Performance analysis of a Scalar Coupled and Decoupled PWM Technique for a Three Level symmetrical Dual Inverter Fed OEWIM Drive

Kavya Venugopalan*[1], Jegathesan V [2] , M. Harsha Vardhan Reddy [3]

[1] Department of Electrical & Electronics Engineering, Karunya Institute of Technology, Coimbatore, Tamil Nadu, India
[2]Department of Electrical & Electronics Engineering, Karunya Institute of Technology, Coimbatore, Tamil Nadu, India
[3] Department of Electrical and Electronics Engineering, G. Pulla Reddy Engineering College, Kurnool, Andhra Pradesh,
[1]kaviyavenu2020@gmail.com

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Abstract: Dual inverter fed IM drive is commonly employed in EV applications. In this application, SVPWM based PWM generator was utilised. However, they produce a high common-mode voltage(CMV). Because of this, bearing of motor will be affected and in turn, results in EMI problems. Hence, to overcome this problem, this work introduced a novel PWM generation techniques named scalar coupled and decoupled PWM topology to control a three-level symmetrical DI fed OEWIM. Hence, to find out the effectiveness of the proposed topologies, its operation is examined under both continuous and discontinuous modes of operation using MATLAB simulation. From the acquired results, it is concluded that this coupled PWM topology topology exhibits reduced CMV and harmonics when compared to decoupled topology.

Keywords: Carrier Comparison approach, Common-mode Voltage (CMV), Continuous PWM (CPWM), Coupled PWM, Discontinuous PWM (DPWM), Modulation Index (MI), Asymmetrical dual inverter

1. Introduction

Now a days, Induction Motor (IM) based drives are widely implemented in various applications such as EV, EHV, etc.,. This is because of its low maintenance and lower weight-volume ratio. However, this drive has to generate adjustable voltages at variable frequency. But it is not practically possible, because inverters output voltage is not a sinusoidal one[1-5]. Hence, to overcome this problem, a large number studies have been carried out so far to obtain a pure sinusoidal voltage with less harmonics. As a result of this, numerous methods for the improvement in the design structure of an IM have been introduced. Thus, various topology of MLI such as NPC, CMLR and FCR have come into existence [6-8]. This, in turn, results in lower harmonics with increase in levels. Consequently, while increasing the levels, the maintaining stability at the input side requires more control. This will increase the complexity of the system. To avoid this problem, two level 3ϕ inverters are introduced [15]. They are arranged in cascaded manner and thus, form a Dual Inverter (DI). In this, the neutral point of star is removed from squirrel cage IM and as a result, all the 6 terminals are in open condition. This is termed as OEW IM. Such type of configuration is carried to obtain reduced CMV. On the basis of DC voltage applied to the inverter, this DI configuration can be categorized into

- Asymmetrical and
- symmetrical DI's.

After deriving the modifications in structural arrangement of IM [9-13], the only way to increase an output voltage of the inverter is the development of novel PWM strategy. Thus, the developed PWM should be in such a manner to reduce the CMV of the inverter.

Majority of the researchers concentrated with SVPWM for OEW [19, 23]. In (18), SV voltages have been selected from 64 vector voltages to achieve better control over IM. Further, classical barrier based PWM is also developed for OEM [20]. Simultaneously, simple PWM method called carrier based PWM topologies have been attempted by [14]. The author discussed about the effect of different methods (ERF, URP, MDS) over IM.

The PWM signals can also be generated using both continuous and discontinuous modulating signals. But it will lead to have many problems like EMR and vibration etc., Hence, to suppress the CMV, new control methods for DI using PWM's are recommended in [16,17]. In this proposed PWM methods, the triple harmonics was eliminated by utilizing space vector combinations.

A triangular PWM was proposed for DI to increase the reliability and efficiency of the system. A reduced SVPWM switching strategies were analyzed for DI [20, 21]. 12-Sided Polygonal Voltage SVPWM topologies were adopted to improve the voltage of DI[22] .

In [26] by choosing a particular ratio of the dc voltage sources, output phase voltage with reduced harmonic content was obtained. In [27], a method based on the enhancement of an output voltage range of an inverter is obtained by increasing the operating speed range of an OEWIM. In [28], a modulation strategy was introduced in which the pulse time of one of the inverters is varied to reduce the voltage THD in DI. A unified SVM strategy was proposed in [29]. For reducing the switching losses in a DI, an SVM strategy was proposed in [30], in which sector identification is not necessary. When compared to other PWM techniques, the switching losses decreased to 50% in this topology.

These two-level inverters can be regulated either independently or dependently. Considering this, PWM techniques are classified into decoupled and coupled PWM, respectively [24]. In SV based decoupled PWM method for DI, a three-level output voltage is obtained when 64 switching states are generated. These 64 switching states are made by considering eight switching states of both the inverters that can be controlled independently[25]. In SVPWM algorithm, the reference voltage as well as sector information must be calculated at each instant. Hence it is an extremely complicated method. To reduce the complexity of SVPWM, a scalar method is introduced. Different control methods based on the scalar approach is presented a lower MI to reduce the CMV.

In all the discussed control strategies even though there was a reduction in ripple and switching losses, CMV had a high value for the entire modulation index. These above said problems can be eliminated by varying the switching frequency. Hence, this work introduced a concept of coupled and decoupled algorithm using scalar approach to reduce the CMV of an inverter unit. To evaluate the effectives of the proposed topology, simulation studies were carried out using MATLAB software.

2. Design of symmetrical Dual Inverter Configuration

In the symmetrical topology of a DI, the inverter connected to the IM is supplied with same dc source voltage. Figure 1 shows a symmetrical three-level inverter developed by attaching two two-level inverters connected to an OEWIM.

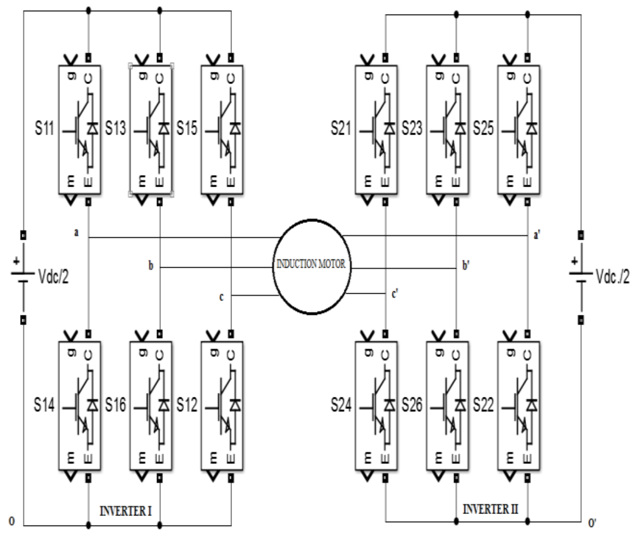


Fig. 1: Symmetrical Dual Inverter configuration

Coupled PWM technique in scalar approach

The main function of PWM technique is varying both an output voltage and frequency. However, they are varied by the switching approach employed in it. In this PWM generation, a reference signals can be carried out by two different approaches namely

(1) Scalar approach

(2) Space Vector approach.

In this work, Scalar approach is implemented to produce reference signal. Thus this topology reduces the complexity in switching states selection.

According to this topology, the reference signal is given by

$$V_a = V_m \cos(\omega t)$$
$$V_b = V_m \cos\left(\omega t - {}^{2\pi}/_{3}\right) \quad (1)$$
$$V_c = V_m \cos\left(\omega t - {}^{4\pi}/_{3}\right)$$

In this, a zero-sequence signal is summed up with the reference signal to improve the quality of output voltage and current quality and it is depicted in figure 2. However, the harmonic distortion is significantly lowered by this addition.

$$V_i^* = V_i + V_{zs} \qquad i = a, b, c \qquad (2)$$

$$V_{zs} = \frac{V_{dc}}{2}(2a_0 - 1) - a_0 V_{max} + (a_0 - 1)V_{min} \qquad (3)$$

Here,

V_{max} & V_{min} - Instantaneous maximum and minimum values of the reference signals.

V_{dc} - input voltage

a_0 – constant (0 to 1).

By varying the value of 'a_0' different modulating signal can be generated. This in turn determines the mode of operation, continuous or discontinuous.

Thus, by selecting *ao* value with these conditions

Vmax + Vmin < 0, then *ao* = 0

Vmax + Vmin ≥ 0, then *ao* = 1, modulating signal of discontinuous PWM technique can be generated.

At *ao=0.5,* this topology undergoes continuous mode of operation.

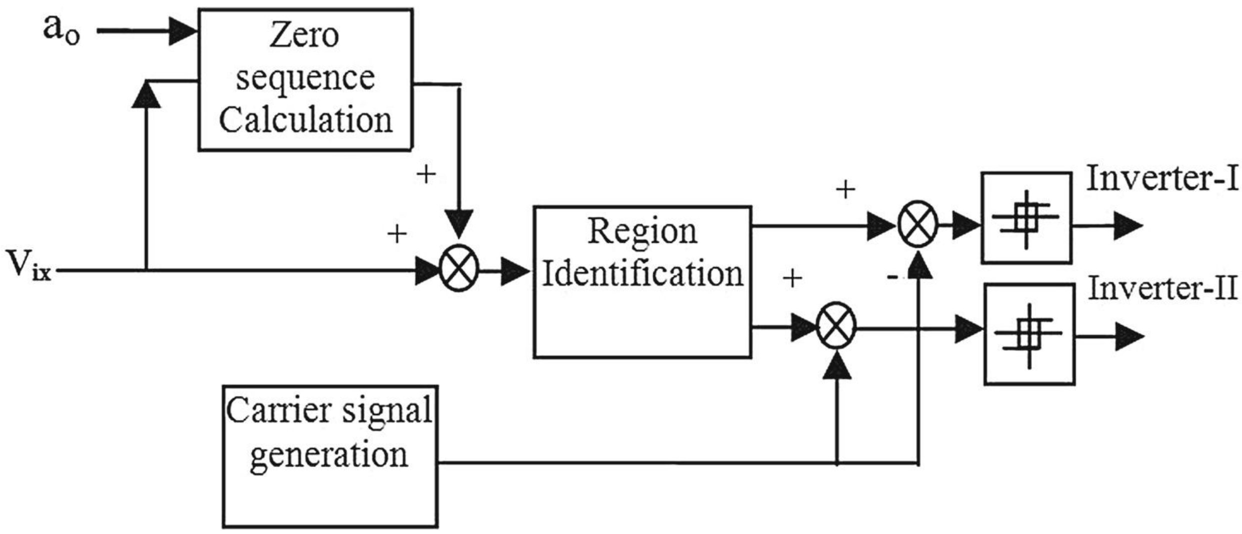


Figure 2. Schematic diagram of coupled PWM for an Asymmetrical DI Configuration

Proposed Decoupled PWM Scheme

This scheme controls the two level inverters independently. Thus, the controlling of two inverters separately , results in reduced switching loss along with less CMV in DI system. The instantaneous reference voltage of inverter I and II can be represented as follows,

.

$V_R = V_m \cos(\omega t)$

$V_Y = V_m \cos(\omega t - 120^\circ)$

$V_B = V_m \cos(\omega t - 240^\circ)$

$V_R = V_m \cos(\omega t - \alpha_1^\circ)$

$V_Y = V_m \cos(\omega t - 120^\circ - \alpha_1^\circ)$

$V_B = V_m \cos(\omega t - 240^\circ - \alpha_1^\circ)$

In this,

α_1 – switching angle of Inverter 2 with respect to Inverter 1. ie. If the angle of inverter 2 is 60, then for inverter 1 it will be zero and their switching sequences are depicted in figure 3.

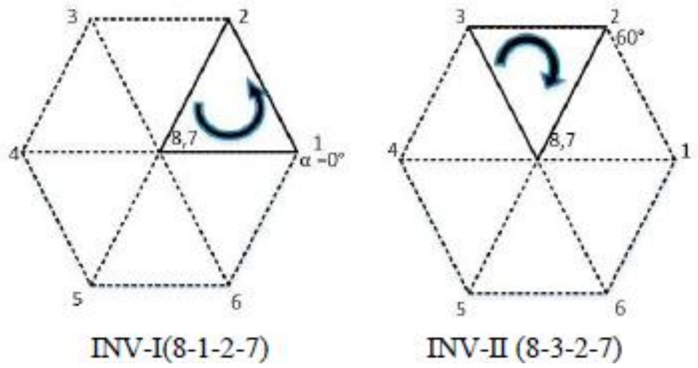


Fig.3 Switching sequences of the individual inverters using PWM1 method for α1=60°

Thus, by varying the switching sequences of the DI results in formation of various switching combinations. Hence, it results in reduced CMV and its combinations is depicted in table 1.

Table-1 Switching combinations of the dual inverter with common mode voltage levels in one sampling period (TS)

S.No	INV-II Switching Angle	Switching Sequences	CMV Levels
1	$\alpha_1 = 60^0$	8-1-2-7/ 8-3-2-7	$+V_{dc}/6$,0, $-V_{dc}/6$(3)
2	$\alpha_1 = 120^0$	8-1-2-7/ 8-3-4-7	0
3	$\alpha_1 = 180^0$	8-1-2-7/ 8-5-4-7	$+V_{dc}/6$,0, $-V_{dc}/6$(3)
4	$\alpha_1 = 240^0$	8-1-2-7/ 8-5-6-7	0
5	$\alpha_1 = 300^0$	8-1-2-7/ 8-1-6-7	$+V_{dc}/6$,0, $-V_{dc}/6$(3)
6	$\alpha_1 = 360^0$	8-1-2-7/ 8-1-2-7	0

Similarly, the some of the variation in switching sequence to eliminate/reduce CMV is depicted in figure x.

According to figure 3, inverter 1 is fixed at sector 1 and inverter 2 is on sector 2. Under this position, CMV is about $+V_{dc}/6$, 0 and $-\frac{V_{dc}}{6}$, similarly, when the inverter 2 is positioned at third sector, CMV becomes zero. At the same time, the switching time of two inverters should not be same. ie. The switching time of inverter 2 is delayed in one half of the T_s. Whereas in the next half of the σ_s , it should be advanced when compared to inverter 1. This, results in generation of CMV. Hence, the main objective of this work is reduced the CMV of a DI system. Hence, in this work, the inverter 2 is phase shifted ahead of inverter 1 and is about 180°. Thus, both the inverters are controlled independently.

3. Results and discussion

Thus, to examine the performance of this proposed PWM algorithm for symmetrical DI fed IM drive, simulation is carried out using MATLAB/Simulink environment. A voltage of 270 V is applied to inverter-1 and 2 which forms an effective DC input voltage of 540 V for the symmetrical DI configuration. The f_s is about 3 kHz.

Performance Under Decoupled PWM topology

In this study, both the continuous and discontinuous modes of operations are discussed. The modulating signal generated for continuous conduction mode and pulses generated for inverter I and inverter II using scalar decoupled PWM technique is depicted in figure 4.

When considering the discontinuous mode of operation, the value of a_0 is either 1 or 0 in the zero-sequence signal equation. On the basis of the given condition, the value of a_0 in the zero-sequence signal is chosen and discontinuous mode of operation takes place.

$V_{max} + V_{min} < 0$, then $ao = 0$ and

$V_{max} + V_{min} \geq 0$, then $ao = 1$

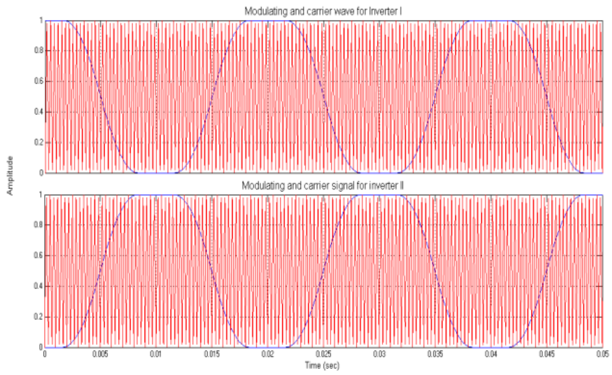
In this work, six different modulating signals are generated in the discontinuous mode of operation. In decoupled algorithm four different modulating signals are produced using the above condition. The modulating signals may be either clamped at 0 or 1 during discontinuous mode.

For each modulating signal, simulation is carried out to observe speed, torque, stator current, phase voltage, THD of current and voltage, and common-mode voltage for different modulating indices (0.3 to 1.154). The modulation index is varied from 1.154 to 0.3.

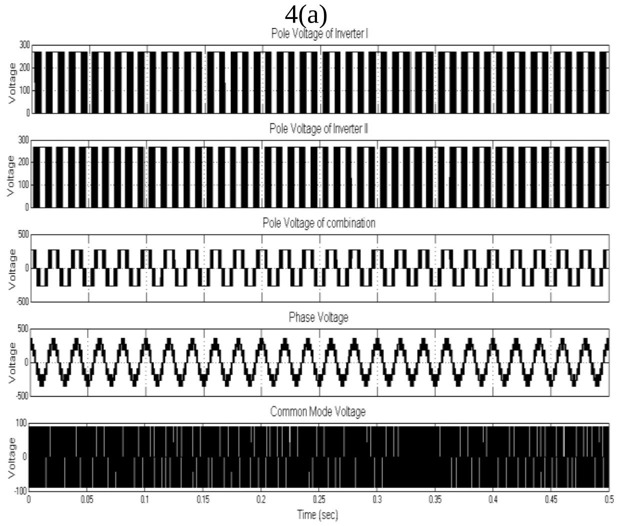
Different switching patterns are obtained for both the inverters, for each modulating signal generated. Hence pole voltage for the different modulating index is also different. From the shape of the phase voltage, it is clear that there are three levels of voltage -270 ($-V_{dc}/2$), 0, +270 ($+V_{dc}/2$). At higher modulation index, the starting current is about 52 A and at lower modulation index, its value is about 24A.

Discontinuous mode of operation

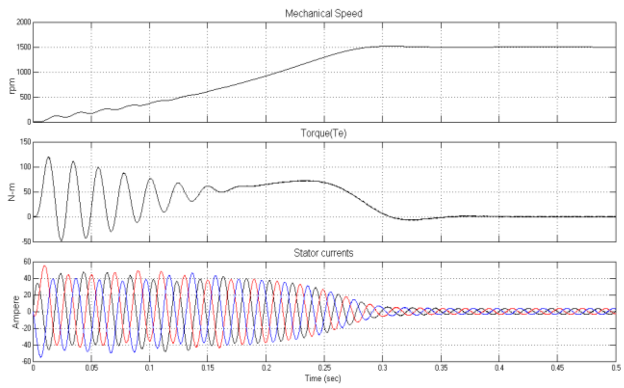
Thus, by varying the modulation index value from 0.3 to 1.154 for the six different modulating signals in the discontinuous mode of operation and is depicted in figure 4.



4(a)



4(b)



4(c)

Fig. 4: Discontinuous mode of conduction with frequency 50Hz. Figure (a) shows the modulating waveform for both inverters (b) shows effective pole voltage, phase voltage and CMV (c) shows the speed, torque, and stator current of OEWIM

Under this condition, the motor speed is found to vary from 400 rpm to 1500 rpm. It is clear that the maximum starting torque is obtained when the modulation index lies between 0.8 and 1. For the high and low value of modulation index, the torque value reaches a steady-state condition when the time is 0.3 seconds, and for modulation index between 0.5 and 0.9, the steady-state torque is attained at 0.2 seconds.

Continuous mode of operation

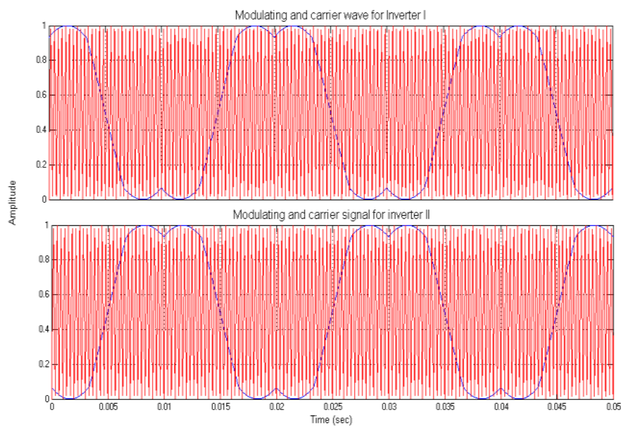
A continuous mode of operation is realized using decoupled PWM technique and is discussed with one modulating signal. To generate this modulating waveform a_0 in the zero-sequence signal is given a value of 0.5. The modulating signal is continuous and generates different switching pulses for the inverters, which in turn produce different pole voltages.

The CMV of the DI for the different modulating index is constant. By increasing the modulating index, the motor speed decreases. It is found that the speed can be varied from 400 rpm to 1500 rpm. For high and low modulation index values the torque reaches a steady-state value at 0.35 seconds, and for modulation index between 0.5 and 0.9, the steady-state value is attained at 0.2 seconds.

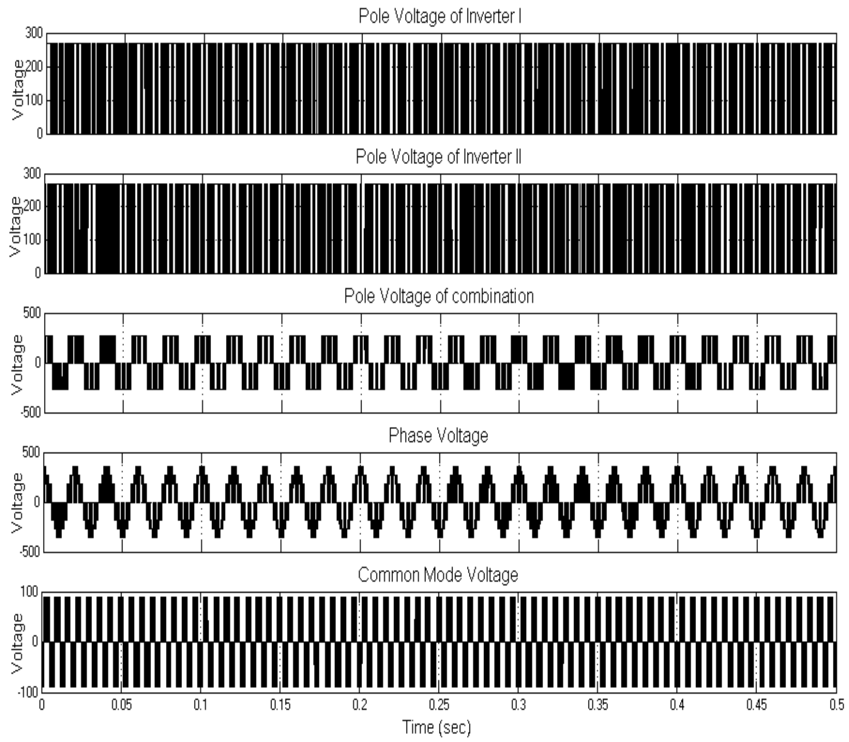
For continuous mode of operation when different modulation index are taken into account and hence, high value of starting current about 52A is obtained and minimum value is about 31 A.

From the analysis, it is concluded that while increasing the modulation index, the starting current also increased. Thus, the THD value of stator current ranges between 1.22 and 13.55.

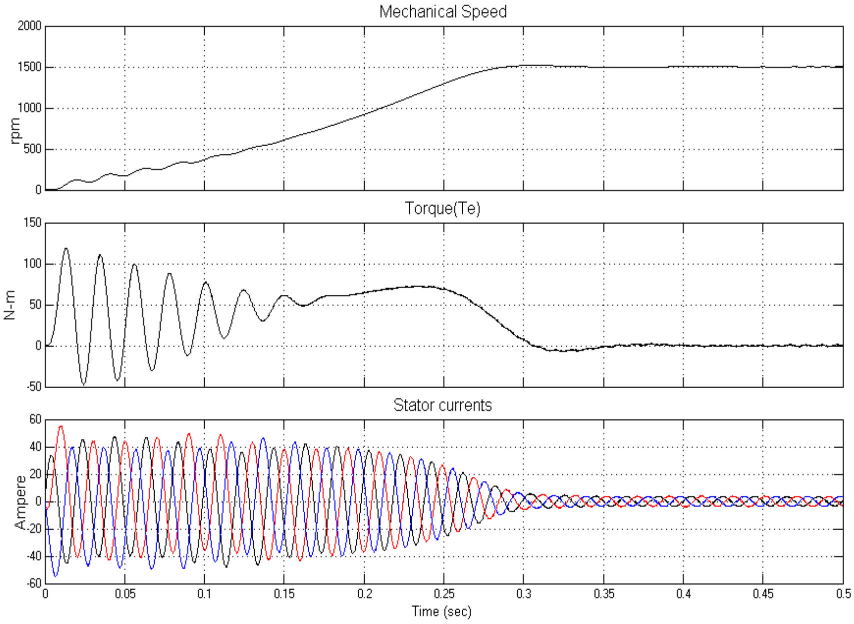
Modulating waveforms for the continuous mode of operation when a_0=0.5 and M=1.154 are shown in fig 5(a) and the corresponding pole voltage, phase voltage, CMV is shown in fig 5(b). The speed, torque, and stator current of OEWIM are shown in fig 5 (c)



5(a)



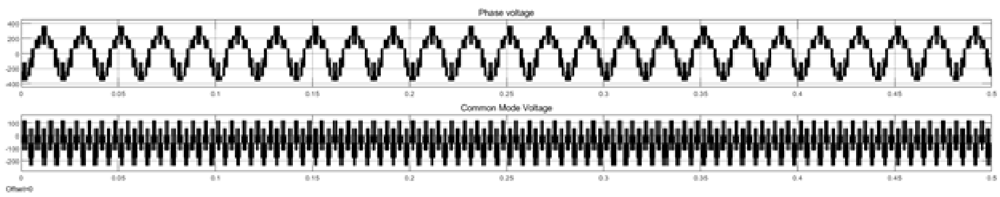
5(b)



5(c)

Fig. 5: Continuous mode of conduction with frequency 50Hz. Figure (a) shows the modulating waveform for both the inverters (b) shows net pole voltage, phase voltage and CMV (c) shows the speed, torque, and stator current of OEWIM

Performance Under coupled PWM topology



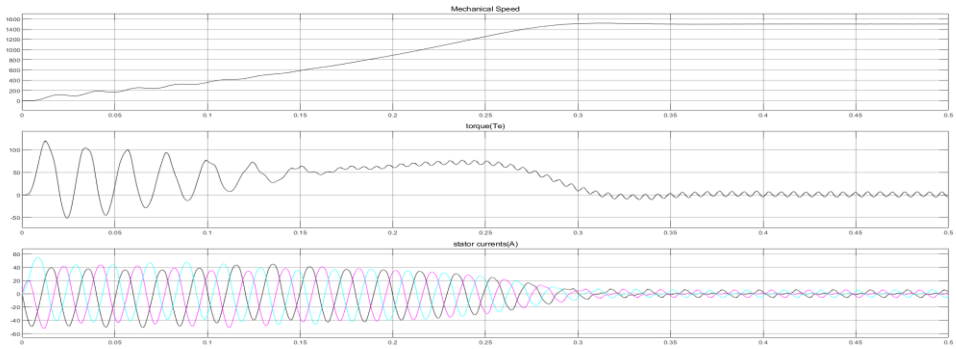


Fig. 6: Continuous mode of conduction (a) phase voltage and CMV (b) shows the speed, torque, and stator current of OEWIM

From the above figure, it is observed from individual pole voltages, that the inverter 1 and inverter-2 is operated with low frequency. The stator currents, torque and speed of IM with coupled PWM algorithm is displayed in fig 6b. From the figure 6b, it is concluded that with this proposed PWM algorithm, magnitude of torque ripple is reduced significantly.

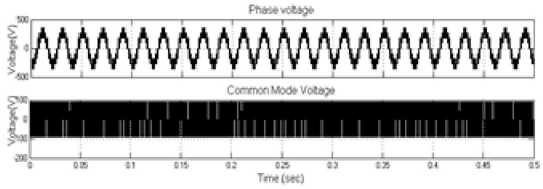
It is also observed that the proposed PWM technique results in small voltage step magnitude but results in higher number of voltage steps. Hence, the output voltage approaches to sinusoidal and thus results in lower harmonics at the output voltage. Thus, it is concluded that the coupled PWM topology is superior than the conventional SVPWM in reducing THD and thereby improves the quality of the output voltage. It also result in reduced switching loss.

Discontinuous mode of operation

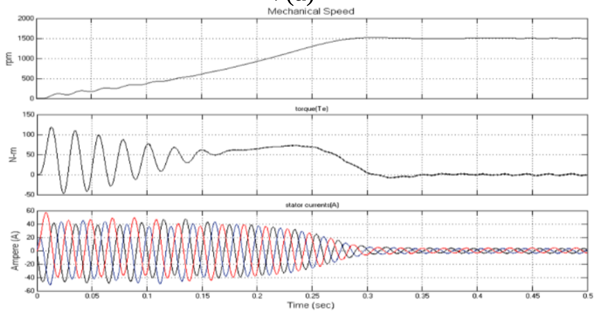
By varying the modulation index value from 0.3 to 1.154 for the six different modulating signals in the discontinuous mode of operation, the speed of the motor is found to varies from 400 rpm to 1500 rpm. As a result, the CMV of the inverter also varies with the modulating index. Thus, the variation in the CMV is about -90 to +90. Similarly, the THD of the stator current also increase with modulation index.

From the analysis, it is observed that while varying modulation index from 0.8 and 1, maximum starting torque is obtained and it reaches its steady-state condition at 0.35 seconds, and for modulation index between 0.5 and 0.9, the steady-state torque is attained at 0.25 seconds.

The discontinuous mode of operation is shown in Fig 7. Fig 7(b) displays speed, torque and stator current of OEWIM.



7(a)



7(b)

Fig. 6: Discontinuous mode of conduction (a) pole voltage/phase voltage /CMV (b) speed, torque, and stator current

From the above, it is observed that both inverter 1 and 2 operates at lower frequency. The stator currents, torque and speed of IM with coupled PWM algorithm is depicted in fig 7b. From the figure 7b, it is concluded that with this proposed PWM algorithm, magnitude of torque ripple is reduced significantly.

Comparative Analysis

Table 2. Comparative analysis of THD (V)

Topology	**THD(V)**
Decoupled	56.18
Coupled	30.27

Thus, a comparative analysis of THD (V) with other topology is depicted in table 2. From the table, it is observed that the proposed coupled PWM exhibits lower THD when compared to proposed decoupled topology. Hence, it is concluded that the proposed coupled methodology more suitable for IM drive applications.

4. Conclusion

In this work, to enhance the efficiency of the DI, two different PWM topologies namely scalar coupled and decoupled PWM topology are formulated. From the results, it is inferred that with the coupled PWM technique for dual inverter fed induction motor drive results in reduced THD. This leads to the lowering in acoustic noise and EMI with nearby systems. As the magnitude of THD is reduced and hence a reduction in both current and torque ripple is achieved. Also, it is concluded that scalar based coupled PWM techniques are of easy implementation for real-time application when compared with decoupled topology.

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