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Direct-drive wind energy application: research on a multilevel modular converter

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Abstract

Direct-drive wind power systems are the focus of this research, which analyses the Modular Multilevel Converter (MMC) in this context. A technique of control is described, and it is applied to a real-world wind power producing system. The AC side frequency may vary across a wider range, and it works with a wide variety of voltage settings. Capacitance parameter determination for modules is also planned. PSCAD/EMTDC is used to model the converter, and the results of these simulations verify the accuracy and viability of the proposed control strategy.

Keyword:

Using a direct-drive wind power system, a modular multilayer converter, and a simulation

Introduction

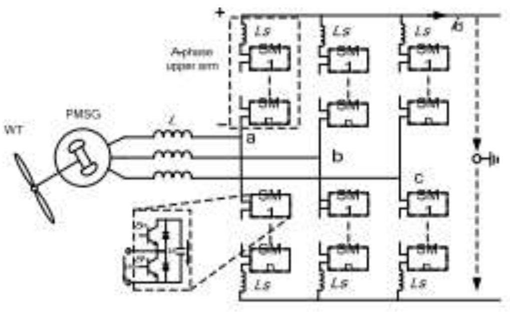
Since the gearbox and field winding are not required, direct drive wind power systems have a straightforward design, are straightforward to maintain, and may be connected directly with DC characteristics. The multi-megawatt (MW) wind turbine system is now a prominent example [1,2]. Connecting a direct-drive wind power system to the grid necessitates the use of a full-power converter. There has not been a significant advancement in the breakdown voltage of power switch components as of yet. Because of its many benefits, including reduced voltage stress on semiconductor switches and immunity to electromagnetic interference, the multi-level converter is well suited for direct drive wind power systems. The multilevel converters employed in the direct drive of wind power systems have been the subject of much study in recent years, both at home and abroad. Neutral -Point-Clamped Converter (NPC), Flying-Capacitor Converter (FCC), and Cascaded H-Bridges are three examples of multi-level converter topologies that have been explored extensively in recent years.

The modular MLC is a novel MLC design with many of the same benefits as conventional MLCs. Modular in nature, simpler in structure, scalable in terms of level, and quicker to install in engineering applications, it offers advantages over both NPC and FFC in terms of fault module inspection and replacement. Furthermore, when a modular multi-level converter is employed, the number of power switching devices does not scale up proportionally with the number of nonlinear growth levels. Modular multi-level converters provide several advantages over cascade H bridges, including reduced power switching device counts, bidirectional energy flow, and the elimination of the requirement for a large, separate DC power supply. Because of the various benefits offered by

the modular multi-level converter, the direct drive wind power system is likely to see widespread use.

Mmc's Basic Design and Working Principle

A. MMC's Basic Operating Theory Figure 1 shows the fundamental architecture of a modular multi-level converter-based permanent magnet direct drive wind power system[5,6,7].



ISSN NO: 0364-4308
Vol 13 Issue 01,JAN 2023

Figure 1. Direct-drive permanent magnetic wind power system based on MMC

The upper and lower arms of each phase of the converter include a current-limiting reactance and N submodules. Current-limiting reactance plays an important role: Firstly, DC voltage requires each phase cascade submodule voltage to support. But the capacitor voltage of each submodule has been in a change in the operation of the state. As a result, the change will lead to interphase circulation and phase circulation. while the current-limiting reactance is able to limit the circulation in a small phase range. Secondly when the converter internal or external malfunction happens, limiting reactance can limit short-circuit current rate. The converter includes a current-limiting reactance and N submodules. The upper and lower arm of the structure of submodule are shown in the enlarged part of the figure 1. Each submodule is consisted of two IGBT switches, two reverse diodes and a capacitor component. Through balance controlling of submodule capacitor voltage, the capacitor can be considered as an ideal voltage source, then each submodule of the input or removal is equivalent to a DC voltage source's input or removal. In order to prevent the direct short-circuit in submodule DC capacitor, the upper and lower semiconductor switches should work in complementary state, i.e. the upper and lower signals gh and gl have to meet gh+gl=1 and ghgl=0. There are two states existing in the working process of the converter submodules, and the relationship between output voltage and submodule capacitor voltage is v0=ghvdc as shown in Table 1. The submodule state can switch between s = 0 and s = 1 by controlling the IGBT state.

Tab. 1 Relationship between the different set of switching states and output of the submodule

Mode	g_h	g_l	v_0	i_m	v_{dc}
S=0	0	1	0	+	→
				-	
S=1	1	0	V_{dc}	+	↑
				-	↓

Transformer Type MMC

Figure 2 depicts the primary circuitry of an n-level converter. To guarantee stable operation, the converter must meet two constraints[5,6,7]: 1) The voltage waves in the submodule capacitor occur in a more compact region. Two) DC bus voltage stability. Voltage-balanced control is used to submodule capacitors to dampen voltage swings.While the stability of DC bus capacitor voltage ensures that the correct amount of power is flowing into or out of the DC capacitor. Furthermore, maintaining the same number of inputted submodules in each phase at all times is required to guarantee DC voltage stability; for example, when a submodule is inputted in the upper bridge arm, the one in the lower bridge arm should be withdrawn, and vice versa. Otherwise, it will lead to capacitor voltage swings and interphase circulation in the submodule[6].

Therefore, at any time it must be met(1):

$$\begin{cases} N_i = C_0 \\ N_{ih} + N_{il} = N_i \end{cases} \quad (i=a,b,c)$$

In the above formula: Ni represents the number of module which is required to be inputted in i-phase; Nih and Nil represent the number of module which is required to be inputted in the upper or lower arm of i-phase; C0 is a constant. It's can be seen from (1), when the number of submodules which is required to be inputted in upper arm is got, the number of lower arm can be known.

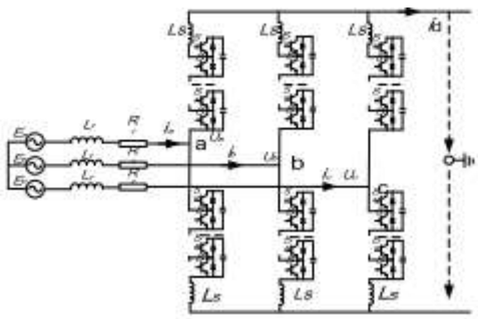


Figure 2. Diagram of n-level modular converter

For the reason of symmetry of the three-phase, a-phase is used as an example. List KVL equations according to upper and lower bridge arm and DC bus capacitor circuit of a-phase, the conclusion is as follows.

$$u_{dc} = N_a v_0 + L_s \frac{d(i_{ah} + i_{al})}{dt}$$

In the above formula: udc is the DC voltage of converter; Ls is the current-limiting reactance, iah is the upper bridge arm current of a-phrase, ial is the lower bridge arm current of a-phase. List KVL equations according to upper and lower bridge arm and DC circuit of a-phase and then simplify them. After that expression of AC side voltage in a-phase converter can be shown as follows:

$$u_a = \frac{(N_{al} - N_{ah})v_0}{2} - L_s \frac{di_a}{dt}$$

When the converter are operating steadily, the fluctuations of DC bus voltage and the voltage drop on current-limiting reactance can be ignored, and the error caused by them can be adjusted by the closed-loop link of control system. At this time (3) can be reduced to:

$$\begin{cases} u_{dc} = N_a v_0 \\ u_a = \dfrac{u_{dc}}{2} - n_{ah} v_0 \end{cases}$$

The converter is connected directly with the permanent magnet wind-driven generator instead of going through a transformer. And the relationship between the positive pole voltage of DC bus and the state of three-phase module are:

$$v_{dh} = \frac{(N_{ah} + N_{bh} + N_{ch})v_0}{2}$$

As a conclusion the relationship between the phase voltage of converter AC side and per arm submodule state is as shown in (6):

$$\begin{bmatrix} N_{ah} \\ N_{bh} \\ N_{ch} \end{bmatrix} = \begin{bmatrix} -1 & 0 & 1/2 \\ 0 & -1 & 1/2 \\ 1 & 1 & 1/2 \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \frac{1}{v_0}$$

It is can be seen from the above equation, when the converter runs, reference voltage of each phase on converter AC side can be obtained from the Operation Control System. And it's very simple to get the number of modules on the arm of each phase from (6). The number of lower bridge arms can be shown from the number of upper bridge arms and their constraints.

Design

The Parameter Of Submodule Capacitor In the modular converter, capacitor is an important factor which determines the total cost and the area size. The design of capacitor parameter reasonable or not has a directly effect on the economy and performance of the converter. Based on capacitive voltage periodic control [6,7], the method of confirming capacitance is designed. From the topology of MMC, each phase has a strict symmetry and shares the same DC bus voltage and impedance. Three-phase power is divided equally by the three arms. Similarly, because of the symmetry of MMC, the phase current is divided equally between the upper and lower arm. The voltage and current expressions of upper arm in a-phase can be shown as:

ISSN NO: 0364-4308
Vol 13 Issue 01,JAN 2023

$$\begin{cases} v_{ah} = \frac{1}{2}v_{dc} - v_a = \frac{1}{2}v_d - \sqrt{2}V_m \sin \omega t \\ i_{ah} = \frac{1}{3}i_d + \frac{1}{2}i_a = \frac{1}{3}i_d + \frac{\sqrt{2}}{2}I_m \sin(\omega t - \varphi_0) \end{cases}$$

In the above formula: vah represents the voltage of a-phase upper arm; iah is the current of a-phase upper arm; vdc is the DC bus voltage, id is the DC bus current, Vm and Im are the RMS of voltage and current in a-phase AC side of the converter, w stands for angular frequency of AC system and ij0 is the initial phase of the current in a-phase. There is instantaneous power flowing in the upper arm of a-phase, and it can be expressed as formula (8):

$$\begin{aligned} p &= v_{ah} i_{ah} \\ &= \frac{1}{6} v_d i_d [1 - k_v \sin \omega t] * [1 + m_i \sin(\omega t - \varphi_0)] \\ &= \frac{1}{6} v_d i_d [(1 - \frac{1}{2} k_v m_i \cos \varphi_0) + \\ & A * \sin(\omega t + \varphi_1) - \frac{1}{2} k_v m_i \cos 2\omega t] \end{aligned}$$

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In the above formula: $k_v = \frac{\sqrt{2}v_m}{v_{dc}/2}$ stands for Voltage modulation ratio, $m_i = \frac{\sqrt{2}i_m/2}{i_d/3}$ is the current modulation ratio. $A = \sqrt{(m_i \cos\varphi_0 - k_v)^2 + (m_i \sin\varphi_0)^2}$, $\varphi_1 = \arctan \frac{m_i \sin\varphi_0}{m_i \cos\varphi_0 - k}$

Known from (8), the current of upper arm of a-phase is made from DC component, fundamental

frequency component and 2 times frequency components. When the current of upper arm is much larger than zero in every exchange cycle, the capacitance of it is in the state of charge and corresponding time bucket is kT+t1~kT+t2. So, the largest energy fluctuations of the capacitance in one exchange cycle can be expressed as (9).

$$\Delta w = \int_{kT+t_1}^{kT+t_2} p(\omega\tau) d\tau$$

In one AC cycles, the voltages of the capacitor can be expressed by (10), at the beginning and ending time of the capacitor charging.

$$\begin{cases} v(kT + t_1) = (1 - \xi)v_s \\ v(kT + t_2) = (1 + \xi)v_s \end{cases}$$

In the above formula:[stands for coefficient of Capacitor voltage fluctuation, vs=kmv0, km represents the deviation coefficient of Capacitor voltage and kmĬ1, so the energy fluctuations in each capacitor can be expressed as:

$$\begin{aligned} \Delta w_{per} &= \frac{1}{2} c_0 v(t_0 + T_c)^2 - \frac{1}{2} c_0 v(t_0)^2 \\ &= \frac{1}{2} c_0 [(1+\xi)v_s + (1-\xi)v_s][(1+\xi)v_s - (1-\xi)v_s] \\ &= 2c_0 \xi v_s^2 \end{aligned}$$

For the AC cycle is much longer than capacitor balance cycle, energy fluctuations of per submodule is equivalent

ISSN NO: 0364-4308
Vol 13 Issue 01,JAN 2023

$$\Delta w = n_s \Delta w_{per}$$

after the charging of one AC cycle. And then the equation is got:

$$c_0 = \frac{V_d I_d}{3n_s k_v \omega \xi v_s^2 \cos\varphi}(1-(\frac{k_v \cos\varphi}{2})^2)^{\frac{3}{2}}$$

Converter Control System

Converter Pulse Width Control

The equivalent PWM waveform of voltage reference wave can be got from the AC side of the converter through coordinated controlling the switch capacity between the various submodules in the converter. Ignoring the pressure drop of current-limiting reactance in the converter, the voltage of converter AC side reference waveform can be expressed as:

$$u_{k,ref}(t) = \frac{u_{dc}}{2} - m\frac{u_{dc}}{2}\sin(\omega t + \varphi_0)$$

In the above formula:

$$m = \frac{u_a}{u_{dc}/2}\,(0<m<1),\ u_{dc}$$

is the DC voltage of converter, Ȧ is the angular frequency of AC system, ij0 is the initial phase angle? The timeline was divided in accordance with the PWM control cycle, and then the average of reference voltage in each control cycle is obtained according to the equivalence principle as [6]:

$$\begin{aligned} v_{k,av} &= \frac{1}{t_b - t_a}\int_{t_a}^{t_b} u_{k,ref}(\tau)d\tau \\ &= \frac{u_{dc}}{2} - m\frac{u_{dc}}{2}(\frac{\cos(\omega t_b + \varphi_0) - \cos(\omega t_a + \varphi_0)}{\omega(t_b - t_a)}) \end{aligned}$$

In the above formula: vk,av is the average of reference voltage of k-phase in a PWM control cycle.

$$N_{kl} = \mathrm{int}(\frac{v_{k,av}}{v_0})$$

$$N_{kh} = N_{kl} + 1$$

int(x) is the integral function, in every PWM control cycle (Tc), the equivalent of Nk,av can be expressed as Nkl and Nkh. Nkl and Nkh in each control cycle time can be got according to the following formula

$$D_k T_c N_{kl} + (1 - D_k)T_c N_{kh} = T_c N_{k,av}$$

The formulation was as follows after reduction:

$$D_k = \frac{N_{k,av} - N_{kh}}{N_{kl} - N_{kh}}.$$

Conversion System Analysis

ISSN NO: 0364-4308
Vol 13 Issue 01,JAN 2023

The direct-drive wind power system implemented in PSCAD/EMTDC makes use of a three-level modular multilevel converter. The permanent magnet generator is equivalent to the regulated voltage and frequency voltage source. We use the following values for the grid voltage (ul), DC-link voltage (udc), submodule DC reference voltage (v0), line equivalent reactance (L), line equivalent resistance (R), current limiter reactance (Ls), submodule capacitance (C0), switching frequency (f), and balance cycle of capacitance (Tc) in our simulation system.

From t=0 to t=1s, the reference active power of the transmission system is Pref=0.4MW, the corresponding source line voltage is ul=690v, and the frequency is f=35 Hz. Equivalent source line voltage is ul=900v, f=45 Hz, and Pref=1.4MW when the simulation duration is greater than 2s. The simulation always uses Qref=0 for the reference reactive power. The simulation results are shown in Fig.5–10.

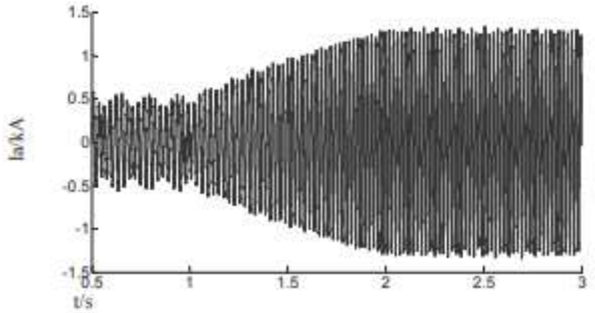

Figure 3. Waveform of phase current ia of converter

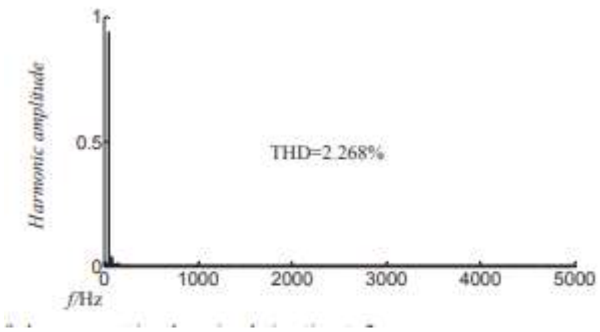

Figure 4. Harmonic spectrum of phase current ia when simulation time t>2s

Figure 3 shows current simulation result of a-phase waveform of ac output current of modular multilevel converter. Figure 4 gives the FFT analysis the current of a-phase when simulation time is t>2s. The simulation results have low sinusoidal distortion figure 4 shows current simulation result of a-phase waveform of ac output current of modular multilevel converter, figure 6 gives the FFT analysis the current of a-phase when simulation time is t>2s. The simulation results have low sinusoidal distortion and THD=2.268%.

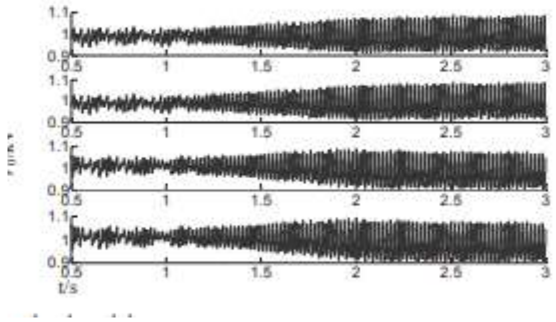

Figure 5. Capacitor voltages of each submodule

Figure 5 shows simulation results of capacitor voltages of each submodule of a-phase. From the result, we can see that voltage fluctuating is less than ±10%, voltage fluctuating increase with the transmission .

ISSN NO: 0364-4308
Vol 13 Issue 01,JAN 2023

power rising. All the modules capacitor voltage balance has been effectively controlled.

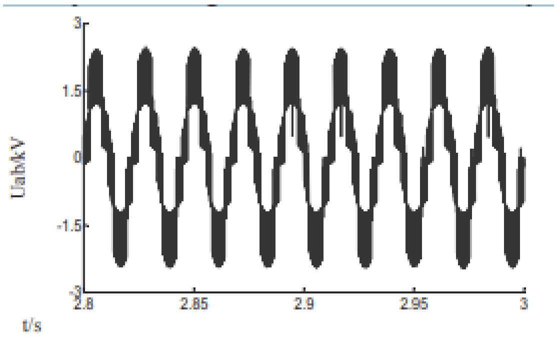

Figure 6. Output line-to-line voltage uab of the converter

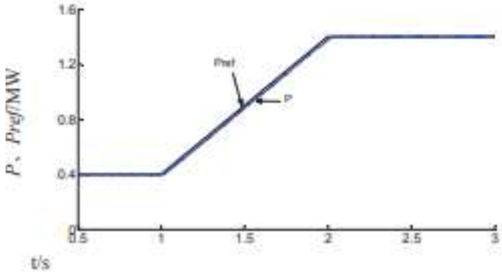

Figure 7. Active power of converter

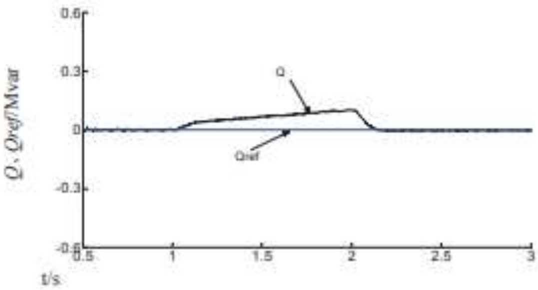

Figure 8. Reactive power of converter

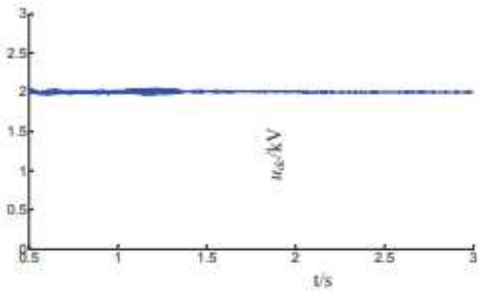

Figure 9. Voltage of DC -bus

The uab waveform of the line voltage at the AC output of the converter is seen in Figure 9. The voltage stress on the IGBT is successfully reduced, and the 5-level waveform is very similar to a sine wave. Figure 8 depicts the simulated active and reactive reference process, while Figure 9 depicts the simulated measured value waveform. The quick reaction time of the dynamic response is less than 0.1s with minor overshoot, and then there is no static error in the steady-state operation, as shown by the active power from the simulation results. The simulation results showed that the reactive power fluctuated when the reference power was altered. When the system is in a stable state, it is free of static faults. In order to function, modular multilevel converters need a power factor of 1, and DC-bus voltage fluctuations of less than 5%.

Conclusion

This study defines a direct drive wind power system appropriate for a modular three-level PWM converter model, performs an in-depth analysis of the operational principle of the modular converter, develops a converter control strategy, and derives a pulse width modulation algorithm. The PI controller was included into the operational control system due to its ability to apply a basic control mechanism with little effort. This paper employs the PSCAD/EMTDC simulation platform to construct a modular three-level converter, the results of which demonstrate the three-level converter's ability to alleviate strain on voltage switching device stands, cut down on harmonic current content, boost power factor conversion, and keep up with system dynamics. The simulation results validate the validity of the algorithms used by the PWM converter system and the effective controllability of the approach of voltage balancing across the submodule capacitors.

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