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An Active Cross-Connected Modular Multilevel Converter (AC-MMC) to the Motor Drive

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Abstract

An active cross-connected modular multilevel converter (AC-MMC) based on series connected half-bridge modules. It is intended for completely enhancing the performance of a medium-voltage motor drive system in the full speed range from standstill to rated speed under all load conditions. At first, the configuration and operation principles of a three phase MMC is introduced. A comprehensive steady state analysis and the equivalent circuit model, which are applicable to an MMC connected to either a DC or an AC bus, are then presented in this thesis. In addition to better understanding of the MMC operation, the analysis and modeling of the MMC also suggest the conditions that ensure the stability operation of the MMC system. The proposed AC-MMC circuit is characterized by the cross connection of upper and lower arm middle taps through a branch of series-connected half-bridge converters, which have an identical voltage and current rating with the sub modules in the upper and lower arms. This cross-connected branch provides a physical power transfer channel for the upper and lower arms. By properly controlling the amount of high-frequency current flowing through the cross-connected branch, the power balance between the upper and lower arms is achieved even at a zero/low motor speed under constant torque condition. Meanwhile, no common-mode voltage is introduced in the whole speed range. A control strategy with focus on sub module capacitor voltage control is also proposed in this paper to guarantee the normal converter operation. Simulation results obtained from a 4160-V, 1-MW model verify the feasibility of the proposal and to using MATLAB/SIMULINK for simulating An active cross connected modular multilevel converter (AC-MMC) for a medium voltage motor drive.

I. INTRODUCTION

MODULAR multilevel converter (MMC) has gained much research attention in recent years, and it is expected to be implemented to medium-voltage motor drives due to its outstanding merits as compared with classic multilevel converters such as flying-capacitor, diode-clamped, and cascaded H-bridge (CHB) converters [1]–[3]. Flying-capacitor and diode-clamped converters require plenty of clamped components when their output voltage level is higher than five [4]–[8]. The limited voltage level prevents them from high-voltage industry application. CHB can be easily extended to a high voltage level by simply increasing the cascaded numbers, but it needs to be equipped with a bulky multi winding transformer and a front-end rectifier to supply power to each H-bridge module [9], [10]. In contrast, MMC could get rid of the heavy, bulky, and costly multi winding transformer without losing themerits brought by floating capacitors and natural modularity. It has been regarded as a promising topology in medium-voltage motor drive applications [2]. However, MMC suffers from an issue of imbalance power between the upper and lower arms when operated at a low speed, which may constrain its application into a narrow range such as pumps, compressors and fans [11], [12]. To solve the inherent issue, several ideas have been presented in the literatures [11]– [15], [17], [18], [20]. The most effective method is to introduce a common-mode voltage and circulating current to the three phase converter, which could bring two degrees of freedom to redistribute power between the upper and lower arms [11]–[14], [20]. This method could be further improved by reshaping the common-mode voltage and circulating current into the square waveform for reducing the peak value of circulating current by 50% [15]. Although these two kinds of methods fully overcome the issue of unbalanced sub module capacitor voltages at a low motor speed, the introduced common-mode voltage does harm to ac motors [16]. To improve the performance, a new control strategy is presented and it introduces neither the common-mode voltage nor the circulating current [17]. This control scheme intentionally reduces the average sub module capacitor voltage and allows a large capacitor voltage ripple as the motor speed decreases. The normal output voltage at decreased speed can still be guaranteed by timely compensating insertion indices. This approach successfully prevents the possible premature failure to motor winding insulation, because no common-mode voltage is injected. However, this property could only convers the range from medium to high speed. At the low motor speed, the common-mode voltage and circulating current can hardly be avoided [18]. In this paper, a novel topology named as active cross connected MMC (AC-MMC) is proposed with its circuit configuration outline in Fig. 1. It aims to mitigate/eliminate the common-mode voltage for medium-voltage motor drives in full motor speed range. The issue of unbalanced power (or called large fluctuation) in full speed range is completely solved by controlling the power redistribution between the upper and lower arms through a physical path formed by the cross-connected branch. A 4160-V, 1-MW simulation model performed MATLAB/SIMULINK confirms the viability of the proposed AC-MMC drive system.

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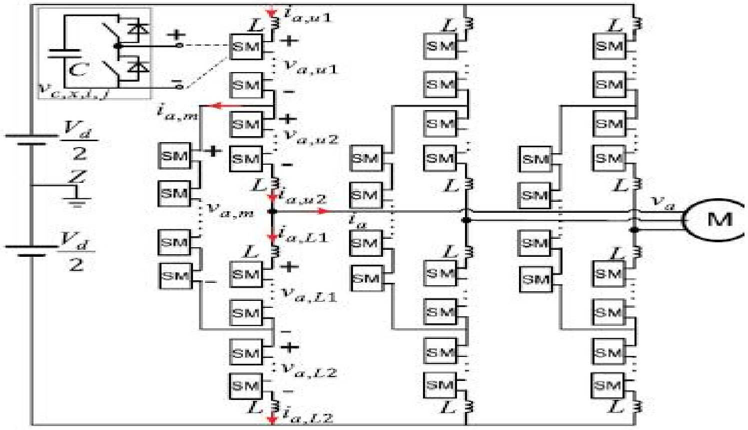


Fig. 1. Active cross-connected MMC.

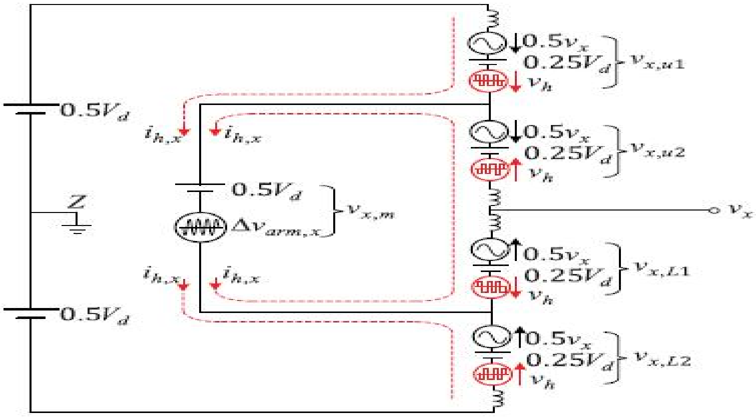


Fig. 2. Equivalent circuit of per-phase leg for AC-MMC.

II. PROPOSED AC-MMC CIRCUIT

A. Circuit Configuration

Fig. 1 shows the circuit diagram of the proposed AC-MMC, which is composed of three phase legs, each containing one upper arm, one lower arm, and one cross-connected branch. Each arm could be further divided into two sub arms and their conjunction node is drawn out to connect with the cross-connected branch. The outer terminals of the sub arms are connected to a dc or ac bus through buffer inductors. The cascaded number of half-bridge modules in the arm and cross-connected branch is determined by the system voltage rating and single semiconductor block voltage. Normally, the branch has the same cascaded number with that of the arm, and the sub modules in the branch have an identical voltage and current rating with the ones in arms.

B. Operating Principle

With the help of the modulation scheme, the converters in the arm and cross-connected branch produce the desired multilevel voltage waveform with the dominant components sticking to the reference voltage. Although various modulation methods could be applied to AC-MMC, this paper prefers the phase shifted pulse width modulation (PSPWM) because of its smooth Performance in a wide motor speed range. The triangular carriers for the sub modules in one sub arm are assigned with a phase angle displacement of 360/(0.5N) degree, where N denotes the number of SMs in each arm. The two sets of carriers for the two sub arms are also phase shifted to maximally eliminate switching ripples. For example, consider the case of $N = 8$, then the phase angles of carriers for one sub arm could be arranged as 0°, 90°, 180°, and 270°, while the carriers for another subarm could be set as 45°, 135°, 225°, and 315°. The cross-connected branch shares the same sets of carriers with the entire arm. To simplify the description of operation principle, the proposed AC-MMC could be represented as a simple circuit by replacing the switching converters with controlled voltage sources. The subarm voltages $vx,u1$, $vx,u2$, $vx,L1$, and $vx,L2$ in one phase leg are assumed to contain three dominant components of dc voltage Vd , output voltage vx , and high-frequency voltage vh ; the equivalent circuit for one phase leg is shown in Fig. 2, where $x = a, b, c$ represent phases A, B, and C, respectively. The high-frequency voltage vh is intentionally introduced into the subarm to create one degree of freedom for redistributing power between the upper and lower arms. Its amplitude Vh is complementary to the output voltage magnitude Vo for fully utilizing the voltage margin. This relationship is summarized in (1). At low motor speed, the output voltage (Vo) would be small, which results in a large high-frequency voltage (Vh) for efficiently balancing power between upper and lower arms. In each arm, the two high-frequency voltages are arranged in a reverse direction to cancel their effect on both dc and ac sides and to avoid the common-mode voltage on the ac ports.

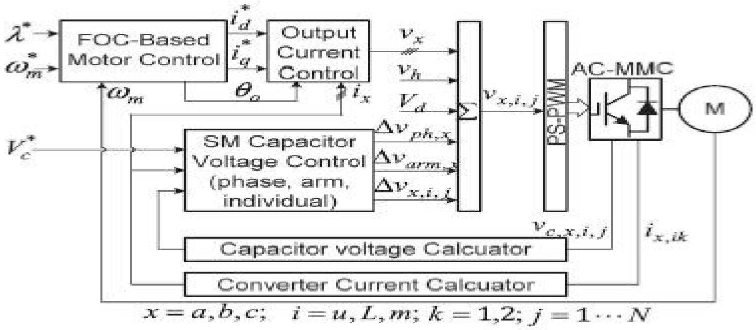


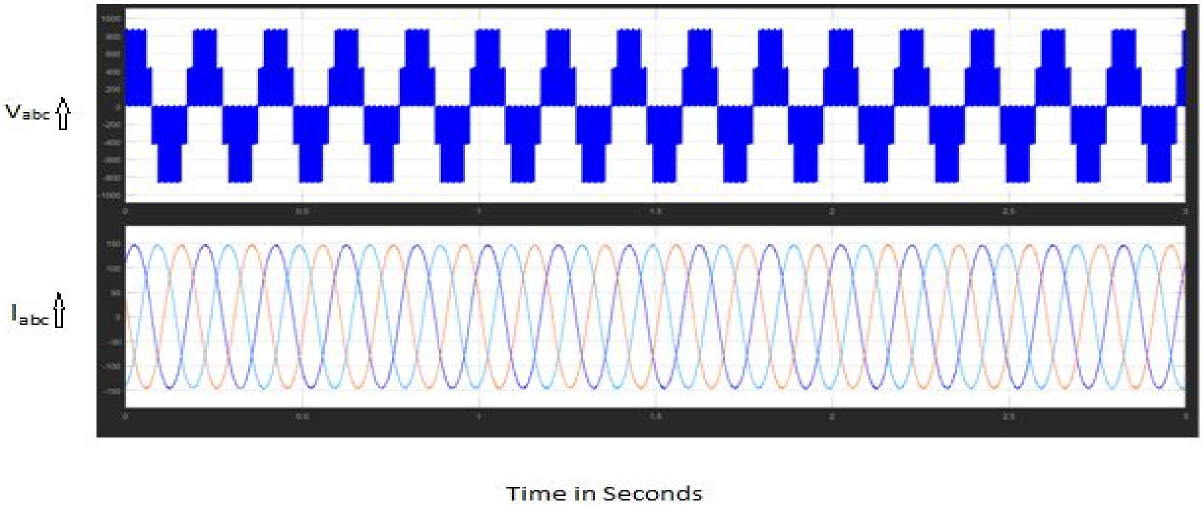
Fig. 3. Overall control block diagram for AC-MMC based motor drive.

C. Power Balance for the Cross-Connected Branch

Similar with the analysis for arms, the instantaneous power of the cross-connected branch can also be derived in terms of the branch voltage and current. As is shown in Fig. 2, the produced voltage *vx,m* includes a dc component $0.5V_d$ and a narrow pulse component Δ*v*arm, *x* . The dc component is used to support the counterpart produced by sub arms, while the narrow-pulse component is employed for exciting the high-frequency current the phase leg. According to the positive direction defined in Fig. 3, the expressions for the branch voltage current can be written as In (11), the first term at the right side is caused by the interaction of the dc voltage and high-frequency ac current, which will never affect the average power of the cross-connected branch. The second term results from the interaction of the small narrow voltage and high-frequency ac current, which has a negligibly small average value. Therefore, the power balance for the cross-connected branch is also automatically achieved. Note that the above analysis does not consider the small amount of converter power loss. In practical use, the power loss should be properly compensated through close-loop controls.

III. SIMULATION RESULTS

A 4160-V, 1-MW simulation model performed in MATLAB/ SIMULINK is built for verifying the feasibility of the proposed AC-MMC along with the control strategy. First, a resistance and inductance (*RL*) load is connected to AC-MMC to confirm the converter steady state performance at low output frequency. And then, a 4160-V, 1-MW induction motor is connected to the AC-MMC to verify the dynamic performance.



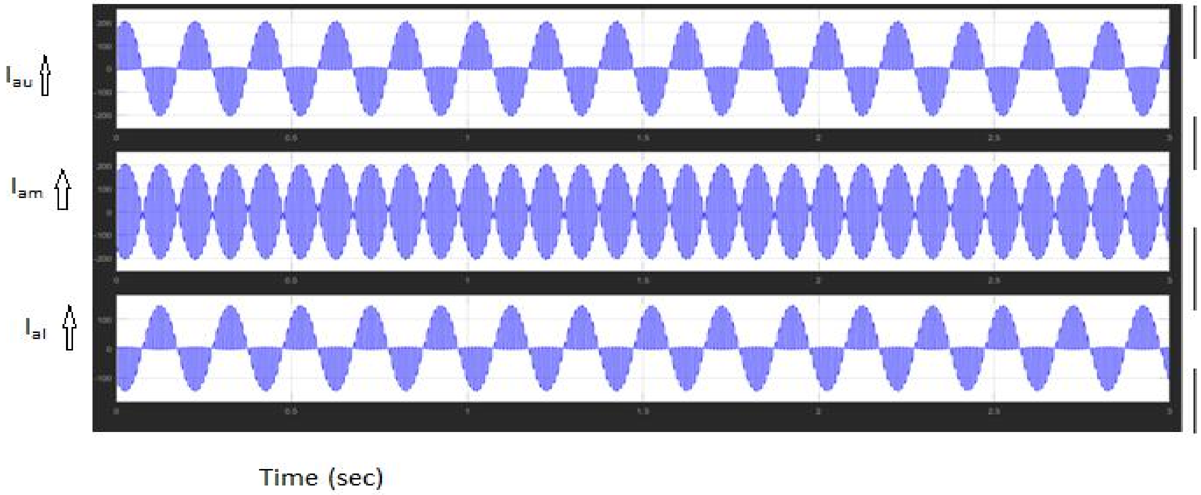
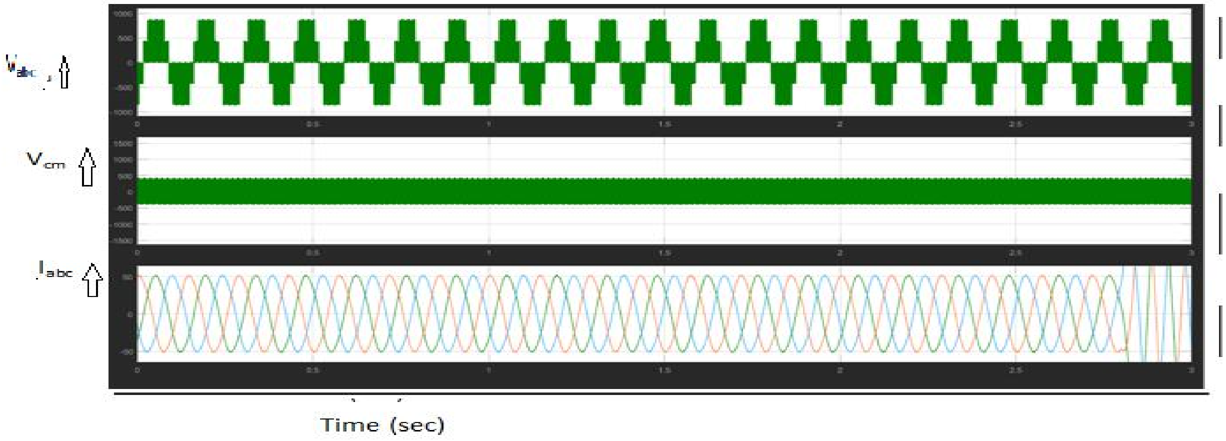
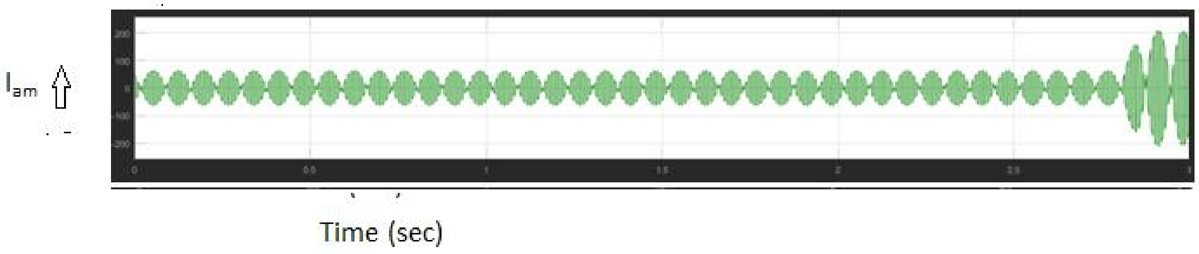


Fig. 4. Simulation results for verifying the converter steady-state performance at output frequency of *fo* = 5 Hz under RL load condition.

Fig. 4 shows the simulation results for confirming the steady state performance of the proposed AC-MMC at low output frequency. In this simulation, the AC-MMC feeds a three-phase Y-type *RL* load with resistance and inductance of 0.18 and 0.63 p.u., respectively. The output frequency is set at *fo* = 5 Hz. When the simulation starts, the AC-MMC supplies a three phase 5-Hz sinusoidal current to the *RL* load with the root mean- square (rms) value of 106 A (0.75 p.u.). Meanwhile, a square-waveform high-frequency current component appears in the arms and cross-connected branch as expected to balance the power between the upper and lower arms. The currents in the upper arm, the cross-connected branch, and the lower arm have the same peak value of 200 A (1 p.u.), which enables the construction of AC-MMC to use identical switching devices. The submodule capacitor voltages in arms and cross-connected branch are balanced very well and maintain their average value at 875 V.



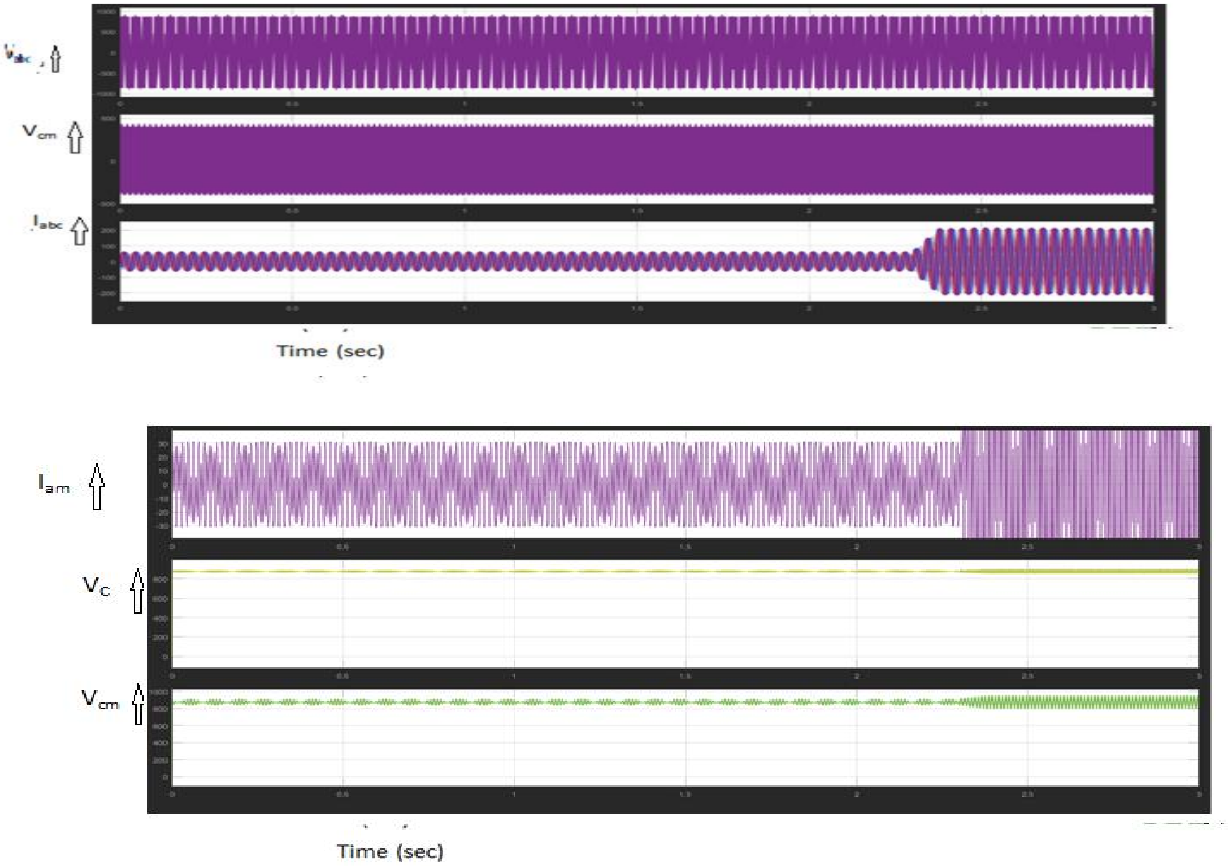


Asynchronous motor at pu=1, ωm = 600 r/min

Fig. 5. Simulation results for confirming the dynamic performance when the motor load torque steeply increases from 0 to 0.9 p.u. at a constant low rotating speed of *ωm* = 140 r/min (0.12 p.u.).

Fig. 5. presents the simulation waveforms for verifying the dynamic performance of AC-MMC in driving an ac motor at low rotating speed with the load torque steeply increasing from 0 to 0.9 p.u. In this dynamic process. The phase-to-neutral voltage is almost not changed and keeps at a low value as expected due to the low constant motor rotating speed of *ωm* = 140 r/min (0.12 p.u.). The measured common-mode voltage also has a small value of approximately ±400 V (0.1 p.u.), which is caused by PWM switching. As the load torque sharply changes, the threephase stator current increases quickly to produce a counterpart electromagnetic torque for keeping the rotating speed constant. The high-frequency current with square waveforms is simultaneously enhanced to make the power balance between upper and lower arms. In the whole process, the average submodule capacitor voltages in arms and cross-connected branches are balanced well and maintain at the reference value of *v* * = 875V. in the presents the experimental waveforms in the dynamic process when motor load torque steeply increases from 0 to 0.9 p.u. at a constant low speed of *ωm* = 850 r/min (0.12 p.u.). As the load torque increases, the three-phase stator current enhances simultaneously to produce a counterpart electromagnetic torque for maintaining the motor rotating speed. The square waveform high-frequency current in the AC-MMC also increases accordingly to keep the power balance between upper and lower arms. The sub module capacitor voltages are balanced well after suffering from a small disturbance. The common-mode voltage is also calculated based on the measured phase-to neutral voltages by using the equation of $vocm = (va + vb + vc)/3$. It can be observed that the common-mode voltage is around ±80 V, which is lower than half of sub-module dc voltage 175 V. This amount is similar with that in

simulated medium-voltage high-power model. As the cascaded number increases in medium/high- voltage application, the percentage of common mode voltage will become small.



Asynchronous motor at pu=0.9, ωm = 140 r/min

Fig. 6. Simulation results for confirming the dynamic performance when the motor load torque steeply increases from 0 to 1.0 p.u. at a constant medium rotating speed of *ωm* = 600 r/min (0.5 p.u.).

Fig. 6 shows the simulation results for confirming the dynamic performance of ac-MMC in driving ac motor at medium rotating speed (0.5 p.u.) with load torque sharply changing from 0 to 1.0 p.u. Due to the constant motor speed of *ωm* = 600 r/min (0.5 p.u.), the phase-to-neutral voltage keeps constant. Meanwhile, the common-mode voltage also stays at about ±400 V (0.1 p.u.) and only contains switching ripples. At time instant of $t = 2.31$ s, the motor is suddenly loaded with full torque. The AC-MMC responses quickly to increase the motor stator current and makes the motor speed maintain at *ωm* = 600 r/min. Simultaneously, the high- frequency current in the inner of AC-MMC is enhanced to properly balance the power between upper and lower arms. In this dynamic process, the sub module capacitor voltages are balanced very well. AC-MMC in the motor speeding up process with a rated electromagnetic torque under no-load conditions. As the motor speed increases, the phase-to-neutral voltage enhances accordingly, but the common-mode voltage keeps at a small value of approximately ±400 V (0.1 p.u.). The common mode voltage can be observed to be always near to half of the submodule dc voltage of 875 V. It can be believed that in the higher cascaded number, the percentage of commonmode voltage will be smaller. The three-phase stator current keeps at 1 p.u. in the motor speeding up process, because the electromagnetic torque is set at 1 p.u. As the stator current frequency increases, the square-waveform high-frequency current in the ACMMC decreases. It is finally forced to be approximately zero when the motor speeds increases near to 1 p.u. In the whole speeding up process, the average submodule capacitor voltages maintain balance and the voltage ripples are always constraint to ±10%.

IV. CONCLUSIONS

The promising multilevel topology Modular Multilevel Converter (MMC) has been proposed for more than one decade and attracting considerable research interests. With the advantages like perfect output waveform, modularized structure, flexible scalability, transformer-less configuration, and high reliability, the MMC can be conveniently used in industrial applications with high- or medium-voltage levels. Although the hardware configuration of an MMC is relatively simple compared with other multilevel converters, the difficulty of designing an MMC system actually lies in the control strategies. Multiple control objectives, such as MMC output and internal dynamics, have to be simultaneously met for the stable operation of the MMC, which makes the implementation of the control system complex and hard to be accomplished in a single controller. In consequence, this thesis aims to investigate the control strategies for MMCs.This paper proposed a new AC-MMC, which solves the major problem of conventional MMC-fed drive at zero- or low speed operation. The circuit architecture and operating principle were illustrated. The mathematical analysis on the power balance under the condition of injecting no common mode voltage was elaborated. A control algorithm was also proposed to make the AC-MMC realize the full speed range operation from standstill to rated speed under all load condition without injecting common-mode voltage. The feasibility of the proposal was proved by both of the simulation and experiment.

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