Abstract

Index Terms: Pulse-width modulation, harmonic currents, pulsating torque, hexagonal voltage space vector-based PWM, do-decagonal voltage space vector PWM, switched capacitor filter, hybrid PWM, advanced bus clamping sequences, open-ended winding induction motor, current THD, RMS torque ripple, capacitor sizing, lower capacitance, voltage fluctuations, feed-forward compensation technique, dominant capacitor voltage ripple, capacitor voltage control loop, phase voltage harmonic spectrum.

The induction motor (IM) motors are widely used in various applications, such as railway propulsion, oil and natural gas, compressors, cranes, pumps, material handling, aircraft systems and ships etc. Some of these applications require precise speed control. However, the motor control operation is achieved by using a voltage source inverter (VSI). The VSI requires a pulse-width modulation (PWM) technique to control the fundamental voltage and frequency. However, the PWM operation results in the generation of the fundamental voltage and the harmonic voltage. The harmonic voltage results in harmonic currents and pulsating torque in the motor drive. The harmonic currents increase the copper losses inside the machine, leading to an increase in heat and thereby reducing the machine's lifetime. The pulsating torque results in increased stress on the shaft and bearings, requiring frequent maintenance. Therefore, this research aims to minimise the harmonic currents and pulsating torques in the motor drive.

There are various PWM techniques available in the literature to mitigate harmonic distortion and pulsating torque in IM. Sine-triangle and hexagonal voltage space vector-based PWM (HSVPWM) techniques are more popularly employed on the IM using a 2-level 3-phase VSI. All HSVPWMs give 15.5% higher fundamental voltage for the same DC bus than sine-triangle PWM. The hexagonal voltage space vectors PWM techniques generate 90.58% of the maximum fundamental voltage in the linear modulation range. However, increasing the DC-bus utilization further causes the inverter to go into overmodulation regions, causing significantly lower-order voltage harmonics (5^{th},7^{th},11^{th}..). These harmonic voltages give rise to harmonic currents and produce pulsating torques (6^{th},12^{th}...). Hence, to utilise the full

DC bus voltage and to mitigate harmonic effects, do-decagonal voltage space vector PWM (DSVPWM) is employed on open-end winding induction motor (OEWIM).

This DSVPWM has the benefit of the removal of all $6h \pm 1$ (where h is an odd number) harmonics in the complete modulation ranges, including overmodulation regions. The DSVPWM improves the linear modulation range to 97.7% of the maximum fundamental voltage. However, implementing this PWM requires two inverters connected on each side of the OEWIM terminals. Inverter-1 is fed from the DC source (Vdc), whereas inverter-2 is linked to the capacitor. The inverter-2 acts as a switched capacitor filter (SCF). This SCF suppresses the harmonics from inverter-1. Hence, the SCF-fed OEWIM topology is chosen to employ DSVPWM in this thesis. Though this PWM and topology has been explored in the literature, the torque and current ripple studies has not been explored for the DSVPWM employed on OEWIM.

In this thesis, detailed analytical expressions for the RMS torque and current ripple are derived for the OEWIM using DSVPWM. This analytical expression was further validated with simulation and experimentation over wide ranges of speeds and compared with existing conventional space vector PWM (CSVPWM). The analytical, simulation and experimental results demonstrated that DSVPWM has better current harmonic performance than CSVPWM throughout the modulation range. The RMS torque ripple performance is comparable to the CSVPWM in low and medium speed ranges, and it improves only after the fundamental frequency (f_1) of 45 Hz. Furthermore, RMS torque ripple analysis was also conducted under loaded conditions, and it was found that DSVPWM improves the torque ripple performance over CSVPWM after f_1 of 40 Hz significantly.

The analytical studies and results demonstrate that DSVPWM has the same RMS torque ripple performance as CSVPWM in the linear modulation range under no-load conditions. To improve the torque ripple performance further on the OEWIM, compared to the existing DSVPWM, a hybrid PWM switching sequence is proposed. This hybrid PWM sequence is a combined sequence of the DSVPWM and advanced bus clamping sequences. Analytical, simulation, and experimental studies demonstrate that the hybrid PWM exhibits equivalent RMS torque ripple performance to DSVPWM at low and medium speed ranges. However, it significantly improves at a higher speed range (f_1>40 Hz), with a marginal improvement in the current THD at higher speed ranges.

The implementation of DSVPWM requires two inverters; inverter-1 is connected to a DC source, and inverter-2 is fed from the capacitor; inverter-2 acts as a switched capacitor filter. The optimum capacitor sizing for the SCF is important from the perspective of cost and size of the converter. A key challenge with the DSVPWM-fed OEWIM drive arises when operating with lower capacitance on the inverter-2 side, as it causes significant voltage fluctuations even with small speed deviations. These fluctuations may exceed the capacitors voltage rating. To mitigate these voltage fluctuations, a feed-forward compensation technique is proposed in the capacitor voltage control loop. Furthermore, this study also demonstrates the effect of the dominant capacitor voltage ripple on the resultant phase voltage harmonic spectrum of the inverter. Additionally, a procedure to reduce the capacitance while achieving good harmonic performance is also analysed. The proposed method is experimentally validated using an OEWIM of 415V, 4 poles, and 2.2 kW, demonstrating its effectiveness.

In conclusion, the main contribution of this thesis regarding the analytical expressions of torque and current ripple is derived for OEWIM using DSVPWM, the hybrid PWM technique is proposed to enhance the torque ripple performance of the OEWIM, the optimum capacitor sizing for SCF has been done, a possible capacitor size reduction method is also shown for SCF-fed OEWIM drives, and a brief outlook of future work is discussed.