time delays that guarantee the real time of simulation. A specialized hybrid processor (SHP) is the basic element of the modular structure of HRTSim and consists of four levels. An interconnection between models of power equipment elements (power transformer, reactor, capacitor, and filter) implemented at the analog microelectronic level is provided at the physical level. The digitally controlled analog switches that represent commutators and power electronic switches are also a part of the physical level. At the same time, the control algorithms of a power converter and single electronic switches are implemented at the periphery processors level along with local fast protective relaying. The central processor (CP) level implements the functions of data collection, processing and transmission. The CP level is also used for local control of SHP components operations, interaction with Server and implementation of HVDC system components' relay protection and control algorithms.

While there are several different SHP corresponding to the number of simulated power system elements, the Server and Client are two general software levels intended to govern all the interactions between subsystems and allow user interaction with the models of power equipment and simulator in a whole. The described HRTSim architecture specifies the following requirements for the development of power equipment models:

- Model versatility. One SHP should reproduce different modifications and types of one kind of power equipment. For example, the model of a power converter should be suitable for simulation of current, voltage sourced converters of any size and having different types of switches, topologies, controllers and switching frequencies.
- Model structural efficiency. The optimal allocation of different power equipment subsystems models within HRTSim environment levels is provided in accordance with the properties of real equipment, and taking into account correspondence between the structure of real equipment subsystems and HRTSim architecture. For example, power equipment models are implemented at the analog microelectronic level while the measuring, protection and control systems are implemented in a digital form at processors level.

To fulfill mentioned requirements and ensure the necessary capabilities of a model, a special approach for synthesis of HVDC system model for hybrid real-time simulation has been developed. That approach consists of the following stages that are also illustrated in Fig. 2:

- Stage 1. The analysis of construction, functional diagrams, operating modes, as well as control and protection systems algorithms of modeled equipment.
- Stage 2. Synthesis of universal mathematical models of power equipment, protection and control systems. Drafting of functional and structural diagrams of models accounting their implementation at the different levels of the HRTSim architecture.
- Stage 3. The hardware implementation of the synthesized models.
- Stage 4. Development of the specialized software that includes a set of programs for all digital levels of HRTSim structure (peripheral processors, CPU, server and clients). The software provides implementation of the auxiliary algorithms of data conversion, real time management and control of the simulation process, as well as the control and protection algorithms of the simulated equipment.

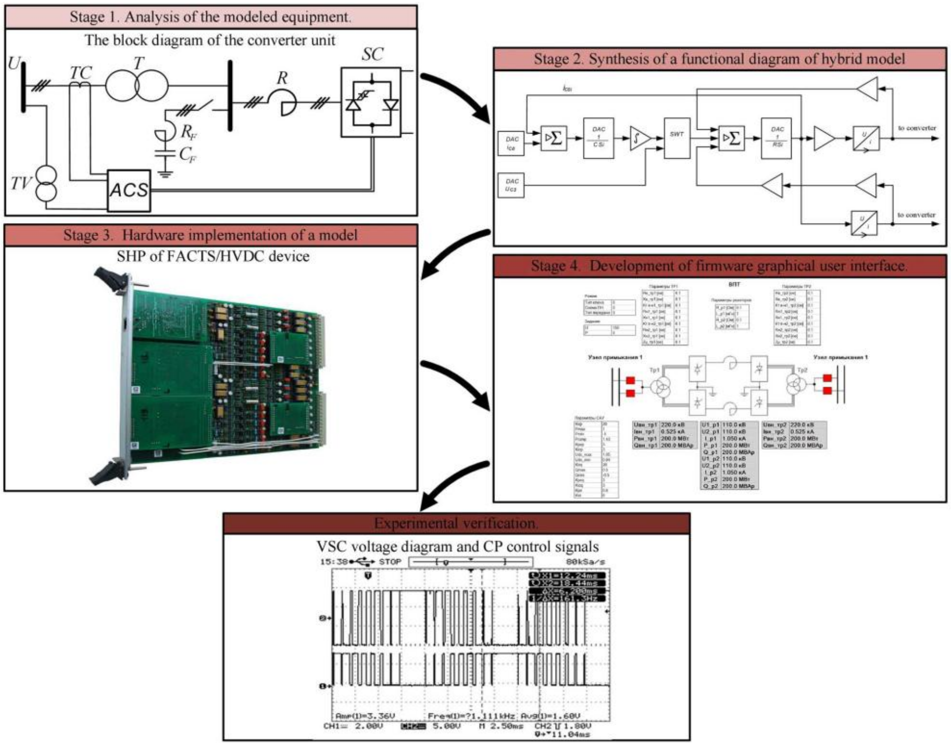


Fig. 2. Algorithm of the HVDC converter hybrid model development.

In addition to experimental studies at the stages 3 and 4, a pre-production computer simulation accounting hardware implementation (functional diagrams, utilized analog and digital microelectronic components) of power equipment hybrid models is done for the estimation of technical characteristics of the hardware part. The example results of implementation of the described approach confirming the capabilities of a hybrid model are given next.

3. Experimental and Simulation Results

According to Fig. 1, the adequacy of the simulation of a power electronic switch and HVDC convertor in general is determined by the errors of the model at the physical and digital levels. The physical part of a power electronic switch model is a microelectronic digitally-controlled analog switch (DCAS). To provide similarity of the model to a real device, the switching algorithms accounting input and output current and voltage values, as well as gate control signal should be implemented at the digital level. Thus, depending on the selected control algorithm, the DCAS can simulate any type of power electronic switches (diodes, SCR, GTO, IGBT, etc.), including anti-parallel pair of different switches. In addition, the digital level is also used to implement the algorithms of generation of firing pulses.

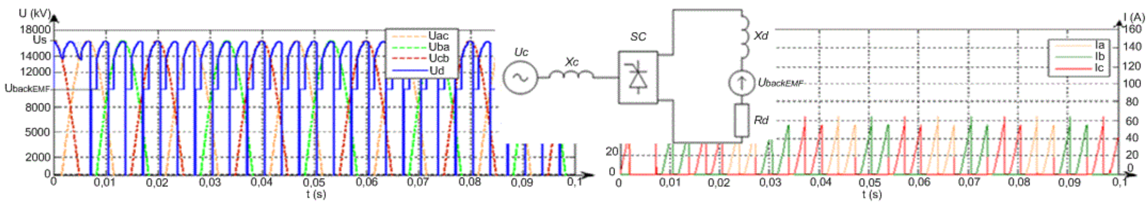
The accuracy of the model at the physical level is determined by the difference in the physical characteristics of converter power electronic switches and their models, which can be considered as ideal switches. The accuracy of the digital part of a switch and converter models is mainly determined by the time delays in the digital channel (Fig. 1):

$$t_{\max} = t_{ADC} + t_{ALGOR} + t_{TRAN} \approx 50\,\mu s \qquad (1)$$

where t_{ADC} is the analog-to-digital data conversion time in periphery processor; t_{TRAN} is a delay of data transmission from ADCP to ComP; and t_{ALGOR} is a runtime of control algorithms and a time of solution of a controller mathematical model.

This delay is constant and negligibly small, even for models of the modern HVDC converters with switching frequency up to 1000 Hz. Since the simulation process is continuous it does not affect real time and cause integration errors.

The developed control algorithms are tested in the mathematical modeling environment before their implementation in microcontrollers. As an example, Fig. 3 and Fig. 4 show the results of testing control algorithms of the rectifier mode of a convertor based on gate turn-off thyristors in MATLAB Simulink:



(a) (b)

Fig. 3. Input and output voltage (a) and current (b) oscillograms.

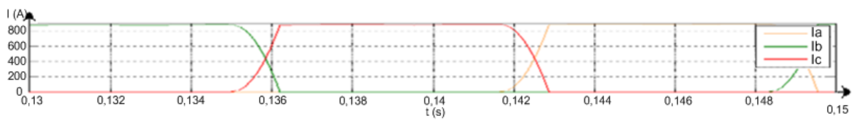


Fig. 4. Commutation currents of a cathode group of switches.

The analysis of frequency response characteristics of the hardware implementation of a hybrid model is provided to assess a capability to simulate a full spectrum of the processes. This analysis is provided at the construction stage with the use of specialized software such as Multisim and then conducted again for the hardware implementation. Fig. 5 illustrates the examples of frequency response characteristics obtained for reactor and filter models of HVDC system. The same characteristics were gained for all elements of HVDC system model. The results of the analysis of those characteristics confirm the capability of adequate simulation of the process in a range of 0 to 10 kHz.

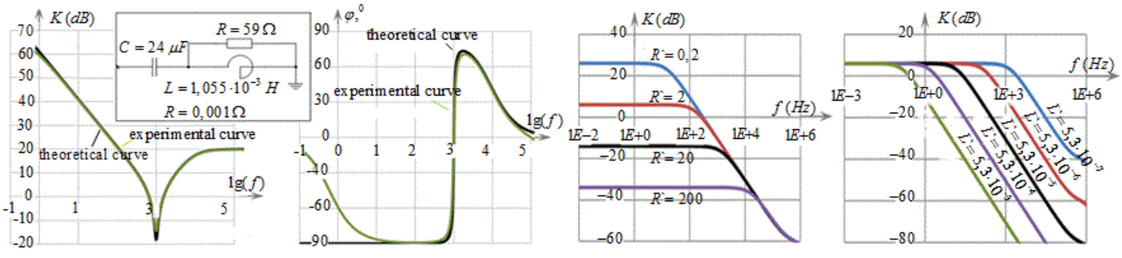


Fig. 5. Amplitude-frequency characteristic (a) and Phase-frequency characteristic (b) of a filter; amplitude-frequency characteristics of reactor's model with variation of *R* (c) and *L* (d) values.

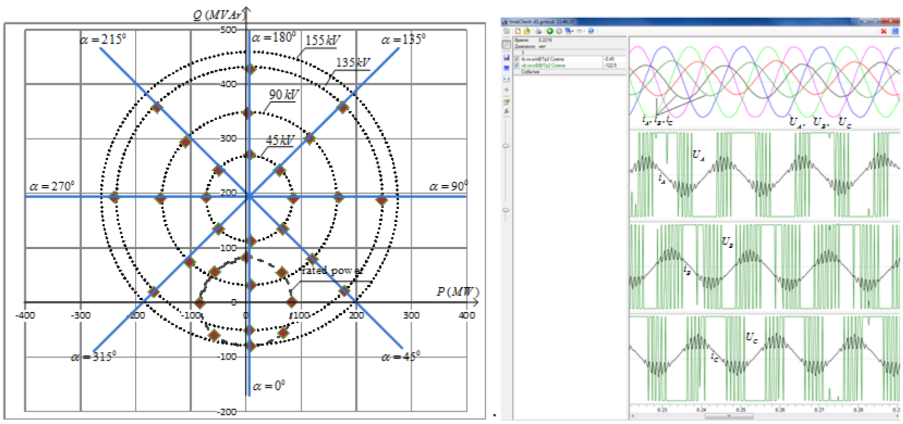


Fig. 6 PQ diagram (a) and oscillograms of three phase currents and voltage (b) of VSC hybrid model.

The frequency response characteristics have been measured for the hardware inductance value of $L = 3{,}123\,\text{mH}$ (Fig. 5, (c)) and the resistance value of $R = 11{,}8\,\Omega$ (Fig. 5, (d)) for the whole possible range of the impedance values of the existing power equipment. The model impedance variation is provided by changing coefficients of digital-to-analog converters of SHP. The given results indicate the possibility of changing the model parameters in a wide range for providing the flexibility of the model.

Fig. 6 shows the VSC PQ diagram and the voltage and current oscillograms obtained for the implemented HVDC model integrated into HRTSim. The PQ diagram (Fig.6, (a)) illustrates the operations of VSC in four quadrants for the normal and overload modes. The active and reactive power consumption and generation modes are simulated for different voltage levels provided by VSC at the AC side.

The shift of PQ diagram along horizontal axis is determined by the losses in the converter unit [13].

The values of active and reactive power measured for the hybrid model correspond to the values calculated in accordance with the known formula [14]:

$$S = 3\frac{U_C U_S}{X}\sin(\alpha) - j3\left(\frac{U_C U_S}{X}\cos(\alpha) - \frac{U_C}{X}\right) = P - jQ \quad (2)$$

where P and Q are the active and reactive power components; X is the equivalent resistance of the network; and α is the angle between system voltage U_S and converter AC output voltage U_C.

The given simulation results obtained at the various stages of model development, as well as a sample of already implemented SHP of HVDC showcase the multi-stage process of model verification and confirm compliance with the above stated requirements for advanced simulation of HVDC systems.

4. Conclusions

The approach to synthesize a hybrid model of HVDC system and its testing results are presented in the paper. The proposed approach allows to:

- satisfy the entire set of requirements for advanced simulation set by the evolving power system operating tasks;
- develop a versatile, flexible and real-time user configurable model of HVDC system.

The hybrid simulation approach complicates the development and testing of power equipment models in comparison with purely digital simulation. However, the scope of models features and capabilities of the hybrid simulator outweigh all the challenges and provides advantages over digital tools.

The results of this work will be applied to the future analysis of the mutual influence of HVDC and large HVAC systems, including the task of multi-terminal VSC HVDC systems operation.

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