Performance Analysis of a Novel Decomposition based PWM Scheme of Dual-Inverter Fed Open-End Winding Five-Phase Motor Drives with DC-link voltage ratio of 2 : 1

by I N Wahyu Satiawan

Submission date: 22-Oct-2022 04:28PM (UTC+0700)
Submission ID: 1932250541
File name: ijertv13n12_122_wahyu01.pdf (663.15K)
Word count: 4571
Character count: 21114

International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 13, Number 12 (2020), pp. 4908-4914

Performance Analysis of a Novel Decomposition based PWM Scheme of Dual-Inverter Fed Open-End Winding Five-Phase Motor Drives with DC-link voltage ratio of 2 : 1

I.N.W Satiawan[1,*], I.B. F. Citarsa[1] and I.K. Wiryajati[1]

[1] *Electrical Dept. Faculty of Engineering, University of Mataram Jalan Majapahit no. 62 Mataram, West Nusa Tenggara – Indonesia,*

Abstract

Development of Pulse Width Modulation (PWM) methods for dual-inverter fed Open-end Winding (OeW) five-phase motor drive is considerably challenging due to availability of a huge number of voltage space vectors and existence of multiple two-dimensional planes. The available PWM schemes were developed using decoupled technique that divides the voltage references into both inverters to reduce complexity. This paper discusses a novel PWM based on Decomposition scheme for dual-inverter OeW five-phase drive with DC-link voltage ratio of 2 : 1. The PWM scheme works at three operation modes. At $1.05 \leq M < 0.7$, inverter 1 is modulated at fundamental switching frequency while inverter 2 operates in PWM mode. At $0.7 \leq M < 0.35$, inverter 1 operates in 180° mode and inverter 2 in PWM mode. At $M \leq 0.35$, only inverter 1 operates in PWM mode while inverter 2 locked at zero switching vector (00000 or 11111), reverting the system into single side supply drive mode. The developed PWM scheme is verified using MATLAB / Simulink and the performance is compared with three PWM methods. Simulation results show excellent performance of the proposed PWM scheme. The quality of inverter output voltages improves significantly over three PWM methods. It is also reveals that the smoother motor torque is achieved especially for $M < 0.7$. Further, the THD of motor current also improves especially for $M > 0.35$ compared with the URS PWM schemes and for $M < 0.7$ compared with the three-level decomposition PWM scheme

Keywords: Pulse Width Modulation (PWM); Dual-inverter fed; Open-end Windings; Decomposition PWM; Unequal Refernce Sharing (URS).

1. INTRODUCTION

In high power application drives, limitation of rating of power electronics components is an important issue. Multi-level inverter is considered as a viable solution to solve the problem. Numerous topology of multi-level inverters has been developed includes Neutral Point Clamped (NPC), Flying Capacitor (FC) and cascaded inverters (Enjeti & Jakkli (1992), McGrath & Holmes (2007), Lu & Corzine (2007)). Among the cascaded inverters, dual-inverter fed OeW drives is relatively new. In an OeW drive, the neutral point of machine is opened, allowing the machine fed from both sides. The structure of dual-inverter fed is simple and easy to realize using two two-level inverters (Stemmler & Guggenbach (1993)). Figure 1 shows the simplified structure of dual-inverter fed OeW five-phase drive. Despite the simple structure, the development of suitable PWM schemes for the OeW structure is challenging especially when a multi-phase machine is considered due to the huge number of voltage space vectors and existence of multiple two-dimentional planes. (Levi et al. 2010; Widana et al. 2020).

A few PWM schemes for dual-inverter fed OeW 5-phase drive with equal ratio of DC-link voltage has been developed (Jones et al, (2011), Jones et al, (2012), Jones & Satiawan (2012), Levi et al, (2012)). Among them, the Decomposition PWM was proven to give the best performance (Satiawan et al, (2014)). More recently some PWM methods for dual-inverter fed OeW 5-phase drive with dc-link voltage ratio of 2:1 has been investigated (Jones et al, (2014)). The developed PWM scheme is based on decoupled PWM method where the voltage references are divided in a certain way and then modulated whether using the same or different modulation techniques. Following the idea in (Jones et al, (2011)), a new PWM scheme for a four-level dual-inverter fed OeW five-phase drive was introduced in (Satiawan et al. 2016; Rinartha et al. 2018) where the three-level Decomposition PWM scheme was adopted with some modifications. It is reported in (Satiawan et al, (2016)) that the quality of inverter output voltages improves compared with the three-level Decomposition PWM scheme. This paper further investigates the performance of the proposed 4-level Decomposition based PWM scheme with respect to of torque, speed and motor current. The simulation results are compared with the four-level URS PWM schemes and three-level Decomposition PWM scheme.

2. METHODOLOGY

2.1. Voltage space vectors of dual-inverter fed OeW five-phase drive

Two-level five-phase Voltage Source Inverter (VSI) presents 32 (2^5) switching states. The switching states can be converted to 31 voltage space vectors in two in α - β and x - y planes by using equations (1) and (2

$$\underline{v}_{\alpha\beta} = v_\alpha + jv_\beta = (2/5)v_{dc}(S_A + \underline{a}S_B + \underline{a}^2 S_C + \underline{a}^{*2} S_D + \underline{a}S_E) \quad (1)$$

International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 13, Number 12 (2020), pp. 4908-4914

$$\underline{v}_{xy} = v_x + jv_y = (2/5)v_{dc}(S_A + \underline{a}^2 S_B + \underline{a}' S_C + \underline{a} S_D + \underline{a}'^2 S_E) \quad (2)$$

where $\underline{a} = \exp(j2\pi/5)$, $\underline{a}' = \exp(-j2\pi/5)$, v_{dc} is inverter dc-link voltage, $S_X (X = A, B, C, D, E)$ are the switching state condition of inverter. Figure 2 shows the voltage space vectors in both α - β and x - y planes where the binary numbers indicates the switching state (s) that generates the voltage vector(s).

In the dual-inverter fed OeW five-phase drive, assuming two two-level VSIs are applied, the available voltage space vectors are formed from combination of 32 switching states of inverter 1 and 32 switching states of inverter 2 that results in 1024 (32 x 32) voltage space vectors. Mapping of voltage vectors depends on the ratio of DC-link voltage of the two inverters. When equal ratio of DC-link voltages is applied, the vectors map in 211 positions (Levi, et al, 2010). When ratio DC-link voltage of 2 : 1 is applied, the vectors map in 781 positions. Fig. 3 (a) and (b) show the mapping of the voltage vectors in α - β plane for ratio DC link of 1:1 and 2:1, respectively. The voltage vectors in the x - y plane generate by different switching combinations but have the same pattern as the vectors in α - β plane hence they are not shown.

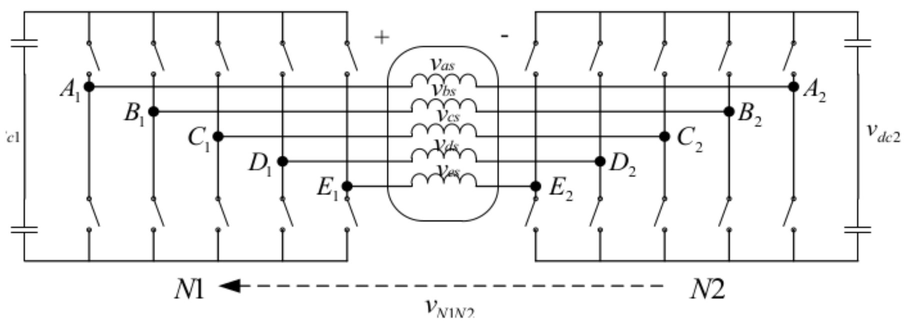
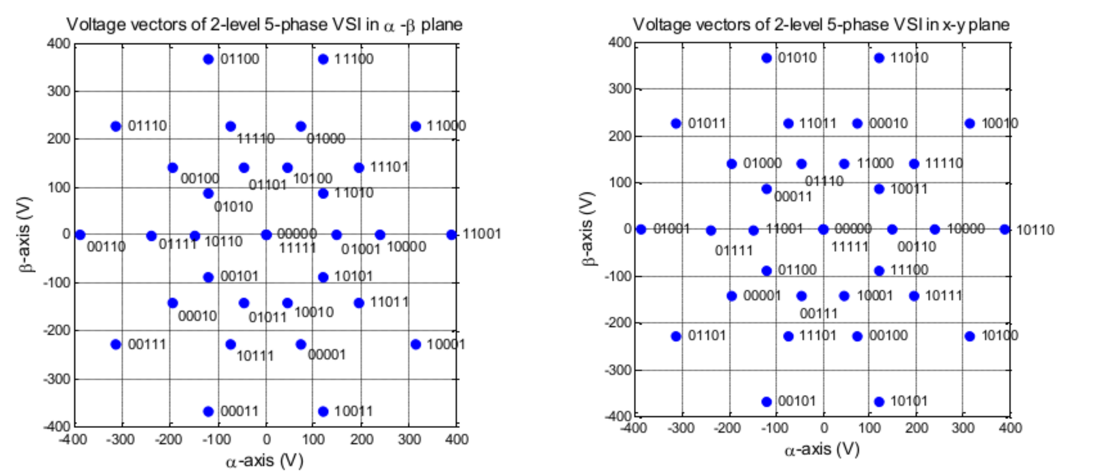


Figure 1. The structure of a five-phase dual two-level inverter fed OeW drive

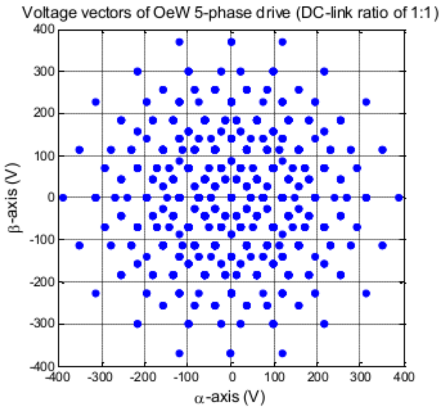


(a) (b)

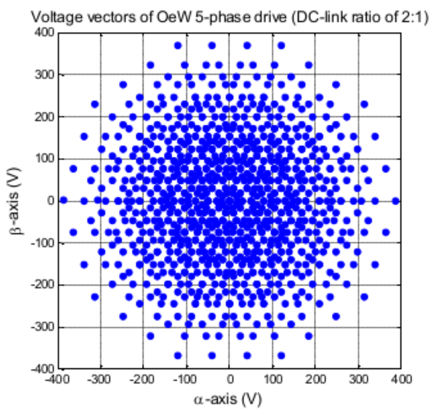
Figure 2. Voltage space vector of two-level 5-phase VSI in both (a) α-β (a) and x-y (b) planes

2.2. Decomposition based PWM method of a dual-inverter OeW five-phase motor drive with DC-link voltage ratio of 2 : 1

Prior to discussing the four-level Decomposition PWM scheme, the URS PWM is reviewed first. In the URS PWM scheme the voltage references are apportioned into two parts and modulated using two-level Space Vector PWM (SVPWWM). The four-level URS PWM scheme divides the voltage references according to modulation index using equation (3) (Jones et al, 2014; Giler et al., 2019).



(a)



(b)

Figure 3. Voltage space vectors of dual-inverter fed OeW five-phase drives with (a). Equal DC-link voltage ratio, (b). DC-link voltage ratio 2 : 1

$$0 \le M \le 0.35 \begin{cases} M_1 = 3M \\ M_2 = 0 \end{cases} \qquad (3)$$
$$0.35 < M \le 1.05 \begin{cases} M_1 = 1.05 \\ M_2 = 1.05(M - 0.35) \end{cases}$$

Equation (3) governs that up to $M = 0.35$ the references are only allocated to inverter 1 (while inverter 2 is switched off). When the references exceed $M = 0{,}35$, the references of inverter 1 is kept at the maximum value while the rest of them go to inverter 2. The divided references are then modulated using equivalent carrier based SVPWM. Based on the type of carriers used by two modulators, the URS PWM can be grouped into 2 types, i.e URS PWM with the opposite carriers (URS1) and URS PWM with same carriers (URS2). (Jones at al, (2014)).

A PWM scheme of 4-level OeW five-phase drive based on Decomposition method is introduced by Satiawan et al, (2016). The PWM scheme adopts the Decomposition PWM of three-level OeW with some modifications. The proposed PWM scheme is realized by operating inverters in three operation modes according to modulation index. At $1.05 \le M < 0.7$, inverter 1 is modulated at fundamental switching frequency while inverter 2 operates in PWM mode. The phase '*a*' gating signals of upper and lower switches are generated by comparing the sinusoidal reference with a certain value as represents by a simple logic in equations (4) and (5)

$$\begin{aligned} &if\ v_{ref} > 0.4 \text{ then } S_{x1(x=a,b,c,d,e)} = 1\,(\text{High}) \\ &else\ \ S_{x1(x=a,b,c,d,e)} = 0\,(\text{Low}) \end{aligned} \qquad (4)$$

$$\begin{aligned} &if\ v_{ref} < -0.4 \text{ then } S_{x2(x=a,b,c,d,e)} = 1\,(\text{High}) \\ &else\ \ S_{x2(x=a,b,c,d,e)} = 0\,(\text{Low}) \end{aligned} \qquad (5)$$

Figure 4. (a) shows the gating signals of upper and lower switches at $M = 1.0$. It is shown that both switches switched off in the same time at particular instant of time giving an additional dead-time for the inverter switches. At $0.7 \le M < 0.35$, inverter 1 operates in 180° mode and inverter 2 in PWM mode. In order to avoid the unbalance condition between two inverters, the DC-link voltage of inverter 1 is reduced 50% and the operation of two inverters are alternated between 180° mode and PWM mode at every 1 period. The phase '*a*' gating signal upper switches of inverter 1 and inverter 2 are shown at Figure 4. (b) and (c). Finally, at $M < 0.35$, only one inverter operates in PWM mode while inverter 2 locked at zero switching vector (00000 or 11111) reverting the system into single side supply drive mode.

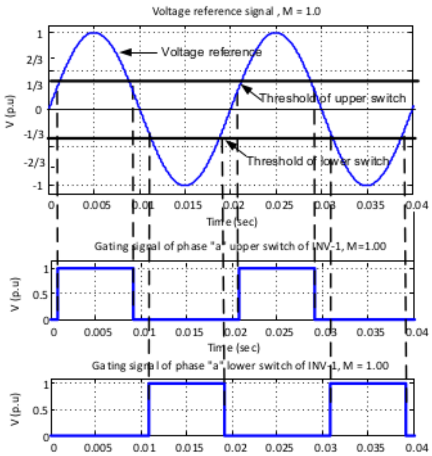
3. RESULTS

The four-level Decomposition PWM method is verified using MATLAB / Simulink. Inverters are modeled using *SimPower Blockset*. Switching frequency of PWM inverter is set at 2 kHz. DC-link inverter 1 is 400 V and DC-link inverter 2 is 200 V. Death-time effect of inverter switches does not included in the simulation. The output voltage of the proposed PWM scheme at $M = 0.9$ along with output voltages obtained by URS PWM schemes and three-level Decomposition PWM scheme are shown at Figure 5. Simulation was repeated from $M = 0.05$ to $M = 1.05$ with 0.05 increment steps to shows the whole performance of the developed PWM scheme. THD of the output voltages for all conditions are noted and presented at Figure 6 along with the THD of the output voltage using URS PWM schemes and three-level Decomposition PWM method.

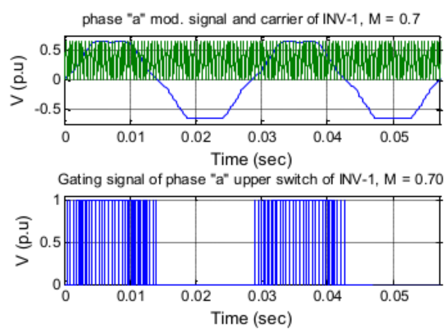
In order to further verify the proposed PWM method, simulations are done based on a five-phase induction motor modeled using MATLAB/Simulink with the machine parameters are shown in Table 1. A simple V/f open-loop control is applied to drive the machine. The machine is run for 3 seconds where a 5 N-m load applied at $t = 1.3$ second and reduced to 2 N-m at $t = 2$ seconds. Torque-speed response at particular $M = 0.9$ (frequency fundamental, $f = 45$ Hz) and $M =$

International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 13, Number 12 (2020), pp. 4908-4914

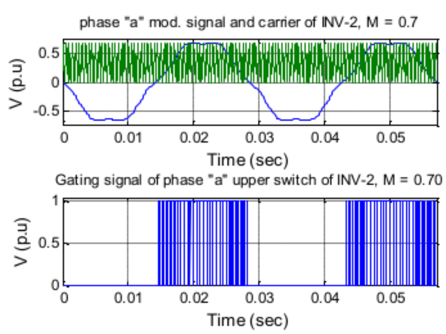
0.6 (frequency fundamental, f =30 Hz) are shown at Figure 7. Meanwhile a part of the steady state motor torque of three PWM methods for various modulation indices is presented at Figure 8.



(a)

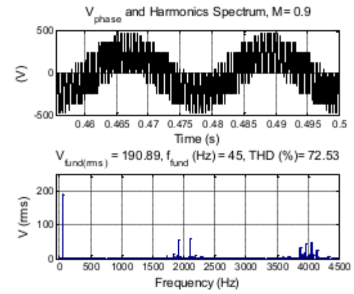


(b)

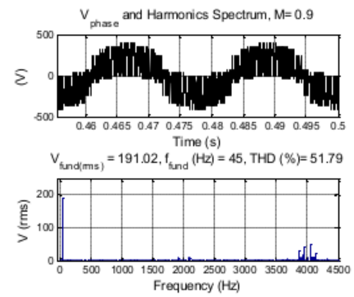


(c)

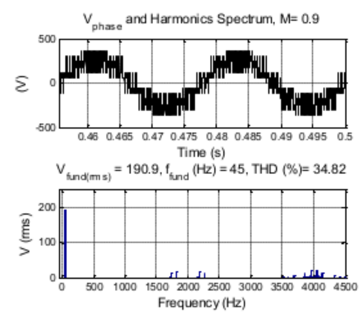
Figure 4. Gating signals of inverter switches using Decomposition PWM for (a) M = 1.0 (b) upper switch of inverter 1 at M = 0.7 (c). upper switch of inverter 2 at M = 0.7



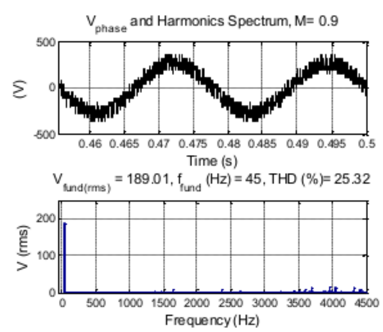
(a) URS with opposite carriers



(b) URS with same carriers



(c). 3-level Decomposition PWM



(d). 4-level Decomposition PWM

Figure 5. Phase voltage output of various PWM methods at M = 0.9

International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 13, Number 12 (2020), pp. 4908-4914

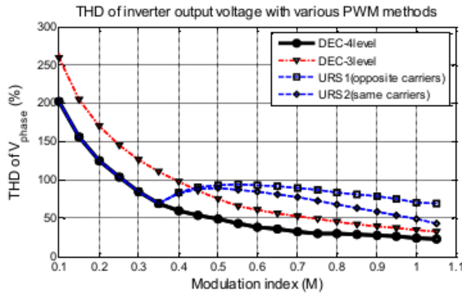
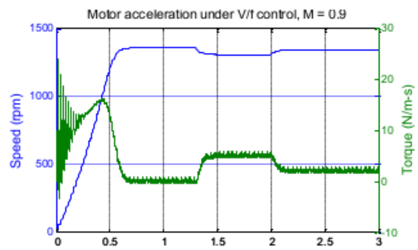


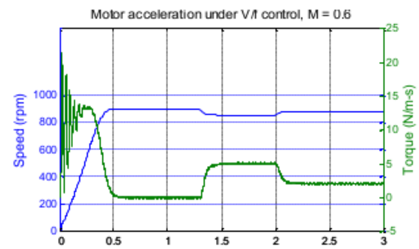
Figure 6. Phase voltage THD comparison of various PWM methods

Table 1. Motor parameters used in simulation

Machine parameters	Value
Stator resistance, R_s [Ω]	10
Rotor resistance, R_r [Ω]	6.3
Stator leakage inductance, L_{ls} [H]	0.04
Rotor leakage inductance, L_{lr} [H]	0.04
Magnetizing inductance, L_m [H]	0.42
Moment of Inertia, J [kg-m^2]	0.05
Load torque, T_L [N-m]	5 and 2
Magnetic poles pair number, P	2
Input voltage (phase to neutral), [V]	220 for $M = 1.0$
Rated frequency, f [Hz]	50 for $M = 1.0$



(a)



(b)

Figure 7. Speed – torque relationship at (a) M = 0.9, (b) M = 0.6

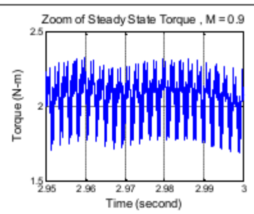
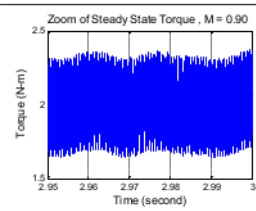
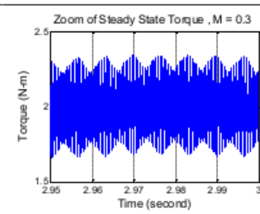
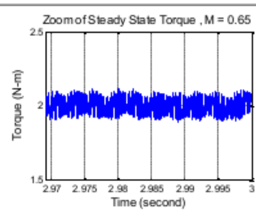
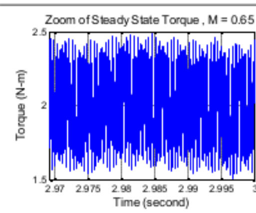
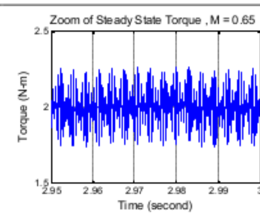
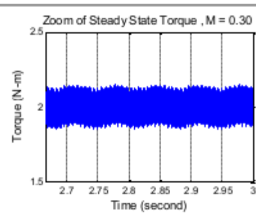
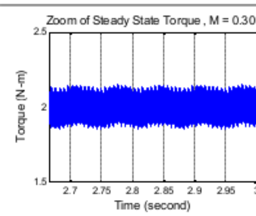
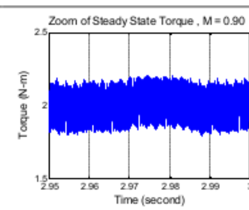
M	4-level Decomposition	4-level URS(same carriers)	3-level Decomposition
0.9			
0.65			
0.3			

Figure 8. Steady state motor torque for various modulation indices and PWM methods

International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 13, Number 12 (2020), pp. 4908-4914

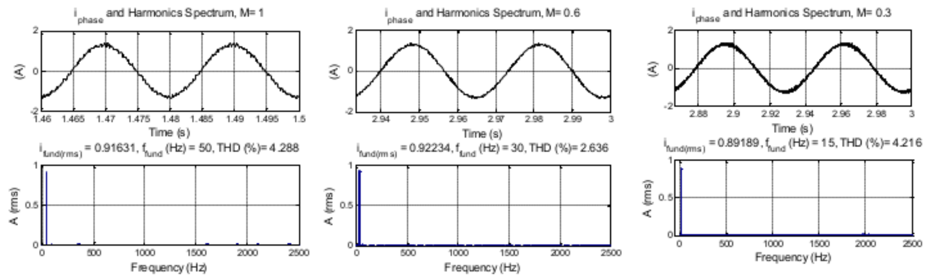


Figure 9. Motor currents at various modulation indices; (a)M = 1.0, (b) M = 0.6 (c) M = 0.3

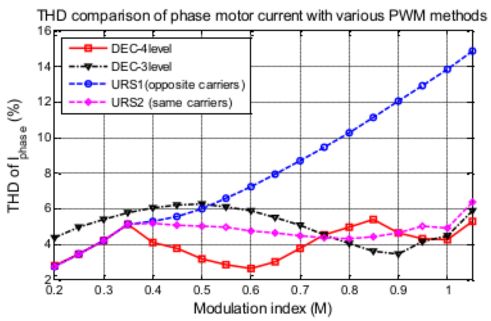


Figure 10. THD comparison of motor currents using various PWM methods

Subsequently, phase motor currents are analyzed. Figure 9 shows motor current of the machine driven by the proposed PWM scheme at various modulation indices. The current THD of various PWM methods and modulation indices is also presented at Figure 10.

4. DISCUSSION

4.1 Phase Voltage Output

It is obviously shown in the Figure 5 that the 4-level Decomposition PWM scheme provides a better control to inverters hence results improved output voltage compared with the others PWM methods. Improvement of output voltage's is indicated by the shape of the voltage waveform that contains more voltage levels and harmonics spectrum contains free low order harmonics, lower switching frequency harmonics and lowest value of voltage THD (Figure 5 (d)). The THD performance of the 4-level Decomposition PWM method is significantly improved over other three PMW methods as shown in the bold line at Figure 6. For M < 0.35 the performance of the 4-level Decomposition PWM and URS schemes is the same as the modulation strategy applied is the same (only one inverter is activated).

4.2 Torque Ripple Analysis

Next, the machine torque-speed relationship is discussed. It is clearly shown in the Figure 7 that the machine has a good dynamic torque –speed response for both operations with and without load. The desired speed was reached in less than 0.6 second. In general motor response is able to justify with the changes of the load in less than 0.2 second. The fast tracking of torque-speed response proves the excellent performance of the proposed Decomposition PWM method. Subsequently, Figure 8 shows that the proposed PWM method generates the smoothest torque with smallest peak-to-peak magnitude compared with two PWM methods especially at M = 0.65. Further investigation reveals that the proposed Decomposition PWM scheme provides the best torque performance for 0.35 < M < 0.7 (when inverters alternately modulated between fundamental and PWM mode in one cycle of operation). At M < 0.35, the torque performance is better than the three-level PWM scheme but the torque performance is exactly the same as the URS PWM method.

4.3 Performance of motor phase currents

The phase currents of the machine as are shown in the Figure 9 reveals that very closely sinusoidal motor currents are achieved which is confirmed by the FFT plot, where total harmonics distortion (THD) is less than 5 %. Further, the THD comparison of motor current (Figure 10) indicates that the load current performs a significant improvement at particular M > 0.35 compared with the URS1 PWM scheme (opposite carriers). Improved THD is also obtained for M < 0.7 compared with the three-level Decomposition PWM scheme. Meanwhile, in comparison with URS2 PWM scheme (same carriers), THD is only improved at particular range of 0.35 < M < 0.7.

5. CONCLUSION

A comprehensive performance analysis of a novel Decomposition based PWM scheme for a four-level open-end winding motor drive has been presented in this paper. The developed PWM scheme adopts the three-level Decomposition PWM scheme of dual-inverter fed open-end winding drive. The proposed PWM is verified using Matlab / Simulink. The results show that improved quality of voltage outputs are achieved over URS PWM schemes especially for M > 0.35. The excellent performance of the decomposition four-level PWM also indicated by the smoother motor torque and lower THD of motor current at particular M < 0.7 over the URS PWM scheme and three-level Decomposition PWM scheme.

ACKNOWLEDGEMENTS

My sincere gratitude goes to Ministery of Research Technology and Higher Educations Republic of Indonesia for the financial support via a research grant dedicated to Mataram University, West Nusa Tenggara, Indonesia

REFERENCES

[1] Enjeti PN, & Jakkli R. Optimal power control strategies for neutral point clamped (NPC) inverter topology. IEEE Trans. on Industry App. 1992; 28(3): 558–566.

[2] Jones M, Satiawan IN, Levi E. A three-level five-phase space-vector modulation algorithm based on the decomposition method. Proc. of the In: Int. Electric Machines and Drives Conference (IEMDC); 15-18 May ; Niagara Falls-Canada: IEEE; 2011. 1219-1224

[3] Jones M, & Satiawan IN. A simple multi-level space vector modulation algorithm for five-phase open-end winding drives. Trans. on Int. Association for Mathematics and Computers in Simulation (IMACS) Journal. 2012; 90(1): 74–85.

[4] Jones M, Satiawan INW, Bodo N, Levi E. A dual five-phase space-vector modulation algorithm based on the decomposition method. IEEE Trans. on Industry Apps. 2012; 48 (6): 1–11.

[5] Jones M, Darijevic M, Levi E. Decoupled modulation techniques for a four-level five-phase open-end winding drive. In:Proc. on Energy Conversion Congress and Exposition (ECCE), 14-18 September; Pittsburgh-USA: IEEE; 2014. 178-186.

[6] Levi E, Jones M, Satiawan W. A multi-phase dual-inverter supplied drive structure for electric and hybrid electric vehicles. In: Procs. of the IEEE Vehicle Power and Propulsion Conference (VPPC); 1-3 September; Lille-France: IEEE; 2010. 1-7.

[7] Levi E, Satiawan INW, Bodo N, Jones M. A space-vector modulation scheme for multilevel open-end windings five-phase drives. IEEE Transactions on Energy Conversion. 2012; 27 (1): 1–10.

[8] Lu S, Corzine KA. Advanced control and analysis of cascaded multilevel converters based on P-Q compensation. IEEE Trans. on Power Electronics. 2007; 22 (4): 1242-1252.

[9] McGrath BP, Holmes DG. Analytical Modelling of Voltage Balance Dynamics for a Flying Capacitor Multilevel Converter. In: Procs. Power Electronics Specialists Conference; 17 – 21 June ; Orlando Florida-USA: IEEE; 2007. 1818-1816.

[10] Satiawan IN, Citarsa IB, & Wiryajati, IK. Performance comparison of PWM schemes of dual-inverter fed five-phase motor drives. Int. Journal of Technology. 2014; vol. 5 (3): 277–286.

[11] Satiawan INW, Citarsa IBF, Wiryajati, IK. A simple PWM scheme for a four-level dual-inverter fed open-end Winding five-phase motor drives. In : Proc. IET International Conference on Clean Energy and Technology (CEAT2016); 14-15 November ; Kuala Lumpur –Malaysia: IET; 2016. 1-7.

[12] Stemmler H, & Guggenbach P. Configurations of high-power voltage source inverter drives. In: Procs. of the European Power Electronics and Applications Conference (EPE). 13 – 18 September; Brighton-UK; 1993. 7-14.

[13] Giler, S. R. B., Loor, C. J. S., Moreira, J. C. M., & Zambrano, B. A. M. (2019). Technical-economic impact of low voltage secondary lines to pre-assembled. *International Journal of Physical Sciences and Engineering*, *3*(2), 21-26. https://doi.org/10.29332/ijpse.v3n2.325

[14] Rinartha, K., Suryasa, W., & Kartika, L. G. S. (2018). Comparative Analysis of String Similarity on Dynamic Query Suggestions. In *2018 Electrical Power, Electronics, Communications, Controls and Informatics Seminar (EECCIS)* (pp. 399-404). IEEE.

[15] Widana, I.K., Sumetri, N.W., Sutapa, I.K., Suryasa W. (2020). Anthropometric measures for better cardiovascular and musculoskeletal health. Comput Appl Eng Educ, 1–12. https://doi.org/10.1002/cae.22202

Performance Analysis of a Novel Decomposition based PWM Scheme of Dual-Inverter Fed Open-End Winding Five-Phase Motor Drives with DC-link voltage ratio of 2 : 1

ORIGINALITY REPORT

11%	8%	9%	8%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

MATCH ALL SOURCES (ONLY SELECTED SOURCE PRINTED)

4%

★ eprints.covenantuniversity.edu.ng

Internet Source

Exclude quotes	On	Exclude matches	< 1%
Exclude bibliography	On		