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Research Article

Performance Enhancement of Modular Multilevel Converter for Motor Drive Application

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ABSTRACT

Modular Multilevel Converters (MMCs) have gained prominence in medium- and high-voltage applications due to their modularity, scalability, and ability to achieve high power quality with low harmonic distortion. However, one of the critical challenges in MMC-based drives is the presence of circulating currents among converter submodules. These circulating currents, typically induced by unbalanced capacitor voltages and phase asymmetries, can lead to increased power losses, thermal stress on submodule components, and ultimately, reduced drive efficiency and lifespan. To control the circulating current in MMC, this paper proposed circulating current control technique which could be able to reduce the circulating current from rated speed to low speed operation under steady state and transient operation. Details waveform analysis is presented in detail. The MALAB based simulation is carried out to check the effectiveness of proposed technique. The details comparison between proposed technique and conventional technique is presented.

Keywords: Circulating current, Sub-Module capacitor voltage, Modular Multilevel Converter Total harmonic Distortion, Field Oriented Control.

INTRODUCTION

The MMC technology has become a significant advancement in power electronics, particularly for HVDC applications, renewable energy integration, and FACTS. Its modular architecture offers advantages such as modularity, scalability and improved performance characteristics [1]. The MMC consists of multiple identical submodules connected in series, allowing for flexible configuration and incremental power handling [1]. This design facilitates easy maintenance and redundancy, enhancing overall system reliability [2]. MMCs are effective in managing power quality and stability, but face challenges such as circulating currents, which can lead to increased losses and potential damage to converter components [2]. Recent advancements in control strategies, including predictive control and advanced modulation techniques, aim to address these challenges and improve MMC performance [1].

Research has focused on various techniques to maintain balanced capacitor voltages, such as phase-shifted PWM and energy balancing algorithms, which help minimize voltage ripple [1]. Several studies emphasize the use of Model Predictive Control (MPC) for MMCs, highlighting its effectiveness in managing capacitor voltage and improving dynamic performance [2]. Adaptive control methods have been explored to enhance the system's response to changing conditions, showing significant improvements in voltage regulation and stability [3]. Combining different control methods, such as feedback and predictive control, has been shown to improve performance and resilience in voltage regulation [4]. Several papers address thermal management strategies in MMCs, emphasizing the importance of effective cooling systems to ensure reliability and longevity under high operational loads [5]. Research has been conducted on methods for detecting and isolating faults within MMC systems, which is crucial for maintaining system reliability and performance [6,7]. Implementing redundancy in submodules has been proposed to enhance the fault tolerance of MMCs [8]. MMCs are widely applied in HVDC systems, with numerous papers exploring their performance in various configurations, including long-distance transmission and grid interconnections (Liu et al., 2019) [9]. The use of MMCs in integrating renewable energy sources, such as offshore wind farms and solar PV systems, has been extensively documented, highlighting their advantages in handling variable power generation [10].

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Many papers include simulation results and experimental validations of MMC performance under different operational scenarios, providing insights into their efficiency, reliability, and control challenges [11]. Studies also focus on the harmonic performance of MMCs, demonstrating their capability to achieve low total harmonic distortion (THD) levels compared to traditional converter technologies [12,13]. Recent research indicates the potential of integrating AI and machine learning algorithms to optimize control strategies for MMCs, enhancing their adaptability and efficiency [14]. Advances in semiconductor materials and devices are discussed, highlighting their impact on improving the performance and efficiency of MMCs [15].

MPC has been recognized as an effective method for managing circulating currents by optimizing switching actions based on predicted future states. This technique enhances the system's ability to respond to variations in operating conditions [16]. Circulating current controllers that modify the reference currents for SMs have been proposed to limit circulating currents effectively. These controllers help ensure balanced operation and prevent excessive currents from flowing through the converter [17]. Research indicates that energy balancing algorithms can be employed to equalize energy levels across SMs, preventing voltage imbalances that lead to circulating currents. Combining these techniques with predictive control can yield substantial improvements [18,19]. Hybrid control strategies that integrate predictive, feedback, and energy balancing techniques have shown promise in improving overall converter performance and mitigating circulating currents [20]. The paper [21,22] explored a predictive control approach that incorporates feedback mechanisms to enhance the stability of MMCs under varying conditions.

BASIC STRUCTURE OF MMC

The basic structure of a Modular Multilevel Converter (MMC) consists of multiple interconnected submodules (SMs) arranged in series to form a converter stack. Each submodule typically includes an energy storage element, such as a capacitor, and power switching devices, usually insulated gate bipolar transistors (IGBTs), which control the charging and discharging of the capacitor to regulate voltage. The series connection of submodules allows the MMC to achieve higher output voltages by summing the contributions from individual SMs. Figure 1 depicts a three-phase MMC circuit layout. Each of the three phase legs that make up MMC contains two arms and an arm inductor. To provide N+1 output levels, each arm is made up of N SMs connected in series. Current passes through SMs during regular MMC operation, charging and discharging the SM capacitor. The switching states of complementary switches S1 and S2 are displayed in Table 1. A capacitor is added to the circuit and the SM output voltage is Vc when S1 is turned on. Likewise, the capacitor is bypassed, and the SM output voltage is 0 when S2 is turned on.

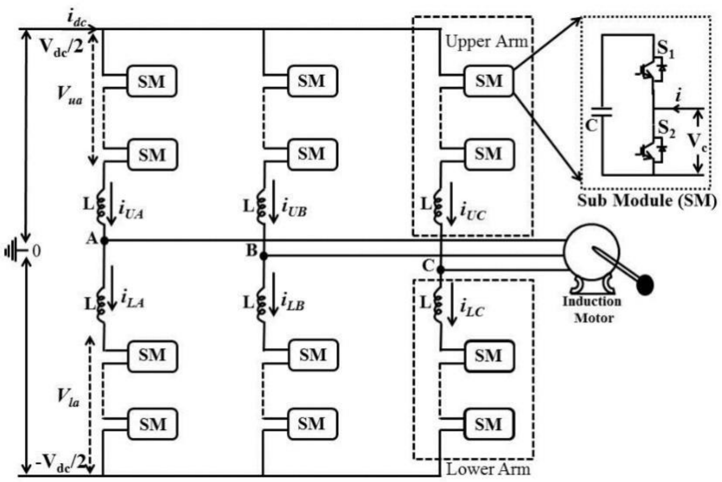

Figure 1. Basic configuration of MMC

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Table 1. SM State

SM State	S1	S2	SM output
ON	ON	OFF	Vc
OFF	OFF	ON	0

CONTROL STRUCTURE OF MMC FED INDUCTION MOTOR DRIVE

Figure 2 shows the conventional control structure of MMC fed Induction motor drive. To control the flux and torque of induction motor, field orientated control (FOC) control is employed. Compared to normal 2 level voltage source converter (VSI), MMC allows the flexible control with good reliability to induction motor drive. Conventional control structure (circulating current suppression control) is used to control the MMC parameters. Phase shifted carrier PWM is used to generate the gate pulses for MMC. To balance the SM capacitor voltage, sort and selection method is used. To reduce the SM capacitor voltage ripple, each SM capacitor voltage is measured and SM voltage balancing algorithm will maintain the SM capacitor voltage ripple at the reference value. To generated the gate pulses for MMC, TMS320F28379D controller is employed. MATLAB Simulink environment is used to generate embedded simulation to interface the MMC control strategy with microcontroller.

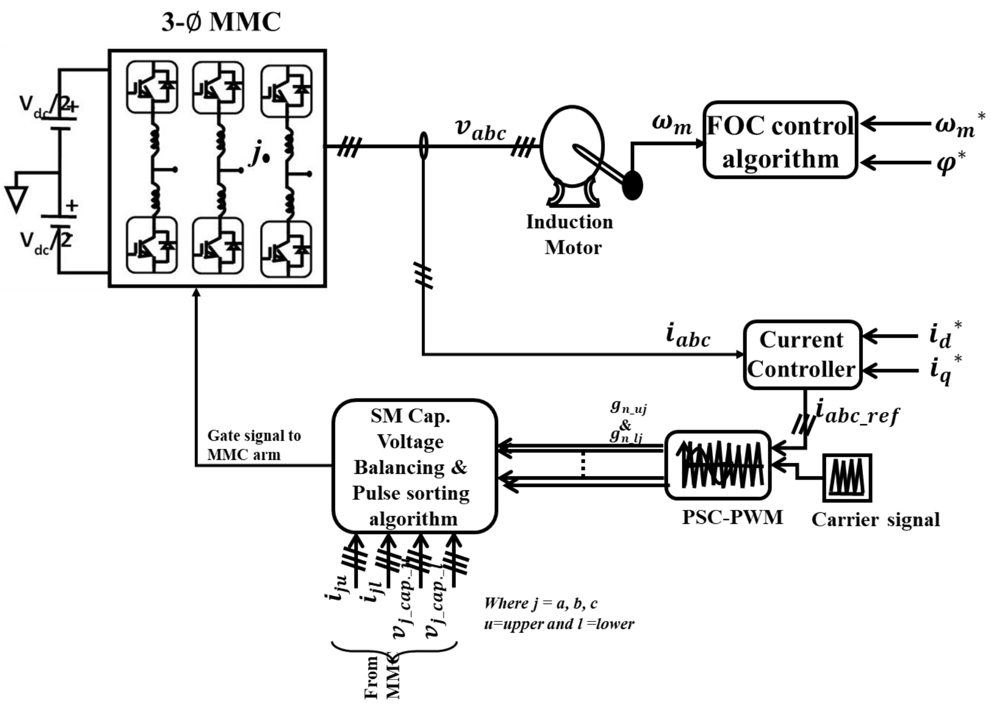

Figure 2. Conventional control structure of MMC fed Induction motor drive

Circulating current flows among the converter phase legs as a result of the intrinsic MMC phenomena. The size of the arm inductor, SM capacitor, and switching device current rating will all be impacted by this circulating current. The second order fundamental frequency current harmonic (i2f), which is the most prevalent component of circulating current, directly increased the current stress on the switching devices and induced conduction loss, which decreased MMC efficiency. The literature review discusses several control strategies to reduce the circulation current in MMC. However, the majority of the literature is on injecting methods to lower the circulating current and eliminating high frequency harmonics. Nevertheless, adding the high frequency component current will raise the arm current peak and have an impact on MMC's ability to handle power.

Power equations of upper arm of MMC [my paper] can be defined as

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$$P_{Au}(t) = \left(\frac{V_{dc}}{2}[1 - msinwt]\right) \cdot \left(\frac{1}{2}I_m\, sin(\omega t - \emptyset) + i_{circ}(t)\right) \tag{1}$$

Simplification of upper arm power equation is as follow

$$P_{Au}(t) = \frac{v_{dc}}{2} i_{circ}(t) - \frac{mv_{dc}I_m}{8} cos\emptyset + \frac{v_{dc}I_m}{4} sin(wt - \emptyset) - \frac{mv_{dc}}{2} i_{circ}(t) sin\ \ wt + \frac{mv_{dc}I_m}{8} cos\ (2wt\ - \emptyset) \tag{2}$$

From equation (2), it is observed that upper arm power of A-phase has two components, i.e. dc component $\frac{v_{dc}}{2} i_{circ}(t) - \frac{mv_{dc}I_m}{8} cos\emptyset$ and ac component $\frac{v_{dc}I_m}{4} sin(wt - \emptyset) - \frac{mv_{dc}}{2} i_{circ}(t) sin\ \ wt + \frac{mv_{dc}I_m}{8}\ cos\ (2wt\ - \emptyset)$. It is evident that both a fundamental frequency and a second order fundamental frequency component are present in the ac component of arm power. Arm current magnitude, switching device current rating, power losses, and converter cost will all rise as a result. However, equation (2) shows that the overall amplitude of the circulating current is greatly decreased by regulating the I2f component of circulating current. Therefore, the voltage differential between the arms needs to be balanced in order to limit the I2f component. The circulating current can be controlled by decreasing the voltage differential between arms or by creating a distinct control algorithm to suppress the I2f.

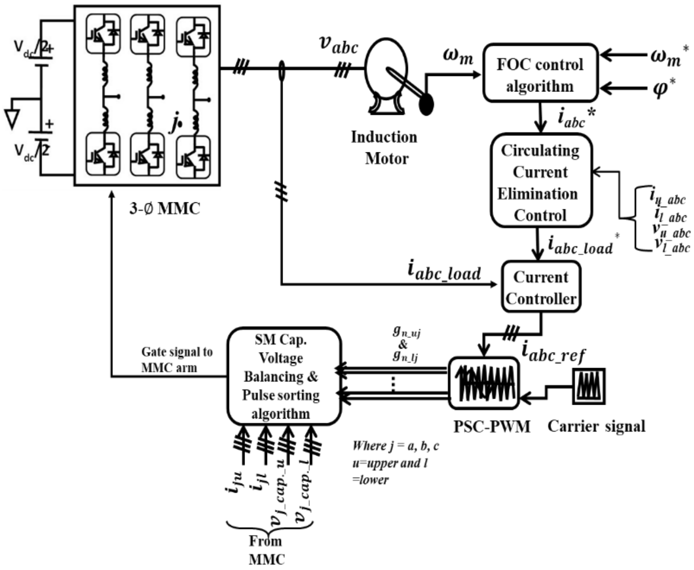

Figure 3. Proposed block diagram of MMC fed drive with circulating current control technique

The suggested control method for removing circulating current is depicted in Figure 3. With the help of the suggested controller, arm voltage and circulating current can be controlled simultaneously, resulting in a nearly equal overall voltage differential between the two arms and the entire elimination of the i2f components of Icirc, which significantly lowers the circulating current.

RESULT DISCUSSION AND ANALYSIS

To check the effectiveness of the proposed technique, the steady state and transient analysis of MMC fed Drive is performed. To verify the performance of proposed technique, comparison is made is conventional technique for constant speed with variable load and variable load with constant speed operation under rated to low frequency operation. For the time duration 0 sec to 5 sec, simulation run for conventional scheme and from 5 sec to 10 sec simulations run for proposed scheme to make appropriate comparison.

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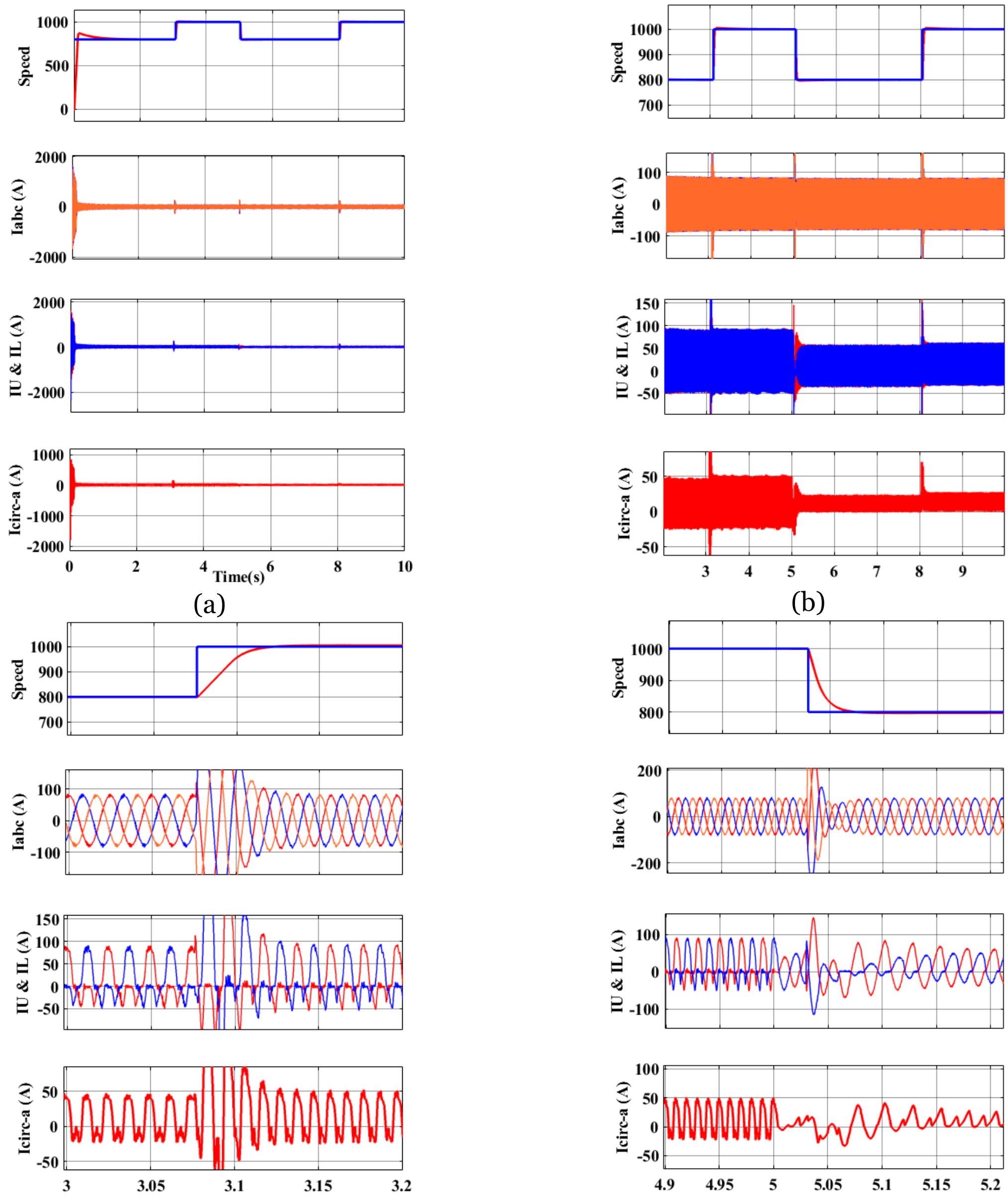

(a) (b)

(c) (d)

Figure 4. MMC fed Induction motor drive operation under constant load with varying speed condition (a) Speed, Iabc, IU & IL and Icirc-a, (b) Zoom view of waveform shown in (a), (c) Speed increases from 800 rpm to 1000 rpm and (d) speed decreases from 1000 rpm to 800 rpm.

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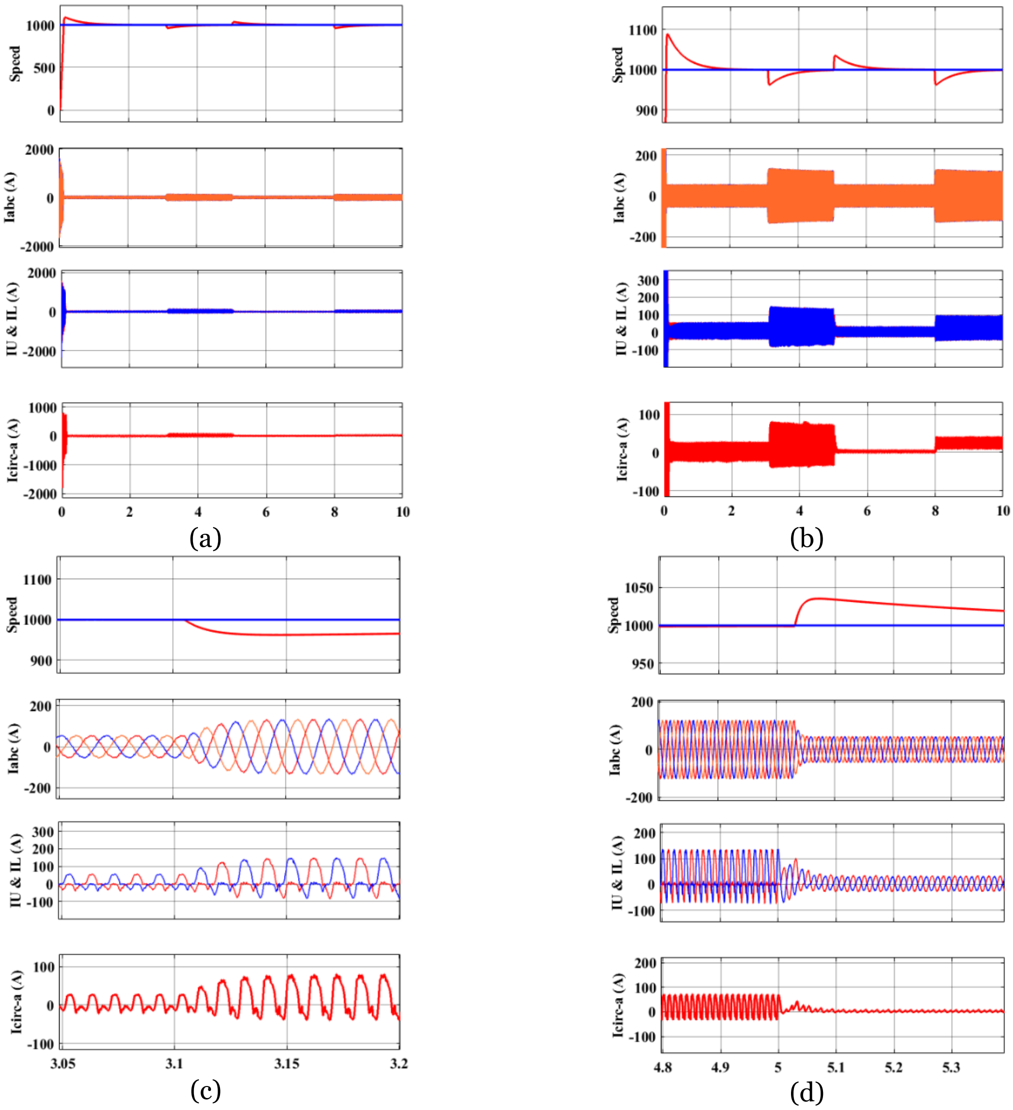

Figure 5. MMC fed Induction motor drive operation under constant speed with varying load condition (a) Speed, Iabc, IU & IL and Icirc-a, (b) Zoom view of waveform shown in (a), (c & d) Effect of sudden change in load on MMC parameter

Figure 4 shows the waveform of MMC fed induction motor drive under constant load with varying speed operation. Figure-4 (a & b) shows the speed, three phase line current, upper and lower arm current and circulating current waveform and it enlarge view. It is observed from the waveform that during the speed transient, circulating current remain unaffected due to proposed control algorithm. It is also evidence that there is a significant reduction in circulating current in proposed scheme as compared to conventional scheme.

Figure 5 shows similar operating condition, but speed is constant with varying load condition. In both case, improvement in circulating current is clearly visible using proposed scheme.

Figure 6 shows MMC fed induction motor drive under constant load of 5000 N-m with low frequency 5 Hz operation. In the low-speed operation also, proposed method can maintain the magnitude of circulating under limit.

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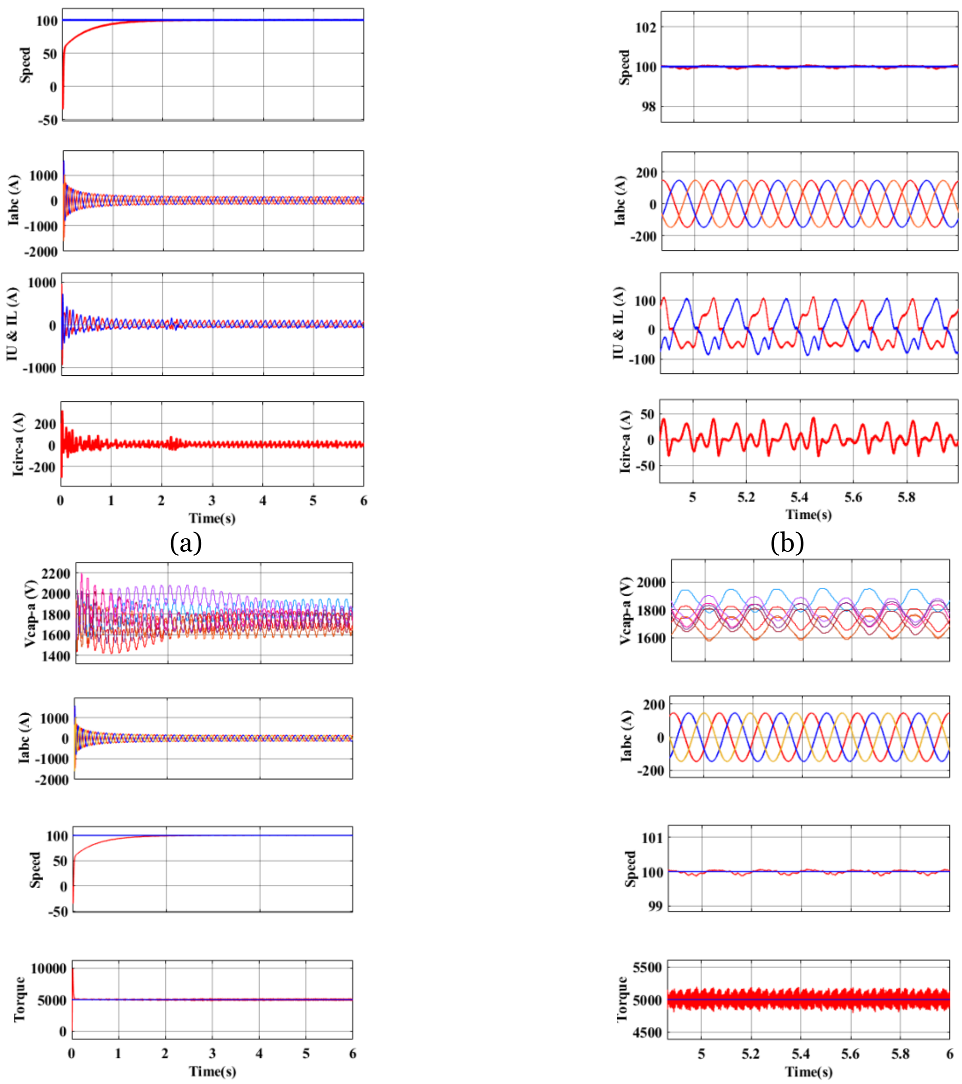
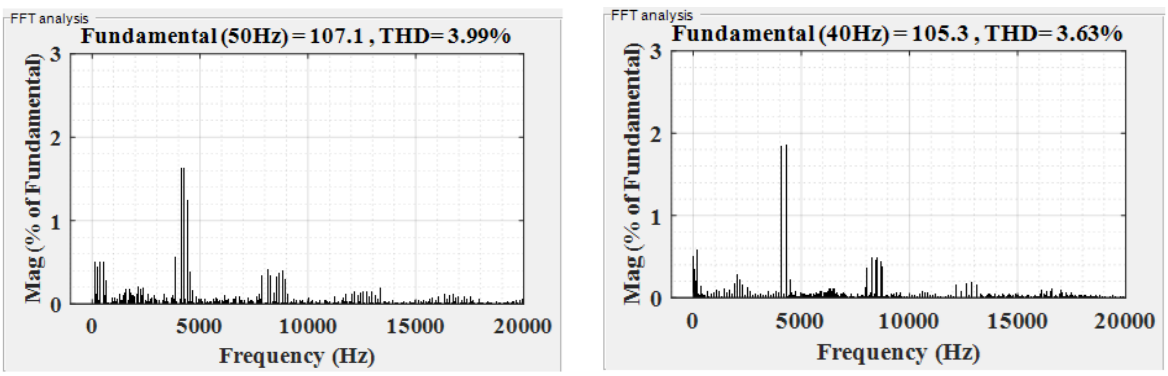


Figure 6. MMC fed Induction motor drive operation under constant load-5000 N-m and 5Hz operation (100 rpm) condition (a) Speed, Iabc, IU & IL and Icirc-a, (b) Zoom view of (a), (c) Effect of low frequency operation on speed, Iabc and Vcap for constant torque condition, (d) Zoom view of waveform shown in (c).

Figure 7 shows the %THD analysis of rated frequency to low frequency operation. It is also observed from the %THD analysis that reduction in circulating current from the line results in smooth and quality current waveshape. It also enhances the peak device current rating as well as rms value of device rating.



(a) (b)

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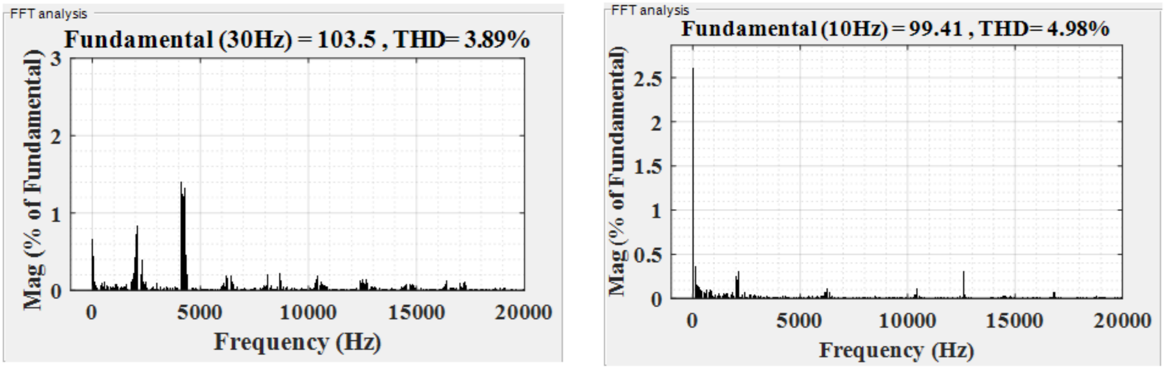

(c) (d)

Figure 7. %THD analysis of line current under rated to low frequency operation (a) 50 Hz, (b) 40 Hz, (c) 30 Hz and (d) 10 Hz

CONCLUSION

In this paper, a new circulating current control technique is proposed. In MMC fed induction motor drive application under entire speed range of operation, it is observed that large amount of circulating current is produced between the arms of MMC. Moreover, it leads to increase in arm current peak as well as device rating and power losses in the MMC. To reduce the effect of circulating current under the entire speed range of MMC, proposed technique could be able to provide good amount of reduction in circulating current as well as maintain the total harmonic distortion under limit. Also proposed technique can deliver the robust dynamic operation of MMC fed induction motor drive.

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