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Control of Open-End Induction Motor by Multi-Objective GA based Selective Harmonic Elimination PWM to reduce Zero Sequence Currents and Torque Ripples

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Abstract

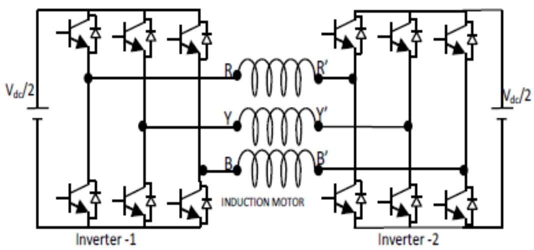
A double inverter powered induction motor with open stator winding has few benefits, including excessive error forbearance functionality, great flexibility and lesser rating of DC input voltage etc. For this Configuration, two types of Modules can be implemented: they are Non-Isolated DC link and Isolated DC link. In these two, Non-Isolated DC link is a good choice due to effective DC-link utilization and ruggedness, which is very beneficial in many applications. However, this module produces more zero sequence currents (Z-SC) by means of common mode (CMMD) voltage, which flows through DC bus. The circulation of Z-SC must be as little as possible since it merely rises the amplitude of currents in all phases. High ripple frequency of currents and torque, in addition results in extra loss, which not only reduces the efficiency, but influences loading ability and quickens the aging of drive. The Triplen harmonics can be defined as harmonics with integer of three times the frequency at fundamental, when they are in Phase in all Phases forms the Z-SC. In this paper, a novel SHE method is chosen to target Triplen harmonics in Single DC Source Module (Non- Isolated) and holding preferred fundamental quantity, which aids in improving the torque handling ability of the motor. In addition, the investigation of dual inverter fed OEW-IM with both common DC source as well as separate DC sources is also explored in the SHE for different number of switching angles and variable Modulation Index (MI) towards the torque ripples and Z-SC reduction given. The foremost challenge related to the SHE method is resolving a set of higher order nonlinear equations with a number of variables. A Multi-objective GA method is provided for that challenge which effects the reduction in Z-SC so that torque ripples will be minimized. Moreover, the novel SHE method reduces the number of harmonics better than the conventional SHE, which further decreases TH-D with decent fundamental quantity. For validation, the essential mathematical formulations and simulation results are presented.

Keywords: Open-end winding induction machine (OEW-IM), Zero sequence currents (Z-SC), Torque ripple, Selective harmonic elimination (SHE), Triplen Harmonics.

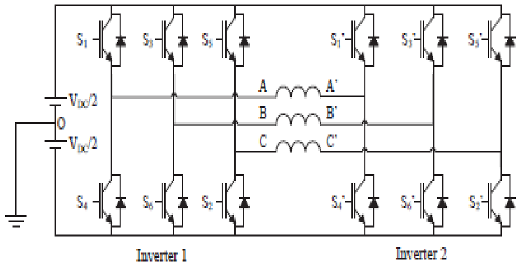
1. Introduction

Compared with the customary single end power supply, the benefits of the OEW-IM with dual end inverters are the regulator of great flexibility, the fault forbearance and redundancy of arrangement [1]. The output voltage could be two times higher than a single inverter [2]. Dual inverter OEW-IM arrangement compared with the midpoint clamped 3L inverter, does not simply exclude necessity of clamping diodes, decreases price, no DC mid-point, and there is no midpoint equilibrium difficulty [3]. Related to the FC 3L inverter, reduces the capacitance requests [1]. Furthermore, double inverter OEW-IM enables to appreciate the hydrides drive with diverse sources of energy; therefore, it is a superlative dynamic structure for modern energy automobiles [2].

OEW-IM can run through a single conjoint DC bus or autonomous DC bus, as given in Fig. Figure 1.b. If the inverters feeding machine undertake the independent configuration of DC bus, Fig. Figure 1.a. there is not any circlet for Z-SC between the inverters. Nevertheless, two inverters side output form motor shaft voltage, it will yield current through shaft and stimulate in effect motor bearings life span. Moreover, the isolated DC bus configuration needs two separate batteries, this turns to the aforementioned restricted applications. On the other side, the inverters arrangement with shared single DC bus scheme entails a single source, which makes simpler hardware design and simplifies employment of the scheme. However, single DC bus permits an occurrence of zero sequence paths inside the primary circuit. It abolishes and restraints that the addition of 3phase currents results zero. If the actual procedures have not regulated the circulation, it may produce greater Z-SC, leading to more losses in motor and ripples in motor torque, it's not advantageous to the improvement of running enactment of the machine control scheme [4]. Hence, the Z-SC issue in the OEW-IM arrangement by a single shared DC bus causes bottleneck problem that can be difficult in the usage of this structure [5-8].



(a)



(b)

Figure 1: OEW-IM structure with (a) Isolated DC Links (b) Common DC Link

Furthermore, the motor lifespan will decrease when the motor is not capable of tolerating the unnecessary temperature produced for the system to operate with torque at full load. In order to suppress Z-SC suggestions a common mode chokes are used [9], to compute the error voltage the current control loop is altered [10], PWM schemes which do not produce zero sequence voltages [11] then control principles to reduce Z-SC [12]. The modelling of an OEW-IM with stationary frame is given by equations (a)-(e).

$$V_s = R_s i_s + \frac{d\lambda_s}{dt} \quad \text{(a)}$$

$$r_r i_r + \frac{d\lambda_r}{dt} - j\omega_r \lambda_r = 0 \quad \text{(b)}$$

$$\psi_s = L_s i_s + L_m i_r \quad \text{(c)}$$

$$\psi_r = L_r i_r + L_m i_s \quad \text{(d)}$$

$$T_e = 1.5P(\lambda_{sd} i_{sq} - \lambda_{sq} i_{sd}) \quad \text{(e)}$$

The two foremost reasons in favor of circulating currents are voltage drops at semiconductor devices, which carries current and dead time castoff to overcome occurrence of short circuit in Pulse Width Modulated drives. The said things identified as reason for distortion in waveform of a traditional Pulse Width Modulated AC drives [13], [14] could also lead to instabilities and voltage loss. More than a number of solutions have been suggested to compensate for these distortions [15-20] in traditional drives with $DorY$ connections. Further, dual inverter is not upfront in the occurrence of the currents Z-SC circulating in inverters. This increases the stresses in current and increases the inverters conduction losses across their switching devices. High amount of Z-SC circulating (Z-SCC) are challenging because they push operators to increase the size of inverters and lessen the efficiency of inverter [21-23].

The efficacy of the suggested Z-SCC reduction technique, by a Selective Harmonic Elimination PWM (SHE-PWM) is given in this paper [24-30]. The fundamental principles of SHE-PWM for a dual VSI fed OEWIM are revised, and then, the recommended SHE method is established for dual inverter fed OEW-IM that adjusts further to permit for the removal of Z-SCC in an OEW-IM that lessens the ripple content in Motor Torque. An Investigation of Z-SCC, Torque ripple and TH-D are given for different modulation indices and number of switching angles. The achievability of the suggested methodology in removing harmonics of inverters voltages, reducing Z-SCC & Torque Ripples is established by the results.

2 Problem Formulation of Open-Ended Induction Motor Fed by Dual Inverter

A systematic approach to the problem is being developed, which includes a set of general scientific methods: analysis, synthesis, induction, deduction,

In OEW-IM, the sum of the motor phase voltages never equals zero, henceforth here exists zero sequence voltages. Zero sequence voltages produce a high in the motor phase windings, which is harmful to the switching devices and the motor itself. To overwhelm the zero-sequence components in the motor phases, each inverter is functioned with an isolated DC power supply, but it is not good for hardware enactment. Therefore, the said difficulty arises when two inverters operate by a single DC source which is shown in Fig Figure 2.

Due to the fact that the addition of OEW-IM 3Ø voltages is certainly not zero, henceforth here the Zero Sequence Voltages (ZSVs) occur and these ZSVs result in a large Z-SC in phase windings of the machine, this is unsafe for switching devices and the machine as well. In order to avoid these Zero Sequence elements in phases of motor, separate DC sources are connected to each inverter, but it is not good for hardware enactment. Therefore, the said difficulty arises when two inverters operate with a common DC single source which is displayed by Fig. Figure 2.

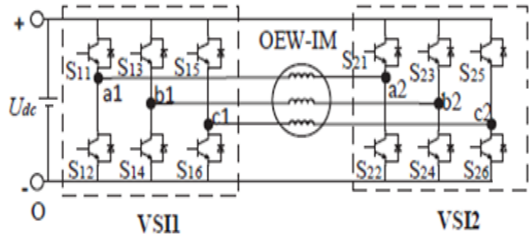


Figure 2: OEW-IM with Common Single DC Source

In OEW-IM arrangement with shared single DC bus, the voltage trajectories engendered through inverters VSI-1 & VSI-2 can be stated as:

$$V_{s1} = \frac{2}{3}\left(V_{a10} + V_{b10}e^{j\frac{2\pi}{3}} + V_{c10}e^{j\frac{4\pi}{3}}\right)$$
$$V_{s2} = \frac{2}{3}\left(V_{a20} + V_{b20}e^{j\frac{2\pi}{3}} + V_{c20}e^{j\frac{4\pi}{3}}\right) \quad (1)$$

Where V_{10}, V_{20} and V_{30} represent leg voltages of phases A, B and C correspondingly. The description for switching characteristic S_{xy} = 1 (x = a phase or b phase or c phase; y= 1 or 2) signifies ON position of top switch of particular phase, while S_{xy} = 0 indicates OFF position of top switch of particular phase. Similarly, the voltage vector on motor windings is represented by two-inverter voltage vector V_{s1}, V_{s2} difference form, namely:

$$V_s = V_{s1} - V_{s2} \quad (2)$$

As both inverters (*Inv-1* & *Inv-2*) are coupled to a shared one DC voltage source V_{dc} the voltage delivered by an inverter, *Inv-1* & *Inv-2* can be known with the depictions: '+' signifies ON, '-' 'signifies OFF situations of the top switch in inverter leg. These devices in inverters operate by complementary rule, if the switch at the top is on, then the lower one in the same leg should be off and converse. The voltage magnitudes are marked by trios containing '+' and '-' signifying the locations of switch at a-phase, b-phase, c-phase correspondingly. For example, trio (-++) specifies voltage magnitude for a phase when top one is off and *b* & *c* phases when lower ones are on. The maximum probable states of all the switches grouping in each phase when top and lower switches are in on and off positions are given in Table Table 1.

Of all eight states of each inverter switches groupings, six are active states of voltages with a supply voltage magnitude in this situation VDC and the remaining two are null voltages. Taking an example, state 1-4' of the arrangement is attained by switching of the voltage of '*Inv1*' and 4' of '*Inv2*'. It can be perceived that excluding the maximum value of voltage magnitude all remaining voltages of the given structure can be comprehended in many ways.

The dual inverter (Fig. Figure 2) and its modulation scheme are designated in [31]. The t_{wo} inverters are modulated in such a way that the instantaneous common mode voltages at each of the machine's two terminals are constant and equal.

Dual Inverter (Fig. Figure 2) with control scheme is designated in [31] and these inverters are controlled in such a way that their instantaneous CMMD voltages of machine both

$$i_o = \frac{V_o}{R_s + j\omega L_o} \tag{5}$$

ends should be constant & equal.

Table 1: Switching combinations to produce different inverter voltage magnitudes

Inverter-1 Positions	Switches in on Position	Inverter-2	Switches in on Position
0 (- - -)	S12, S14, S16	0' (- - -)	S22, S24, S26
1 (+ - -)	S11, S14, S16	1' (+ - -)	S21, S24, S26
2 (+ + -)	S11, S13, S16	2' (+ + -)	S21, S23, S26
3 (- + -)	S12, S13, S16	3' (- + -)	S22, S23, S26
4 (- + +)	S12, S13, S15	4' (- ++)	S22, S23, S25
5 (- - +)	S12, S14, S15	5' (- - +)	S22, S24, S25
6 (+ - +)	S11, S14, S15	6' (+ -+)	S21, S24, S25
7 (+ + +)	S11, S13, S15	7' (+ + +)	S21, S23, S25

The CMMD voltages of machine both ends given as

$$v_{c1N} = \frac{v_{A1N} + v_{B1N} + v_{C1N}}{3} \tag{3}$$

$$v_{c2N} = \frac{v_{A2N} + v_{B2N} + v_{C2N}}{3} \tag{4}$$

Where V_{A1N}, V_{B1N}, V_{C1N}, V_{A2N}, V_{B2N}, V_{C2N} represent the pole or leg voltages of *inv1* & *inv2* respectively, and V_{C1N} say *CMMD* of '*Inv1*' & V_{C2N} say *CMMD* of '*Inv2*'. Thus, the *CMMD* acting through stator windings is given by $V_{cm}=V_{C1N}-V_{C2N}$.

For all the switching combinations of '*Inv1*' & '*Inv2*', the *CMMD* voltages acting through phase windings of a motor are shown above Table Table 2. From this table it can be understood that it has overall twenty switch groupings, so they produce no *CMMD* voltages at motor phase windings [32]. These grouping switches will not yield any circulation current yet non-isolated DC supply feeds to power inverters '*Inv1*' & '*Inv2*'.

In Fig. Figure 3, it shows Z-SC flow over the DC supply link amongst dual inverters. Equation for Z-SC model is stated as follows [33].

Table 2: CMMD Voltages of machine winding phases

$\frac{-V_{dc}}{2}$	$\frac{-V_{dc}}{3}$	$\frac{-V_{dc}}{6}$	0	$\frac{V_{dc}}{6}$	$\frac{V_{dc}}{3}$	$\frac{V_{dc}}{2}$

0-7'	0-2' 0-4' 0-6' 1-7' 3-7' 5-7'	0-1' 0-3' 0-5' 1-2' 3-2' 5-2' 1-4' 3-4' 5-4' 1-6' 3-6' 5-6' 2-7' 4-7' 6-7'	0-0' 1-1' 2-2' 3-3' 4-4' 5-5' 6-6' 7-7' 1-5' 2-6' 3-1' 4-2' 5-3' 6-4' 2-4' 3-5' 4-6' 5-1' 6-2' 1-3'	1-0' 3-0' 5-0' 2-1' 2-3' 2-5' 4-1' 4-3' 4-5' 6-1' 6-3' 6-5' 7-2' 7-4' 7-6'	2-0' 4-0' 6-0' 7-1' 7-3' 7-5'	7-0'

Common Mode (*CMMD*) Voltages

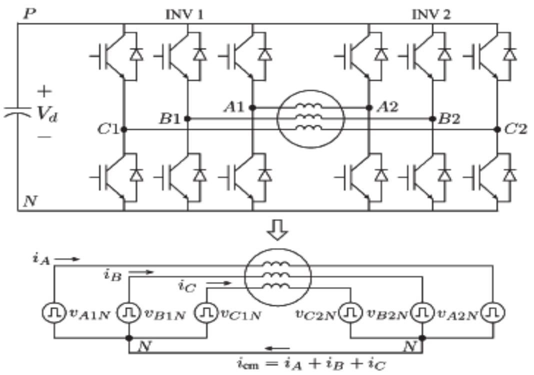


Figure 3: Equivalent circuit of OEW-IM with Zero sequence currents

The *OEW-IM* arrangement zero sequence voltage given by:

$$V_o = \frac{1}{3}(V_{a10} - V_{a20} + V_{b10} - V_{b20} + V_{c10} - V_{c20}) \quad (6)$$

Where R_s denotes winding resistance stator, L_0 denotes winding leakage inductance of stator and its equivalent to zero sequence inductance. Clearly, the extent of *Z-SC* be subject to the amount of zero (*ZSV*) sequence voltage. So, these voltages come mostly from the motor and inverter itself. The ZSV is produced by control strategy, voltage drop and dead time of switches, so on [35], the motor back EMF (*BEMF*) there are harmonics owing to spatial harmonics of a machine. In several situations, sinusoidal *BEMF* is presumed, and the harmonics are unnoticed. Nevertheless, the third harmonic cannot be ignored in *OEW* with a common single DC supply arrangement since it comprises zero sequence. The fundamental 3Ø *BEMF* is as follows.

$$\begin{bmatrix} v_{emf1,a} \\ v_{emf1,b} \\ v_{emf1,c} \end{bmatrix} = \begin{bmatrix} v_{emf1}\sin(\Phi_e + \pi) \\ v_{emf1}\sin\left((\Phi_e + \pi) - \frac{2\pi}{3}\right) \\ v_{emf1}\sin\left((\Phi_e + \pi) - \frac{4\pi}{3}\right) \end{bmatrix} \quad (7)$$

Where V_{emf1} is the fundamental component amplitude of *BEMF*. Then, the 3rd harmonic elements of 3Ø *BEMF* is designated as follows.

$$\begin{bmatrix} v_{emf3,a} \\ v_{\mathrm{emf}\,3,b} \\ v_{emf3,c} \end{bmatrix} = \begin{bmatrix} v_{emf3}\sin(3(\theta_e + \pi)) \\ v_{emf1}\sin(3(\theta_e + \pi) - \theta_3) \\ v_{emf1}\sin(3(\theta_e + \pi) - \theta_3) \end{bmatrix} \quad (8)$$

Where V_{emf3} represents the 3rd harmonic amplitude of the *BEMF*. The BEMF zero sequence component is shown in equation (9).

$$v_{emf,0} = \sum_{i=a,b,c} (v_{emf1,i} + v_{enf3,i}) = -3V_{emf3}(3\theta_e + \theta_3) \quad (9)$$

The fundamental components void in (9) and *BEMF* zero sequence component contains 3rd harmonic components. Figure below shows, waveforms for *BEMF* zero sequence component and initiated Z-SC. It is tough to recompense vemf0 through feed forward to the voltage reference for the reason that its magnitude and phase offset are typically unidentified.

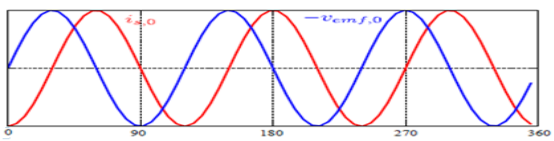


Figure 4: Zero sequence voltage and current due to 3rd harmonic of back EMF

3 Conception of multi-objective GA based SHE-PWM

This section analyses the principle of the SHE-PWM dual VSI, in order to produce a pulse width modulation signal, which can remove harmonics from output voltage waveform.

To achieve this the following must done: i) define a set of significant commutating angles for number of equations that are obtained from theory of Fourier analysis and ii) use of the calculated angles and several equilibriums to build definite pattern.

The Fourier series extension of voltage wave by a general SHE PWM is given as

$$v(\omega t) = \sum_{n=1}^{\infty} (a_n \cos(n\omega t) + b_n \sin(n\omega t)) \quad (10.a)$$

Pertaining to *PWM* scheme the features of odd functions & *QWS*, *an*=0, for all *n*, and voltage wave equation are as follows:

$$v(\omega t) = \sum_{n=1}^{\infty} b_n \sin(n\omega t) \quad (10.b)$$

ω- output voltage frequency in radians.

A generalized equation of bn for '*N*' number of commutation angles for odd values of n is shown by:

$$b_n = \frac{2V_{dc}}{n\pi}\left[2\sum_{j=1}^{N}(-1)^{j-1}\cos n\alpha_j - 1\right] \quad (11)$$

The *SHE* procedure needs *N* commutation angles α_1, α_2..., α_N, in the first quarter period for individual inverter. One angle in N no. of angles controls the fundamental component, then remaining angles i.e., N – 1 used to remove N – 1 number of harmonics in inverter [34], the chopping angles desired to remove lower order odd number harmonics for a 3Ø *VSI* like 3rd, 5th, and 7th etc. This quantifies in between zero and π/2.

The general equations to eliminate N-1 number of harmonics obtainable in [33] and [34] can be given as:

$$-\sum_{j=1}^{N}(-1)^j \cos(\alpha_j) = \frac{2+M\pi}{4} \quad (12)$$

$$-\sum_{j=1}^{N}(-1)^j \cos(n\alpha_j) = 0.5 \ldots (12) \quad (13)$$

Numerous multi objective issues necessitate concurrent optimization at more than a few challenging objectives. Properly, it can be detailed, supposed to find $\bar{x} = (x_1, x_2, x_3, \ldots, x_n)$ that minimizes 'p' number of objective functions $G(\bar{x}) = (g_1(\overline{x_1}), g_2(\overline{x_2}), g_3(\overline{x_3}), \ldots, g_p(\overline{x_n}))$ contained by a viable domain. Usually, the solution is not even one, but many called a Pareto optimal set. To a particular multi objective problem *G(x)*, the Pareto-optimal set *P* is defined as: $P_s = \{x\hat{I}W\$x'\hat{I}W: F(x')\pounds F(x)\}$. The technique for an optimization usually tries to determine a specified number of Pareto-optimal solutions, which are reliably disseminated in the Pareto-optimal set, these elucidations, afford the adequate understanding of the problem to achieve the final decision. Conversely, a priori expression of the predilections to the essential objectives, is often tough to choose in advance. In addition, these techniques can merely discover one solution at a time. Further solutions could not be attained without a number of computations with free constraints reset. What is better, GAs genetic algorithms preserve a population and various liberated solutions can be searched for concurrently as shown in Fig. Figure 5. GAs capability for catching various set of solutions in one run and its exception on or after mandate to impartial partiality statistics that concentrates on this instant is better than above-mentioned methods. MOGA is characterized by its fitness consignment and multiplicity conservation approach. Hereafter, to optimize the no. of switching angles concurrently by means of evolutionary methodology, this paper affords a method entitled as genetic algorithm with multi objective for *SHE PWM* applied to dual inverter fed *OEW-IM*.

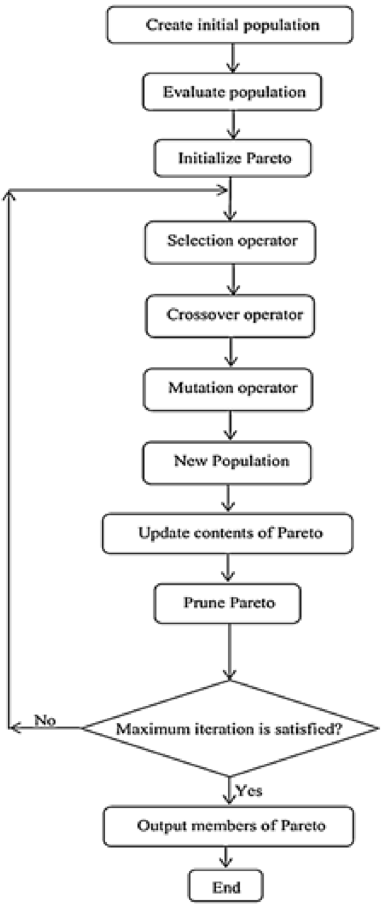


Figure 5: The flowchart of multi-objective genetic algorithm

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4 Proposed scheme for modelling of double VSI FED OEW-IM

From previous sections it can be concluded that the tripled harmonics are present, when single source based dual inverter fed to OEW-IM leads to *Z-SC* and then causes Torque Ripples. Desired shape of the output voltage from two inverters with the preferred harmonics content and amplitude of the main harmonic factor is obtained by the scheming of the switching angles in the full choice of the amplitude MI. Maximum Index is unique for the numerous wide varieties of angles. With the growing of the modulation index, the time range between commutations is getting shorter. To remedy the complexity of equations to find switching instants, the range of switching angles is typically stored low to make the calculations simple. However, to be able to successfully lessen the harmonics content material of two inverters output waveform and generate higher pleasant spectrum through removal of unique decrease order harmonics, *TH-D* and torque ripples discount, greater variety of switching angles is taken for two inverters. Hence, this case examines the use of N values three and five, number of switching angles for dual inverters fed *OEW-IM*.

For a dual VSI, there are VSIs distributed by *DC* bus at source side and serving OEW-IM at load end. In different words, it is determining gating styles for each inverter in order that a targeted harmonics engendered with the aid of the 2 converters adds as much as zero. The inclusive AC voltages will not now comprise undesirable harmonics, and yet those harmonics can exist on each inverter output. It is not like the traditional technique where targeted annoying harmonics are reduced within output voltage of individual converter.

In this technique, the same quantity (N=3 & 5) of commutation angles is executed for every inverter, same as the case of traditional method, and each inverter is functioned with identical switching frequency. The predominant distinction is that the pulse styles of every inverter module are extraordinary, and every module is needed to produce essential issue with the preferred modulation index M, it has $2*(N-1)$ degrees of freedom (DOFs) to remove harmonics better than the conventional case $N-1$ harmonics. These sorts the corresponding figures for general voltages of inverter more than what can be generated with traditional technique and as a result permits extra harmonics to cast off. It must be noted that, even though gating forms are dissimilar for every inverter running with suggested modulation method, the fundamental factor and wide variety of commutating angles are identical.

Case (i): Proposed SHE with three switching angles

Consider the case of a dual inverter in which the preferred range of switching angles in each inverter Modulation sample is three (i.e., N=3). The traditional Modulation method, in which every inverter functioned with an equal sample as the other, has in consequence the best two levels of harmonics removed, as in example, 3rd & 5th [by equation (11)]. However, inside the proposed technique, the 3rd, 5th, 7th, & 9th harmonics add as much as zero to the total AC voltage that doubles the range of harmonics in comparison with the traditional method.

With N = 3, set of equations that must be resolved to determine angles for two Inverters are given as:

$$\text{Cos}(1\alpha_1^A) - \text{Cos}(1\alpha_2^A) + \text{Cos}(1\alpha_3^A) = (2 + M\pi)$$
$$Cos\ (1\alpha_1^B) - Cos\ (1\alpha_2^B) + \text{Cos}\ (1\alpha_3^B) = (2 + M\pi)$$
$$[\text{Cos}(3\alpha_1^A) - \text{Cos}(3\alpha_2^A) + \text{Cos}(3\alpha_3^A)] + [\text{Cos}(3\alpha_1^B) - \text{Cos}(3\alpha_2^B) + \text{Cos}(3\alpha_3^B)] =$$
$$[\text{Cos}(5\alpha_1^A) - \text{Cos}(5\alpha_2^A) + \text{Cos}(5\alpha_3^A)] + [\text{Cos}(5\alpha_1^B) - \text{Cos}(5\alpha_2^B) + \text{Cos}(5\alpha_3^B)]] \quad (14)$$
$$[\text{Cos}(7\alpha_1^A) - \text{Cos}(7\alpha_2^A) + \text{Cos}(7\alpha_3^A)] + [\text{Cos}(7\alpha_1^B) - \text{CCos}(7\alpha_2^B) + \text{Cos}(7\alpha_3^B)]$$
$$[\text{Cos}\ (9\alpha_1^A) - \text{Cos}\ (9\alpha_2^A) + \text{Cos}\ (9\alpha_3^A)] + [\text{Cos}\ (9\alpha_1^B) - \text{Cos}\ (9\alpha_2^B) + \text{Cos}\ (9\alpha_3^B)]$$

Where $a_1^A, a_2^A, a_3^A \& a_1^B, a_2^B, a_3^B$ are switching angles for Inv-1 and Inv-2 respectively, for **N**=3 with different Modulation Indices the optimal values of noteworthy parameters are shown in Table 3 below.

Table 3: MI vs THD and ZSC with three Commutation Angles

S. No	MI	THD (%) Conventional SHE PWM	THD (%) Proposed SHE PWM	ZSC (Amps) Conventional SHE PWM	ZSC (Amps) Proposed SHE PWM
1	0.2	67.54%	50.42%	11.5	7.9
2	0.4	61.52%	48.23%	9.2	5.16
3	0.6	59.25%	46.34%	7.8	3.85
4	0.8	57.52%	42.42%	6.65	2.95
5	1	55.25%	36.71%	4.95	1.2
6	1.2	52.64%	35.81%	4.75	1.16

Case (ii): Proposed SHE with Five switching angles

Considering the case of a dual inverter, it is preferred that a wide variety of switching angles in individual inverter modulation be N = 5. In a *PWM* traditional methodology, the two inverters function individually with identical samples. As an alternative, now the most effective number of harmonics are being removed, as the 5th and 7th [by equation (11)]. Conversely, in the suggested method, the 3rd, 5th, 7th, 11th, 13th, 15th, 17th & 19th harmonics appear as much as zero in the overall output voltage which is double the quantity of harmonics that may be removed with the traditional method.

For N = 5, the expressions that need to resolve for obtaining both inverters (1&2) angles are

$$\cos(1\alpha_1^A) - \cos(1\alpha_2^A) + \cos(1\alpha_3^A) - \cos(1\alpha_4^A) + \cos(1\alpha_5^A) = (2 + M\pi)/4$$

$$\cos(1\alpha_1^B) - \cos(1\alpha_2^B) + \cos(1\alpha_3^B) - \cos(1\alpha_4^B) + \cos(1\alpha_5^B) = (2 + M\pi)/4$$

$$\begin{aligned}
&[\cos(3\alpha_1^A) - \cos(3\alpha_2^A) + \cos(3\alpha_3^A) - \cos(3\alpha_4^A) + \cos(3\alpha_5^A)] + \\
&[\cos(3\alpha_1^B) - \cos(3\alpha_2^B) + \cos(3\alpha_3^B) - \cos(3\alpha_4^B) + \cos(3\alpha_5^B)] = 1 \\
&[\cos(5\alpha_1^A) - \cos(5\alpha_2^A) + \cos(5\alpha_3^A) - \cos(5\alpha_4^A) + \cos(5\alpha_5^A)] + \\
&[\cos(5\alpha_1^B) - \cos(5\alpha_2^B) + \cos(5\alpha_3^B) - \cos(5\alpha_4^B) + \cos(5\alpha_5^B)] = 1 \\
&[\cos(7\alpha_1^A) - \cos(7\alpha_2^A) + \cos(7\alpha_3^A) - \cos(7\alpha_4^A) + \cos(7\alpha_5^A)] + \\
&[\cos(7\alpha_1^B) - \cos(7\alpha_2^B) + \cos(7\alpha_3^B) - \cos(7\alpha_4^B) + \cos(7\alpha_5^B)] = 1 \\
&[\cos(9\alpha_1^A) - \cos(9\alpha_2^A) + \cos(9\alpha_3^A) - \cos(9\alpha_4^A) + \cos(9\alpha_5^A)] + \\
&[\cos(19\alpha_1^B) - \cos(9\alpha_2^B) + \cos(9\alpha_3^B) - \cos(9\alpha_4^B) + \cos(9\alpha_5^B)] = 1 \\
&[\cos(11\alpha_1^A) - \cos(11\alpha_2^A) + \cos(11\alpha_3^A) - \cos(11\alpha_4^A) + \cos(11\alpha_5^A)] + \\
&[\cos(11\alpha_1^B) - \cos(11\alpha_2^B) + \cos(11\alpha_3^B) - \cos(11\alpha_4^B) + \cos(11\alpha_5^B)] = 1 \\
&[\cos(13\alpha_1^A) - \cos(13\alpha_2^A) + \cos(13\alpha_3^A) - \cos(13\alpha_4^A) + \cos(13\alpha_5^A)] + \\
&[\cos(13\alpha_1^B) - \cos(13\alpha_2^B) + \cos(13\alpha_3^B) - \cos(13\alpha_4^B) + \cos(13\alpha_5^B)] = 1 \\
&[\cos(15\alpha_1^B) - \cos(15\alpha_2^B) + \cos(15\alpha_3^B) - \cos(15\alpha_4^B) + \cos(15\alpha_5^B)] = 1 \\
&[\cos(17\alpha_1^A) - \cos(17\alpha_2^A) + \cos(17\alpha_3^A) - \cos(17\alpha_4^A) + \cos(17\alpha_5^A)] + \\
&[\cos(17\alpha_1^B) - \cos(17\alpha_2^B) + \cos(17\alpha_3^B) - \cos(17\alpha_4^B) + \cos(17\alpha_5^B)] = 1
\end{aligned} \tag{15}$$

Where $a_1^A, a_2^A, a_3^A, a_4^A, a_5^A \& a_1^B, a_2^B, a_3^B, a_4^B, a_5^B$ are switching angles for Inv-1 and Inv-2 correspondingly, for *N*=5 with different range of Modulation Indices the optimal values of noteworthy parameters are shown in the below Table Table 4.

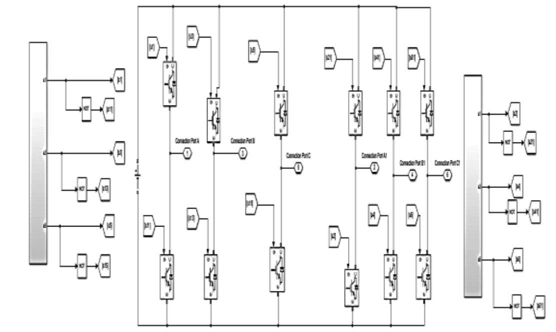
Table 4: MI vs THD and ZSC with Five Commutation Angles

S. No	MI	THD (%)		ZSC (Amps)	
		Conven-tional SHE PWM	Proposed SHE PWM	Conventional SHE PWM	Proposed SHE PWM
1	0.2	60.45%	40.25%	8.35	5.2
2	0.4	61.52%	48.23%	6.29	4.6
3	0.6	59.25%	46.34%	4.78	2.8
4	0.8	57.52%	42.42%	3.82	1.9
5	1	55.25%	36.71%	3.5	0.4
6	1.2	52.64%	35.81%	2.89	0.38

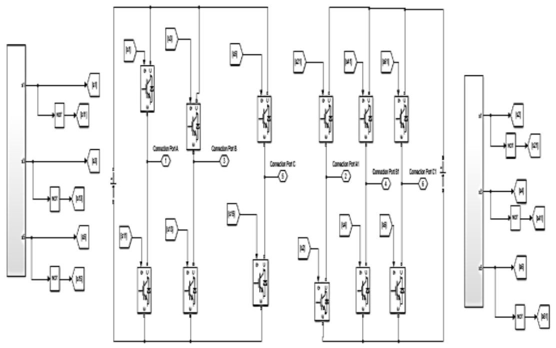
4

5 Simulation Results

To confirm the proposed SHE-PWM approach, dual inverter OEW-IM has been simulated in Matlab-Simulink. In this paper, by means of fixing the nonlinear trigonometric equations using Multi-Objective GA, appropriate switching instances for the Inverters legs with Common DC input voltage and separate DC sources have been completed. The major goal of this scheme is to lessen the Zero Sequence currents and minimize Torque ripple at a nominal value via disposing of Triplen Harmonics and decreasing the TH-D of dual inverter voltages. The Simulink version for the scheme demonstrated in Fig. Figure 6.a, Figure 6.b, at the same time as the parameter values for probable MI values is given in above Tables Table 3, Table 4.



(a)



(b)

Figure 6: Simulink model for double inverter with non-isolated or single DC Source (a); with Isolated DC Sources (b)

Figure Figure 7-**Error! Reference source not found.** illustrates simulation outcomes of Line Voltages, FFT evaluation of dual inverter voltages, Z-SC, and torque at 50 *N-m* given load torque at rated speed provided whilst the dual inverter tested with OEW-IM. In addition, the simulation parameters on this situation are listed in Table Table 5. The line-line voltages, Z-SC and Torque Ripples of dual inverter with unity modulation index are proven in Figure Figure 6-Figure 8, correspondingly. As FFT spectrums of output AC voltages of dual inverter illustrate in Fig. Figure 9, Triple order harmonic such as 3rd and 9th have been removed whilst N=3 and 3rd ,9th & 15th have been eliminated when *N*=5 absolutely due to proper switching angles and input DC voltage.

Fig. Figure 7.a, b displays the simulation results with 3rd harmonic reduction and FFT investigation, on condition that in Fig. Figure 8.a, b for Proposed *SHE* manage dual inverter fed *OEW-IM* with common *DC* supply and separate resources respectively.

Table 5: Parameters used in the Dual Inverter Fed OEW-IM with Single DC source

DC source voltage (V_{dc})	400 V
Stator resistance, R_s	0.435 Ω
Rotor resistance, R_{pr}	0.816 Ω
Stator leakage inductance, X_{ls}	0.754 Ω
Rotor leakage inductance, X_{lpr}	0.754 Ω
Mutual Inductance, X_m	26.13 Ω
Motor Inertia, J	0.089 Ω
No. of Poles, P	4
Rated frequency, f_s	50 Hz

It indicates that the proposed scheme for double inverter with isolated dc sources can be able to reduce the 3rd harmonics. So, Z-SC decreased to 1.2 Amps with 3 angles but for independent DC sources case the 3rd harmonics reduced to 0.7 amps further, so Z-SC obviously gets rid of and the ripples in torque additionally decreased as shown in Fig. Figure 9.a, b. Mainly current and next back emf features the torque. Henceforth, in the currents without harmonic elimination, the intended excessive frequency torque is visible. Concentrating on overall harmonic content of inverter voltages proven in Figures Figure 7-Figure 9 it may be determined that the TH-D is low and the lower order harmonics reduced.

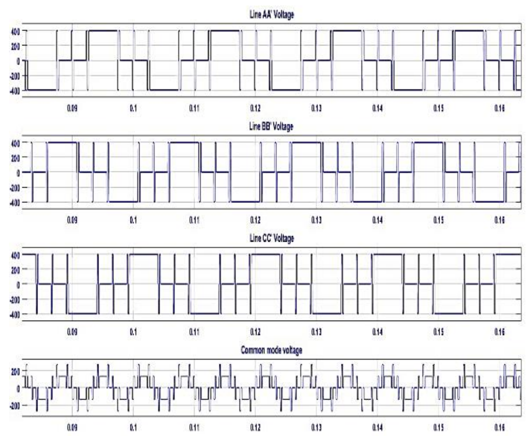


Figure 7.a: Line Voltages between Inverters with Proposed SHE PWM for three Commutation Angles and common source

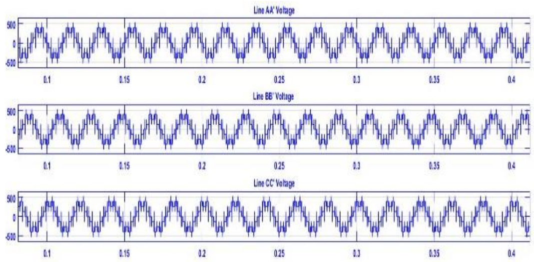
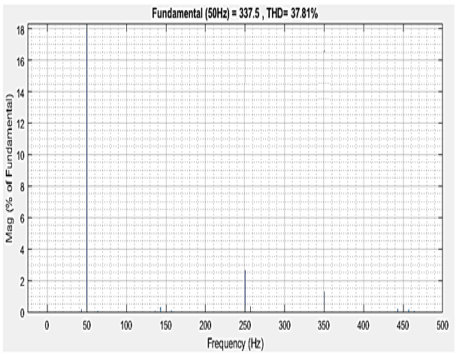
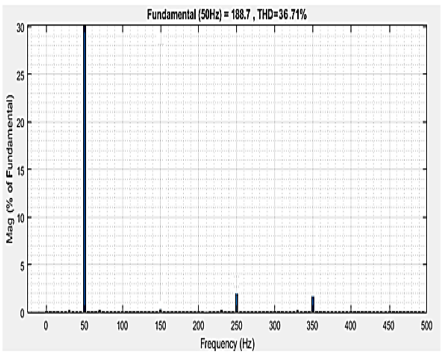


Figure 7.b: Line Voltages between Inverters with Proposed SHE PWM for three Commutation Angles and separate DC sources



(a)



(b)

Figure 8: THD with Proposed SHE PWM for three Commutation Angles and common DC source (a); for separate DC sources (b)

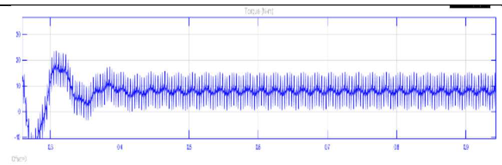


Figure 9.a: Torque with Proposed SHE PWM for three Commutation Angles and common DC source

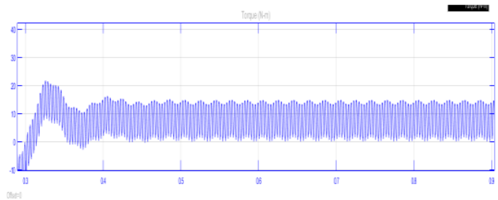


Figure 9.b: Torque with Proposed SHE PWM for three Commutation Angles and separate DC sources

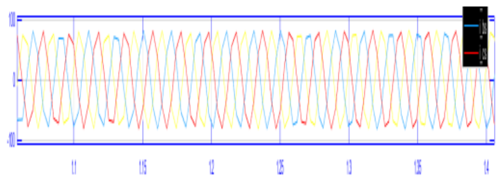
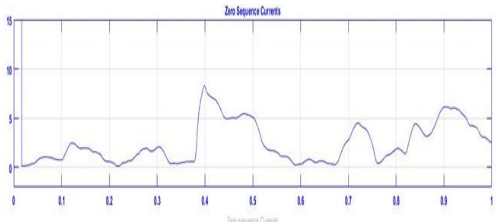
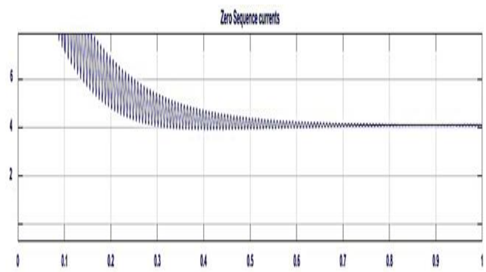


Figure 9.c: Stator currents with Proposed SHE PWM for three Commutation Angles and separate DC sources



(a)



(b)

Figure 10: Zero sequence currents with Proposed SHE PWM for common DC source three Commutation

Angles (a); for Separate DC sources and three Commutation Angles (b)

Figs. Figure 11-Figure 14 presents simulation outcomes acquired for the machine with Proposed SHE PWM for five Commutation Angles. It indicates that through enforcing five commutation angles the waveforms of inverter voltages have much less TH-D and much less third harmonics that the Z-SC reduced to 0.4 Amps. The TH-D is less in addition to Z-SC and torque ripples, as compared to the ones shown in Figs. Figure 7-Figure 10, due to the suppression of wide variety of lower harmonic currents (3rd, 5th, 7th, 9th, 11th, 13th, 15th, 17th). Evidently, *Z-SC* decreased, and torque ripples minimized in five commutation angles rather than in three commutation angles.

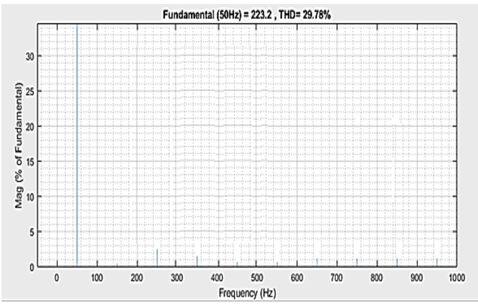
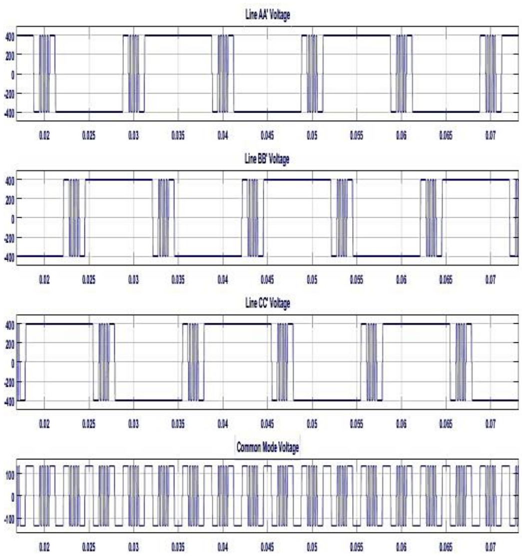
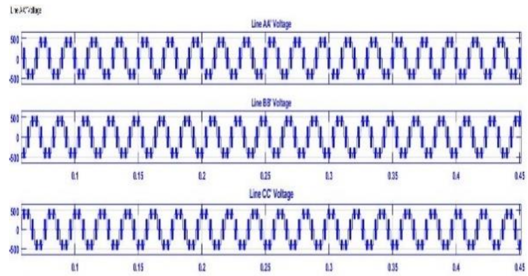


Figure 11: THD with Proposed SHE PWM for five Commutation Angles and common DC source

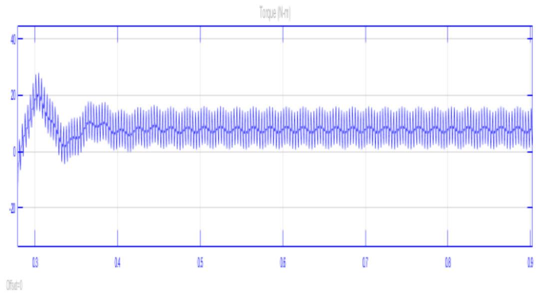


(a)

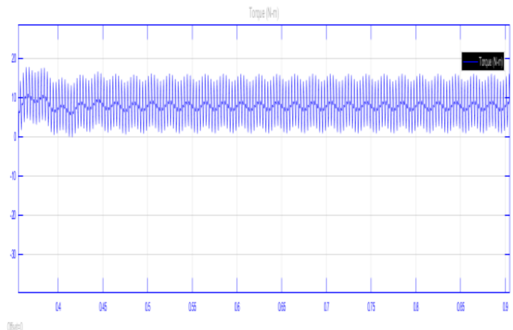


(b)

Figure 12: Line Voltages between Inverters with Proposed SHE PWM for five Commutation Angles and common DC source (a); for five Commutation Angles and separate DC sources (b)

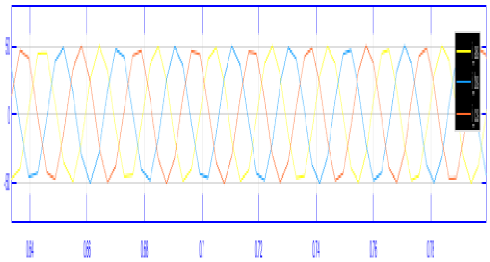


(a)

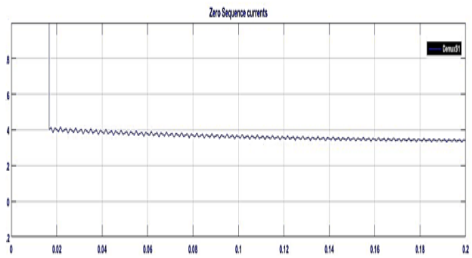


(b)

Figure 13: Torque with Proposed SHE PWM for five Commutation Angles and common DC source (a); for five Commutation Angles and separate DC sources (b)



(a)



(b)

Figure 14: Stator currents with Proposed SHE PWM for five Commutation Angles and common DC source (a); for five Commutation Angles and common DC source (b)

In truth, the Triplen harmonic suppression is greater for dual inverter functioning with separate DC sources as compared to single commonplace DC source proven in figs Figure 7(b)-Figure 14(b) in both 3&5 commutation angles. But dual inverter with separate DC sources needs two batteries or *DC* sources and faces the common mode voltages problem. The primary aim of the implemented manipulate techniques in this paper is to regulate the *Z-SC* so that the torque ripples is minimized and TH-D reduced. Dual inverter feeding *OEW-IM* with common DC supply as well as separate DC sources configurations with proposed *GA* primarily based, *SHE-PWM* scheme is executed in both three-commutation angles and five commutation angles modes. To show the capability of suggested method when compared with the most current approach in dealing with *Z-SC*, torque ripples and *TH-D* different Modulation Index values are used. This evaluation suggests that, whilst Modulation Index *M* is 0.9, the conventional approach could lessen the rms value of *ZSCC* by 68.7% and the proposed approach reduces it by 86.3%. With the MI reduced to 0.6, the figures are 65.8% of reduction by conventional technique and 86.6% for the suggested method. From these results, it is clear that the proposed approach is superior to the current SHE approaches; furthermore, it may be used by wider range of switching angles.

Table 6: ???

6 Conclusions

In double inverter structure, feeding the inverters by a common DC source is very beneficial if Z-SC currents can be controlled. The same inverters and OEW-IM drive configuration with a single DC supply is the better decision for several applications of electric drives. Meanwhile the source voltage of magnitude VDC, a maximum voltage magnitude of 1.7VDC can be appreciated at the machine windings. So that a small rating battery can be used as the DC source which is a precise beneficial characteristic. This paper suggested a novel technique with SHE to reduce ripples in torque, Z-SC & T-HD of open-ended induction drive that also removes common mode circulation current thus facilitating double inverter to supply power from a non-isolated DC source. In addition, comparison of both the common DC source and separate DC sources connected to dual inverter structure is made in view of ripples in torque, ZS-C and TH-D by the proposed as well as conventional control technique. It is obvious that a common DC source arrangement has somewhat higher ZS-C, TH-D and torque ripples than separate DC sources arrangement as shown in Table.5. The Common DC source structure has produced 0.43 amps and separate DC source's structure has produced 0.25 amps when controlled by the proposed SHE control technique. Therefore, with the proposed control method the common DC source structure can perform close to that to separate DC sources with fewer hardware requirements, cost and complexity of control.

	Conditions	Torque ripples (peak-to-peak)	THD					Zero seq. currents (Rms) (Stator current-32A RMS)
			Line voltages	3rd	5th	7th	Fundamental	
Two inverters with separate DC sources modulated by conventional SHE PWM	3, 5, considered in two inverters (3 angles)	18.8Nm	48.31 %	33%	30%	28%	38%	8.85A
	3, 5, 7 & 9 considered in two inverters (5 angles)	14.3N-m	41.38 %	25%	24%	15%	42%	7.92A
Two inverters with Separate DC sources modulated by proposed SHE PWM	3,5,7 & 9 considered in two inverters (3 angles)	15.8N-m	35.9%	28%	29%	22%	44%	7.84A
	3,5,7, 9,11,13,15, 17 & 19 considered in two inverters (5 angles)	11.58N-m	28.86 %	21%	23%	20%	47%	6.98A
Two inverters with single DC source modulated by conventional SHE PWM	3, 5 considered in two inverters (3 angles)	17.97 N-m	46.96 %	38%	49%	36%	26%	7.274A
	3, 5, 7 & 9 considered in two inverters (5 angles)	16.4N-m	39.49 %	28%	26%	18%	39%	8.23A
Two inverters single DC source modulated by proposed SHE PWM	3, 5, 7 & 9 considered in two inverters (3 angles)	16.8 N-m	30.95 %	30%	33%	27%	36%	6.56A
	3, 5, 7, 9, 11, 13, 15, 17 & 19 considered in two inverters (5 angles)	12.48N-m	30.58 %	23%	25%	22%	44%	5.25A

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