The performance analysis of dual-inverter three phase fed induction motor with open-end winding using various PWM schemes

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The performance analysis of dual-inverter three phase fed induction motor with open-end winding using various PWM schemes

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Abstract
Induction motor with scheme open end winding (OEW) has attract many attention in the recent time as a compromising alternative of multi-level inverter. The structure contains of simplicity in generating multi-level inverter and has potential ability to obtain a better quality output due to higher number of the available switching states and voltage vectors.' Based on the method to divide the voltage references, various Pulse Width Modulation (PWM) schemes for the dual-inverter fed induction motor with OEW have been discussed in this paper. The first one is developed by equally splitting the voltage references to two inverters and termed as Equal Reference Division Pulse Width Modulation (ERD PWM). In the second PWM scheme, the voltage references are devided according to moduation index (M). At M > 0.525, one inverter is modulated using maximum voltage reference while the other one inverter is modulated proportionaly according the change of voltage reference. The PWM scheme is named as Unequal Reference Division Pulse Width Modulation (URD PWM). In the third PWM scheme, the two inverters are modulated using different method, i.e one inverter is controlled in slow switching PWM and the second inverter are modulated using fast switching PWM. Hence the thirs PWM is named as Mixed Devider Switching (MDS) PWM scheme. The results shows that the MDS PWM provide the best voltage Total Harmonic Disortion (THD) performance among the three PWM schemes. Further the speed-torque acceleration shows that the dual-inverter fed structure is able to control the speed to reach the desired speed at t = 0.25 s. The speed is able to adjust when the load is apply at t = 0.4 s. The motor current THD and the mechanical torque reveal that the MDS PWM provide the best among three PWM schemes.

Keywords Dual-inverter fed · Open-end winding · Mixed divider switching · V/f constant · Signal processing

1 Introduction

Variable speed drive (VSD) has been widely used in many applications, includes, rolling mills, pumping applications [1] and Hybrid / electric vehicles (H/EV) [2, 3]. It is well known that the most effective way to manage performance induction motor are controlling the frequency of Induction motor input voltage. Its therefore, VSD requires inverter(s) to generate adjustable frequency voltages. Since the inverter output voltage is are not purely sinusoidal, numerous efforts have been taken to obtain voltages that contain less low order harmonics content. The main concern of the research includes development of the PWM methods and improvement of the structure of the inverter that leads to the development of multi-level inverter technology. Various topology of multi-level inverter includes Neutral Point Clamp (NPC), Floating Capacitor Inverter

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(FCI) and cascaded inverter [4–6]. Among the cascaded inverter, dual-inverter feed OEW drives attracts many attentions in the recent time due to its simplicity and higher potency to achieve multi-level operations. Stemmler H and Guggenbach P was introduced new structure supply induction motor with inverter drives [7].

In the supply dual-inverter three phase, the center star point of the configuration induction motor is opened, and the induction motor is supplied from left and right sides. Figure 1 point out the simplify of dual-inverter three phase fed induction motor with OEW. The inverter structure may operate to achieve 3-level operation when ratio DC-link voltage is equal [8, 9] and 4-level operation for DC-link with ratio of 1:2 is applied [10, 11]. The available publications concern on the development of modulation strategy of dual-inverter fed multilevel inverter has main goal to improve the quality of the inverter output voltages [12], reducing the effect Common Mode Voltage (CMV) [13] and simplify the modulation techniques [14]. The CMV that trigger CMC may appear and flow in the induction motor windings. To solve the problem caused by CMV, the particular switching strategy is developed in [15]. Further research also develops the open-end winding drives by supplying the motor with a combination of multi-level inverter in the both sides [16]. Supplying the induction motor with multilevel inverters in both sides increases the complexity in line with the potency to achieve improved output voltages.

It is however, the available publications relating the VSD using dual-inverter fed OEW is still very limited. This paper discusses VSD of three-phase induction motor fed from left and right sides using two-level inverters. A simple open loop v/f constant method is applied as shown in the Fig. 2. The performance of the induction motor is evaluated for various PWM schemes. The torque-speed-response, phase motor current quality and torque ripple is deeply analysed. This paper proves that the dual-inverter fed OEW is veasible to apply in VSD system. The main contribution of this paper is on the simplicity of the developed PWM methods and development analysis into machine's performance for dual-fed OeW drive system. Comparing with the space vector based PWM method, the prosedure to develop PWM pulses are much simpler which is directly obtained by comparing the modulation signals and the carrier signal. In particular to the MDS PWM, besides of its simplicity, the performance is the same as space vector based PWM as discussed in literatures.

2 Open end winding 3-phase motor drives

2.1 Voltage Space vector of dual-inverter two level with Induction motor 3-phase

Prior to reviewing the PWM methods of the dual-inverter fed system, the space vector voltages of the dual-inverter fed OEW 3-phase motor drives is discussed first. A 3-phase two-level VSI produces 8 (2^3) switching states. the voltage space vectors of two-level VSI is generated by using Eq. (1). The voltage space vectors of two-level inverter mapped in 6 active vectors and 2 zero vectors in the origin of the decagon as shown in the Fig. 3a. In the dual-inverter fed, 64 switching states are available as a result of the combination of 8 switching states from inverter-1 and 8 switching states from inverter-2. The voltage space vectors of dual-inverter fed are governed by Eq. (2). When two inverters apply the same (equal) DC-link voltage, the 64 switching combinations mapped in 19 voltage vectors as are shown in the Fig. 3. In Fig. 3b the labels in decimal number indicates the switching state combination when it is converted into binary value. The first number relates to switching states for inverter 1 and the second number relates to switching states for inverter 2 [17].

$$\begin{aligned} \underline{v}_{\alpha\beta} &= v_\alpha + jv_\beta \\ &= 2/3\left(v_{aO}(t) + v_{bO}(t)e^{j2\pi/3} + v_{cO}(t)e^{j4\pi/3}\right) \end{aligned} \tag{1}$$

with $v_{xO}(t)_{(x=a,b,c)}$ = instantaneous load phase voltages

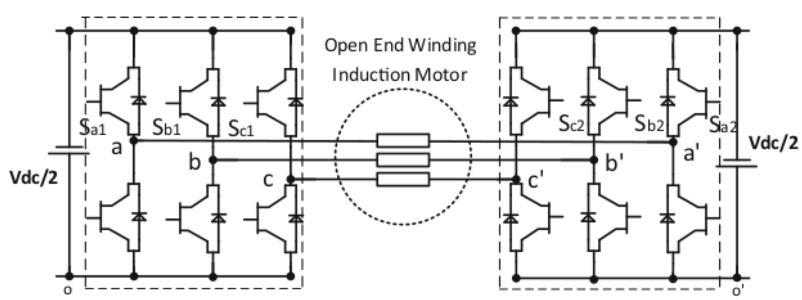

Fig. 1 Configuration of the dual-inverter fed three-phase induction motor drives with OEW

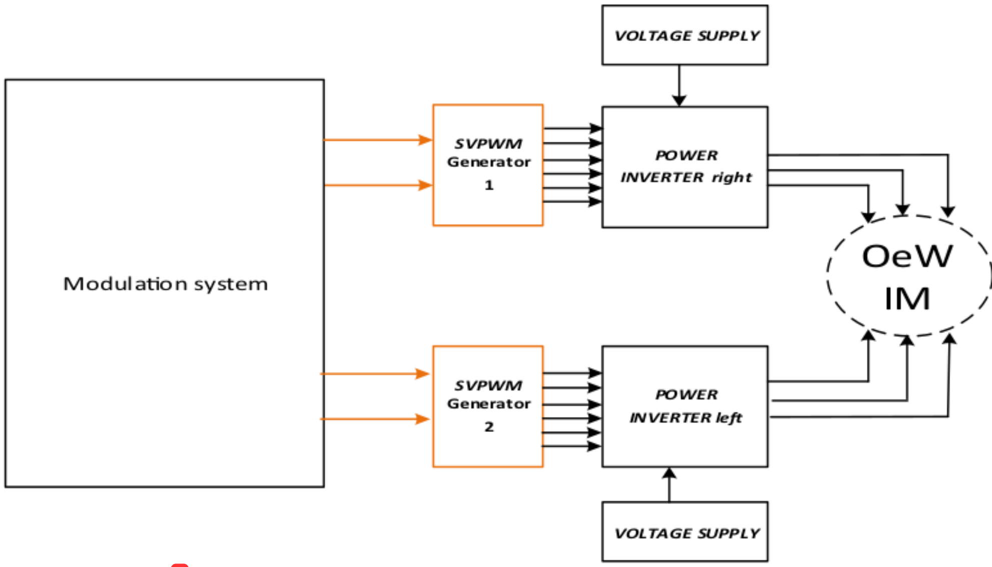

Fig. 2 Schematic diagram the dual-inverter three phase fed three-phase induction motor OEW with open loop using *v/f* constan

$$\underline{v}_{\alpha\beta(dual)} = \underline{v}_{\alpha\beta(invright)} - \underline{v}_{\alpha\beta(Iinvleft)} = 2/3\Big\{\left(v_{aO}(t) + v_{bO}(t)e^{j2\pi/3} + v_{cO}(t)e^{j4\pi/3}\right) - \left(v_{a'O'}(t) + v_{b'O'}(t)e^{j2\pi/3} + v_{c'O'}(t)e^{j4\pi/3}\right)\Big\} \quad (2)$$

2.2 Review of PWM schemes

It was mentioned in many literatures that Various PWM Schemes for the dual inverter three phase fed induction motor with OEW drives have been discussed. The majority of the research in the development of PWM schemes includes space vector PWM (SVPWM) for the dual inverter fed induction motor with OEW [18, 19]. In [18], the proper space vector voltages are selected among the 64 vector voltages to achieve more effective control of inverters. SVPWM method involves numerous steps of trivial procedures, starting from selecting the suitable voltage vectors among the 64 available switching states, calculating time application of the used vector and arranging the proper switching pulses. Further, implementation of the classical carrier based PWM is also deeply discussed in [20].

Simple PWM methods based on carrier based PWM have presented comprehensively in Wiryajati et al. [14] where the idea is adopted from [21]. There will be four PWM methods are developed by using simply dividing the voltage references to both modulators of the two inverters. The PWM methods are termed as Equal Reference Division (ERD) PWM, Unequal Reference Division PWM and Mixed Divider Switching (MDS) PWM. The ERD PWM method works by simply dividing the references equally to both modulators and then modulated using space-vectors equivalent Carrier Base (CB) method. The URD PWM method divides the voltage references proportionally based on modulation index (M) using Eq. (3). Modulation index is defined as comparison of a voltage reference (v^{**}) and a half of DC-link voltage (v_{dc}), $M = v^{**}/\ 0.5\ v_{dc}$ [18]. While M_1 and M_2 are the individual modulation index of inverter right and inverter left respectively [17]

$$\begin{aligned} 0 \le M \le 0.575 \quad & \begin{cases} M_1 = 2M \\ M_2 = 0 \end{cases} \\ 0.575 < M \le 1.15 \quad & \begin{cases} M_1 = 1.15 \\ M_2 = 2(M - 0.575) \end{cases} \end{aligned} \quad (3)$$

Equation (3) governs that at M $<$ 0.575 only one inverter is activated using two-level PWM method while one inverter is switched off. When M $>$ 0.575, two inverter operated in space vector (SV) PWM method however when M is reduced, the reference for one inverter will statically kept for the maximum value, and the other inverter will reduced proportionally with respect of modulation index. The URD PWM provides multilevel operation especially for M $>$ 0.575.

There are the same operation system between Mixed Divider Switching (MDS) PWM method and URD PWM at $M < 0.575$ which is only one inverter is activated but when $M > 0.575$ both inverters operated in different modulation techniques. The first inverter operates in 180

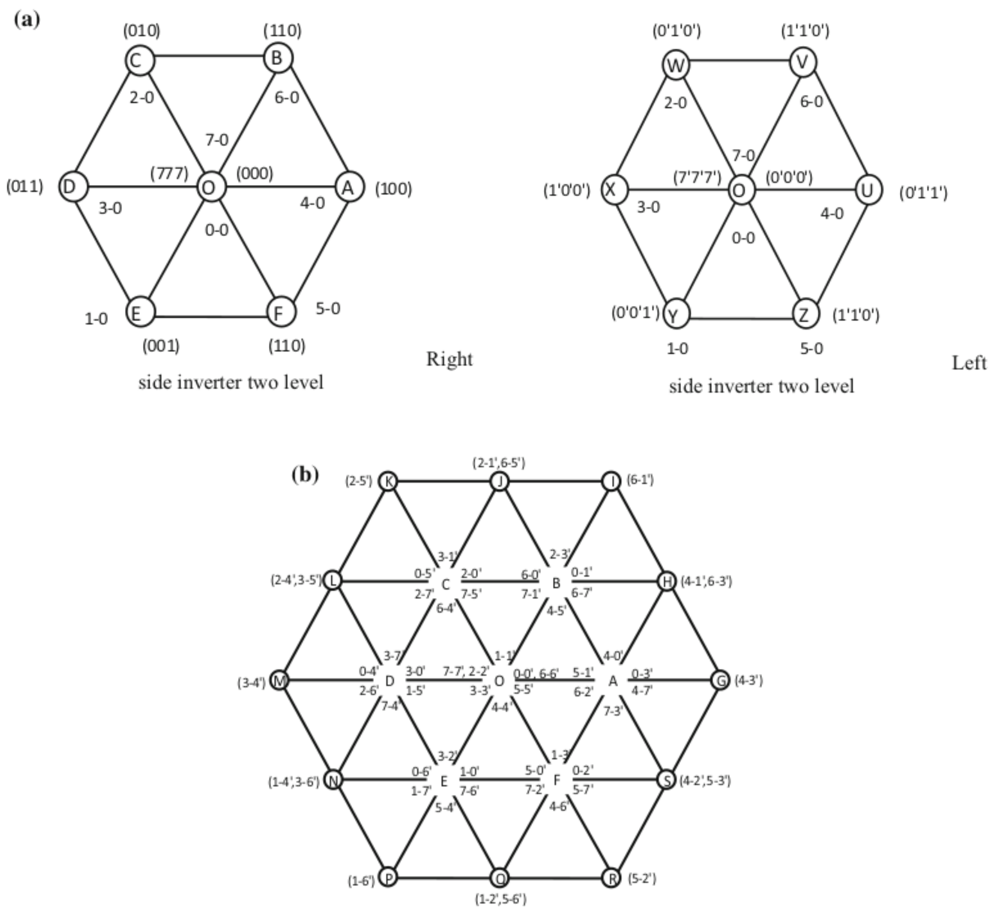

Fig. 3 Voltage space vectors of; **a** two-level right and left side inverter VSI. **b** dual-inverter three phase induction motor drive with OEW

conduction mode while the second inverter operates in SV PWM method. The modulation signals of the second inverter are obtain by subtracting the phase sinusoidal reference signals and the square waveforms i.e. the phase output voltage of the first inverter. The term MDS refer that both inverters operate in different frequency, one inverter operates in fundamental switching and the second inverter works in fast switching (1 kHz). The MDS method also generate the multi-level operation for $M > 0.575$. The MDS method develop real level voltage where the different among levels are shown clearly. Figure 4 shows the output voltages in particular M = 1 generated by various PWM schemes and the quality of the voltage outputs in term of THD value is shown in the Fig. 5. It is clearly shown in Fig. 5 that the MDS PWM performs the best voltage quality among the PWM methods indicates by the lowest voltage THD especially when $M > 0.575$. The improvement of the voltage quality is related with the voltage space vectors used in the modulation strategy as discussed in Wiryajati et al. [14]. It is explained that ERD PWM applies only 8 switching states (7 voltage vectors) among 64 switching states. Meanwhile the URD and MDS utilizes 2 different set of switching states, at $M > 0.575$ the URD PWM utilizes 32 witching states and the MDS PWM utilizes 30 switching states. At $M < 0.575$, the URD and MDS PWM applies the same 8 switching states. The MDS PWM applies the most effective switching states than the URD although the URD applies 2 states more than the MDS PWM. The URD PWM applies zero vectors at $M > 0.575$ that effect into the shape of the voltage waveform as shown in Fig. 3b.

3 Results and discussion

Based on the PWM methods developed in Wiryajati et al. [14], the induction motor performance, in term of rotor speed, torque and current ripple are investigated. The three-

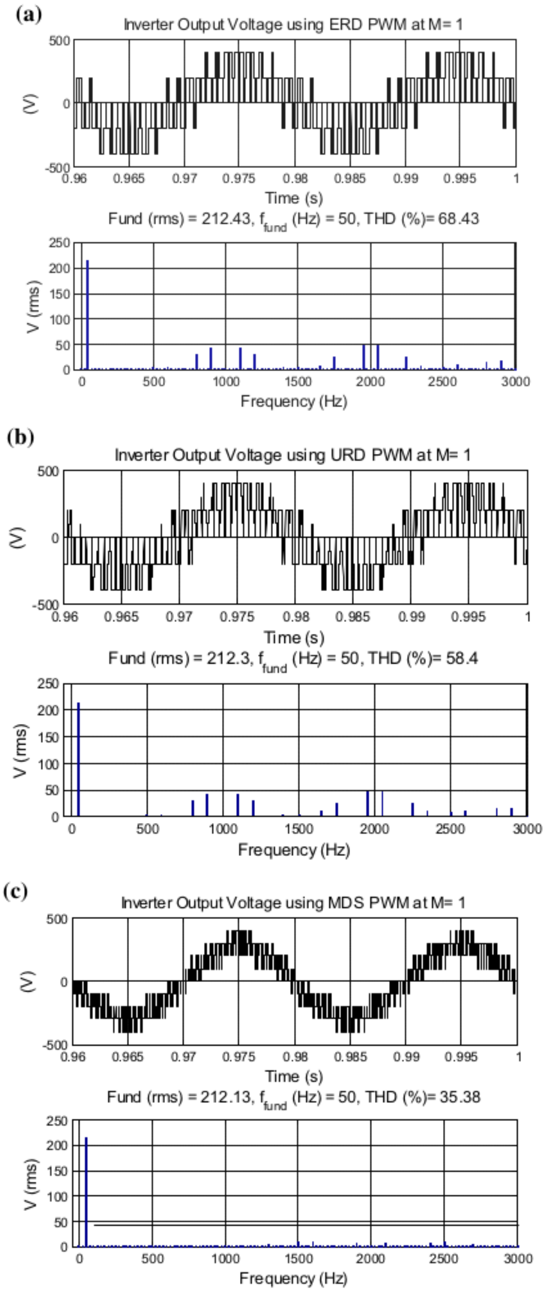

Fig. 4 Phase Inverter output voltage at $M = 1.0$ for; **a** ERD PWM, **b** URD PWM, **c** MDS PWM

phase induction induction motor is modeled using phase variable form as discussed in [22, 23]. The induction motor parameters are shown in the Table 1. The motor parameters that are used in the simulation are

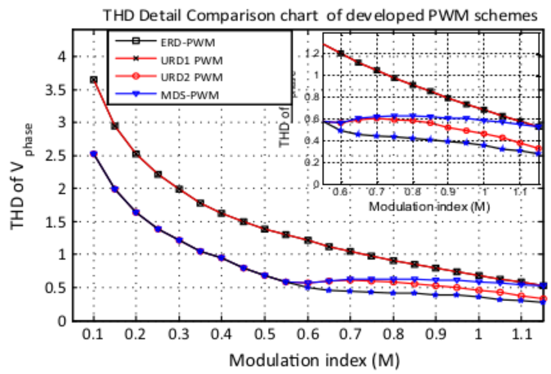

Fig. 5 THD detail comparison chart of the inverter output voltage with various PWM schemes

Table 1 Induction motor parameters

Induction motor parameter	Value
Stator resistance, R_s (Ω)	10
Rotor resistance, R_r (Ω)	6.3
Stator leakage inductance, L_{ls} (H)	0.043
Rotor leakage inductance, L_{lr} (H)	0.04
Magnetising inductance, L_m (H)	0.42
Moment of Inertia, J (kg m^2)	0.05
Load torque, T_L (N m)	5
Magnetic poles pair number, P	2
Input voltage (phase to neutral) (V)	220
Rated frequency, f (Hz)	50

The induction motor is fed from both side and controlled using a simple *v/f* open loop control method. The inverter output voltage is set that at M = 1 the frequency fundamental is 50 Hz. Induction motor and PWM signals are modeled using Matlab / Simulink and the inverter switches are modeled using SimPower Blockset. The motor is run without load for 0.4 s. A 5 Nm load is given at 0.4 s for 0.3 s before it is released again at t = 0.7 s. Motor acceleration, voltage input and motor currrent using MDS PWM at M = 0.7 and M = 1.0 are shown in Figs. 6 and 7

It is depicted in Fig. 6 that rotor speed reached the maximum speed at frequency 50 Hz at less than 0.25 s. When the load 5 Nm is applied at t = 0.4 the speed is slightly reduced and returned to its normal speed at 1500 RPM at t = 0.7 when the load is released. Inline with the speed, the mechanical torque achieved stability value at 0 at t = 0.4 s. When the load is applied the torque change as shown in the speed-torque response. Mean while the voltage inout motor indicate a constant waveform while the current change due to the load changes. At M = 0.7 the

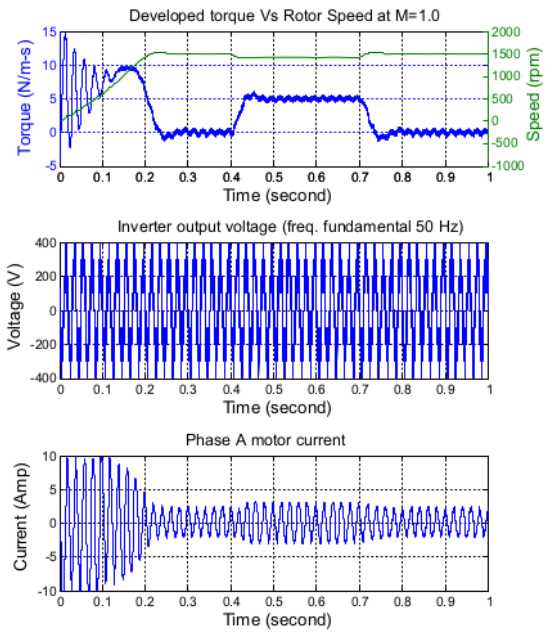

Fig. 6 Motor acceleration at $M = 1.0$, 50 Hz: torque-speed response, inverter voltage output and phase '*a*' motor current

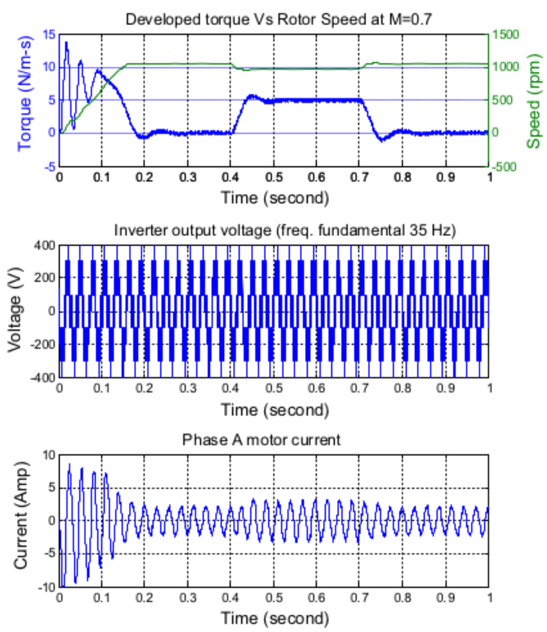

Fig. 7 Motor acceleration at $M = 0.7$, 35 Hz: torque-speed response, inverter voltage output and phase '*a*' motor current

speed-respons shows the similar acceleration but the maksimum speed reached at 1050 RMP. Figures 6 and 7 indicate that the induction motor is succesfuly controlled using v/f method for various speed a she magnitude and the frequency of the inverter outout is changed. For the other PWM speed URD and ERD PWM method, the pattern speed respons are closely similar than that given by the MDS PWM in term of time to achieve the steady speed and torque however the detail of the performance is discussed in the next section.

3.1 Motor current ripple

Further, the motor current quality with various PWM schemes are observed. Figure 8 show the waveform of motor current over 2 periods at M = 1.0 for various PWM schemes. Harmonics spectrum of the current indicates that at particular $M = 1.0$ ($f = 50$ Hz) the quality of the motor current when the motor by the MDS PWM method looks the best among ERD and MDS PWM. However at $M = 0.7$, the Mixed Divider Switching (MDS) PWM successfully creating the best current results in quality among the four compared PWM methods.

In order to get the whole performance of the current, simulation was repeat for $0.1 < M < 1.15$ with 0.05 increment steps. The value of current THD is presented in the Table 2 and Fig. 9.

Table 2 and Fig. 9 reveal that at $M > 0.575$, the THD value of the current with MDS PWM is significantly lower than ERD and URD1 PWM meanwhile URD2 PWM provide the best THD performance at $M > 0.9$. Further at $M < 0{,}575$ the current performance is the same as the PWM scheme applied is the same. The results indiate that the quality of the voltage produces by inverters give significant influence into the current quality. It is also shown in the Fig. 9 that the value of THD f the current using MDS PWM more fluctuated. This result is influented by the operation of inverters where in MDS PWM the operate in inverter in 180 conduction mode and one inverter in PWM mode and the others PWM methods operate both inverters in PWM mode.

3.2 Torque ripple

Subsequently the quality of the mechanical torque ripple of the induction motor is investigated. Steady state torque for various PWM schemes at $M = 1.0$ and $M = 0.7$ are shown in the Figs. 10 and 11. In general the mechanical torques of the induction motor supplied with MDS PWM are smoothest torque compared with the three PWM schemes. As shown in the figure the minimum and the maximum value of the torque is smaller than the induction motor run with ERD and URD. This is indicate that the MDS PWM is able to develop smoothest torque hence provides less fluctuated in the motor speed. Further investigation also

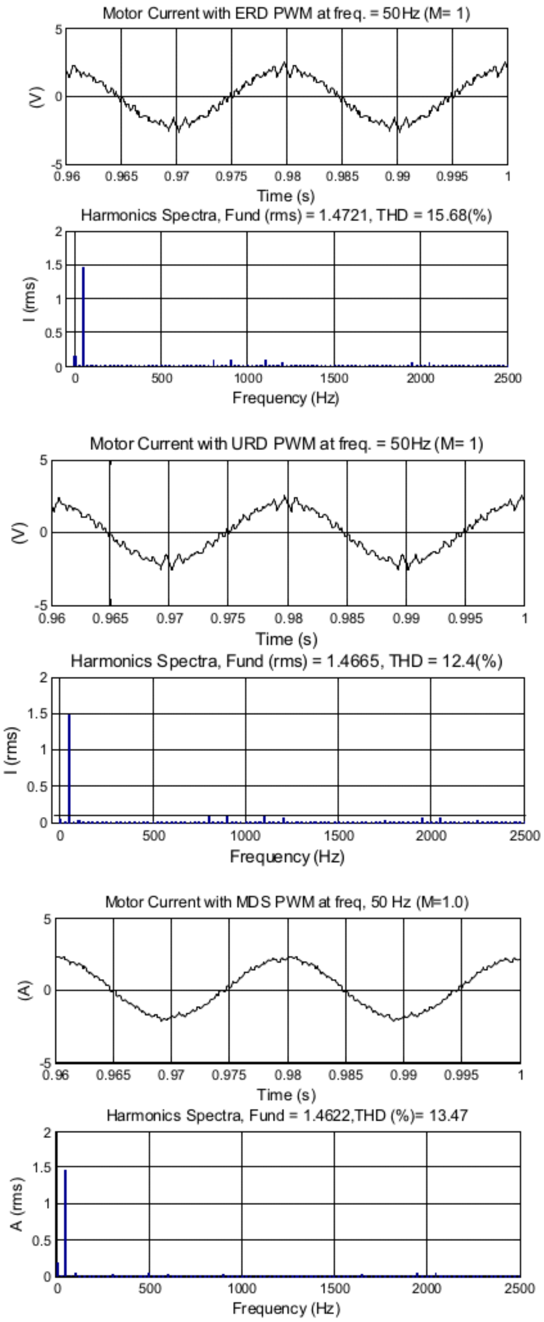

Fig. 8 Motor current and harmonics spectrum with various PWM schemes at M = 1.0

reveals that at M > 1.0 the form of the torque with MDS PWM is more oscillated. The oscillatory torque is related with the fluctuated current THD value of MDS PWM.

Table 2 The various PWM shceme comparation of current THD and the output voltage

M	THD of load current in %			
	ERD	URD1)	URD2	MDS
1.15	14.14	14.14	4.101	7.897
1.10	13.67	13.53	4.739	6.717
1.05	13.07	12.90	5.488	5.913
1.00	15.57	12.39	6.404	13.75
0.95	12.34	11.37	6.792	5.345
0.90	12.23	11.05	7.381	8.316
0.85	11.33	10.28	7.605	5.685
0.80	10.86	9.441	7.573	5.265
0.75	11.22	8.938	7.691	6.698
0.7	10.47	8.126	7.463	5.187
0.65	10.33	7.461	7.208	5.151
0.6	9.951	7.323	7.426	5.424
0.55	9.558	6.625	6.625	6.625
0.5	0.91	6.092	6.092	6.092
0.45	8.634	5.829	5.829	5.829
0.4	8.142	5.846	5.846	5.846
0.35	7.641	5.761	5.761	5.761
0.3	8.107	6.874	6.874	6.874
0.25	13.44	9.107	9.107	9.107
0.2	2.565	2.423	2.423	2.423
0.15	2.081	1.876	1.876	1.876
0.10	3.235	1.833	1.833	1.833

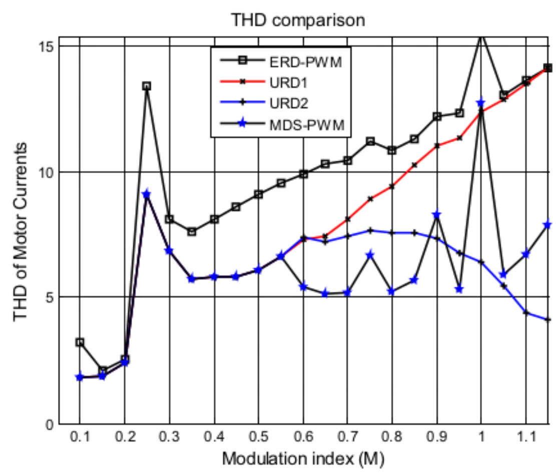

Fig. 9 THD comparison of the load motor currents

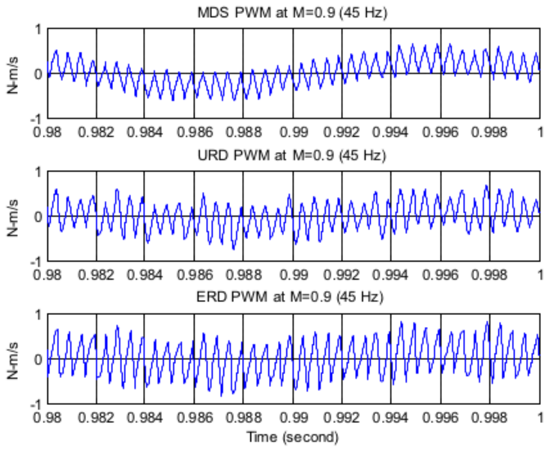

Fig. 10 Steady state mechanical torque of motor for various PWM schemes at M = 0.9 (45 Hz)

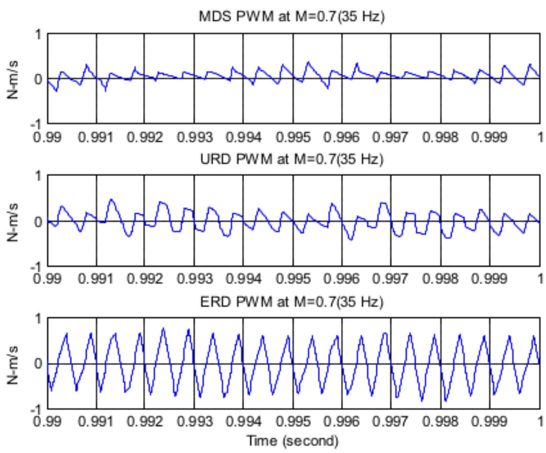

Fig. 11 Steady state mechanical torque of motor for various PWM schemes at M = 0.7 (35 Hz)

4 Conclusion

This paper investigates the performance of various PWM schemes for two inverters fed a three-phase induction induction motor. The PWM schemes are developed by simply divide the voltage references and modulated using the same or different PWM scheme with simple carrier based PWM method. The 3-phase motor is controlled in v/f open loop control schems. Simulation results show that among the three PWM schemes, the MDS PWM performs the best result with the best voltage THD performance for all modulation index. Further the three PWM schemes shows their capability to control the motor to give a variable speed. In line with the voltage performance, the MDS PWM also provides the best speed-torque respons, and the most excellent current quality among the three PWM methods.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Human participants and/or animals rights This article does not contain any studies with human participants or animals performed by any of the authors.

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