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An Advanced Simulation Model for VSC HVDC Transmission

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ABSTRACT

The research of this simulated project is based on the hybrid simulation model for the voltage source converter high voltage direct current (VSC HVDC). This research main aim is based on the needs to implement new methods and tools for obtaining the required information to evaluate the mutual influence of HVDC and HVAC systems. This research presents important topics like commutation process, hybrid simulation for the advanced modeling of VSC HVDC. The simulation results obtained from this research by the prototype of specialized hybrid processor of VSC HVDC model confirms the amount of harmonics, efficiency and effectiveness of the approach with the help of the detailed representation of commutation process by using power semiconductor devices and simulation in VSC and EPS without any limitation on their duration.

This research also provides the extension of simulation results to one more level. Actually, the simulation results of this research are that the phase to phase voltage of VSC HVDC is a three level result. But this three level simulation result is extended to five level simulation result which can be concluded at the end of the project.

Keywords— Power system simulation, real-time systems, hybrid simulation technology, VSC HVDC.

I. INTRODUCTION

If electricity is blood of our economy, then the power grids are circulatory system. The world is growing in complexity, with increasing technologies, requirements for power grids and demand for respective jobs. The key points that change in power grids and power consumption are linked with smart grid technologies. These are grids with intelligent control techniques that allow based on the power consumption level in a building/office (precisely determined by equipment, lights and electric sockets), for the setting of optimal operation modes (e.g. washing clothes at night, when power rates are lower). They can quickly respond to any problems (e.g. voltage surges), thereby preventing damage to equipment, and automatically recover after a breakdown. These technologies reduce losses in power systems and make power delivery more reliable and increase continuity. They can also help consumers choose an energy supplier and manage consumption and spending. In addition, users who own their own micro generators may have large additional power to sell.

Another trend is the evolution of distributed generation. A total blackout is a favorite incident of writers in disaster films, insidious hackers or natural calamities interrupt power mains and the entire city falls into darkness. Distributed power allows for the prevention of such a scenario, as local accidents in separate grid sections will not lead to global implications. Developed countries have put it on their active agendas as far back as the 2000s: in particular, the USA passed a law offering considerable benefits to small electricity producers after a major accident in the power system on the north-east of the USA and in Canada in 2003. The share of centrally produced electricity has been declining since then. There are no equivalent initiatives in Russia yet, but as companies lack funds to upgrade the mains, distributed power may become a topical issue in Russia in the near future, creating a need for respective specialties.

The growing complexity of electrical power system (EPS) has to face 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:

1. The independent control of active and reactive power.
2. The provision of reverse of power flow without changing the polarity of the voltage.

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].

1. 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. 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. According to this, 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,

1. The high complexity associated with the analysis of disturbance processes in case of low observability of the EPS.
2. The limited applicability of the measurement results to set up the ACS of hybrid HVAC and HVDC systems.
3. The occurrence of previously unobserved disturbances.
4. The existence of a wide range of all possible pre emergency modes of EPS.
5. 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 considered as a primary source of information for the analysis of HVDC and HVAC systems. However, it can be used to obtain and verify the results of EPS simulation [8], [9]. At the same time, the reliability and accuracy of the simulation results will depend on the type of simulation methods and tools that are chosen.

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. 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:

1. The phase-phase operation of VSC.
2. The use of high-speed fully controlled power semiconductors.
3. 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]-[13],

1. The models of EPS elements must be three-phase (or more) to account properly for all the unbalanced conditions.

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2. The simulator must be capable (scalable) to implement an EPS model of any size.
3. 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).
4. 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. 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 Multiterminal 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 [15], [16], [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 turnoff 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.

A. Hybrid Simulation Concepts

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:

1. 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.
2. The methodologically accurate with guaranteed instrumental 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.
3. All types of commutation of power equipment, including the power semiconductors, are carried out on a model physical level.
4. The interconnection between a physical model and mathematical simulation levels is provided by means of appropriate voltage-current converters.
5. 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.

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

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.

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 modelled via integrated microelectronic digitally controlled analog switches (DCAS).

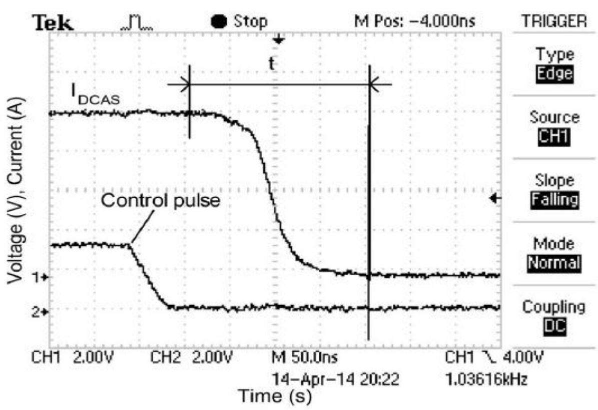

Figure.3.1 current waveform of the DCAS commutation

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 the switching time (t) is about 300 ns, while a switching time of IGBT is more than 3 µs. 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.

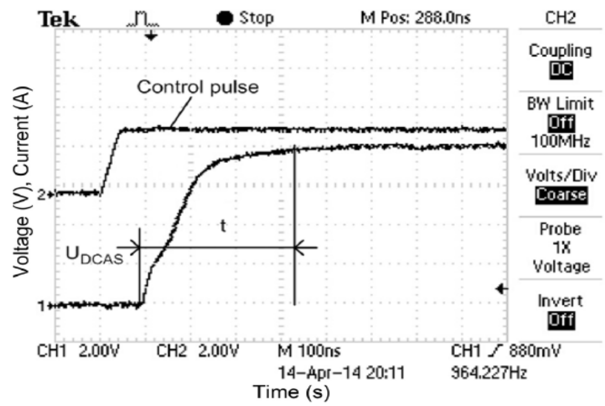

Figure.3.2 Voltage waveform of the DCAS commutation

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.

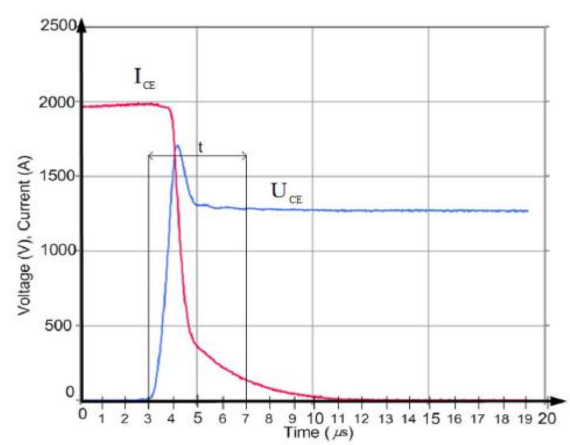

Figure.3.3 Current and voltage waveforms of IGBT

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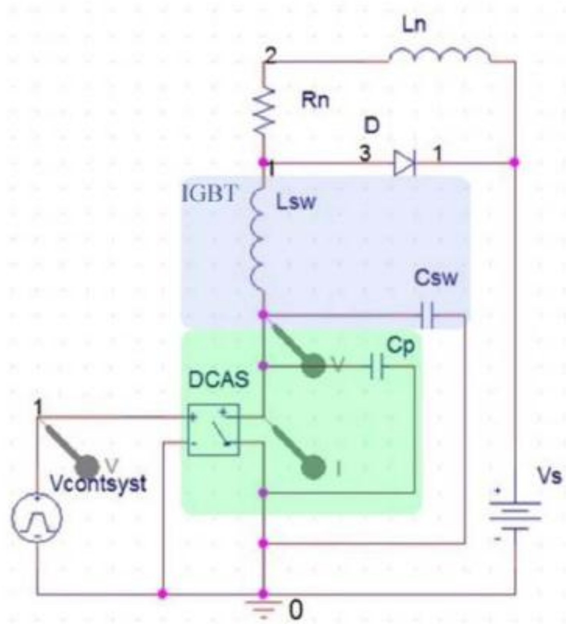

Figure.3.4 Scheme of IGBT commutation process without the snubber circuit

Note:

- Csw, Lsw -- equivalent capacity and inductance of IGBT
- Cp - coupling capacitance of DCAS
- Rn, Ln- equivalent load
- D – Bypass diode

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

The scheme of IGBT commutation process (type 5SNR) without the snubber circuit is shown in Figure 4.6. 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 Figure 4.7 and in figure 4.8

The scheme of IGBT commutation process (type 5SNR) with the snubber circuit presented in [21] and [22] is shown in Figure 4.9

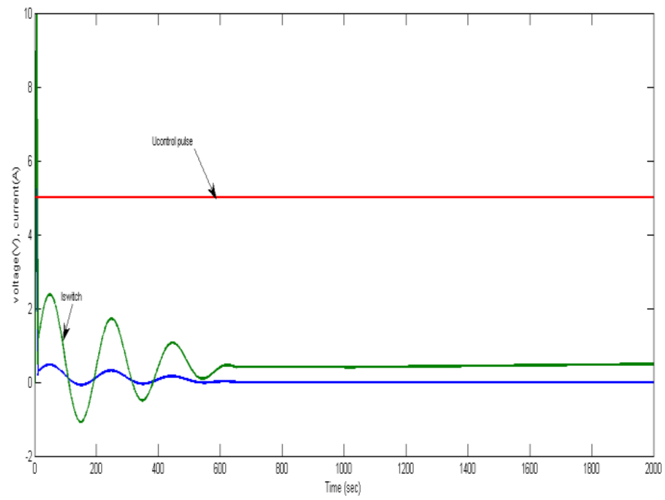

Figure.3.5 Turn-on process without the snubber circuit

The current and voltage oscillograms of the IGBT in different operation modes with the snubber circuit are shown in Figure 3.8, 3.9.

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

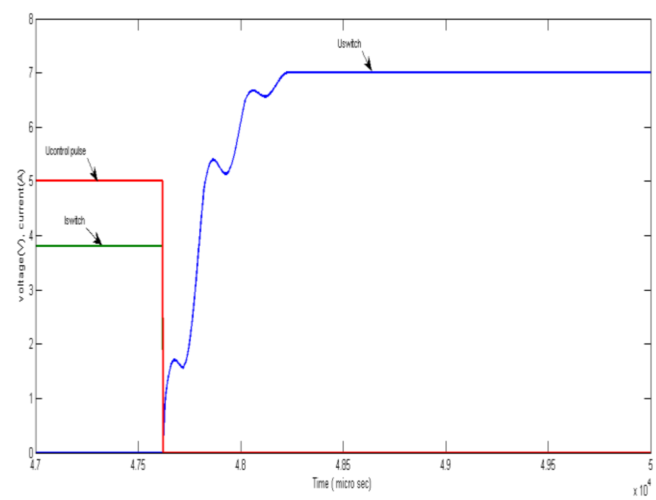

Figure.3.6 Turn off process without the snubber circuit

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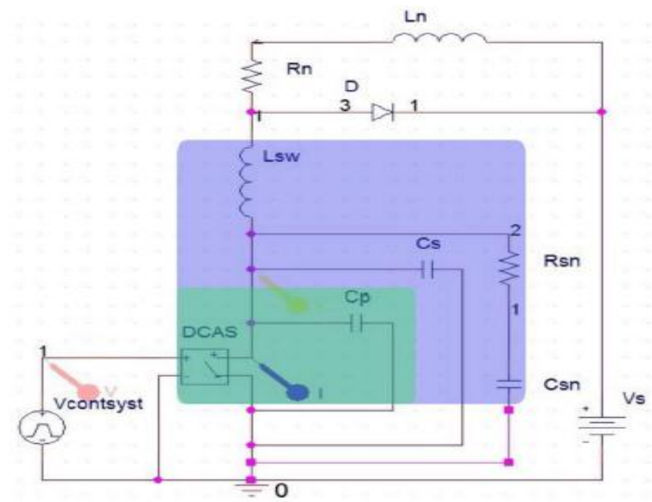

Figure.3.7 Scheme of IGBT commutation process with the snubber circuit

Note: Csn, Rsn – snubber circuit.

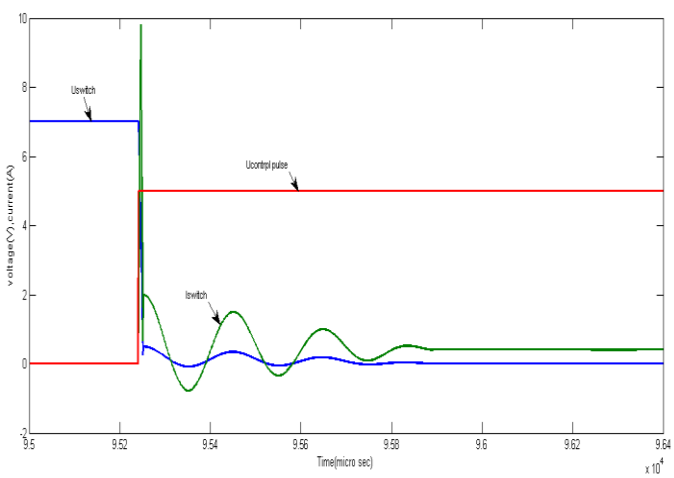

Figure.3.8 Turn on process with the snubber circuit

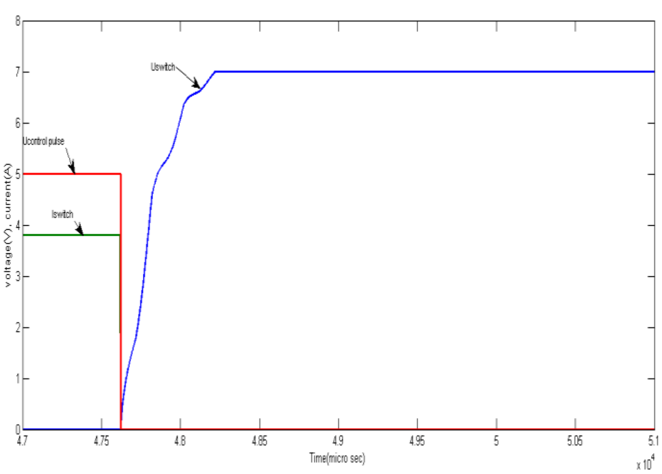

Figure.3.9 Turn off process with the snubber circuit

IGBT (5SNR) is about 5 μs (see Figure 3.3). The difference may be caused by errors in the recalculation of the parameters of the IGBT (5SNR) 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.

IV. SIMULATION RESULTS

The project is about the analysis and simulation of the VSC HVDC. The advantages and importance of voltage source converter and high voltage direct current transmission is discussed in earlier chapters. Now we will see the simulation and their corresponding results of VSC HVDC model. The scheme of experimental research of the VSC HVDC model is shown in the below figure 4.1.

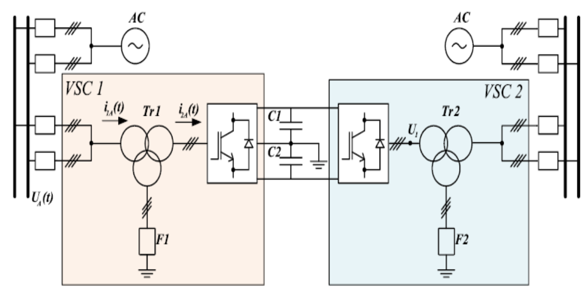

Figure.4.1 Schematic diagram of VSC HVDC model

The brief discussion of the above schematic is as follows:

The term AC in the figure represents alternating current obtained from the generating station which is to be transmitted. This obtained or generated power is stepped up to a very high voltage (to reduce losses and increase transmission efficiency) by means of suitable three phase step up transformer Tr1 as shown in figure 5.1. Necessary equipment's is placed like filters to reduce harmonics if present (F1 in figure) and other means.

This high voltage alternating current (HVAC) is converted to high voltage direct current (HVDC) by using rectifier converter station. Even though it is converted to DC there may be some amount of ripples or harmonics present in the obtained output (HVDC) of the rectifier station. Hence it is necessary to filter out these harmonics by means of capacitor filters C1 and C2 as shown in the above figure 5.1. Now it is ready to transmit power in

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HVDC with low transmission losses to a very long distance of over 500 km and above.

The parameters of the study system scheme are resented in the below table.

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

Table 4.1 Parameters of the study scheme

After transmitting over a long distance it is required to convert high voltage direct current (HVDC) to the high voltage alternating current (HVAC) by means of inverter station. This conversion is required because all the industries and household appliances operate on AC. After conversion, this HVAC is stepped down to low voltage depending on requirement of voltage by means of step down transformer Tr2 as shown in figure 5.1. But in this project after converting to HVAC it is again fed to the grid.

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 obtained waveform of voltage (U (t)), current (I (t)), as well as the calculated values of apparent (S (t)), active (P (t)) and reactive (Q (t)) powers are shown in below figure 5.2 and 5.3.

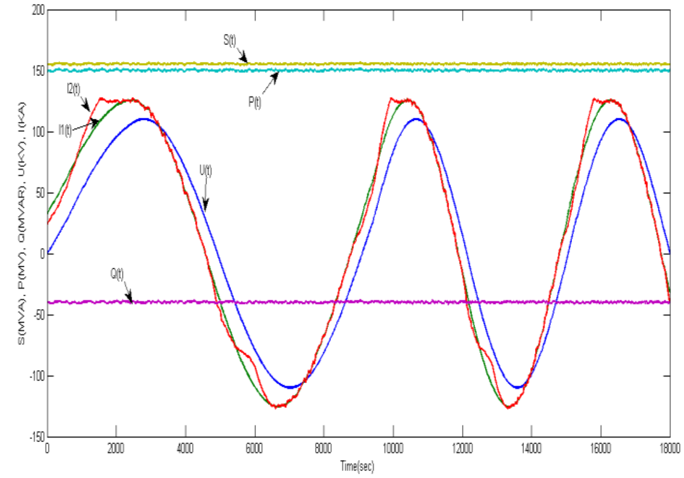

Figure.4.2 Mode of consumption of P(t) and generation of Q(t)

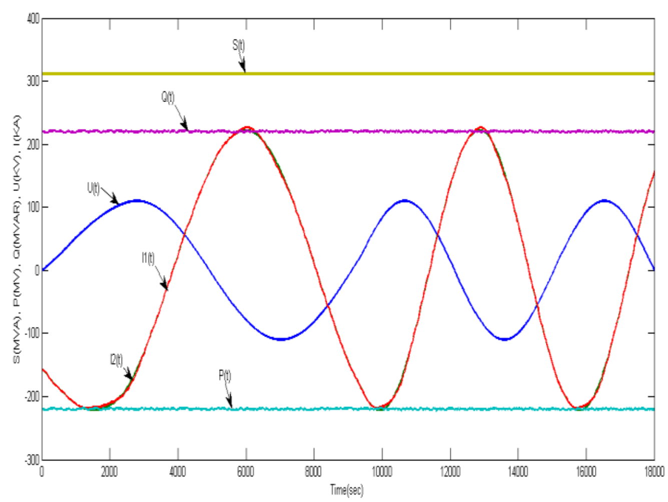

Figure.4.3 Mode of generation of P(t) and consumption of Q(t)

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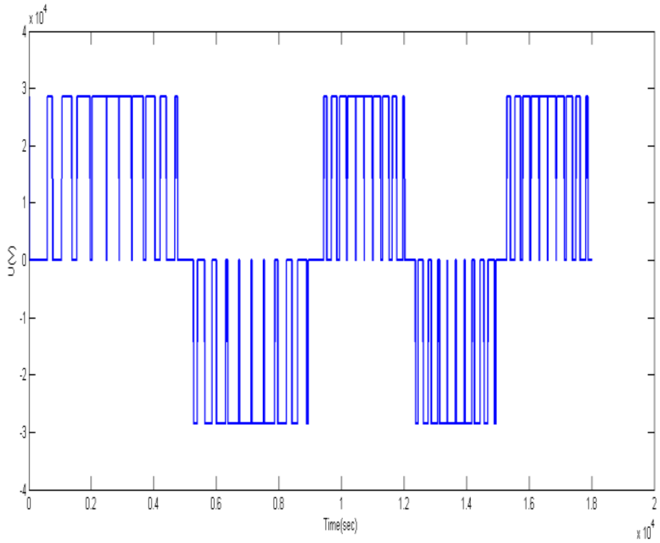

Figure.4.4 Phase voltage of VSC HVDC model

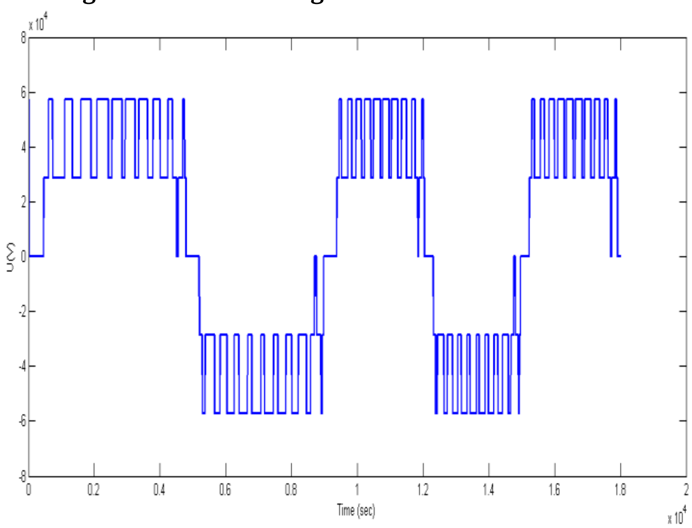

Figure.4.5 Phase to phase voltage of VSC HVDC model

V. CONCLUSION

We finally conclude that complexity in electrical power system can be easily solved or analysed by using the hybrid simulation. The above research concludes that the reliability, efficiency of transmission and stability of the electrical power system can be improved by using this hybrid simulation of VSC HVDC model. 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.

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