HYBRID MODULAR MULTILEVEL CONVERTER FOR VECTOR-CONTROLLED INDUCTION MOTOR DRIVE

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Abstract: Application of traditional modular multilevel converter (MMC) for medium voltage induction motor drive is difficult especially at low frequencies of drive due to large peak to peak ripple of sub-module (SM) capacitor voltage. In this paper, a hybrid MMC is used to obtain lower peak-to-peak capacitor voltage ripple, specifically at low motor speed. Field oriented control strategy for induction motor created on closed-loop speed controller is suggested to have an accurate and wide speed range of speed. The Matlab/Simulink is used for simulation, the simulation results of induction motor drive with hybrid and traditional MMC are obtained and compared from the point of view of capacitor voltage ripple. The results show the reduction voltage ripple of SM capacitor as the hybrid MMC is operated.

Keywords: medium voltage induction motor, Hybrid strategy, lower motor speed, voltage ripple of capacitor, field oriented vector control

1. Introduction

Modular multilevel converter (MMC) has got a lot of interest in high-power medium-voltage applications in the last years, due to their modularity, scalability, transformer-less operation, low harmonics, low expense of redundancy, high efficiency, low device switching frequency, reduce filter requirement and quality output waveforms, etc. [1-7]. There are four kinds of multilevel inverter topologies:

cascade H-bridge (CHB), flying capacitor (FC), neutral point clamped (NPC), and modular multilevel converter [8]. As shown in "Fig. 1", the MMC is consisted of Series connection of sub-modules making the arm of the converter to build the output voltage stepwise.

Figure 1. MMC circuit configuration in variable speed drives [8].

Due to the simple structure and modular construction, MMC has used with medium voltage and high-power variable speed drives as a viable solution in recent years. However, the biggest problem for MMC drives is that the SM capacitor voltage ripple peak-to-peak value increases with constant load at low speeds, so it

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is especially challenging for MMC to drive the motor at constant torque at low speeds [9]. The MMC is acceptable to the load torque that is compatible with a square with rotational speeds such as pumps and fans [10]. In order to overcome motor static frictions a high starting torque is needed. Therefore, steps are necessary to minimize the SM capacitor peak-to-peak voltage ripples to provide appropriate torque at low speed ranges. The most efficient method to minimize the capacitor voltage ripple peak-to-peak at the moment is injection of high frequency circulating current through MMC arms, in comparison with the same frequency common-mode voltage on the three phase ac terminals [11-20]. It is possible to charge and discharge the SM capacitors continuously to minimize the peak-to-peak voltage ripple due to a high frequency power transfer between the MMC arms, this caused by the injected voltage and current. Sinusoidal circulating current and common-mode voltage are injected. While it is also possible to use the square wave-forms [16-19], or the Coordination of the third-order current harmonic [20] to minimize the magnitude of the circulating current to minimize losses. But these methods have disadvantages and the following limitations:

- It is so difficult to control and inclusion of the injected common-mode voltage and circulating current waveforms, and the control loops of the MMC (like the voltage balancing and the output current control [10]) can conflict, this causes problems of instability, particularly at transient operations.
- The MMC arms are injected with high values of circulating current, which increases both load current and power losses significantly, thus higher cooling requirements are necessary.

This paper suggests a hybrid MMC strategy that connects between the DC-link and the traditional

MMC by adding a series switch between them, to reduce the above limits of the traditional MMC in variable-speed drive applications. Due to this strategy, the peak-to-peak capacitor voltage ripple can be minimized, especially at low frequencies, this major advantage of hybrid MMC. In addition, the common-mode voltage does not apply on the motor terminals. As well as the load current that remains with the rated value for the entire speed range. So, the suggested hybrid MMC is suitable for variable-speed drive applications. In this paper, the hybrid MMC is used to drive the medium voltage induction motor. Field oriented vector control strategy for induction motor is suggested to get precise speed control. Lower peak-to-peak ripple of (SM) capacitor voltage is noted when hybrid MMC is used compared with traditional MMC.

2. The Hybrid MMC: Analysis And Operation

2.1. The Hybrid MMC Strategy

The suggested hybrid MMC circuit configuration as shown in "Fig. 2". A series switch S_S is added between the dc voltage source and MMC converter. This series switch can be used to connect or disconnect the MMC converter from dc source. As this series switch can be used either IGBT or thyristor. In addition, it is necessary to filter the harmonics of the voltage switching, therefor an RC snubber circuit is required [21]. Two grounding resistors R_g for grounding the converter.

Figure 2. Hybrid MMC circuit configuration in variable speed drives [8].

The voltage relationships exist under Kirchhoff's Voltage Law:

$$u_o = \frac{1}{2} \left(u_l - u_u - L \frac{di_o}{dt} \right) \quad (1)$$

$$u_d = u_l + u_u + 2L \frac{di_c}{dt} \quad (2)$$

Where i_c is the circulating current per phase. It can be calculated by:

$$i_c = \frac{1}{2} (i_u + i_l) \quad (3)$$

By summation of the circulating current in each phase the dc current i_{dc} can be calculated. The ac output current i_o of MMC would be split equally between these two arms and the arm currents can be written as:

$$\begin{cases} i_u = i_c + (1/2) i_o \\ i_l = i_c - (1/2) i_o \end{cases} \quad (4)$$

The ac output voltage and current can be expressed as:

$$u_o = U_{OM} \cos(\omega t)$$

$$i_o = I_{OM} \cos(\omega t - \varphi) \quad (5)$$

Where U_{OM} and I_{OM} are the amplitudes, φ is the phase lag angle. ω is the angular frequency, and the amplitude of the output voltage U_{OM} can be written as:

$$U_{OM} = \frac{1}{2} m U_{dc} \quad (6)$$

Where m represents the modulation index adjusting between 0 to 1. If the converter is used in variable-speed drives, thus a constant Volt/Hertz ratio must be achieved. If the motor operates at rated speed ω_{rated} , $m = 1$, an adjustable motor speed modulation index can be determined as:

$$m = \frac{\omega}{\omega_{rated}} \quad (7)$$

The operating of hybrid MMC is same as the traditional MMC when the series switch S_s is

closed, u_d equals U_{dc} . The average voltages of the arm can be estimated by:

$$\begin{aligned} u_u &= \frac{1}{2} U_{dc} (1 - m \cos(\omega t)) \\ u_l &= \frac{1}{2} U_{dc} (1 + m \cos(\omega t)) \end{aligned} \quad (8)$$

"Fig. 3", clarifies the traditional MMC main waveforms with suitable harmonic minimization control [22], i_c and i_{dc} are dc currents, with the magnitudes of $I_{dc}/3$ and I_{dc} , respectively. Based on the power balance between input dc and output ac (i.e., $U_{dc} I_{dc} = \frac{3}{2} U_{OM} I_{OM} \cos \varphi$), I_{dc} can be expressed as:

$$I_{dc} = \frac{3}{4} m I_{OM} \cos \varphi \quad (9)$$

When ($m = 1$) the motor at rated speed with rated output current then "(9)" can be written as:

$$I_{dc(rated)} = \frac{3}{4} I_{OM(rated)} \cos \varphi \quad (10)$$

Figure 3. Sketch map of traditional MMC operating waveforms.

2.2. Operation Principle of Hybrid MMC

As shown in "Fig. 4", the series switch S_s operates at switching frequency of f_h ($f_h = 1/T_h$) with duty cycle D , the currents i_{dc} and i_c are written as:

$$I_{dc} = \begin{cases} I_{dc(rated)}, & \text{if } (S_s = 1) \\ 0, & \text{if } (S_s = 0) \end{cases} \text{ and } i_c = \frac{1}{3} i_{dc} \quad (11)$$

Based on "(6)", u_d can then be represented as:

$$u_d = \begin{cases} U_{dc}, & \text{if } (S_s = 1) \\ m U_{dc}, & \text{if } (S_s = 0) \end{cases} \quad (12)$$

And the average voltage of u_d is

$$\bar{U}_d = DU_{dc} + (1 - D)mU_{dc} \quad (13)$$

Figure 4. Schematic map of hybrid MMC operating waveforms.

The hybrid MMC arms voltages can expressed as:

$$\begin{cases} u_u = 1/2 u_d - 1/2 m U_{dc} \cos(\omega t) - \Delta u_d \\ u_l = 1/2 u_d + 1/2 m U_{dc} \cos(\omega t) - \Delta u_d \end{cases} \quad (14)$$

As comparing "(8)" with "(14)" the ac voltage component does not change at the arm voltage. Applied "(14)" into "(2)" to calculate Δu_d

$$L \frac{di_c}{dt} = \Delta u_d \quad (15)$$

Where Δu_d is used for controlling of the current circulating i_c . Despite of this current controllability, the S_s series switch will achieve zero-current switching. It is necessary to achieve the power balance in the hybrid MMC, which gives:

$$U_{dc} I_{dc(rated)} D = \frac{3}{2} U_{OM} I_{OM} \cos \varphi \quad (16)$$

If the motor operates at rated of speed power then D is equal 1, but other speeds D can be written as:

$$D = \frac{m I_{OM}}{I_{OM(rated)}} \quad (17)$$

If a constant load is applied at the motor then ($I_{OM} = I_{OM(rated)}$). So "(17)" can be simplified to

$$D = m \quad (18)$$

The peak-to-peak value of the capacitor voltage of the hybrid MMC in [8] can be expressed as:

$$\Delta U_{C(pp)} = \left(2 - \frac{\omega}{\omega_{rated}}\right) \frac{I_{OM(rated)}}{2\omega_{rated}C} \quad (19)$$

Where C represents capacitance value of SM. Thus, the traditional MMC peak-to-peak capacitor voltage ripple can be obtained by [19]:

$$\Delta U_{C(pp)} = \frac{I_{OM}}{2\omega C} \quad (20)$$

3. Control Scheme

The control scheme is suitable for the suggested hybrid MMC to fed the drive the motor based on Field-oriented control (FOC), can be divided into four main blocks, (A) the series switch control block, (B) the energy balancing control block and (C) Induction motor FOC block (D) the phase-shifted carrier PWM(PSC-PWM). The overall diagram of the control system is shown in "Fig. 5", [23].

Figure 5. The overall diagram of the control system [23].

3.1. Series switch control block:

Series switch control block is shown in "Fig. 6", this block used to adjust the duty cycle D ($D = 0 \sim 1$) to achieve the balancing of power between the input dc and output ac by using PI controller. When the balance is obtained, the nominal voltage must be equal to U_{dc}/N for all SM capacitors in each phase. The frequency of the carrier f_h is 10 times of the output frequency f_o , and the generated duty cycle signal S_{gate} is

applied to the energy balancing control block and the series switch [23].

Figure 6. The series switch control [23].

3.2. Energy balancing control block:

The energy balancing control is shown in "Fig. 7", a phase energy balance control is implemented in this block in order to ensure equal energy distribution in each phase. The average capacitor voltage of each phase $U_{C(avg-j)}$ must be equal to $U_{C(avg)}$ to obtain an adjusting component current ΔI_{cj} . This current is added with $1/3 I_{dc(rated)}$ to produce the I_{c-ref} . The duty cycle D is multiplied with I_{c-ref} to obtain the circulating current reference. The purpose of this process is to make the actual circulating current to track the I_{c-ref} . Thus, the controlled variable is Δu_d .

Figure 7. Circulating current control [8].

3.3. IM FOC BLOCK

Field-oriented control is a high-efficiency control strategy that similar to the DC machine speed control system [24]. As shown in Fig.8 the FOC block of IM include speed and torque controller loops. And they are applied in the $d-q$ coordinate system. The model equations are listed in [25]. Where i_q and i_d are the stator currents, and ω_r is the rotor frequency. ω_s and ψ_r are respectively

stator current frequency and rotor flux, and they can be determined as:

$$\psi_r = \frac{L_m}{T_r p + 1} i_d \quad (21)$$

$$\omega_{sl} = \frac{L_m i_q}{T_r \psi_r} \quad (22)$$

$$\theta = \int \omega_s dt \quad (23)$$

Where L_m is the mutual inductance between the stator and rotor, T_r is the time constant ($T_r = L_r/R_r$), L_r and R_r are the rotor inductance and the rotor resistance respectively, p is the differential operator and θ is the rotor angle. FOC of IM block include of four controller loops: flux controller loop to obtain i_d^* , i_d controller loop that is useful to control the excitation of motor, speed controller loop to obtain i_q^* and i_q controller loop is compatible with the output torque.

Figure 8. IM FOC block [26].

Finally, references u_{uj}^* and u_{lj}^* in "Fig. 5", are applied to the phase-shifted carrier PWM (PSC-PWM) to build the output voltage stepwise [27]. Also, the other modulation strategies of the MMC are presented in [3]. The purpose of using phase-shifted carrier PWM (PSC-PWM) to improve the equivalent switching frequency and minimize the harmonics of output voltage.

4. Simulation And Results

In order to verify the efficiency of the suggested hybrid MMC-fed IM drive shown in "Fig. 9", a 4160V 1MW hybrid MMC is simulated by using the MATLAB /Simulink software 2018. The hybrid MMC is implemented with twenty sub-modules (SMs) per phase. The parameters of the hybrid MMC and IM are listed in "Table 1". The suggested hybrid MMC is simulated in three states in order to show the difference reduction of the peak-to-peak SM capacitor voltage ripple between the traditional MMC and suggested hybrid MMC with variable-speed motor drive. The first state is performed at full speed and constant applied load torque, the second state is performed at constant applied load torque at medium speed with traditional MMC and hybrid MMC, and the final state is performed at low

speed with traditional MMC and hybrid MMC at constant applied load torque.

The simulation model of hybrid MMC is shown below.

Figure 9. The simulation model of hybrid MMC.

State 1:

In this state proposed hybrid MMC is operated as a traditional MMC, the IM is operated with rated speed of 1200 rpm and the load torque increases from zero to 7490N·m at time of 2 second from instant of starting. "Fig. 10 (a) ", and "Fig. 10 (b) ", shows the load torque of the motor and the applied load. The motor torque has above of 2000 N·m to overcome the moment of inertia of the motor. As it can be shown in the "Fig. 10 (c) ", the stator currents increase to its rated value of 212A when the motor load torque rises to its rated value of 7490N·m, and the nominal capacitor voltages u_{CAu} u_{CAI} value of 700V with a peak-to-peak ripple of 35V the capacitor voltage ripple is increase to 55V due to increase the output current as shown in "Fig. 10 (d) ". The controller modifies the magnetic current i_d , while the current i_q , component tunes the load torque and has an equal to applied load torque value as shown in "Fig. 10 (e) ". The output voltage of the converter keeps at a rated frequency to set the motor desired speed as shown in "Fig. 10 (f) ".

Table 1. Parameters of drive system

Hybrid MMC parameters	
Parameters	Value
Number of SMs per arm N	10
DC-source voltage U_{dc}	7kV
Nominal SM capacitor voltage U_C	700V
SM capacitance C_{SM}	4000 μ F
Arm inductance L	1mH
Rated output frequency $f_{o(rated)}$	60Hz
Rated phase current I_{OM}	212A
PSC-PWM frequency f_c	1kHz
S_s switching frequency f_h	$10 \times f_o$
Snubber resistance	200 Ω
Snubber capacitance	1 μ F
IM parameters	
Parameters	Value
Rated active power P_s	1250hp
Number of pole pairs pp	3
Rated speed ω_r	1200 rpm
Rated line-to-line voltage U_{rated}	4160V
Stator rms current I_s	150A
Power factor $\cos \varphi$	0.968
Mechanical load torque T_{rated}	7490N·m
Stator Flux linkage ψ_s	9Wb
Rotor Flux linkage ψ_r	8.35Wb
Stator resistance R_s	0.21 Ω
Rotor resistance R_r	0.146 Ω
Stator leakage inductance L_{ls}	5.2mH
Rotor leakage inductance L_{lr}	5.2mH
Magnetizing Inductance L_m	155mH
Moment of Inertia J	47.6kg·m ²

Figure 10. Simulation results of traditional MMC to drive the IM at full speed of 1200 rpm with sudden load torque: (a) Motor speed; (b) load torque of the motor; (c) three-phase motor stator currents; (d) SM capacitor voltages per phase; (e) I_d , I_q current component of the motor; (f) output voltages of the converter.

State 2:

In this state the MMC is operated as a traditional MMC and a hybrid, the IM is operate with medium speed of 600 rpm and the load torque increases from zero to 7490N·m at 2 second from instant of starting. "Fig. 11 (a) ", and "Fig. 11 (b) ", shows a good speed and torque dynamic response when the applied load is changed. As it can be shown in the "Fig. 11 (c) ", that the stator currents are sinusoidal waveforms with high-quality with amplitude of 50A, and increase to its rated value of 212A when the motor load torque rises to its rated value of 7490N·m, and the nominal capacitor voltages u_{CAu} u_{CAL} of hybrid MMC with value of 700V with a peak-to-peak ripple of 35V and increased to 70V due to increase the output current as shown in "Fig. 11 (d) ". "Fig. 11 (e) ", shows that the nominal capacitor voltages u_{CAu} u_{CAL} of traditional MMC with value of 700V with a peak-to-peak ripple of 40V and increased to 180V due to increase the output current. The controller modifies the magnetic current i_d , while the current i_q component tunes the load torque and has an equal to applied load torque value as shown in "Fig. 11 (f) ". The output voltage of the converter keeps at frequency of 30Hz to set the motor desired speed as shown in "Fig. 11 (g) ".

Figure 11. Simulation results of hybrid MMC and traditional to drive the IM at medium speed of 600rpm with sudden load torque: (a) Motor speed; (b) load torque of the motor; (c) three-phase motor stator currents; (d) SM capacitor voltages per phase; (e) SM capacitor voltages per phase of traditional MMC; (f) I_d , I_q current component of the motor; (g) output voltages of the converter.

State 3:

In this state the MMC is operated as a traditional MMC and a hybrid, the IM is operate with low speed of 200 rpm and the load torque increases from zero to 7490N·m at 0.2 second from instant of starting. "Fig. 12 (a) ", and "Fig. 12 (b) ", shows a good speed and torque dynamic response when the applied load is changed. "Fig. 12 (c) ", shows the stator currents with high-quality sinusoidal waveforms at low frequency with amplitude of 50A, and increase to its rated value of 212A when the motor load torque rises to its rated value of 7490N·m. The nominal capacitor voltages u_{CAu} u_{CAI} of hybrid MMC with value of 700V with a peak-to-peak ripple of 180V due to increase the output current as shown in "Fig. 12 (d) ". "Fig. 12 (e) ", shows that the nominal

capacitor voltages u_{CAu} u_{CAI} of traditional MMC with value of 700V with a peak-to-peak ripple of 410V due to increase the output current. The controller modifies the magnetic current i_d , while the current i_q component tunes the load torque and has an equal to applied load torque value as shown in "Fig. 12 (f)". The output voltage of the converter keeps at frequency of 10Hz to set the motor desired speed as shown in "Fig. 12 (g)".

Figure 12. Simulation results of hybrid MMC and traditional to drive the IM at low speed of 200rpm with sudden load torque: (a) Motor speed; (b) load torque of the motor; (c) three-phase motor stator currents; (d) SM capacitor voltages per phase; (e) SM capacitor voltages per phase of traditional MMC; (f) I_d , I_q current component of the motor; (g) output voltages of the converter

Table 2. Peak-to-peak ripple of SM capacitor voltage

Speed (rpm)	Traditional MMC	Hybrid MMC
1200 rpm	55 V	55 V
600 rpm	180 V	70 V
200 rpm	410 V	180 V

Lower values of peak-to-peak ripple in SM capacitor voltage are noticed in hybrid MMC

compared with traditional MMC as shown in “Table 2”.

5. Conclusions

This paper suggested hybrid MMC to drive IM. Because of lower peak-to-peak capacitor voltage ripple at low frequency with constant load torque as seen in the simulation results, the suggested hybrid MMC is acceptable for variable-speed drives. This paper suggested a suitable control strategy that Proportional to the variable-speed motor drives. Also, the other advantages of this strategy are that it does not introduce higher switching losses and conduction; it can offer a protection to dc link from short circuit.

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Conflict of interest

The authors whose listed their names in this paper certify that they have no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

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