a New Type Real-time Simulation Platform for Modular Multilevel Converter Based HVDC

LIU Dong, TANG Guang-fu, HE Zhi-yuan, PANG Hui
China Electric Power Research Institute, Beijing, 100192, China

liudong@epri.sgcc.com.cn

***Abstract*—This paper focused on a new type simulation platform. Restricted by the number of network nodes and time step, traditional all digital simulation platform is not fast enough for the modular multilevel converter Based HVDC (MMC-HVDC). This paper presented a real-time digital-analog hybrid simulation platform including 49-level MMC, described the method of calculating the proportion of the platform to the original system. The characteristics of the simulation platform were designed according to the dynamic response features of actual system and its converter was simulated by analog devices. Depending on the special communication interface the simulation platform can also be used to verify the function of converter valve based controller (VBC) used in the Nanhui MMC-HVDC project. Experiment results of severe bipolar short circuit fault are compared with that by off-line digital simulation platform PSCAD, showing that most of the dynamic characteristics are basically identical. Thus the simulation system is verified available for optimization of dynamic parameters and real-time test of control system in planning of MMC-HVDC system.**

Keyword*：*MMC; HVDC; real-time simulation; analog simulative platform; proportion caculation; short circuit fault

I. INTRODUCTION

Modular multilevel converter based HVDC (MMC-HVDC) transmission system has many advantages such as no commutation failure, low harmonic, no need of reactive power compensation, etc.[1]. It can also control active and reactive power independently. In recent years, this technology and related projects in the world have been rapidly developing.

Before china's first MMC-HVDC project comes into operation, its system configuration, main circuit parameters, reliability and robustness are all needed to be comprehensive analyzed. In particular, the control and protection system hardware platform and software algorithms are required to be ensured reliable operation of the project.

Currently the real-time simulation technology in traditional HVDC is widely used. The system hardware of digital simulation commonly uses paralleled multi-CPU computers, which includes a wealth of models of power networks and controlling components in its program[2]. For example, data-conversion software in the Real-time Digital Simulator (RTDS) can transfer models of PSS/E and EMTDC format into RSCAD format to achieve real-time simulation for large-scale networks with ac/dc electromagnetic transient phenomena.

For MMC-HVDC transmission system, one converter could consist of hundreds even thousands of sub-modules, each sub-module in simulation system are equivalent to a independent voltage source, so the converters' characteristics are difficult to be simulated[3]. In addition, communication between sub-modules and converter valve based controller (VBC) in control lobby are carried out through one-to-one fiber-optics, so it is difficult to verify communicate arithmetic through the existing digital simulation interface.

This paper presents the digital-analog hybrid real-time simulation system to verify the dynamic characteristics, fault features and VBC of the first MMC-HVDC project in china. On the basis of Substitution Theorem the theoretical principle of digital-analog hybrid simulation is expounded. In the last part of the paper experiment result about dc bipolar short circuit are given, showing that the simulation system has laid a solid foundation for the project.

II. SUMMARY of MMC-HVDC

Voltage source converter topology used in power transmission system can be of various forms, most of which are modular multilevel converters and two level converters.

There are six legs in a 49-level MMC, each leg consists of 56 uniform sub-modules (8 for standby) to follow the voltage reference waveform from the SCP. Each sub-module (SM) in converter can be equivalent to a separately controlled dc voltage source. Ac voltage of approximate sine wave can be reached by switching function of sub-modules. When the ladder number of the output voltage (shown in Fig.1) exceeds 29, harmonic content will meet the standard of the IEEE.

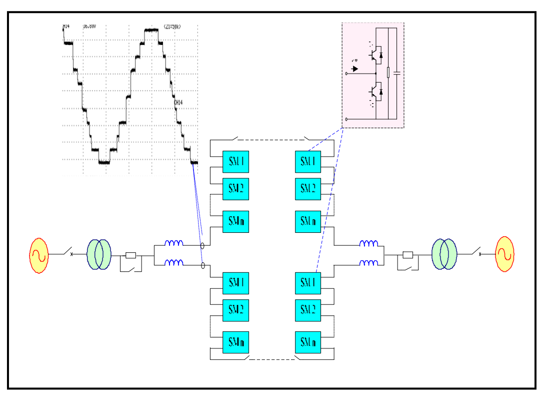
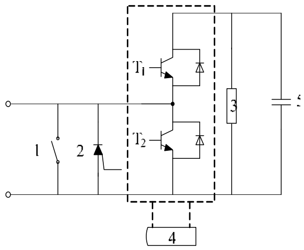


Fig.1 Typical structure of MMC-HVDC

Each sub-modules in MMC valve consists of two IGBTs connecting in series with a dc capacitor and resistor in parallel, a fast bypass switch auxiliary components, sub-module controller(SMC) and thyristor for short circuit protection. Compared with the VSC valve of series-connected IGBTs directly, MMC increases switch states greatly, the storage components distributed in sub-module also lead to complicated features[4] such as loop current between legs and phases, so the real-time simulation of MMC-HVDC becomes more difficult.



(1.bypass switch，2. thyristor，3.paralelled resistors，4.SMC，5.capacitor)
Fig.2 Structure of sub-module in MMC Valve

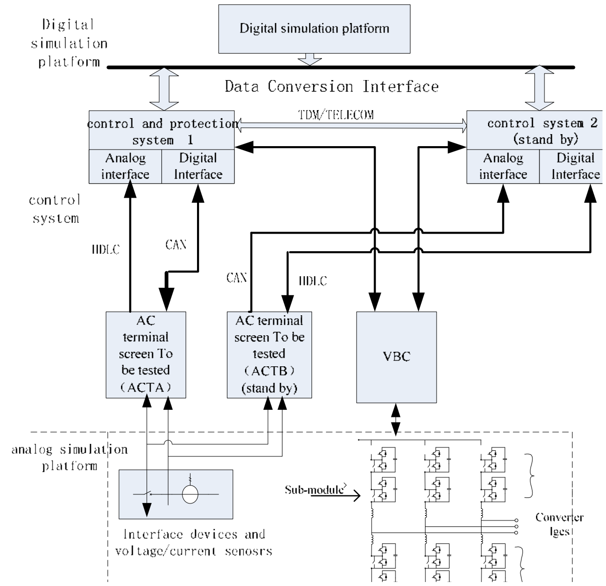
III. STRUCTURE of the SIMULATION SYSTEM

A. Establishing simulation steps

- Separate the original power network, determine tasks and interfaces separately for digital and analog simulation subsystems;
- Simplify the digital simulation of the structure of the ac power's equivalent network, so the size of network could be adapted to the algorithm; and then completed the simulation program;
- Calculate the proportion of the analog simulation subsystem to real project; calculate parameters and thus verify analog components;
- Connect voltage and current sensors to establish appropriate measure method and, adjusted signal proporation of the digital-analog transfer interface;
- Connect the VBC and SCP to physic simulation platform to test communication system.
- Compare the experiment data of steady a transient state characteristics with that of off-line digital simulation, analysis the causes of differences and correct it.

B. Structure of the platform

Fig.3(a) is the sketch diagram of the simulation system. it comprises of following subsystems: digital simulation platform, analogy simulation platform, interface devices and control system, Fig.3(b) gives the real image of the system. , Fig.3 (c) is a sketch map of communication between VBC and SCP.



(a)

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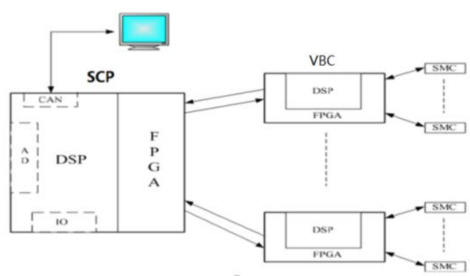


(c)

Fig.3 Structure of the real-time simulation with VBC and SCP.

Digital simulation platform is based on PSCAD/EMTDC, and mainly implements the real-time simulation for the wind farm and AC networks connected to two MMC-HVDC converter stations. Real-time simulation modeling is based on node analysis technology, turning ac networks into equivalent Norton models of equivalent resistances in parallel with the current source at each calculating step. The node admittance inverse matrix of equivalent transient circuit is multiplied by the injection current vector in the node, to determine the instantaneous voltage value of the nodes[5]. Nodes used to separate two subsystems should have relatively stable voltages and current flow.

The analogy simulation platform mainly includes ac/dc switch field, each of them has valve reactors, dc line, transformers, and converters of more than 300 sub-modules as well as relevant sensors and controllers, etc. The platform can implement dynamic simulation for two terminal MMC-HVDC transmission system. As an important part of the system, interface hardware connects analog simulation platform to digital, which is shown as below:

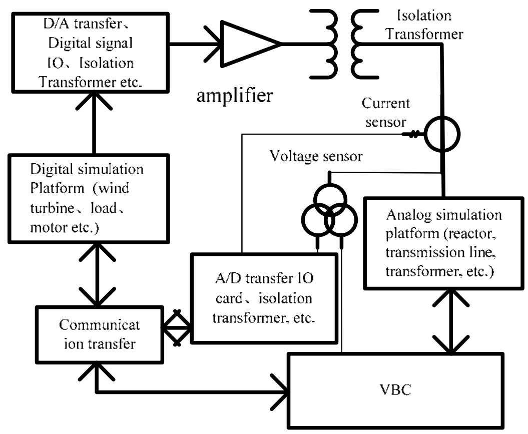


Fig.4 Interface of digital and analog subsystem

Interface voltage of digital side is calculated by the simulation program and sent by D/A transfer, then through the amplifier into analog subsystem. From analog side of the interface sensors take the value of current and voltage and send the data into digital subsystem through A/D transfers, while the closed-loop interaction is formed.

As the low power of simulation platform components, the voltage amplifier can be used to drive it. For the MMCs and sub-module's SMCs, external low voltage source is necessary to supply power for its controller.

IV. SIMULATIVE PROPOPROPORATIONN

The parameter proportion of the simulation system to the project is the most important question, so several factors must be considered firstly:

1) Reasonable operation range and security limitation of devices.

The lightest current under normal operation condition should be larger than the minimum operating current to ensure the accuracy of analog devices. Under fault states the maximum fault current of the devices should not lead to component saturation and keep in the safe range. The following circuit equation should be satisfied:

$$\left|\frac{\tau^2 U_S^2}{X} - \frac{\gamma\tau^2 U_S^2}{X}\right| \le \sqrt{3}\tau U_S I_{S\max} \quad (1)$$

Here $U_C = \gamma\tau U_S$, U_C is the phase voltage of MMC, τ is transformer proportion, $I_{S\max}$ is the largest current in safe area, so we can get the equation:

$$1 - \frac{\sqrt{3}XI_{S\max}}{\tau U_S} \le \gamma \le 1 + \frac{\sqrt{3}XI_{S\max}}{\tau U_S} \quad (2)$$

Substitutes $U_C = \gamma\tau U_S$ into $U_C = uMU_{dc}/\sqrt{2}$ and then γ can be represented as $\gamma = uMU_{dc}/(\sqrt{2}\tau U_S)$, here u is the utilization proportion of dc voltage. Insert γ into equation (2) to get the safety operation field of modulation proportion M:

$$\frac{\sqrt{2}(\tau U_S - \sqrt{3}XI_{S\max})}{uU_{dc}} \le M \le \frac{\sqrt{2}(\tau U_S + \sqrt{3}XI_{S\max})}{uU_{dc}} \quad (3)$$

Change equation (3) to per-unit model:

$$\frac{\sqrt{2}(\tau^* - X^* I_{S\max}^*)}{uU_{dc}^*} \le M \le \frac{\sqrt{2}(\tau^* + X^* I_{S\max}^*)}{uU_{dc}^*} \quad (4)$$

2) Parameters of digital and analog components

Increasing analog voltage reference value could hold simulation accuracy and reduce the fault current.

3) Sequence of choosing parameter proportion

At first the capacity proportion between ac and dc system should be confirmed, considering modeling strategy, energy stored in the capacity, stray inductance of analog components and so on. After giving the ac/dc apparent power proportion and voltage proportion, the residuary parameters such as ac/dc current can be calculated through circuit theorem.

B. Simulation equivalence

In the analogy simulation platform, high power switching devices in the sub-models are simulated by field-effect semiconductor switches with excellent frequency and loss characteristics. We also use technology of negative-resistance compensation to offset voltage drop made by small devices.

According to Substitution Theorem complex networks simulated by digital simulation can be equivalent to Daviunan circuit, including voltage source and the equivalent series resistance, which depends on the calculation step and structure of the software platform[6]. Amplitude of voltage source realized by active amplifier is:

$$E(t) = V_{node} + I_b * R_E \quad (5)$$

Subsystem implemented by analog simulator is simplified to be Norton circuit in a branch of pure digital form, including the equivalent current source with resistance connected in series and parallel. At each calculation step, current and voltage information from sensors is transferred into real-time digital simulation system.

Each sub-model on MMC simulator implements half duplex communication with VBC through HDLC communication protocols, realizing functions of instruction acquisition, supervisory control, alarm and state data communication. Thus optical communication interface can match with actual VBC and achieve real-time closed-loop online testing.

V. APPLICATION of SIMULATION SYSTEM

This chapter is about simulation for the dynamic state and fault state of the MMC-HVDC system. Take dc bipolar short circuit for example, firstly the principle of this type fault and its phenomenon are introduced, then comparative analysis is given to compare the simulation result from off-line digital platform with that from real-time simulation system.

A. Introduction of the Nanhui project

Nanhui VSC-HVDC demonstration project connects Nanhui wind farm to the 35kV bus of Dazhi transformer station. Nanhui wind farm is located in east of Shanghai and consists of 11 set of 1.5MW turbines. Turbines are connected to ac system through two 35kV lines before the VSC-HVDC project putted into operation (see Fig.5).

Nanhui project has rated dc voltage of ±30kV, dc current of 300A, converter capacity of 20MVA with 49-level modular multilevel structure. Transmission line between the two stations is about 8km.

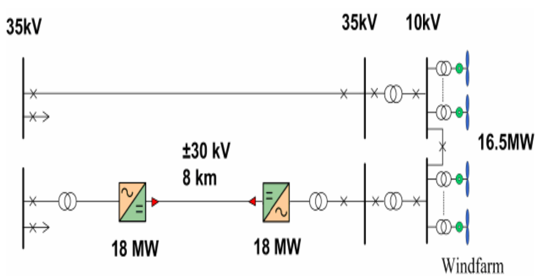


Fig.5 Main circuit of the project

B. Off-line digital simulation for Nanhui Project

Off-line digital simulation mentioned in this chapter is to verify the MMC-HVDC control procedure of starting/stopping, response speed to power/voltage instructions and protection strategies to different fault states, while the function of SCP and VBC system could only be verified on the digital-analog hybrid simulation platform.

After MMC-HVDC dc bipolar short circuit occurred, capacitors in MMC discharge firstly through the failure grounding point, further more the ac networks come to be three-phase short circuit through the loop made by grounding point, dc lines, converter legs, reactors and secondary winding of transformer.

Fig.6 shows the direction of short circuit current and its pathway. On the assumption that all energy stored in capacitors in MMC before the fault transfers into leg reactors, then:

$$\frac{1}{2}Li_d^2 = n\frac{1}{2}CU_0^2 \qquad (6)$$

So the fault current on dc lines i_d is $U_0\sqrt{nC/L}$, the ac phase current is $I_S = E_0/(X_s + X_C)$. Here n is the number of sub-modules each MMC leg have, X_s is ac power system's equivalent impedance, U_0 is capacitor's initial voltage before fault occurred.

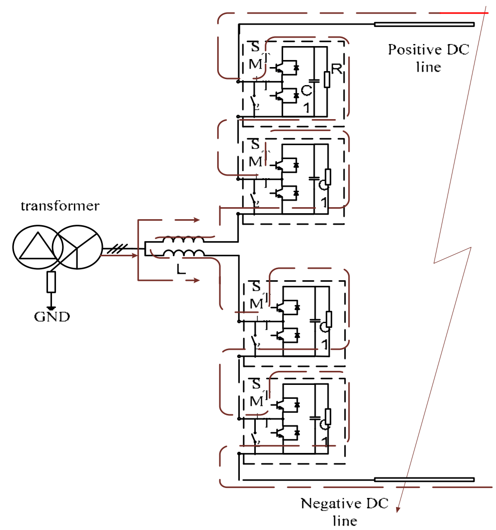
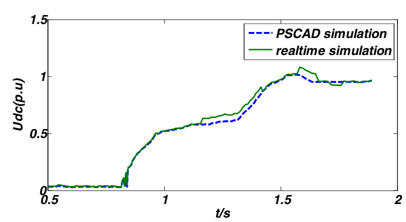


Fig.6 Current direction after dc short circuit occurred

C. Digital-analog hybrid real-time simulation

Parameters of the real-time simulation platform are set as follows: the transformer is in DYn11 connection, its secondary winding neutral is grounded through 2000 Ω resistance; transformer's line voltage of valve side is 142V, short-circuit impedance ratio is 0.08; leg reactor is about 0.15p.u.; dc voltage ± 140V. In the experiment, MMC's capacity is 18MVA (converted to real project). According to different value of active power to be transmitted, reactive power can be independently adjusted from +13MVar to -9MVar.

From the following figures we can see that waveforms of real-time experiment are fit well for that of off-line digital simulation when MMC-HVDC is in starting process.



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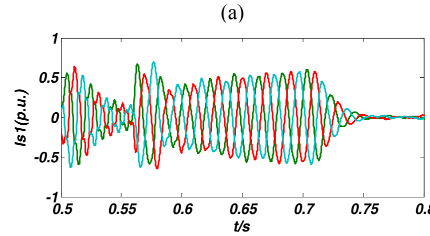

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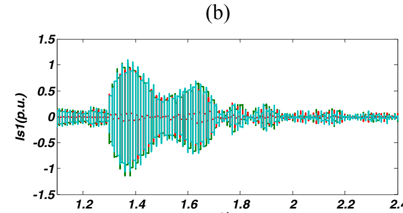
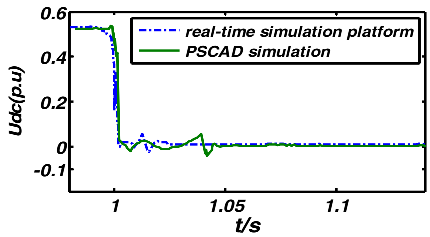


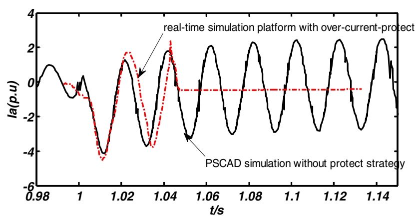
(c)

Fig.7 Real-time experiment waveforms, (a) is waveforms when MMC was in charging process, (b) is the offline simulation waveform of ac phase current when MMC started unlocking while (c) is that of real-time experiment.

When MMC was operating under steady-state, we connected the positive and negative dc bus directly by computer controlled contactors, and then the dc voltage dropped to almost zero in split second. According to the anticipated control strategy, MMC valve should be latched by VBC immediately after the fault, and almost all bypass thyristors should be triggered to protect sub-modules from huge fault current.



(a)



（b）

Fig.8 Simulation waves of dc voltage and ac current

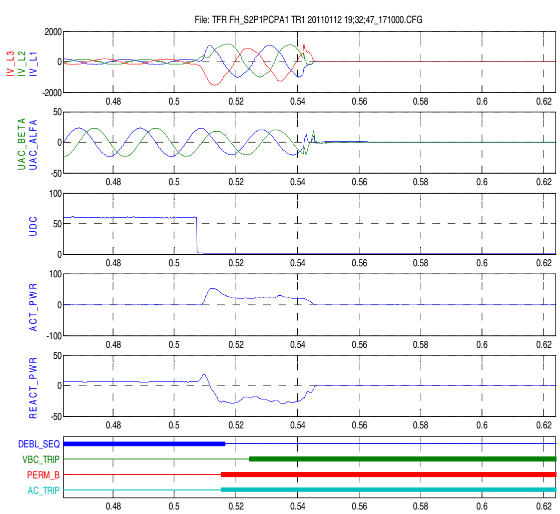


Fig.9 Waveform of protection after shortcut occurs

The result is shown as above: attention is paid to the current which flowed through the converter leg, it is about 700A (converted to real value) 1ms after failure. After another 3ms VBC blocked the whole converter, SCP acted to lock the MMC-HVDC system by tripping ac circuit breakers and thyristors on sub-modules. Current in converter valves then rose to the peak value of 1500A after 2-3ms, but it was still in allowable range. So we can conclude that the logic of dc low-voltage and over-current protection after bipolar short-circuit is correct and the main protection operated reliably.

VI. CONCLUSION

This paper has dealt with a new type real-time simulation system for MMC-HVDC, proposed its structure and modeling principles. The hybrid simulation platform includes digital subsystem and analog subsystem, each part played different role as elaborated above. In the platform, converter was precisely simulated by analog devices. This type simulation platform can real-timely executive on-line test for VBC depending on its special communication interface. Experiment result has verified the validity and effectiveness of the real-time simulation for MMC-HVDC system that is connected to wind farm and 35kV ac power networks, the effective level of its control system such was also predicted to a certain extent.

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刘栋

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作者简介：

刘栋(1982—)，男，博士研究生，研究方向为电压源换相直流输电控制策略及仿真技术研究，liudong@epri.sgcc.ac.cn；

汤广福(1966—)，男，博士，教授级高级工程师，博士生导师，研究方向为 FACTS、HVDC 及其相关试验方法；

贺之渊(1977—)，男，博士，高级工程师，研究方向为 FACTS、HVDC 及其相关试验方法。