Research on Power Interface Algorithm of Power Hardware-in-the-loop Simulation for Isolated Operation of Modular Multilevel Converters

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Abstract. A current source type power interface algorithm is proposed for the power hardware-in-the-loop (PHIL) simulation of modular multi-level converters (MMC) operating with an isolated gird such as a wind farm. To improve the stability and accuracy of hybrid simulation system, a virtual impedance and the running method is proposed for MMCs. A simulation model based on the proposed interface algorithm is established in MATLAB. The test results show that the hybrid simulation system maintains high stability and accuracy. At the power interface, the relative error of voltage is less than 2%, and the relative error of active power is less than 2%. The proposed power interface algorithm is applicable to MMCs operating with an isolated grid.

1. Introduction

The modular multi-level converter (MMC) has the advantages of low land occupation, small harmonics, independent and adjustable reactive power, and black start. The flexible direct current transmission based on MMC has been connected to the grid and power grid in recent years. Asynchronous interconnection, large-capacity long-distance DC transmission and other fields have been widely used, which is an important development direction of DC transmission technology. In order to improve the capacity of power transmission and transformation systems, modular multi-level converters are generally composed of thousands of sub-modules with the same structure or function, including a large number of power electronic switching devices, with strong nonlinear characteristics and short control period. It is difficult to use traditional power simulation software for complete and efficient modelling and simulation. In order to conduct more accurate and efficient research and testing of power systems including modular multilevel converters, digital physics hybrid simulation technology, also known as power hardware-in-the-loop (PHIL), has been developed based on real-time simulation. That is to say, the modular multi-level converter is simulated by using a physical dynamic model device, and the AC/DC power grid is simulated by using a digital real-time simulation model, and the two are combined into one unit by a power amplifier, a voltage current transformer, and the like.

Since the delay and noise of measurement and power amplification are easy to reduce the accuracy and stability of digital physical hybrid simulation system, reasonable power interface algorithm is one of the key technologies to realize hybrid simulation. In the current PHIL interface algorithm, the Ideal Transformer Model (ITM) is the simplest and most common method, but when the digital equivalent impedance and the physical side equivalent impedance are relatively large, there is a problem that the system stability is deteriorated. Literature [13] proposed a Time-variant First-order Approximation (TFA) based on predictive compensation, but it is easy to produce ill-conditioned matrices, which is difficult in real time. Literature [14] cleverly utilizes the inherent delay characteristics of transmission lines, and proposes a Transmission Line Model (TLM), which effectively improves the accuracy of the simulation system, but its application has great limitations. Reference [15] proposed a Part Circuit Duplication (PCD), but it requires multiple iterations to improve the simulation accuracy, which is difficult to achieve in digital-analog hybrid simulation. The literature [16] proves that the Damping Impedance Method (DIM) has good stability and accuracy, and its application difficulty lies in good impedance matching.

The existing power interface algorithm is generally a voltage source type, that is, the emulator drives the power amplifier to operate as a voltage source, which conforms to the grid-connected operation law of general power electronic equipment. However, the modular multilevel converter has a black start capability and is capable of islanding, in which case the grid connected to it actually has current source characteristics. For example, a wind farm side converter connected to an offshore wind farm outputs an AC voltage for a wind farm's collector system, and the wind turbine is connected to the grid through a phase locked loop, and controls the grid current. In the island operation mode, the existing general power interface algorithm is not fully applicable.

Based on the above background, this paper proposes a current source type digital physical hybrid simulation damping impedance interface algorithm, and proposes an impedance parameter tuning method for modular multilevel converters, which can be applied to modular multilevel commutation. Hybrid simulation of the island operation mode.

2. PHIL Simulation System

As shown in Figure 1, the PHIL simulation system, the power amplifier, the voltage/current sensor and the interface control algorithm together form a power interface for implementing the interactive operation of the digital simulation system and the physical dynamic model system.

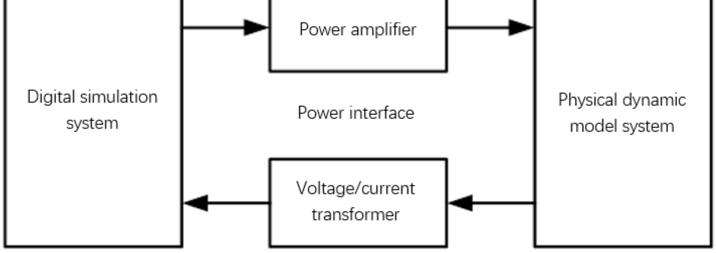

Figure 1. Diagram of PHIL simulation system

The digital simulation system is based on electromechanical or electromagnetic transient real-time simulation technology, which is used to simulate the operating characteristics of the AC-DC grid. It can greatly improve the flexibility of the simulation system and reduce the cost. In this paper, the digital simulation system is used to simulate the wind farm. The physical dynamic model system simulates the research object based on the principle of the reduction ratio equivalent, or directly uses the actual power system to improve the simulation accuracy of the complex nonlinear system. In this paper, the physical dynamic model system is used to simulate the modular multilevel converter. The power interface implements the interaction of energy and signals between digital and physical systems according to a certain algorithm. The actual medium power interface inevitably introduces delay and noise, which is easy to reduce the accuracy and stability of the simulation system. It is necessary to develop a reasonable power interface algorithm for a specific application.

3. Power interface algorithm for MMC island operation

According to the circuit substitution theorem, the power interface algorithm can have two basic modes: voltage source and current source. When MMC-HVDC is connected to the isolated operation mode of wind farm, the modularized multilevel converter controls the port voltage and the wind farm controls the grid-connected current, so the power amplifier is more suitable for running in the current source mode.

Figure 2 shows the schematic diagram of an improved power interface algorithm proposed in this paper based on the damping impedance method, which is applicable to the isolated island operation mode of the modular multilevel converter. Where s is the complex frequency domain operator, $U_A(s)$ is the equivalent power source of the digital simulation model based on Davinan's theorem, and $Z_A(s)$ is the equivalent impedance of the digital model. $U_B(s)$ is the equivalent power supply of the modular multilevel converter moving mode system, and $Z_B(s)$ is the equivalent impedance of the moving mode system. $Z^*(s)$ is the virtual impedance of the modular multilevel converter added in the proposed algorithm. It is the key to the success of the algorithm to match the impedance value accurately.

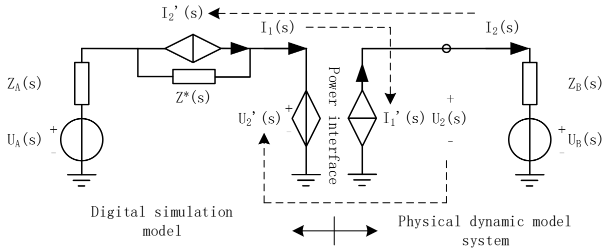

Figure 2. Diagram of power interface algorithm

In each step:1) The port voltage $U_2(s)$ and port current $I_2(s)$ of the converter are measured through a voltage and current transformer and fed back to the digital real-time simulator. 2) calculate the converter port current $I_1(s)$ according to the real-time simulation model including the power interface model, and output it through the power amplifier. For the side of the digital model, according to the circuit theorem, the following calculation formula can be obtained.

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$$\begin{cases} U_A(s) = U_1(s) + I_1(s)Z_A(s) \\ U_1(s) = U_2^{'}(s) + (I_1(s) - I_2^{'}(s))Z^{*}(s) \end{cases} \tag{1}$$

Where U2 '(s) and I2' (s) represent the measured value, and the measurement delay is ignored, and the following equation can be obtained:

$$\begin{cases} U_2^{'}(s) = U_2(s) \\ I_2^{'}(s) = I_2(s) \end{cases} \tag{2}$$

For the Physical dynamic model system, the following calculation formula can be obtained according to the circuit theorem:

$$\begin{cases} U_2(s) = U_B(s) + I_2(s)Z_B(s) \\ I_2(s) = I_1(s)e^{-sT} \end{cases} \tag{3}$$

Where T is the output response time constant of the power interface。In the hybrid system，Set $U_B(s)$=0，Due to the (1-3), The transfer function of network voltage to converter port voltage can be obtained as follows:

$$\frac{U_2(s)}{U_A(s)} = \frac{\dfrac{Z_B(s)}{Z_A(s)+Z^*(s)}e^{-sT}}{1+\dfrac{Z_B(s)-Z^*(s)}{Z_B(s)+Z^*(s)}e^{-sT}} \tag{4}$$

Therefore, Open loop transfer function:

$$G(s) = \frac{Z_B(s)-Z^*(s)}{Z_B(s)+Z^*(s)} \tag{5}$$

According to Nyquist stability criterion, the stability condition of the hybrid simulation system is:

$$\left|\frac{Z_B(s)-Z^*(s)}{Z_B(s)+Z^*(s)}\right| < 1 \tag{6}$$

In particular, when $Z^*(s)=Z_B(s)$, that is, when the virtual impedance of the modularized multilevel converter is equal to the equivalent internal resistance of the modularized multilevel converter's dynamic mode, G(s)=0, the hybrid simulation system is stable, and the accuracy of the simulation system is not affected by power amplifier delay and noise.

From the above derivation, it can be seen that the key to improve the stability and accuracy of power interface is to accurately match virtual impedance.

4. MMC power interface impedance matching

Figure 3 is a schematic diagram of a three-phase modular multilevel converter. It includes one converter transformer and six arms, each of which is composed of N submodules in series. In the figure, the circuit topology of the common semi-bridge submodule is also given, and the capacitance of each submodule is C.

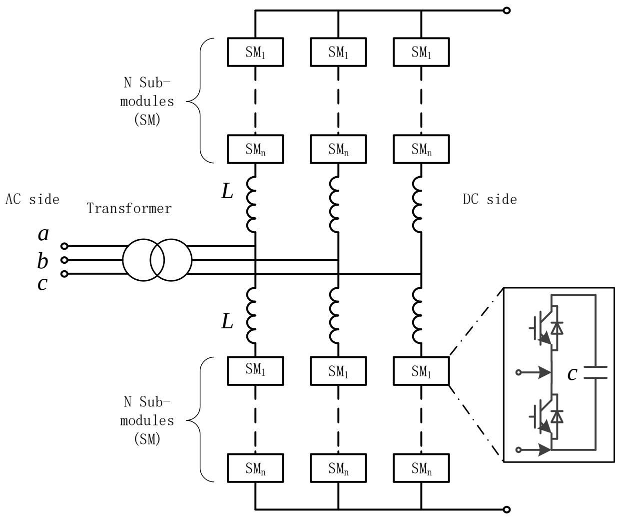

Figure 3. Diagram of a modular multi-level converter

For ac side, the impedance of upper and lower bridge arms of the same phase is a parallel relationship, so the equivalent inductance of a phase loop is:

$$L_x = L_T + L/2 \qquad x=a,b,c \tag{7}$$

LT is the transformer leakage inductance, L is the bridge arm inductance。

When MMC is working, sub-modules of upper and lower bridge arms are input alternately. If at a certain moment, the input number of upper bridge arms of a certain phase is N_{px}, and the input number of lower bridge arms is N_{px}, then the equivalent capacitance of a phase loop is:

$$C_x = \left(\frac{1}{N_{px}} + \frac{1}{N_{nx}} \right) C \qquad x=a,b,c \tag{8}$$

Generally, there are:

$$N_{px} + N_{nx} = N \tag{9}$$

When MMC is blocked, all submodules are removed, that is, the number of inputs is 0, and the equivalent capacitance is infinite.

In addition, the switch device IGBT's on and off resistance has typical values of 10^{-2} and 10^{6} Ω level, thus the conduction resistance can be ignored and resistance is infinite when turned off。

In conclusion, the accurate matching value of MMC's virtual impedance can be obtained through feedback of its working state, namely:

1)normal work:

$$Z^*(s) = sL_x + \frac{1}{sC_x} \tag{10}$$

2)Blocking state:

$$Z^*(s) = sL_x \tag{11}$$

5. Simulation

In order to verify the effectiveness of the proposed power interface algorithm, a simulation system of wind farm connected to the grid through flexible and straight is established in MATLAB, as shown in Figure 4. The wind farm adopts the lumped model, that is, one asynchronous machine is used instead of the whole wind farm, and the wind farm adopts the constant speed control mode; MMC adopts the efficient model based on the Davinan's theorem, the DC side is connected with the constant DC source, the AC side is controlled by the direct voltage, and the amplitude and phase of the voltage of the PCC are stabilized.

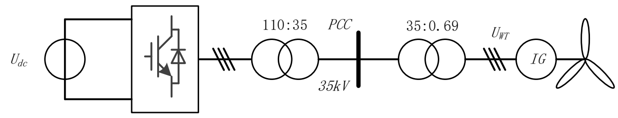

Figure 4. Wind power with MMC simulation system

The main parameters of the simulation system are shown in Table 1

Tab.1 Parameters of the simulation system

MMC rated power	200MW	rated DC voltage	200kV
Number of MMC modules	110	MMC module capacitance	50mF
MMC arm inductance	100mH	PCC rated voltage	35kV
Rated frequency	50Hz	rated voltage of DG	690V
Number of poles	2	rated speed	1600 rpm

The PCC point is used as the power interface partition point, and the delay (DT) is added to simulate the impact of power interface, and the validity of the interface algorithm is verified. Among them, when t = 0.6s, the wind speed steps to the rated value, and the wind power starts to rise; when t = [0.8 0.82] s, the PCC point has two-phase phase short circuit fault. The simulation results are shown in Figure 5 and Figure 6.

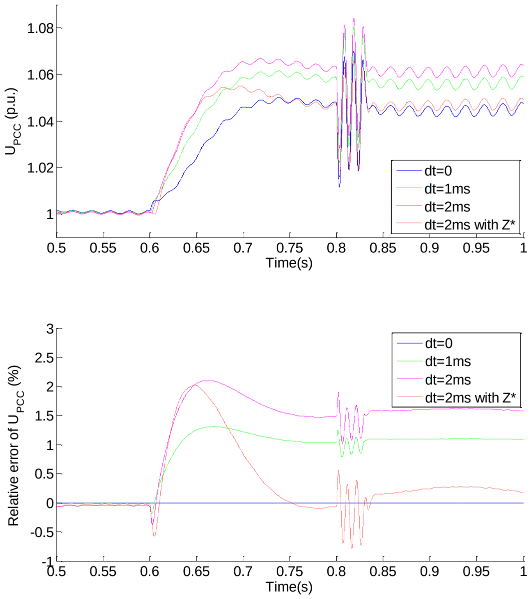

Figure 5. Simulation results of UPCC

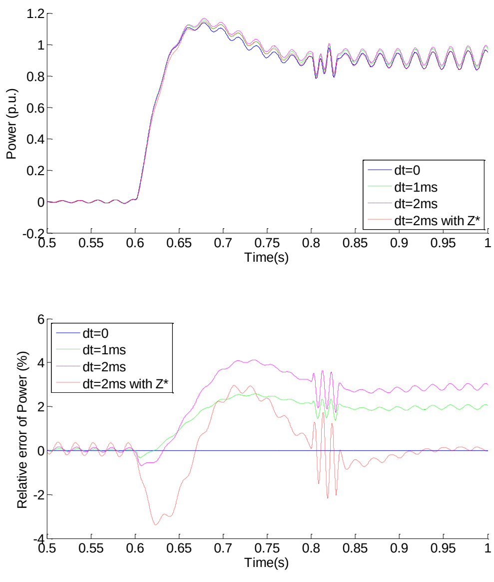

Figure 6. Simulation results of Power at PCC

It can be seen from the simulation results that with the increase of interface delay DT, the simulation error increases gradually (relative to the case of DT = 0). In the case of the same interface delay (DT = 2ms), the virtual impedance compensation can effectively reduce the simulation error, in which the maximum error of the parallel point voltage is less than 2%, and the steady-state error is reduced from about 1.6% to about 0.25%; the maximum error of the parallel point power is less than 3%, and the steady-state error is reduced from about 3% to about 0.25%.

In the period of asymmetric fault, the second harmonic appears in the voltage and power. The virtual impedance compensation is also helpful to improve the simulation accuracy of the transient process.

6. Test verification

Based on RT-LAB and MMC dynamic model test system, a validation test system of power interface algorithm is built, and the test system is shown in Figure 7. RT-LAB simulates the wind turbine, measures the grid connected current at PCC point, and injects it into MMC dynamic model system through power amplifier. MMC dynamic model system simulates the converter station at the side of the wind farm to control the AC voltage of the parallel grid point of the wind farm.

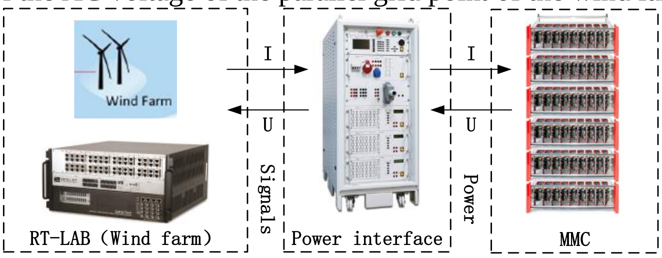

Figure 7. Test bench of Power Interface

In the test system, each arm of MMC is built with 30 module building block type test modules. The voltage of each module is 40V, so the rated AC voltage is 1.2KV. In order to adapt to the lower shunt voltage, it is necessary to convert the parameters of the wind turbine in Table 1 accordingly.

The start-up process of the test system is shown in Figure 8, in which the MMC adopts carrier phase-shift control with carrier frequency of 600Hz. It can be seen that MMC can stably control the voltage of parallel nodes.

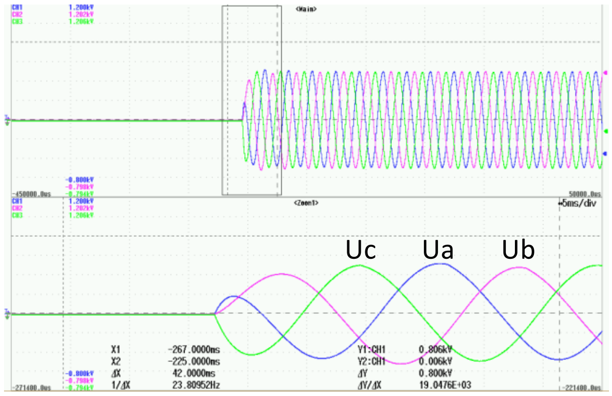

Figure 8. Test of system start

Figure 9 shows the PCC voltage waveform when the wind farm (single equivalent unit) is connected to the grid. It can be seen that after the wind power grid connected, the switching harmonic in the grid voltage has increased, but it is still basically stable.

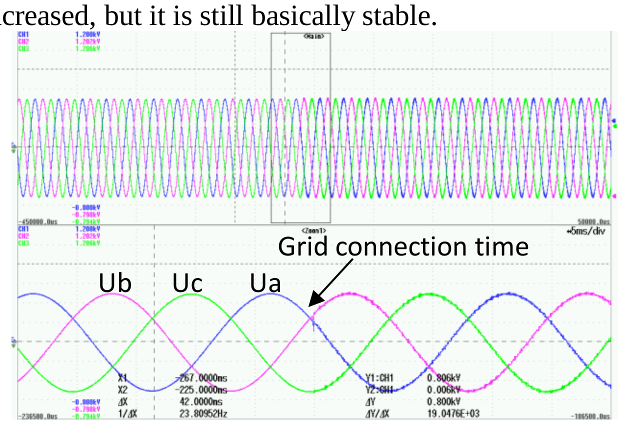

Figure 9. Test of wind power integration

Fig. 10 and Fig. 11 further compare the parallel dot voltage without or with increased virtual impedance compensation. It can be seen from Figure 10 that when there is no virtual impedance compensation, there is a certain ripple in the output voltage; when virtual impedance compensation is added, the voltage stability is enhanced, and the output voltage is smoother and more stable, as shown in Figure 11.

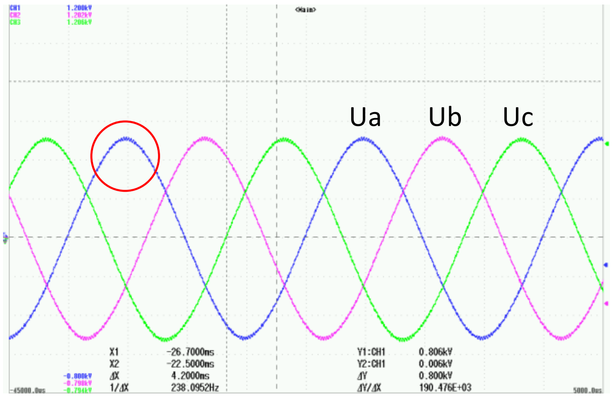

Figure 10. Voltage of PCC (without compensation)

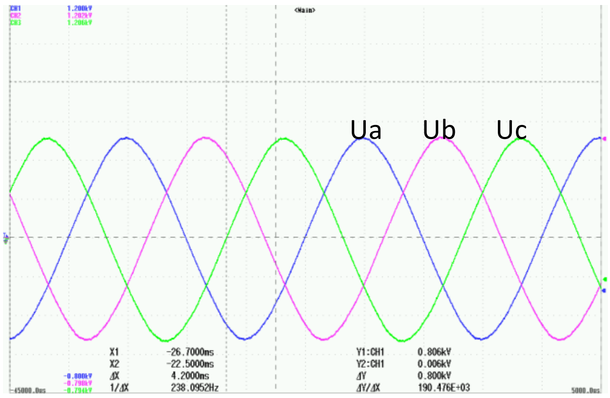

Figure 11. Voltage of PCC (with compensation)

7. Conclusion

Digital physical hybrid simulation is an efficient power system research method, which combines the advantages of digital simulation, such as safety, high efficiency and physical dynamic model accuracy. It is especially suitable for grid connected operation test of complex power electronic equipment such as modular multilevel converter.

In order to meet the need of the modularized multilevel converter connected to the wind farm and other islanding power grid operation modes, a current source type digital physical hybrid simulation interface algorithm is proposed, and the impedance matching is carried out according to the topological structure and working state of the modularized multilevel converter.

The simulation test shows that the hybrid simulation system maintains high stability under the system disturbance, in which the relative error of voltage at the interface is less than 2% and the relative error of active power is less than 3%. The dynamic model test further shows that the virtual impedance compensation can effectively eliminate the ripple in the voltage of the junction and improve the voltage stability. Therefore, the proposed power interface algorithm is suitable for islanding operation mode of modular multilevel converter, and has certain application value.

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