International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 12, No. 3, September 2021, pp. 1326~1334
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v12.i3.pp1326-1334

Stator flux in direct torque control using a speed and torque variation-based sector rotation approach

Siti Azura Ahmad Tarusan[1], Auzani Jidin[2], Mohd Luqman Mohd Jamil[3], Kasrul Abdul Karim[4]
[1,2,3,4] Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Malaysia
[1,2] Power Electronics and Drives Research Group, CeRIA, UTeM, Malaysia
[3,4] Electrical Machine Design, Power Electronics and Drives Research Group, CeRIA, UTeM, Malaysia

Article Info

Article history:

Received Jan 17, 2021
Revised May 11, 2021
Accepted Jul 19, 2021

Keywords:

Direct torque control
Sector rotation strategy
Stator flux
Various speed
Various torque

ABSTRACT

A typical problem of traditional DTCs is that the stator flux fails to regulate at low running speeds. The regulation of stator flux in DTC is disrupted because of the demagnetization of zero-voltage vector at low-speed operation. One of the solutions to solve the problem is to use a fixed sector rotation technique. The concept is based on decreasing stator flux droop, a simple technique for changing the flux locus sector at a certain angle. This method, however, is only effective at low working speeds at one value of torque. As a result, the stator flux droop effect at various speeds as well as torque must be studied. The study is carried out in this paper using simulation (MATLAB/Simulink) and a practical setup (dSPACE board) where both have performed similar outcomes. The comparison is done between the conventional method (without a strategy) and the proposed method (with strategy). In summary, the effect of stator flux droop has been found to have an inverse linear relationship to the speed and torque variation.

Corresponding Author:

Siti Azura Ahmad Tarusan
Faculty of Electrical Engineering
Universiti Teknikal Malaysia Melaka
76100 Durian Tunggal, Melaka, Malaysia
Email: sitiazura@utem.edu.my

1. INTRODUCTION

Direct Torque Control (DTC), sometimes known as a "bang-bang" control, is gaining popularity in the AC drives industry due to its rapid control and simple algorithm structure compared to Field Oriented Control (FOC) [1]. DTC controls the torque and flux inside the hysteresis band by converting the control implementation into a circular flux locus using the proper voltage vector [2]–[4]. Nonetheless, the benefits of DTC have resulted in several serious issues, such as inadequate stator flux management at low speeds, large ripples in torque and stator flux variables, and switching frequency variation [5]–[10].

DTC's performance can also be considerably improved by employing space vector modulation, often known as DTC-SVM. In the space vector modulator, the synthesised main method is used to sample the reference stator voltage [11]–[13]. As a result, the problem is solved since the DTC torque ripple is reduced and the switching frequency is fixed. However, it has a flaw in that it necessitates a sophisticated algorithm and a lot of digital signal processing. The duty cycle-based technique, on the other hand, is being developed to improve the DTC system. It is implemented using the torque slope profile, which is adapted using the proper voltage vectors within their interval period [14]–[17]. Although the torque ripple is reduced, the mathematical model used to carry out the method is complicated and difficult. Furthermore, the DTC is enhanced by the employment of a multilevel inverter provided by [18]–[22], which causes the enormous algorithm integrated into the DTC look-up table.

As previously stated, DTC degrades stator flux performance at low operating speeds. In the control concept of DTC, the existence of zero-voltage vector demagnetization may interrupt the regulation hence causing a stator flux droop performance [23]. Thus, several enhancements are suggested, as in [18], [24]-[27]. The stator flux is improved by utilising a fixed sector rotation approach described in [25], however it only focuses at low operating speeds. As a result, this technique is used in this research to examine the effect of stator flux performance under varied speed and torque conditions. The research is carried out with the help of the MATLAB/Simulink software and a practical setup (a utilization of dSPACE DS1104 controller board). The evaluation is implemented by comparing a conventional technique (without strategy) and a new method (with strategy) in the DTC scheme.

2. MODIFIED STRUCTURE OF CONVENTIONAL DTC

Figure 1 shows a modified structure of conventional DTC where the shifted angle is added as in the modified sector in order to analyse the effect of flux droop. As similar to the conventional DTC [4], some elements keep maintained, such as the control element (torque and flux hysteresis comparators), drive element (lookup table and two-level inverter) and the feedback element (voltage and current calculation, sector detection and also torque and flux estimators). This structure is improved by using the shifted angle adapted into the sector detection to add with the original angle like suggested in [24]. Therefore, each sector is rotated at a new angle. The conventional inverter or two-level inverter applied in DTC has performed the mapping vector that contains eight voltage vectors, as illustrated in Figure 2(a). The eight voltage vectors are classified into two zero voltage vectors (V0 and V7) and six active voltage vectors (V1 – V6) formed into the hexagonal diagram. There are six sectors separately by 60° on the stator flux d-q plane to generate the operation of voltage vectors, as shown in Figure 2(b). This sector is used to employ the circular locus of the stator flux trajectory generated by two possible voltage vectors or tangential voltage vector for increasing or decreasing the stator flux. The selected voltage vectors produce a fast torque response in the DTC drive system [4].

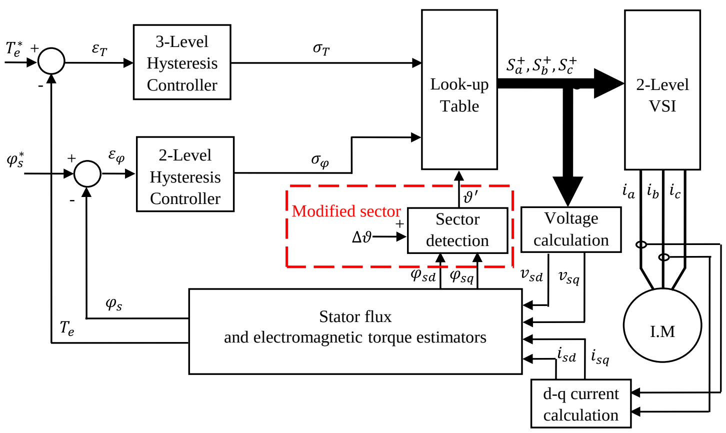
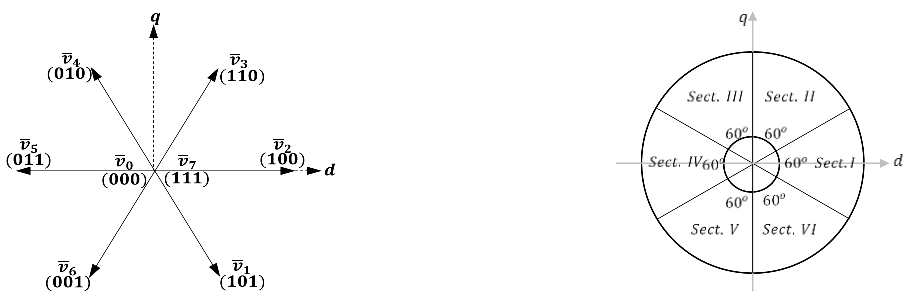


Figure 1. The modified sector with shifted angle in the conventional DTC drive system [24]



(a) (b)

Figure 2. The design of; (a) mapping vector of two-level inverter circuit and (b) d-q plane of stator flux [4]

3. OPERATION OF STATOR FLUX

Figure 3 shows the cross-section of the circular stator flux locus trajectory to identify the variation stator flux operation. For instance, in sector *VI*, the active voltage vector $\bar{v}_2$ represents the increased flux, while voltage vector $\bar{v}_3$ represents the decreased flux. As soon as it enters sector *I*, the active voltage vector is changed into $\bar{v}_3$ and $\bar{v}_4$ to increase and decrease the stator flux. This condition keeps continuously for the next sector by using a particular active voltage vector. It is observed that the same magnitude and angle of the voltage vector maintain the stator flux variation into consistent movement. This event is relevant for the ideal case in Figure 3(a) which the selected voltage vector fully controls the stator flux due to the negligible of stator resistance.

On the other hands, the normal operation of torque employs the active voltage vector and zero-voltage vector [25]. The active voltage vectors are applied for the increase or decrease torque while zero-voltage vector is applied as the torque at the persistent condition. As the motor runs at low operating speed, the ideal case as discussed previously is insignificant. It is due to the demagnetization by zero-voltage vector in which the torque is reduced as applied by the zero-voltage vector so that it grasps the stator flux movement [24]. The change of stator flux utilized by zero-voltage vector is expressed in equation (1) that it contains the voltage drop of stator resistance. Hence, the possibility of flux droop may occur as the stator flux keeps reducing until it reaches over the limit of lower band flux hysteresis [25].

As for the solution to the stator flux droop problem, the proposed strategy in [24] is used by tuning the sector rotation into a particular angle to reduce flux droop. The strategy is called a fixed sector rotation strategy. The shifted angle, $\Delta\vartheta$ is added to the original angle, θ_n to perform a new sector rotation for the voltage vector as stated in equation (2), as shown in Figure 4. The lookup table remains the same as the conventional DTC for selecting the appropriate voltage vector to generate switching for the inverter. As a result, the voltage vector performs a good tangential on the particular sector to minimize the stator flux droop. In this paper, the analysis is conducted by studying the effect of shifted angle, improving stator flux droop, $\Delta\varphi_s$ to the variation of speed, ω_m and the variation of torque.

$$\theta_n{}' = \theta_n + \Delta\vartheta \quad (1)$$

$$\theta_n{}' = \theta_n + \Delta\vartheta \quad (2)$$

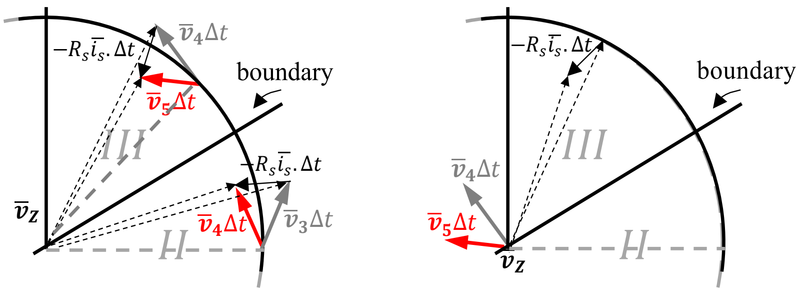


Figure 3: The operation of stator flux in; (a) ideal case and (b) demagnetization by zero voltage vector [24]

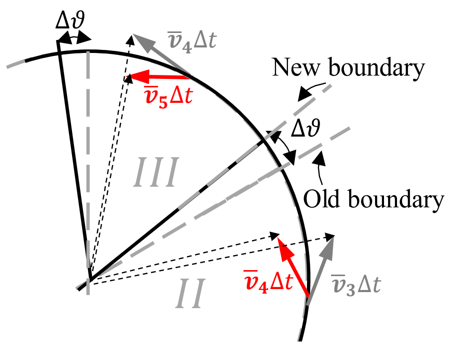


Figure 4: The modified sector by using fixed sector rotation strategy [25]

4. RESULTS AND DISCUSSION

The comparison between the conventional method with the proposed method is performed to realize the analysis on the effect of stator flux droop in DTC. It is conducted through the simulation and practical setup using the induction motor parameter as listed in Table 1. The software of MATLAB/Simulink package is applied to run the simulation. At the same time, a 1.1 kW squirrel-cage induction motor driven by the 100V supply voltage of a two-level inverter circuit is employed for the practical setup. It is attached with the controller board of dSPACE DS1104 with a sampling time of 50μ to perform the control algorithm of the DTC scheme. Figure 5 shows the practical setup to implement the DTC scheme.

Table 1. The list specification of induction machine

Induction Machine			
Rated power, P	1.1 kW	Frequency, f	50 Hz
Rated speed, $\omega_{m(rated)}$	2800 rpm	Stator self-inductance, L_s	0.47979 mH
Rated torque, $T_{e(rated)}$	4 Nm	Rotor self-inductance, L_r	0.47979 mH
Rated flux, $\varphi_{s(rated)}$	0.8452 Wb	Mutual inductance, L_m	0.4634 mH
Stator resistance, R_s	6.1 Ω	Combined Inertia, J	0.0565 $kg.m^2$
Rotor resistance, R_r	6.2293 Ω	Numbers of pole pairs	1

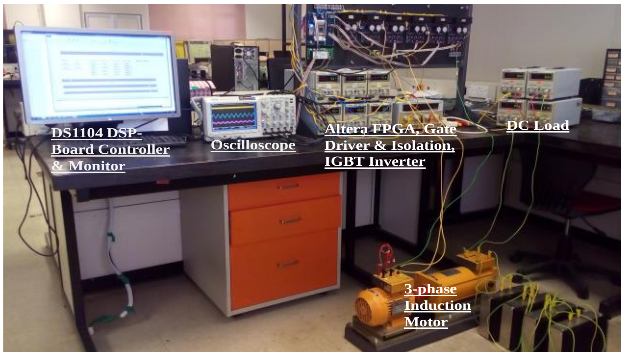


Figure 5. The practical setup of DTC drive system

The test based on various torques is carried out in this analysis by preparing three sets of reference torques: 1.1 Nm, 1.5 Nm, and 1.9 Nm. Meanwhile, the stator flux reference is set to 0.8452Wb. The modest figure of stator flux, 0.8452 Wb, must be expanded for detail examination, according to the motor specification. As a result, it is multiplied by 10 to get 8.452 Wb. Then it subtracts with 8 to get 0.452 Wb. As a result, the stator flux waveform is presented between 0.452 Wb, which is close to the actual stator flux value. In the practical setup, the stator flux adjustment is set to 0.02 Wb/div (similar to the real value). The different speeds for analysing the stator flux droop are established on a specific range from 200 rpm to 450 rpm. Only three speed ranges (200 rpm, 300 rpm, and 450 rpm) are shown in the comparative findings. Fortunately, the practical results for each operating speed and torque are consistent with the simulation results.

The stator flux droop in the conventional approach has attained an estimated 0.0152 Wb, which is the lowest among the three sets of speeds, according to the high operating speed of 450 rpm. Figure 6(i) shows that the stator flux droop at 1.9 Nm torque is the lowest of the group, requiring only a 10° shifted angle to lessen the droop. Meanwhile, to reduce flux droop, stator flux at 1.1 Nm and 1.5 Nm necessitates modifying the angle to 13° (0.0202 Wb) and 11° (0.0182 Wb), respectively, as shown in Figure 6(ii) and Figure 6(iii). In comparison to the previous speed, the stator flux droop has increased slightly for all torque at the medium working speed of 300 rpm. For a torque of 1.9 Nm, the stator flux droop is 0.0252 Wb. As a result, the least shifted angle of 13° is required to minimise droop, as shown in Figure 7(i). Figures 7(ii) and 7(iii) show the shifted angles of 14° (0.0262 Wb) and 15° (0.0272 Wb) required by the individual torques of 1.5 Nm and 1.1 Nm to enhance the stator flux.

Adjusting the low operating speed to 200 rpm reveals that all stator flux exhibits the greatest stator flux droop. Figure 8(iii) shows that 1.1 Nm torque has the highest droop of stator flux with 0.0452 Wb among speed and torque. To reduce stator flux droop, a 17° shifted angle must be used. In the conventional method, for torques of 1.9 Nm and 1.5 Nm, the droop of stator flux was 0.0302 Wb and 0.0352 Wb, respectively. As a result, both (1.9 Nm and 1.5 Nm) must apply the respective shifted angle of 14° (1.9 Nm) and 15° (1.5 Nm) to minimise stator flux droop, as shown in Figures 8(i) and 8(ii). When all of the results are compiled into Table 2 and plotted into the graph shown in Figure 9 for the individual torque, (shifted angle and flux droop against speed). Further, all of the torque and speed which respect to shifted angle and flux droop is emphasized in Figure 10. It is discovered that the shifted angle, $\Delta\vartheta$ is inversely proportional to the variation of speed, ω_m and torque, T_e as expressed in (3). In summary, it has been demonstrated that the stator flux droop, $\Delta\varphi_s$ effect has an inverse linear relationship with speed, ω_m and torque T_e variation as specified in (4).

$$\Delta\vartheta \propto \frac{1}{\omega_m} \propto \frac{1}{T_e} \quad (3)$$

$$\Delta\varphi_s \propto \frac{1}{\omega_m} \propto \frac{1}{T_e} \quad (4$$

Table 2. The result of the stator flux droop at various operating speed and torque

Torque (Nm)	Speed (rpm)	Flux droop (Wb)	Shifted angle (°)
1.9	450	0.0152	10
	300	0.0252	13
	200	0.0302	14
1.5	450	0.0182	11
	300	0.0262	14
	200	0.0352	15
1.1	450	0.0202	13
	300	0.0272	15
	200	0.0452	17

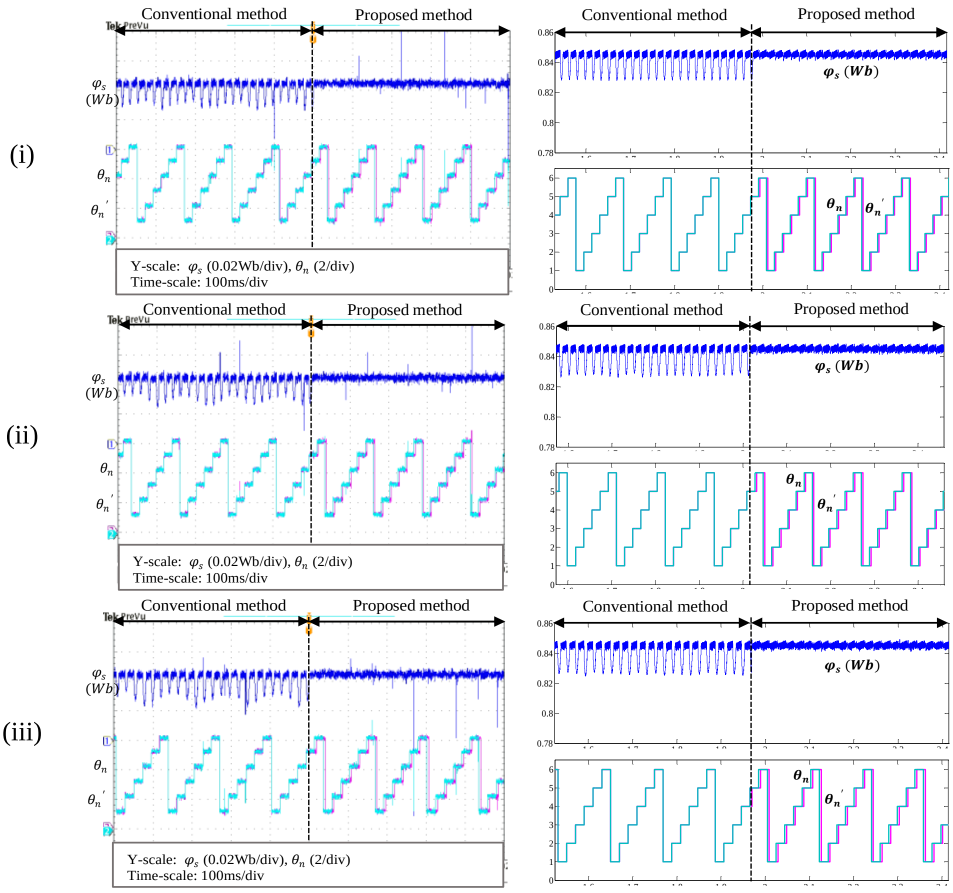


Figure 6: (a) The experiment and (b) simulation result of stator flux, φ_s (upper), sector, θ_n and modified sector, $\theta_n{}'$ (lower) for the torque of; (i)1.9 Nm, (ii)1.5 Nm and (iii)1.1 Nm at 450 rpm

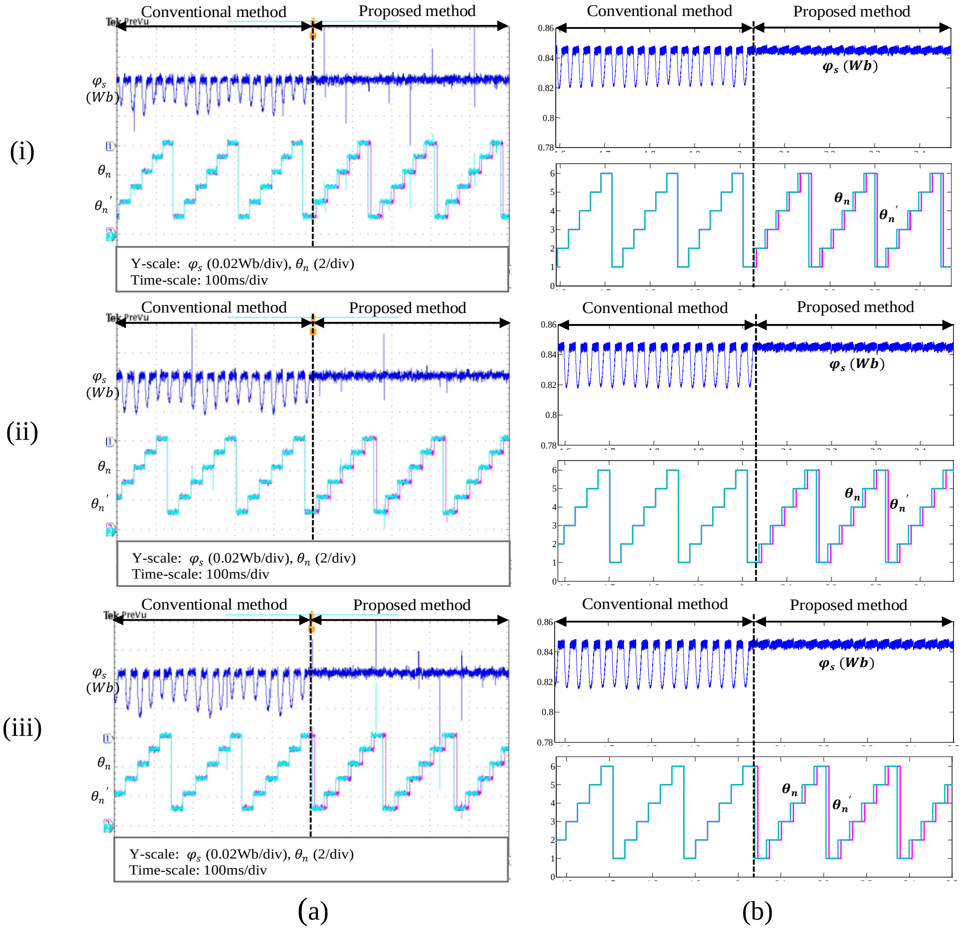
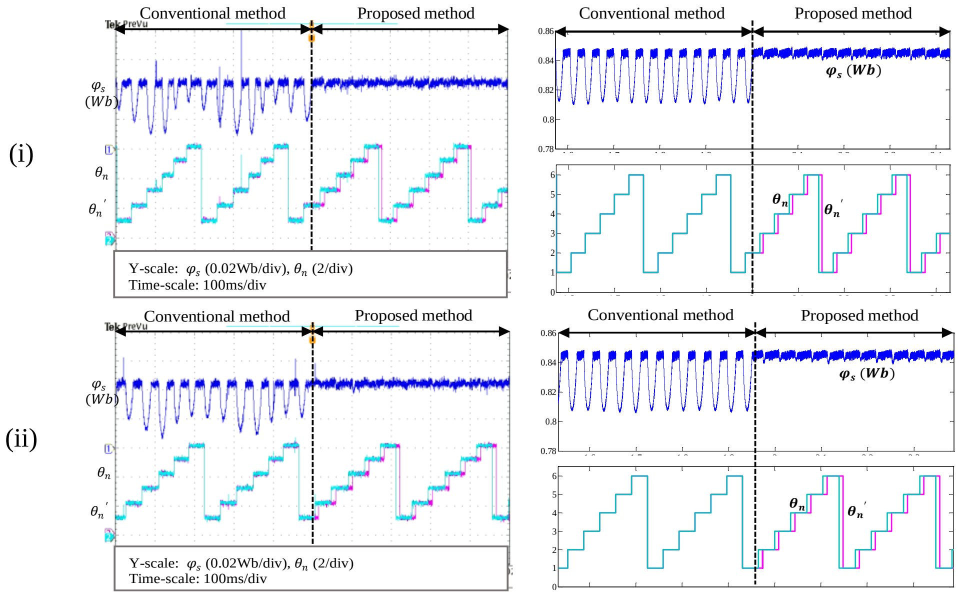
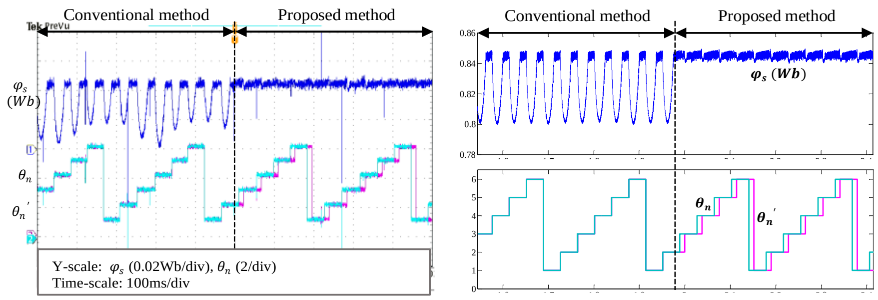


Figure 7: (a) The experiment and (b) simulation result of stator flux, φ_s (upper), sector, θ_n and modified sector, $\theta_n{}'$ (lower) for the torque of; (i)1.9 Nm, (ii)1.5 Nm and (iii)1.1 Nm at 300 rpm

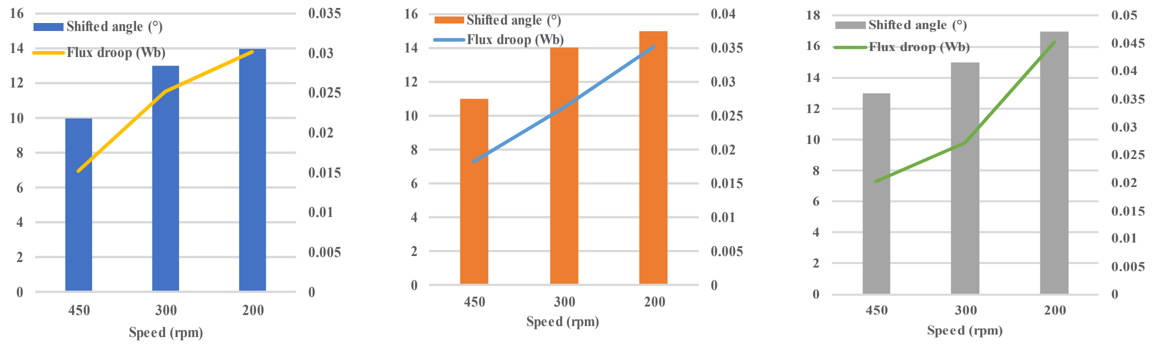


(iii)



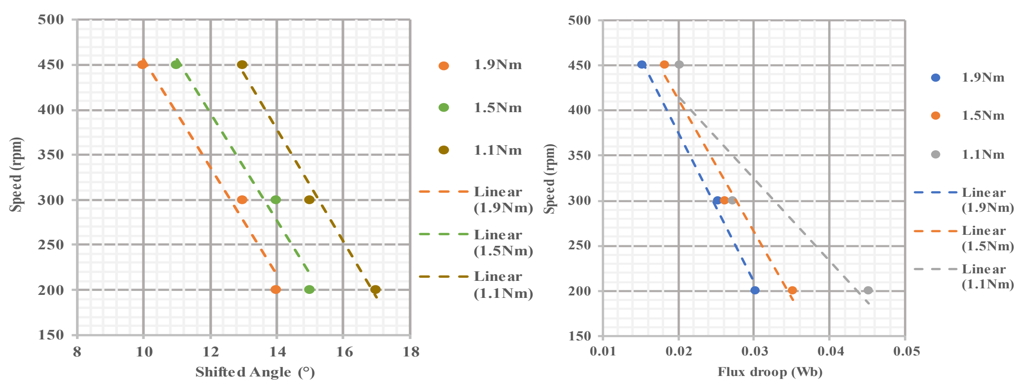
(a) (b)

Figure 8. (a) The experiment and (b) simulation results of stator flux, φ_s (upper), sector, θ_n and modified sector, $\theta_n{}'$ (lower) for the torque of; (i) 1.9 Nm, (ii) 1.5 Nm and (iii) 1.1 Nm at 200 rpm



(a) (b) (c)

Figure 9. Graph of speed against shifted angle and flux droop at the torque of: (a) 1.9 Nm, (b) 1.5 Nm and (c) 1.1 Nm



(a) (b)

Figure 10. Graph of various torque and speed against: (a) shifted angle and (b) flux droop

5. CONCLUSION

The effect of stator flux performance in DTC using a fixed sector rotation strategy based on previous researched is studied and accomplished. The assessment is conducted between the conventional method (without a fixed sector rotation strategy) and the proposed method (with a fixed sector rotation strategy). It involves the various speed and torque by using simulation and practical setup.

It is proven that the practical setup has achieved similar results to the simulation setup as the stator flux droop is highly minimized in the proposed method. The shifted angle performs the opposite proportional to the various condition of torque and speed. In overall, it can be summarized that the effect of stator flux droop has an inverse linear relationship to the variation of torque and speed.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by the Ministry of Higher Education, Malaysia, (MOHE) and Universiti Teknikal Malaysia Melaka (UTeM).

REFERENCES

[1] U. R. Chinthakunta, K. K. Prabhakar, A. K. Singh, and P. Kumar, "Direct torque control induction motor drive performance evaluation based on torque error status selection methods," *IET Electr. Syst. Transp.*, vol. 9, pp. 113–127, 2019.

[2] D. Casadei, G. Grandi, G. Serra, and A. Tani, "Effects of flux and torque hysteresis band amplitude in direct torque control of induction machines," *IECON Proc. (Industrial Electron. Conf.*, vol. 1, pp. 299–304, 1994.

[3] S. Allirani, N. S. Lakshmi, and H. Vidhya, "Performance analysis on direct torque controlled induction motor drive with varying hysteresis controller bandwidth," *Int. J. Power Electron. Drive Syst.*, vol. 11, pp. 1165–1174, 2020.

[4] I. Takahashi and T. Noguchi, "A New Quick-Response and High-Efficiency Control Strategy of an Induction Motor," *IEEE Trans. Ind. Appl.*, vol. IA-22, pp. 820–827, 1986.

[5] R. H. Kumar, A. Iqbal, and N. C. Lenin, "Review of recent advancements of direct torque control in induction motor drives – a decade of progress," *IET Power Electron.*, vol. 11, pp. 1–15, 2018.

[6] M. Ouhrouche, R. Errouissi, A. M. Trzynadlowski, K. A. Tehrani, and A. Benzaioua, "A Novel Predictive Direct Torque Controller for Induction Motor Drives," *IEEE Trans. Ind. Electron.*, vol. 63, pp. 5221–5230, 2016.

[7] M. K. Rahim, A. Jidin, and T. Sutikno, "Enhanced torque control and reduced switching frequency in direct torque control utilizing optimal switching strategy for dual-inverter supplied drive," *Int. J. Power Electron. Drive Syst.*, vol. 7, pp. 328–339, 2016.

[8] N. R. N. Idris and A. M. Yatim, "Direct torque control of induction machines with constant switching frequency and reduced torque ripple," *IEEE Trans. Ind. Electron.*, vol. 51, pp. 758–767, 2004.

[9] S. A. A. Tarusan, A. Jidin, M. L. M. Jamil, K. A. Karim, and T. Sutikno, "A review of direct torque control development in various multilevel inverter applications," *Int. J. Power Electron. Drive Syst.*, vol. 11, pp. 1675–1688, 2020.

[10] A. Jidin, K. A. Karim, K. Rahim, L. Raj, Logan Victor, S. Ramahlingam, and T. Sutikno, "A Review on Constant Switching Frequency Techniques for Direct Torque Control of Induction Motor," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 7, pp. 364–372, 2017.

[11] M. A. Usta, H. I. Okumus, and H. Kahveci, "A simplified three-level SVM-DTC induction motor drive with speed and stator resistance estimation based on extended Kalman filter," *Electr. Eng.*, vol. 99, pp. 707–720, 2017.

[12] B. R. Vinod, M. R. Baiju, and G. Shiny, "Five-Level Inverter-Fed Space Vector Based Direct Torque Control of Open-End Winding Induction Motor Drive," *IEEE Trans. Energy Convers.*, vol. 33, pp. 1392–1401, 2018.

[13] M. Jafari, K. Abbaszadeh, and M. Mohammadian, "A novel DTC-SVM approach for two parallel-connected induction motors fed by matrix converter," *Turkish J. Electr. Eng. Comput. Sci.*, pp. 1599–1611, 2018.

[14] T. Yuan, D. Wang, Y. Li, S. Tan, and S. Zhou, "Duty ratio modulation method to minimise torque and flux linkage ripples for IPMSM DTC system," *Electron. Lett.*, vol. 53, pp. 1188–1190, 2017.

[15] D. Mohan, X. Zhang, and G. H. B. Foo, "A Simple Duty Cycle Control Strategy to Reduce Torque Ripples and Improve Low-Speed Performance of a Three-Level Inverter Fed DTC IPMSM Drive," *IEEE Trans. Ind. Electron.*, vol. 64, pp. 2709–2721, 2017.

[16] W. Chen, C.-L. Xia, Y.-Y. Zhao, Y. Yan, and Z.-Q. Zhou, "Torque Ripple Reduction in Three-Level Inverter-Fed Permanent Magnet Synchronous Motor Drives by Duty-Cycle Direct Torque Control Using an Evaluation Table," *J. Power Electron.*, vol. 17, pp. 368–379, 2017.

[17] Z. Zhang and X. Liu, "A Duty Ratio Control Strategy to Reduce Both Torque and Flux Ripples of DTC for Permanent Magnet Synchronous Machines," *IEEE Access*, vol. 7, pp. 11820–11828, 2019.

[18] S. A. A. Tarusan, A. Jidin, and M. L. M. Jamil, "The simulation analysis of torque ripple reduction by using optimal voltage vector in DTC fed by five-level CHB inverter," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 20, pp. 1665–1676, 2020.

[19] D. Mohan, X. Zhang, and G. H. Beng Foo, "Generalized DTC Strategy for Multilevel Inverter Fed IPMSMs with Constant Inverter Switching Frequency and Reduced Torque Ripples," *IEEE Trans. Energy Convers.*, vol. 32, pp. 1031–1041, 2017.

[20] S. A. L. Ramahlingam, A. Bin Jidin, T. Sutikno, and L. L. Raj, "Improvise 3-level DTC of induction machine using constant switching frequency method by utilizing multiband carrier," *Int. J. Power Electron. Drive Syst.*, vol. 7, pp. 638–647, 2016.

[21] S. Priya, A. Suresh, and M. R. Rashmi, "GCMT-249 Investigation and Performance Analysis of Direct Torque Control of 3phase Induction Motor using 7 Level Neutral Point Clamped Multilevel Inverter," *Indian J. Sci. Technol.*, vol. 9, pp. 1–7, 2016.

[22] S. Suresh and P. Rajeevan, "Virtual Space Vector-Based Direct Torque Control Schemes for Induction Motor Drives," *IEEE Trans. Ind. Appl.*, vol. 56, pp. 2719–2728, 2020.

[23] N. R. N. Idris and A. H. M. Yatim, "An improved stator flux estimation in steady-state operation for direct torque control of induction machines," *IEEE Trans. Ind. Appl.*, vol. 38, pp. 110–116, 2002.

[24] L. Kyo-Beum, S. Joong-Ho, I. Choy, and Y. Ji-Yoon, "Improvement of Low-Speed Operation Performance," IEEE Trans. Ind. Electron., vol. 48, pp. 1006–1014, 2001.

[25] W. W.S.H and D. Holliday, "Minimisation of flux droop in direct torque controlled induction motor drives," *IEE*

Proceedings-Electric Power Appl., vol. 151, pp. 694–703, 2004.
[26] B. Singh, S. Jain, and S. Dwivedi, "Torque ripple reduction technique with improved flux response for a direct torque control induction motor drive," *IET Power Electron.*, vol. 6, pp. 326–342, 2013.
[27] I. M. Alsofyani and N. R. N. Idris, "Simple flux regulation for improving state estimation at very low and zero speed of a speed sensorless direct torque control of an induction motor," *IEEE Trans. Power Electron.*, vol. 31, pp. 3027–3035, 2016.

BIOGRAPHIES OF AUTHORS

Siti Azura Ahmad Tarusan received the B.Eng. degrees from Universiti Teknologi Malaysia, Johor Bahru, Malaysia, in 2008 and M.Eng. degrees from Universiti Malaya, Malaysia, in 2012. She is currently pursuing PhD under Power Electronics and Drives Research Group (PEDG) in the Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia. Her research interests include power electronics and motor drive systems.

Auzani Jidin received the B.Eng. degrees, M.Eng. degrees and Ph.D. degree in power electronics and drives from Universiti Teknologi Malaysia, Johor Bahru, Malaysia, in 2002, 2004 and 2011, respectively. He is currently an academician in Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia. He is also an active researcher in Power Electronics and Drives Research Group (PEDG) that established under the same faculty. His research interests include power electronics, motor drive systems, field-programmable gate array, and DSP applications.

Mohd Luqman Mohd Jamil received B.Eng. degree from the Universiti Teknologi MARA, Shah Alam, Malaysia, in 2000, M.Sc. degree from University of Newcastle upon Tyne, U.K., in 2003, and Ph.D. degree from The University of Sheffield, Sheffield, U.K., in 2011, all in electrical engineering. He is currently an academician in Faculty of Electrical Engineering, University Teknikal Malaysia Melaka, Melaka, Malaysia. He is also an active researcher in Power Electronics and Drives Research Group (PEDG) that established under the same faculty. His research interests include the design, control and analysis of permanent-magnet machines.

Kasrul Abdul Karim received the M.Sc. from University of Bradford and Ph.D. degrees from the University of Nottingham, UK, in 2003 and 2011, respectively He is currently an academician in Faculty of Electrical Engineering, University Teknikal Malaysia Melaka, Melaka, Malaysia. He is also an active researcher in Power Electronics and Drives Research Group (PEDG) that established under the same faculty. His research interests include electrical machine design, power electronics, and electric vehicle.