Design and Simulation of Modular Multilevel Converter Fed Induction Motor Drive
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ABSTRACT
Traditional modular multilevel converter (MMC) applications in medium voltage induction motor drive are difficult, particularly at low speeds because of the higher amplitude of the voltage ripple of the sub-module capacitor. This paper uses a hybrid MMC to achieve a lower peak-to-peak voltage ripple of the sub-module capacitor particularly at low frequencies. The vector control strategy with the closed-loop speed control is used to indicate an accurate and wide-speed range. MATLAB / Simulink is used to simulate and obtain the simulation results of hybrid and traditional MMC with induction motor drive and compare from the standpoint of capacitor voltage ripple. The results are shown the reduction of peak-to-peak voltage ripple of the sub-module capacitor as the hybrid MMC is operated.

1. INTRODUCTION
Multilevel converter topologies in the power electronic industries are generally accepted as one of the latest technological advances. One of its applications with variable speed motor drive due to its higher performance [1-2]. Therefore the modular multilevel converters in recent years are become efficient topology in high and medium-power applications because of their efficiency, modularity, low redundancy expense, scalability [3-6]. They have reshaped power transmission systems based high voltage source converters (VSC-HVDC) [7, 8], and are considered to be the key technology for developing successful DC Super Grids [9]. They are used in the medium-voltage motor drive applications in recent years [10-16]. MMC presents more advantages in relation to the three most widely used topologies [17, 18], namely flying capacitor (FC), neutral point clamping (NPC), and cascaded H Bridges (CHB) as shown in Figure 1 [19]. MMC has major advantages: it can easily increase the number of levels without increased control complexity or unequal distribution of losses and does not need costly and bulky isolation transformers.

Despite the advantages of the MMC, the peak-to-peak capacitor voltage ripple is one of the main problems that appeared in the variable speed drive applications, which must be taken into consideration. The peak-to-peak capacitor voltage ripple will increase when the motor operates at a low speed. This because that the capacitor voltage ripple is inversely proportional to the frequency and is proportional to the amplitude of the load current, and also the value of the sub-module (SM) capacitor should be taken into consideration [20]. Therefore it is difficult to drive the motor at low speeds with constant torque.

This paper suggests a hybrid topology by adding a controllable series switch that connects between the MMC and the DC bus voltage. The main advantage of this topology is to reduce the peak-to-peak voltage ripple of the SM capacitor, specifically at low motor speeds. In this paper, the hybrid MMC is used to drive a medium voltage induction motor, also the vector control strategy is used to get accurate speed control. Lower peak-to-peak voltage ripple of the SM capacitor can be observed when hybrid MMC is used compared with traditional MMC.

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2. THE HYBRID MMC: ANALYSIS AND OPERATION

Figure 2 shows the suggested hybrid MMC circuit diagram. A controllable series switch is applied between the MMC and the DC-bus voltage in order to minimize the average arm voltages of the MMC, leading to minimize capacitor voltage ripples [21]. The thyristor and IGBT can be used as this switch. In addition, a snubber circuit [22] is required to filter the harmonics of the switching voltage. The converter can be grounded to the earth by two grounding resistors $R_g$. The three-phase MMC circuit as well-known, each phase includes two arms (upper and lower) are attached by two buffer inductors $L$; each arm includes $N$ identical half bridge SMs which are connected in series to build the output voltage stepwise, and SM has a capacitor with average voltage of $U_{dc}/N$. The output voltage term is $u_{jo}$ in phase of $j$ ($j \in \{A,B,C\}$), the output current is $i_{jo}$, and the DC bus voltage is $U_{dc}$, and the MMC dc terminal voltage is $u_{dc}$, the upper and lower arm voltages are $u_{ju}$ and $u_{jl}$ respectively, the upper and lower arm currents are $i_{ju}$ and $i_{jl}$ respectively.

$$u_{jo} = U_{O} \cos(\omega t + \delta_j)$$
$$i_{jo} = I_{O} \cos(\omega t + \delta_j - \phi)$$

Where $\delta_j$ is the phase angle of the output ($\delta_A = 0^\circ, \delta_B = 120^\circ, \delta_C = 240^\circ$), and the angular frequency is $\omega$, and the phase lag angle is $\phi$, and the magnitudes of the output voltage and current are $U_O$ and $I_O$ respectively. The magnitude of the output voltage can be expressed as:

$$|u_{jo}| = U_O$$

$$|i_{jo}| = I_O$$

The upper and lower currents of the MMC can be expressed as:

$$\begin{cases} i_{ju} = i_cj + \frac{1}{2} i_{jo} \\ i_{jl} = i_cj - \frac{1}{2} i_{jo} \end{cases} \quad (1)$$

Where $i_cj$ represents the circulating current inside the arms of phase $j$. The MMC output voltages and currents can be expressed as:

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\[ U_o = \frac{1}{2} m U_{dc} \]  

Where the modulation index ratio is \( m \), which represents \( V/f \) ratio and adjusting between 0-1. It must be approximately ensured constant when the converter used in variable-speed drive application, the modulation index can be written as:

\[ m = \frac{\omega}{\omega_{\text{rated}}} \]

The average arm voltages of the MMC per phase can be written as:

\[
\begin{align*}
    u_{ju} &= \frac{1}{2} U_{dc}(1 - m \cos(\omega t)) \\
    u_{jl} &= \frac{1}{2} U_{dc}(1 + m \cos(\omega t))
\end{align*}
\]

When the power balance between the DC side and ac output side is achieved, the rated DC current \( I_{dc} \) component can be expressed as:

\[ I_{dc} = \frac{3}{4} m I_o \cos \varphi \]

### 2.2. Operation Principle of Hybrid MMC

Figure 3 shows the operation principle of the hybrid MMC. When the series switch is switched on, the dc terminal voltage \( u_d \) equal to \( U_{dc} \). When the series switch is switched off, the dc terminal voltage \( u_d \) of MMC is minimized to twice of the output voltage amplitude (\( 2U_o \)) per phase, this leads to reduce the capacitor voltage ripple. The switching frequency of series switch is \( f_s (f_s = 1/T_h) \) is 10 times of the output voltage frequency \( f_o \) [23]. The DC currents of the hybrid MMC are expressed as:

\[ I_{dc} = \begin{cases} I_{dc(\text{rated})} & \text{if } (S_s = 1) \\ 0 & \text{if } (S_s = 0) \end{cases} \]  

and \( i_c = \frac{1}{3} i_{dc} \)

Based on (3), the expression of dc terminal voltage \( u_d \) is:

\[ u_d = \begin{cases} U_{dc} & \text{if } (S_s = 1) \\ m U_{dc} & \text{if } (S_s = 0) \end{cases} \]

The average dc terminal of \( u_d \) is:

\[ \bar{U}_d = D U_{dc} + (1 - D) m U_{dc} \]

The arm voltages of hybrid MMC for phase A are [23]:

\[ \begin{align*}
    u_{ju} &= \frac{1}{2} u_d - \frac{1}{2} m U_{dc} \cos(\omega t) - \Delta u_d \\
    u_{jl} &= \frac{1}{2} u_d + \frac{1}{2} m U_{dc} \cos(\omega t) - \Delta u_d
\end{align*} \]

Where \( \Delta u_d \) is used to control the circulating current \( i_c \). The balancing of the active power between ac and dc terminals can be achieved by varying the duty cycle \( D \): \( \frac{U_{dc}I_{dc(\text{rated})}}{D} = \frac{3}{2} U_o I_o \cos \varphi \), the balance...
must be occurred when the motor speed varies. Hence the duty cycle $D$ can be derived for constant torque drives with $I_o = I_{o(rated)}$ [25].

$$D = m = \frac{\omega}{\omega_{rated}}$$  \hspace{1cm} (11)

The peak-to-peak voltage ripple of The SM capacitor of hybrid MMC in [23] can be expressed as:

$$\Delta U_{C(PP)} = \left(2 - \frac{\omega}{\omega_{rated}}\right) \frac{I_{o(rated)}}{2\omega_{rated}C}$$  \hspace{1cm} (12)

Where the capacitance of SM is $C$. The capacitor voltage ripple of traditional MMC can be obtained by [19]:

$$\Delta U_{C(PP)} = \frac{I_o}{2oC}$$  \hspace{1cm} (13)

3. CONTROL SCHEME

Figure 4 shows the suggested control scheme for hybrid MMC to drive the induction motor based on vector control strategy, it includes of five main blocks, that are the series switch control block, circulating current control block, induction motor vector control block, the SM balancing control block, and the phase-shifted carrier PWM(PSC-PWM).

![Control Scheme Diagram]

Figure 4. The suggested control scheme for hybrid MMC

3.1. Series Switch Control Block

The power balance between dc input and ac output must be achieved to ensure a stable operation of the hybrid MMC. It is necessary to measure the average voltage of the SMs capacitors ($U_{C,\text{all(avg)}}$) to keep it equal to $U_{dc}/N$ as a reference value because the difference between the input and output powers would affect the stored energy in the capacitors. So the duty cycle $D$ is adjusted for this purpose as shown in figure 5 [23]. The $U_{C,\text{all(avg)}}$ represents the dc average voltage of all the SMs capacitors. To obtain the dc average voltage of the SMs capacitors, the SM capacitor voltages of the upper and lower arms must be calculated, it can be expressed as [26]:

$$u_{c,\text{avg,ju}} = \sum_{i=1}^{N} u_{cap,ju}(i)$$  \hspace{1cm} (14)

$$u_{c,\text{avg,ji}} = \sum_{i=1}^{N} u_{cap,ji}(i)$$  \hspace{1cm} (15)

Subsequently, the average voltage of SMs capacitors in phase $j$ is obtained [27]

$$u_{c,\text{avg,j}} = \frac{1}{2N} \sum_{j=1}^{2N} u_{cap,\text{ji}}(i)$$  \hspace{1cm} (16)

The $u_{c,\text{avg,all}}$ is obtained by summation the average voltage of the SMs capacitors in phase $j$. it can be expressed as [28]:

$$u_{c,\text{avg,all}} = \frac{1}{2} \sum_{j=1}^{N} u_{c,\text{avg,j}}$$  \hspace{1cm} (17)
Due to the sensitivity of PI controller to the harmonics, a moving average filter (MAF) is used to obtain the dc average voltage of the SMs capacitor.

![Series switch control block](image)

**Figure 5. Series switch control block [23]**

### 3.2. Circulating Current Control Block

The stored energy in each phase \( j \) must be kept balanced by modifying the dc component of the circulating current [23]. As shown in Figure 6, the dc average voltage of all SMs capacitors of three-phase \( (U_{C, all(avg)}) \) is compared with the dc average voltage of SMs capacitors in phase \( j \) \((U_{C(avg-j)})\). PI control is used to minimize this voltage variation and to produce a dc circulating current \( \Delta f_{jc} \). After that, this current added to the \( 1/3 I_{dc \text{ rated}} \) component to obtain \( I_{c-ref} \). It is necessary to multiply \( I_{c-ref} \) by the duty cycle, and the circulating current reference will be obtained [23]. The aim of that is to force the actual circulating current to follow \( I_{c-ref} \). Thus the controlled variable is \( \Delta u_d \). So the circulating current control is used for this purpose.

![Circulating current control](image)

**Figure 6. Circulating current control [23]**

### 3.3. Vector Control Block

Vector control is a high-efficiency control strategy that similar to the DC machine speed control system [29]. Figure 7 shows the implementation of vector control fed induction motor. The motor speed \( \omega_m \) is compared to the desired speed \( \omega_{m,ref} \) in the speed control loop, and the error is applied to PI control to produce \( i_{q,ref} \). In \( i_{d,ref} \) control loop the \( i_{q,ref} \) is compared to the \( i_{q} \) which is equivalent to the output torque, and the error is applied to PI control to obtain \( u_{q,ref} \). In flux control loop the flux of the motor \( \psi_r \) is compared to the desired flux \( \psi_{r,ref} \), obtaining the \( i_{d,ref} \) which compared to the \( i_{ds} \) to obtain \( u_{d,ref} \) using PI controllers.

The motor excitation can be controlled from the id control loop. Finally, the generated \((d-q)\) voltages are converted to reference output voltages \((ABC)\) by inverse Clarke-Park transformation. The mathematical equations [30]:

\[
\psi_r = \frac{L_m}{T_r p+1} i_{ds} \quad (18)
\]

\[
\omega_{sl} = \frac{i_{m} i_{ds}}{T_r \psi_r} \quad (19)
\]

\[
\omega_x = \omega_r + \omega_{sl} \quad (20)
\]

\[
\theta_e = \int \omega_x \, dt \quad (21)
\]

Where \( T_r \) is the time constant \((T_r = L_r / R_r)\), \( \omega_{sl} \) is the angular slip speed, \( p \) is the differential operator and \( \theta_e \) is the rotor flux angle, and \( \omega_x \) is the synchronous speed.
3.4. Capacitor Voltage Balancing Control Block

When the SM is activated, current would be pass through the SM causes the charge and discharge and the capacitor voltage fluctuation occurs. Due to the difference in switching time in each sub-module, the capacitor voltage in the same arm is imbalanced [27]. So the capacitor voltage balancing control is used to avoid the imbalance of the capacitor voltage. Figure 8 shows the implementation of the capacitor voltage balancing control blocks for upper and lower arms. This method is different compared to individual-balancing listed in [31]. The upper and lower arm reference voltages can be expressed as [26]:

\[
\begin{align*}
    u_{ref-ju}(i) &= \frac{u_{ref-ju}}{N} + K_p \left( \frac{u_{c-avg-ju}}{N} - u_{cap-ju}(i) \right) \times \text{sign}(i_j) \\
    u_{ref-jl}(i) &= \frac{u_{ref-jl}}{N} + K_p \left( \frac{u_{c-avg-jl}}{N} - u_{cap-jl}(i) \right) \times \text{sign}(i_j)
\end{align*}
\]

(22) (23)

Where \( K_p \) represents the proportional gain, “\text{sign}(x)” denotes signum function it can be written as:

\[
\text{sign}(x) = \begin{cases} 
1, & x \geq 0 \\
-1, & x < 0 
\end{cases}
\]

(24)

The produced references \( u_{ref-ju}(i) \) and \( u_{ref-jl}(i) \) will be applied to the PWM modulator to generate the gate control pulses for the semiconductor switches to build the voltage stepwise.

3.5. The Phase-Shifted Carrier PWM Block

Phase-shifted PWM technique is another comprehensive multi-carrier modulation since it improves the equivalent switching frequency and minimize the harmonics of output voltage and easy to design. This
method requires \( N \) identical triangular carriers with the amplitude of \( U_{dc}/N \). Each sub-module have a triangular carrier with frequency of \( f_c \), and the phase displacement between them is \( 2\pi/N \). Carriers of the phase-shifted PWM are shown in Figure 9. Figure 10 shows the Block diagram of the Phase-shifted PWM.

Where \( \theta \) is the displacement angle of the carriers between the upper and lower arm. For power electronic converters, the higher equivalent switching frequency and lower harmonic content of the output voltage mean that the required filter components are smaller and cost less. The lowest output voltage harmonic content of MMC can be obtained by selecting the displacement angle as follows [16]:

\[
\theta = \begin{cases} 
0, & N \text{ is odd} \\
\frac{\pi}{N}, & N \text{ is even}
\end{cases}
\]  

(25)

4. SIMULATION AND RESULTS

To evaluate the effectiveness of the proposed hybrid MMC, a 1MW, 4160V hybrid MMC is simulated in MATLAB/Simulink environment, with ten half-bridge SMs per arm. Detailed parameters of the proposed converter are listed in Table I. In order to verify the dynamic performance of hybrid MMC, a 6-pole 4.16kV/1MW three phase induction motor (IM) with a constant load torque, was simulated, with the motor parameters in Table I. The hybrid MMC was simulated under three cases to show the reduction of peak-to-peak voltage ripple of the SM capacitor and compared with the traditional MMC. The feasibility of the suggested system is verified by comparing it with the system in [23].

| Table 1. Simulation Parameters |
|-------------------------------|
| Hybrid MMC parameters         |

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4.1. Case 1:

In this case, the hybrid MMC is operated the same as a traditional MMC, the induction motor operates at rated speed of 1189 rpm and no-load torque, after 2 second period a step load torque 7490N.m is applied to the induction motor as shown in Figure 11 (a), the motor speed remains the same as before this because the PI controller returns it to the reference value as shown in Figure 11 (b). The increase of the load torque leading to increase the quadrature current $i_{qs}$ which is proportional to the output torque while the direct current $i_{ds}$ remains constant since the flux is constant as shown in Figure 12 (a). Figure 12 (b) shows the increase of the stator currents amplitude from 50A to its rated value of 212A. The DC-bus current $i_{dc}$ will increase from 37Amp to 147Amp as shown in Figure 13 (a). Due to the increase of output current the arm currents $i_{Al}, i_{Am}$ are increased from 37 Amp to 155 Amp which are approximate equal to $(\frac{1}{2}i_o + \frac{1}{3}i_{dc})$ as shown in Figure 13 (b), also the peak–to–peak voltage ripple of the SM capacitor is increased from 25V to 55V with average voltage of $U_{dc}/N$ (700V), this because of equation (13) as shown in Figure 14 (a). The output voltage of the converter with rated frequency at steady state to fit the rated motor speed is shown in Figure 14 (b).
4.2. Case 2:

In this case, the hybrid MMC is operated as a traditional and hybrid MMC, the motor is operated at low speed of 200 rpm, at 2 second period a step load torque is increased from zero to its rated value of 7490 Nm.
N.m as shown in Figure 15 (a). Figure 15 (b) shows a good-dynamic performance of vector control to get accurate speed control and return the motor speed to its reference value when the load is changed. As the load torque is increased the quadrature current $i_{dq}$ is also increased as shown in Figure 16 (a). Figure 16 (b) shows increase the stator currents amplitudes form 50A to 212A with high-quality sinusoidal waveforms. Figure 17 (a) shows the gate signal of the series switch $S_s$ that appeared after each time period of 0.01 second, this means that the switching frequency $f_s$ of the series switch is equal to 100Hz ($10 \times f_o$), also the dc terminal voltage $u_d$ is appeared after each time period of 0.01 as shown in Figure 17 (b). As the output current is increased the DC-bus current and arm currents are also increased to their rated value as shown in Figure 18 (a) and Figure 18 (b) respectively. Figure 19 (a) shows the peak-to-peak voltage ripple of the SMs $u_{cap}$ of the traditional MMC significantly increases from 115V to 432V with average value of 700V this because equation (13). If the operating frequency is further reduced, the voltage ripple of the capacitor will become extremely large, causing the entire converter to fail to operate normally, while the average value of the SM capacitor voltage of hybrid MMC is stable at 700V and increased from 40V to 140V this because equations (12). Also, there is a good response of voltage balancing control to keep the balance between the SMs capacitor during the load change. Most importantly, compared to Figure 19 (b), the SM capacitor voltage ripple reduction was 292V, which proves that the hybrid MMC has lower capacitor voltage ripple. The converter output voltage with frequency of 10Hz at steady state to get the desired speed is shown in Figure 20.
Figure 17. Simulation results of case 2 (a) Sgate, (b) dc terminal voltage

Figure 18. Simulation results of case2 (a) DC-bus current, (b) Arm current of phase A

Figure 19. Simulation results of case2 (a) traditional MMC SM capacitor voltages of phase A, (b) hybrid MMC SM capacitor voltages of phase
4.3. Case 3:

In this case, the hybrid MMC is operated at very low frequency (5Hz) to show its ability for reduction of capacitor voltage ripple. The motor is operated with very low speed of 100rpm, and the load torque is increased from zero to 7490N.m at 4 second period as shown in Figure 21 (a). The motor speed is maintained with the reference value because of the closed loop speed control as shown in Figure 21 (b). The \( i_{dq} \) component follows the load torque and has a value which is proportional with the output torque while the direct current \( i_{dc} \) remains constant since the flux is constant as shown in Figure 22 (a). Figure 22 (b) shows the increasing the stator currents amplitudes form 50A to 212A with high-quality sinusoidal waveforms. Since the output frequency is 5Hz, this means that the series switch is operated at frequency of 50Hz as shown in Figure 23 (a), also the dc terminal voltage \( u_{dc} \) is appeared after each time period of 0.02 as shown in Figure 23 (b). Since the load torque is increased the DC-bus current and arm currents are also increased to their rated value as shown in Figure 24 (a) and Figure 24 (b) respectively. Figure 25 (a) shows the peak-to-peak voltage ripple of the SM capacitor \( u_{cA} \) \( u_{cB} \) of the traditional MMC that significantly increases from 225V to 860V with average value of 700V. In practice this required to increase the size of the capacitor, leading to increase cost, therefor it is difficult to drive the motor at low speed with traditional MMC. Compared with traditional MMC the peak-to-peak capacitor voltage ripple, the hybrid MMC can operate with a lower peak-to-peak capacitor voltage ripple with 60V to 170V at the same speed as shown in Figure 25 (b). The converter output voltages are set to get the required motor speed as shown in Figure 26.
Figure 22. Simulation results of case 3 (a) $I_d$ and $I_q$ current component of the motor, (b) motor stator currents

Figure 23. Simulation results of case 3 (a) Sgate, (b) dc terminal voltage

Figure 24. Simulation results of case 3 (a) DC-bus current, (b) Arm current of phase A
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Figure 25. Simulation results of case 2 (a) traditional MMC SM capacitor voltages of phase A, (b) hybrid MMC SM capacitor voltages of phase

Figure 26. Converter output voltages

Table 2 shows a lower values of peak-to-peak voltage ripple of SM capacitor of the hybrid MMC compared with the traditional MMC, this because of the series switch, reducing the average arm voltage of the MMC, leading to reduce the storage energy in the SM capacitor.

| Speed (rpm) | Traditional MMC | Hybrid MMC |
|-------------|-----------------|------------|
| 1189 rpm    | 55 V            | 55 V       |
| 200 rpm     | 432 V           | 140 V      |
| 100 rpm     | 860 V           | 170 V      |

5. CONCLUSION

This paper introduced a hybrid MMC to drive the induction motor. The results show that the ability of hybrid MMC to drive the induction motor at constant load torque with wide speed range. Compared with the traditional MMC, the hybrid MMC exhibits lower peak-to-peak voltage ripple of the SM capacitor without increasing the capacitor value as shown in the simulation results when the induction motor is operated at low speed. The motor can be operated with very low speed of 100rpm with peak-to-peak capacitor voltage ripple of 170V compared with high value of 860V in traditional system. A suitable control is introduced for the hybrid MMC in order to minimize the peak-to-peak voltage ripple of capacitor and to obtain high-quality sinusoidal waveform of the induction motor current without using any additional filter.

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