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Flying-Capacitor Modular Multilevel Converters with Coupled Inductors

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ABSTRACT

In this paper, the coupled inductor scheme instead of non-coupled inductors is suggested to reduce the dimension, weight and cost of the magnetic core. The simulation results have verified the effectiveness of the flying-capacitor MMC with coupled inductors and its control method for medium-voltage induction motor drives at low-speed operation.

1. Introduction

The MMC is regarded as one of the promising topologies in medium-voltage adjustable-speed AC motor drives. One of the main challenges of MMC-fed motor drives is that an AC voltage fluctuation exists at the fundamental frequency in each submodule (SM) capacitor [1]. The magnitude of the AC voltage fluctuation in the SM capacitors is inversely proportional to the fundamental frequency, consequently limiting the operation range of the motor.

The magnitude of capacitor voltage fluctuation at a low fundamental frequency can be reduced by the injection of high-frequency common-mode voltage and circulating current. This method can fully eliminate the SM capacitor voltage fluctuation. However, injecting the high common-mode voltage brings harmful effects on the induction motor (IM), such as a failure of motor winding insulation and motor bearing. A flying-capacitor MMC can reduce the SM capacitor voltage ripple without injecting the common-mode voltage [2]. However, the coupled inductors can be substituted for the non-coupled inductors in this converter to reduce the size and cost of the system.

In this paper, a flying capacitor MMC with coupled inductors is proposed to reduce the dimension, weight and cost of the magnetic core. The validity of the proposed inverter is verified by simulation results for a 4160-V, 1250-hp IM drive system.

2. Low-Speed Operation of Flying-Capacitor MMC with Coupled Inductors

2.1 Circuit configuration and operating principle

Fig. 1 shows the circuit structure of the flying-capacitor MMC with coupled inductors, where each arm consists of four submodules. The coupled inductor with coupling coefficient $k = 0.95$ is connected between two sub-arms and the midpoint of the upper and lower arms is also connected through a flying-capacitor C_F.

A high-frequency voltage is injected into each sub-arm of the converter side, rather than the common-mode voltage into the motor. During the low speed operation, the high-frequency voltages generate high-frequency currents to transfer and balance the power fluctuation between the upper and lower arms through the flying-capacitor C_F. Therefore, the SM capacitor voltage ripples are maintained within allowable ranges (lower than ±10% of rated capacitor voltage).

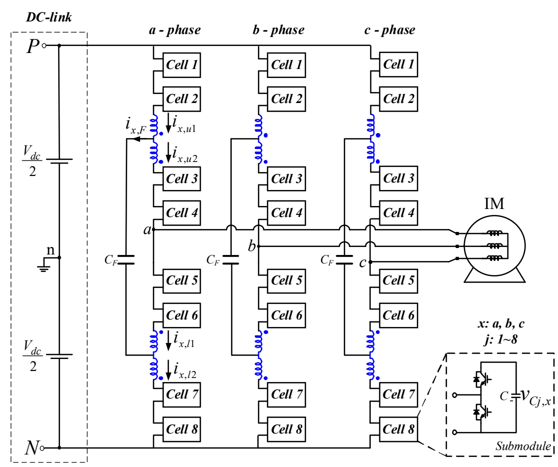

Fig. 1. Circuit configuration of the flying-capacitor MMC with coupled inductors.

2.2 Control method

In order to achieve the accurate motor speed operation and the good balance of SM capacitor voltages, a combination of control schemes is adopted. Fig. 2 shows the control block diagram of the flying-capacitor MMC which mainly comprises two parts. Firstly, the motor speed control is applied for a stable speed operation of the IM by generating reference stator voltages v_{as}^*, v_{bs}^* and v_{cs}^* based on the motor speed and currents, which is shown in Fig. 2(a). To satisfy the required magnitude and frequency of the stator voltages, the SM capacitor voltages have to be balanced by other capacitor voltage control. Secondly, the leg, arm and individual balancing controls are employed to balance the SM capacitor voltages.

Fig. 2(b) shows the control block diagram of the leg balancing control, where $\Delta v_{ph,x}^*$ is the output voltage command. In this control, v_C^* is the SM capacitor voltage reference, and $\overline{v_{Cx}}$ is the average SM capacitor voltage of each leg. The feedforward DC current $i_{d,fwd}$ and the DC current $i_{d,x}$ are calculated as

$$i_{d,fwd} = \frac{v_{s,x} i_x}{V_{dc}} \tag{1}$$

$$i_{d,x} = 0.5(i_{x,u2} + i_{x,l1} + i_{x,F}) \,. \tag{2}$$

Fig. 2(c) shows the control block diagram of the arm balancing control. $\overline{v_{C,u,x}}$ and $\overline{v_{C,l,x}}$ are the average SM capacitor voltage of the upper and lower arms. The high-frequency current feedforward $I_{h,fwd}$, and the high-frequency current $i_{h,x}$ are given, respectively, as

$$I_{h,fwd} = \frac{0.25 V_{dc} i_x - v_{s,x} i_{d,fwd}}{V_h} \tag{3}$$

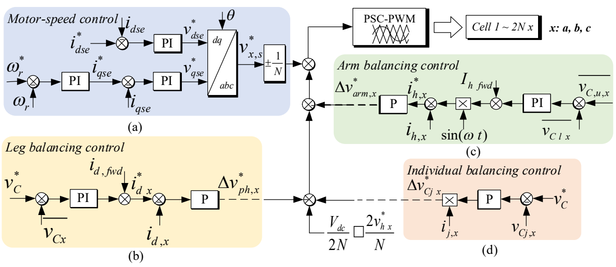

Fig. 2. Block diagrams for the SM capacitor voltage controls. (a) Motor speed control. (b) Leg balancing control. (c) Arm balancing control. (d) Individual balancing control.

TABLE I CIRCUIT PARAMETER USED FOR SIMULATION

Parameters	Symbol	Value
Converter		
DC-link voltage	V_{dc}	7000 V
Self-inductance	L	2 mH
Coupling coefficient	k	0.95
Flying-capacitor	C_F	0.4 mF
Number of SMs per arm	N	4
SM capacitance	C	2000 µF
SM capacitor voltage reference	v_C^*	1750 V
Carrier frequency	f_c	2000 Hz
Injected frequency	f_h	180 Hz
Induction Motor		
Output power	P_o	1250 hp
Rated line-to-line voltage	V_{LL}	4160 V
Stator current	I_s	150 A
Fundamental frequency	f_0	60 Hz
Rated speed	n_{rated}	1189 rpm
Rated torque	T_{rated}	7490 N m
Number of pole pairs	P	3
Moment of inertia	J	47.6 kg m^2

$$i_{h,x} = \frac{i_{x,F}}{2}. \tag{4}$$

Fig. 2(d) shows the control block diagram of the individual balancing control, where $v_{Cj,x}$ and $i_{j,x}$ are the capacitor voltage and current of each SM.

Finally, voltage commands of each SM are given as

$$v_{Cj,u,x}^* = \frac{V_{dc}}{2N} - \frac{v_{s,x}^*}{N} \mp \frac{2v_{h,x}^*}{N} - \Delta v_{ph,x}^* \mp \Delta v_{arm,x}^* + \Delta v_{Cj,x}^* \tag{5}$$

$$v_{Cj,l,x}^* = \frac{V_{dc}}{2N} + \frac{v_{s,x}^*}{N} \mp \frac{2v_{h,x}^*}{N} - \Delta v_{ph,x}^* \pm \Delta v_{arm,x}^* + \Delta v_{Cj,x}^* . \tag{6}$$

Then they are normalized by the DC capacitor voltage v_C^* to achieve normalized modulation signals which are compared with triangular waveforms having a phase angle shift of 90^0 ($360^0/N$) and a carrier frequency f_c.

3. Simulation Results

In Table I, the converter and the IM parameters for the simulation are listed. Fig. 3 shows the simulation results with load torque changes during low-speed operation. Initially, the motor speed command is changed from standstill to 50 rpm (2.5 Hz). A start-up current is lower than double the rated current, which makes it possible to generate a start-up torque. Each arm needs to conduct the start-up current to transfer the power from DC side to the motor. Therefore, the SM capacitor voltage ripples are initially high. However, those ripples are maintained within allowable range and follow the reference v_C^* due to the power fluctuation transferred between the upper and lower arms through the flying capacitor C_F.

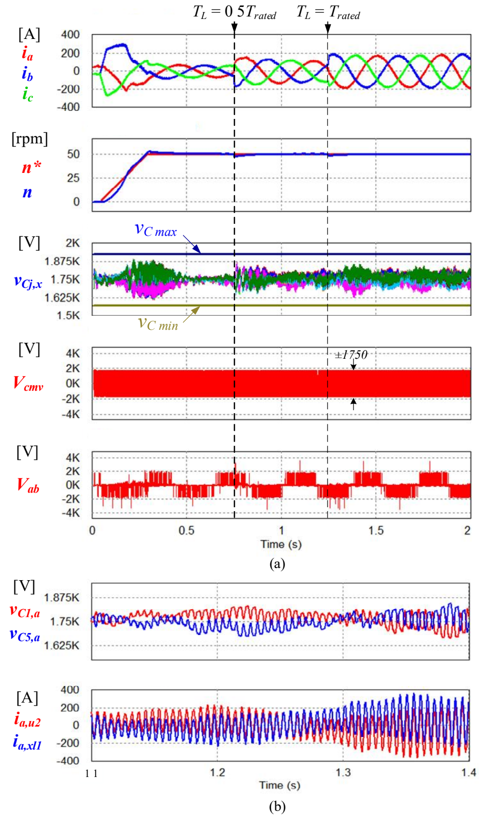

Fig. 3. Simulation results at low-speed operation (n^*= *50 rpm*) when the load torque is changed from *0* to $0.5T_{rated}$ at t = 0.75 s, and from $0.5T_{rated}$ to T_{rated} at t = 1.25 s. (a) Overall waveforms. (b) Time-expanded waveforms around t = 1.25 s.

When the load torque is applied, the SM capacitor voltage ripples are also mitigated. Fig. 3(b) shows the time-expanded waveforms around t = 1.25 s, in which the magnitude of high-frequency current increases and the SM capacitors are charged or discharged based on this current. The common-mode voltage, $v_{cmv} = (v_{an} + v_{bn} + v_{cn})/3$, has a value of ±1750 V ($\pm v_C^*$).

4. Conclusions

In this paper, a flying-capacitor MMC with coupled inductors for low-speed operation of induction motor drives has been proposed, where the dimension, weight and cost of the magnetic core can be reduced compared to non-coupled inductors. The simulation results have confirmed the valid operation of the suggested scheme. A stable operation of induction motor drives has been obtained for a low-speed region with allowable SM capacitor voltage ripples.

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References

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[2] S. Du, B. Wu, N. R. Zargari, and Z. Cheng, “A flying-capacitor modular multilevel converter for medium-voltage motor drive,” *IEEE Trans. Power Electron.*, vol. 32, no. 3, pp. 2081–2089, 2017.