A Hybrid Simulation Model for VSC HVDC

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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.

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;

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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 cannot 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 simu-
lation 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 sys-
tem 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 nor-
  mal, emergency and post-emergency operating conditions
  of EPS.

Furthermore, to solve the above mentioned problems,
the simulation systems should meet the following require-
ments [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 tran-
  sient processes modeling in power equipment and EPS as
  a whole);

- the real-time simulation and the possibility of intercon-
  nection with external devices and systems.

Currently, digital modeling complexes are widely used for
an analysis of the EPS (RTDS, HYPERSIM [9], [14] and others).
These complexes have shown to be successful in the simula-
tion 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 simu-
lations 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 parti-
tioning 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 pro-
cessors, 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 mod-
eling 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 electromechan-
ical 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 comprehen-
  sive mathematical models of corresponding types of the
  simulated equipment;

- the methodologically accurate with guaranteed instrumen-
  tal error solution of differential equation systems in real
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.

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).
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 \( \mu s \) (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.
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.

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 resent 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

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic voltage, kV</td>
<td>110</td>
</tr>
<tr>
<td>Basic power, MVA</td>
<td>200</td>
</tr>
<tr>
<td>Basic frequency, Hz</td>
<td>50</td>
</tr>
<tr>
<td>Switching frequency, Hz</td>
<td>1050</td>
</tr>
<tr>
<td>AC nominal voltage, relative units (r.u.)</td>
<td>1</td>
</tr>
<tr>
<td>AC active resistance, (r.u.)</td>
<td>0.02</td>
</tr>
<tr>
<td>AC inductive resistance, (r.u.)</td>
<td>0.155</td>
</tr>
<tr>
<td>Transformer voltage rating</td>
<td>110/28.6/10</td>
</tr>
<tr>
<td>Resistance of high voltage winding of the transformer:</td>
<td></td>
</tr>
<tr>
<td>active resistance, (r.u.)</td>
<td>0.0114</td>
</tr>
<tr>
<td>inductive resistance, (r.u.)</td>
<td>0.2625</td>
</tr>
<tr>
<td>Resistance of medium voltage winding of the transformer:</td>
<td></td>
</tr>
<tr>
<td>active resistance, (r.u.)</td>
<td>0.01</td>
</tr>
<tr>
<td>inductive resistance, (r.u.)</td>
<td>0.6597</td>
</tr>
<tr>
<td>Resistance of low voltage winding of the transformer:</td>
<td></td>
</tr>
<tr>
<td>active resistance, (r.u.)</td>
<td>0.007</td>
</tr>
<tr>
<td>inductive resistance, (r.u.)</td>
<td>0.0734</td>
</tr>
<tr>
<td>Magnetoizing branch, (r.u.)</td>
<td>300</td>
</tr>
<tr>
<td>Value of capacity of Filter, (r.u.)</td>
<td>0.03091</td>
</tr>
<tr>
<td>Active resistance of Filter, (r.u.)</td>
<td>11.44</td>
</tr>
</tbody>
</table>

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


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