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Improvement of Based Sector and Comparison Speed and Electromagnetic Torque of Direct Torque Control

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ABSTRACT

Direct torque control is one type of vector control used to operate an induction motor. Efficient control rules for induction motor drives offer a great chance to save energy. In comparison to DC batteries, supercapacitor (SC) technology is commonly recognised as one of the most promising and energy-efficient technologies for next-generation energy storage systems. Rotating equipment generates vibration, which causes rotor dynamic. Battery applications also provide high torque current for induction motor start-up. The goal of these investigations and analyses is to improve the performance of the electrical device system for six sector and twelve sector direct torque control methods employing DC battery and supercapacitor. The direct torque control model is separated into seven sections: input energy storage, voltage source inverter, flux and torque estimate, sector detection, flux and torque controller, vector selection table, and induction motor. The paper focuses on the improvement of based sector for six sector and twelve sector technique of induction motor in MATLAB/Simulink simulation framework by employing different energy storage (supercapacitor and DC battery). The output of the system designed in MATLAB Simulink has been examined in terms of rotor speed and electromagnetic torque. In terms of rotor speed, the twelve-sector approach requires 0.04 second speed transition to reach steady state response, but the six-sector method requires 0.06 second when a load disturbance is added for DC battery and supercapacitor. When compared to the six-sector approach for DC battery and supercapacitor, the electromagnetic torque that employs the twelve-sector method provides more smoothly following the load torque. When a load disturbance is applied, the electromagnetic torque in the twelve-sector approach produces a spiky torque of around 15.5N, whereas the electromagnetic torque in the six-sector method produces 18N. In terms of electromagnetic torque, the usage of a supercapacitor generates 15N, whereas the use of a battery provides around 50N for the six sector and twelve sector methods.

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1. Introduction

Energy demand worldwide is rising at an unprecedented pace. This has already shown its impact on the depletion of energy sources and environmental issues (global warming and the weakening of the ozone layer). This growing pattern of energy insufficiency will, of course, intensify in the future. Significant energy savings can be achieved by controlling the speed of the electric motor system using variable frequency drives (VFDs) was also stated by Aazmi *et al.,* [1]. A variable-frequency drive is described as a sort of adjustable-speed drive used in electromechanical drive systems to regulate AC motor velocity and torque by varying motor input and voltage frequencies. The basic technological concept of VFD is managing motor speed was also mentioned by Van Rhyn and Pretorius [2]. System efficiency can be increased if a motor's speed can be adjusted to meet the demands of the process. To save energy in a domestic air conditioning unit, for example, one can either increase the temperature or decrease the fan speed conducted by Schibuola, Scarpa, and Tambani [3]. However, because the induction motor is working at ordinary acceleration, the energy saved is been mentioned by Ram, Rahi, and Sharma [4]. The main drawback of induction motor is the connection between the magnitudes of its stator and rotor.

As a result, the DTC approach has been introduced as the most effective torque control technique for induction motors in order to optimise the dynamic behaviour of the asynchronous machine was highlighted by Liu and Zhang [5]. The use of a DC battery that is not suited for induction motors to provide strong torque and high current during motor start-up as the primary store for DTC with induction motor was also mentioned by Kumar and Revankar [6]. Furthermore, the typical DTC method employs six non-zero voltage vectors by the voltage source converter since the required torque is satisfied for just a few switching points and the majority of voltage vectors introduce a torque that is either larger or less than the desired torque. Induction motors create vibrations that lead to rotor dynamic analysis, which includes speed, torque, and current. Based on the results, improving the based sector of DTC can lead to an increase in the efficiency of induction motor operation that were conducted by Douiri *et al.,* [7] and Noroozi *et al.,* [8]. Field oriented control (FOC) and direct torque control are the two most popular control methods used by IM (DTC). Unlike FOC, Aktas *et al.,* [9] mentioned that DTC does not need coordinate transition, PWM signal generators, current controllers, or a location encoder with delays and mechanical transduction.

In this paper, the direct torque control used as control technique of VFD for the induction motor. The main storage for the system that been compared which are DC battery and supercapacitor. Based on the system, the improvement-based sector for DTC from six sector to twelve sector can increase the efficiency of the induction motor based on rotor speed and electromagnetic torque. The contribution for this work is the improved based sector of direct torque control give better performance based on rotor speed and electromagnetic torque by using different type of main storage which are battery and supercapacitor. Rotating machinery like induction motor produce vibrations that leads to rotor dynamic which are speed and electromagnetic torque.in addition, the uses of DC battery as main storage is not suitable to cater high torque at motor start-up for induction motor. The combination of twelve sector method to the direct torque control using supercapacitor is the proposed work that compared with others which give better performance of rotor speed and electromagnetic torque output.

1.1 Direct Torque Control

Takahashi and Depenbrock pioneered this control approach, known as direct control torque (DTC), in the mid-1980s were stated by Patil *et al.,* [10] and Gasbaoui *et al.,* [11]. Kaushal B. Sontakke mentioned that the DTC induction motor drive system has lately gained popularity because of its instant dynamic control and ability to deliver equivalent power in DC machines [12]. Because of its good torque response and rapid control algorithm, the DTC method may be utilised to replace the well-known FOC approach was reviewed by Hannan *et al.,* [13]. Furthermore, the DTC drive system eliminates the need for a speed encoder, lowering the cost of motor drive application. The torque and flux regulation in the field-oriented drive (FOC) drive mechanism rely on the utilization of the stator current components along the d and q axes. In contrast, the DTC drive mechanism achieves independent control of torque and flux by incorporating additional voltage vectors. During the initial startup of an induction motor, indirect rotor field-oriented control (IRFOC) exhibits slower response to rotor flux and electromagnetic torque compared to other methods. However, direct stator field-oriented control (DSFOC) demonstrates superior performance compared to IRFOC but still falls short of DTC, as indicated by research conducted by Leandro *et al.,* [14] and Arpit *et al.,* [15]. The torque reference magnitudes and stator flux reference are subtracted from the corresponding estimated input signal values in this control system theory. The result is an erroneous signal detected by band controllers with hysteresis.

1.2 Six Sector Control System of DTC

Since single-phase induction motors are identical to three-phase induction motors, it is best to start with three-phase induction motors while learning about the DTC control structure. Although the control structures of the motors are identical, the voltage vectors are different due to the different topologies of the inverters used was also mentioned by Sutikno *et al.,* [16]. The stator flux and electromagnetic torque of DTC's three-phase induction motor are operated independently by using two-level and three-level hysteresis comparators, as seen in Figure 1.

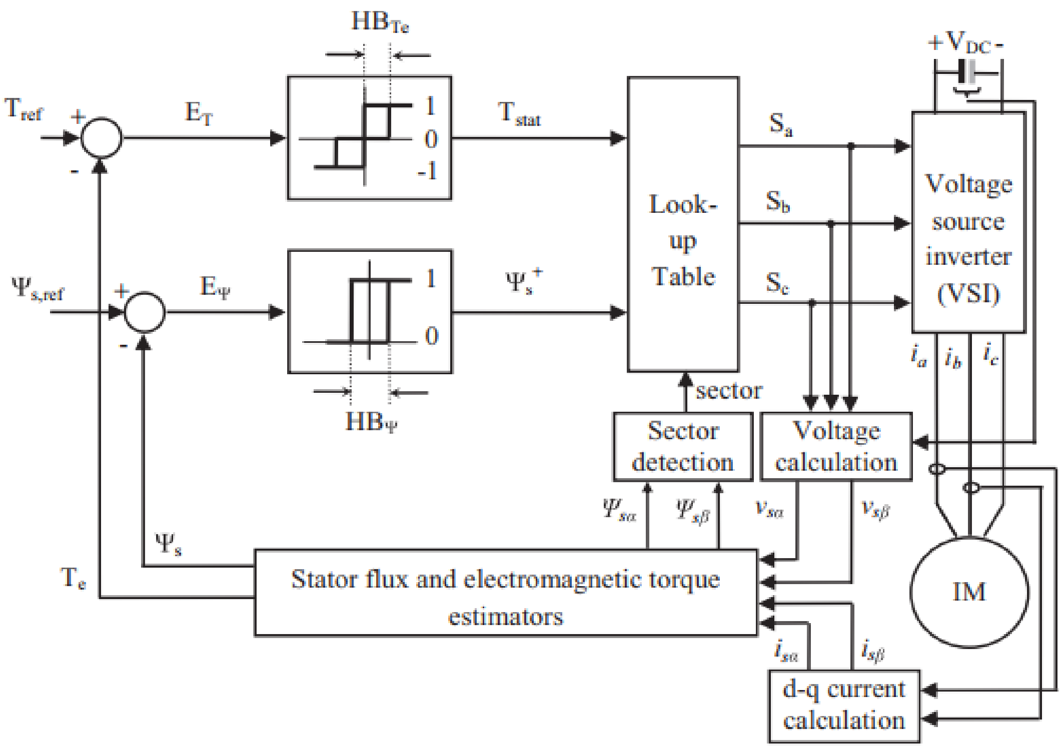

Fig. 1. Direct torque control of induction motor

The basic idea behind DTC is to select the best voltage vector based on the stator flux and torque, then rotate the flux to get the desired output torque was also stated by Ammar *et al.,* [17]. Six sectors of 60^0 each divide the stator flux angle for the output voltage field. The DTC switching table produces a logic signal from the three inputs, S_a, S_b and S_c which are used to allow the VSI switches to control the motor. The induction motor stator receives its input from the three-phase VSI output. The VSI chooses the stator vector based on the hysteresis band contribution and the stator flux. The stator vector is determined using Eq. (1) as a stationary reference point.

$$\psi_s = \int (V_s - R_s i_s) dt \tag{1}$$

Because the resistive voltage drop is modest, the stator flux fluctuation matches to the voltage vectors. Two active voltage vectors will be applied in each sector to obtain a circular stator flux to increase or decrease the stator flux, as shown in Figure 2. As shown in Figure 2(b), in sector 1, V2 is used to enhance stator flux, whereas V3 is used to reduce stator flux. The electromagnetic torque can be increased by both V2 and V3. V5 and V6 engines are used to reduce torque. When the torque is reduced, V6 is triggered to raise the stator flux, while V5 is used to decrease the stator flux.

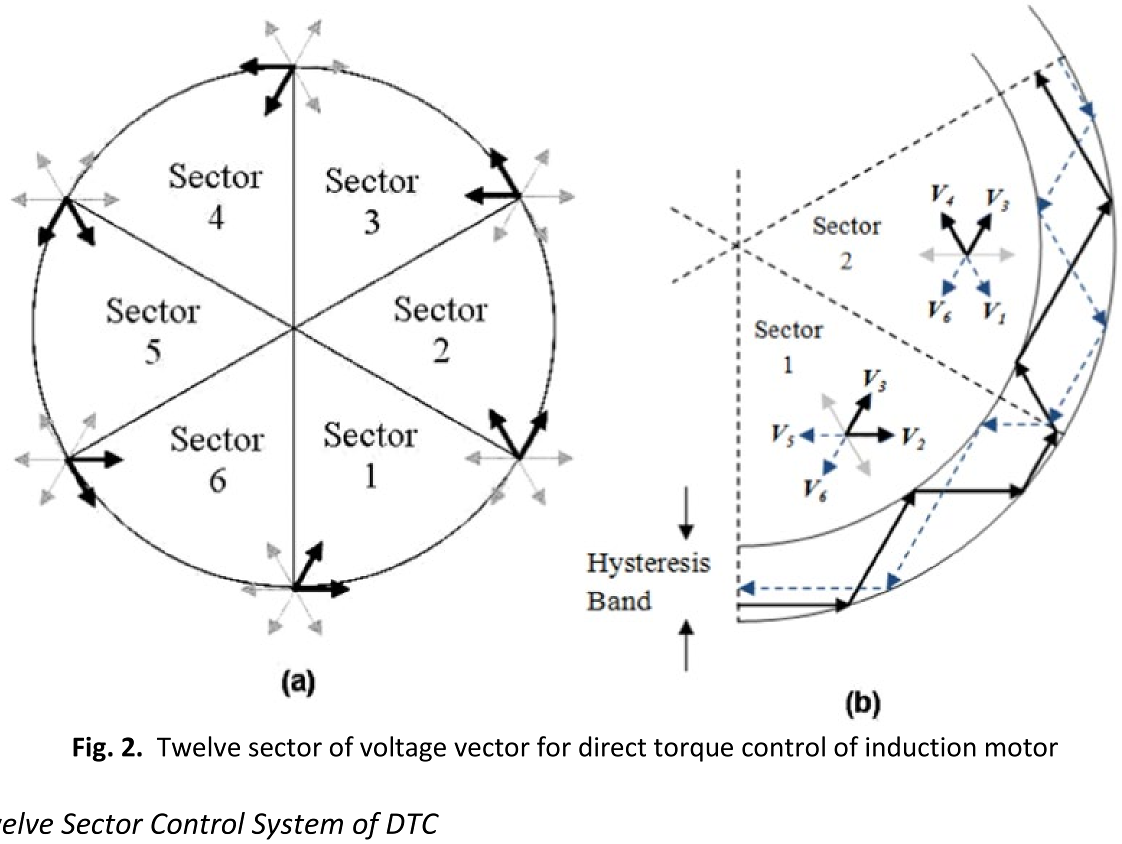

Fig. 2. Twelve sector of voltage vector for direct torque control of induction motor

1.3 Twelve Sector Control System of DTC

There are two vectors by sector in the classic DTC that cause ambiguity in the flux control and are hence not utilised (V_i, V_{i+3}). In addition, with the modified DTC, both vectors (V_{i+2}, V_{i+5}) are not employed since they bring uncertainty into the torque control. To address the issue of ambiguity in the torque and flux, the vector shall divide the position of the stator flux into 12 sectors rather than 6, with six active vectors employed for the same sector. Nevertheless, because the tangential component of the voltage vector is extremely low, the variation in torque must also be modest, as it is critical to develop the notion of a little rise in torque. Figure 3 shows the twelve sector division of the control system. Noroozi *et al.,* [8] mentioned that to make greater use of these tensions, a comparator with four levels of hysteresis for the pair is utilised, allowing the microscopic and significant variations in torque and flux generated by these identical vector voltages to be characterised according to their phase shift with respect to the area limits.

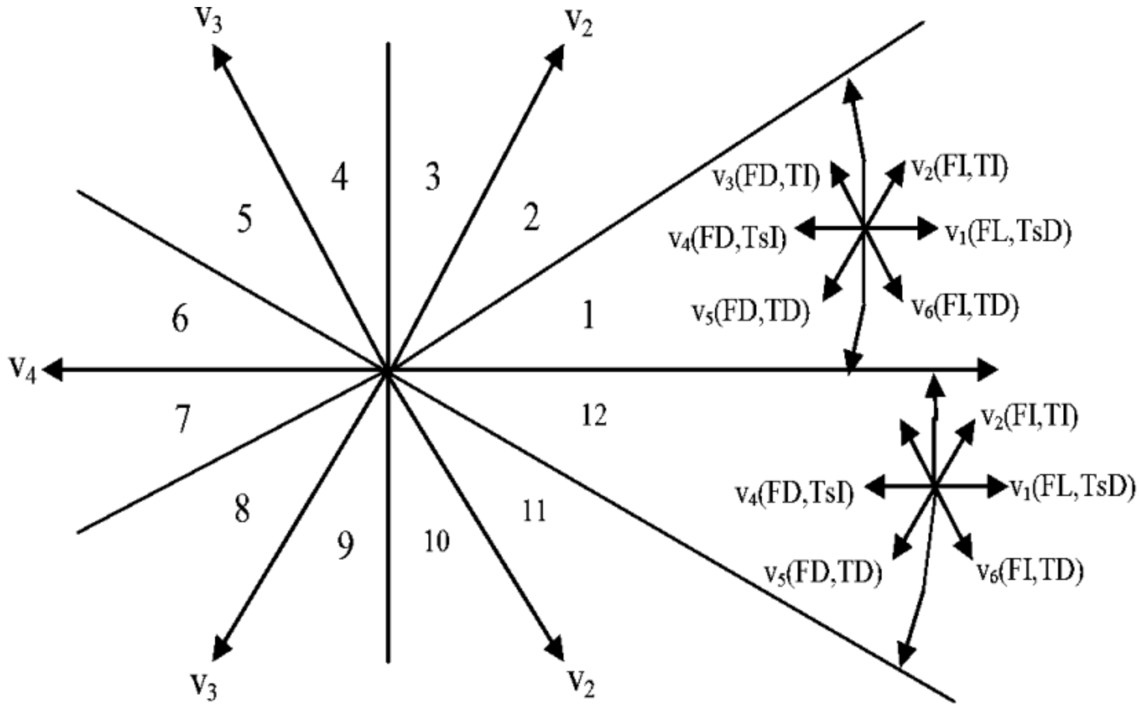

Fig. 3. Twelve sector of voltage vector for direct torque control of induction motor

2. Methodology

2.1 Simulation Model of DTC of Induction Motor

Figure 4 shows the conventional direct torque control of the induction motor simulation model in MATLAB/Simulink. The simulation model consists of function subsystem block including flux controller block, torque controller block, switching table block, dc-ac converter block and stator flux linkages block. The flow of the working principle of the system based on the sequences that been label by number. The specification of the 3-phase induction motor used is 2.2kW, 1485rpm, four poles with the frequency of 50hz and rated voltage 400V. The use of supercapacitor and DC battery are been used as energy storage for direct torque control system. The six-sector method and twelve sector method been implemented in the system for getting the result of rotor speed and electromagnetic torque.

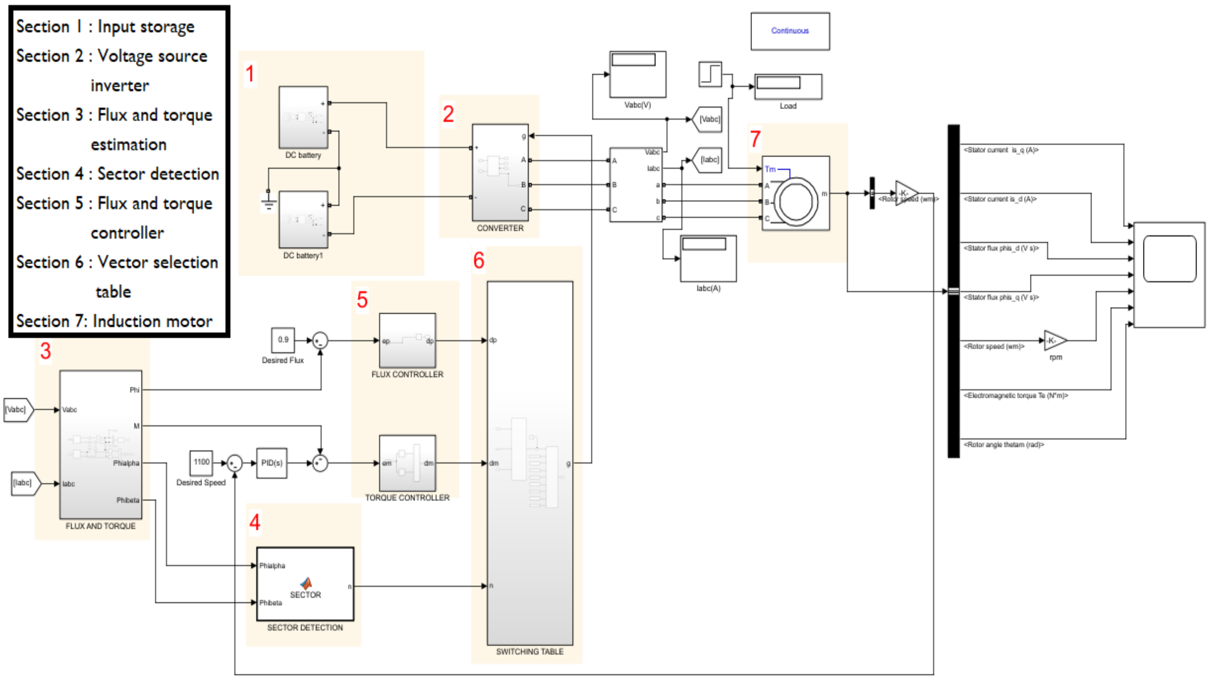

Fig. 4. Simulation model of direct torque control of induction motor

2.2 Model Supercapacitor as Main Storage

The supercapacitor was chosen as the principal energy storage device for this project due to the benefits of the supercapacitor being utilised for energy storage through numerous charge and discharge cycles at high current and short duration. Figure 5 shows that the system of a supercapacitor as main storage using MATLAB. It consists of a supercapacitor and bidirectional DC-DC converter. A boost bidirectional DC-DC converter is used to convert a fixed voltage into a higher DC voltage, and the output DC voltage can be varied to control the speed of the motor. For testing the uses of the supercapacitor to supply for the variable frequency drive, the input supply would be around 400V supply to the variable frequency drive.

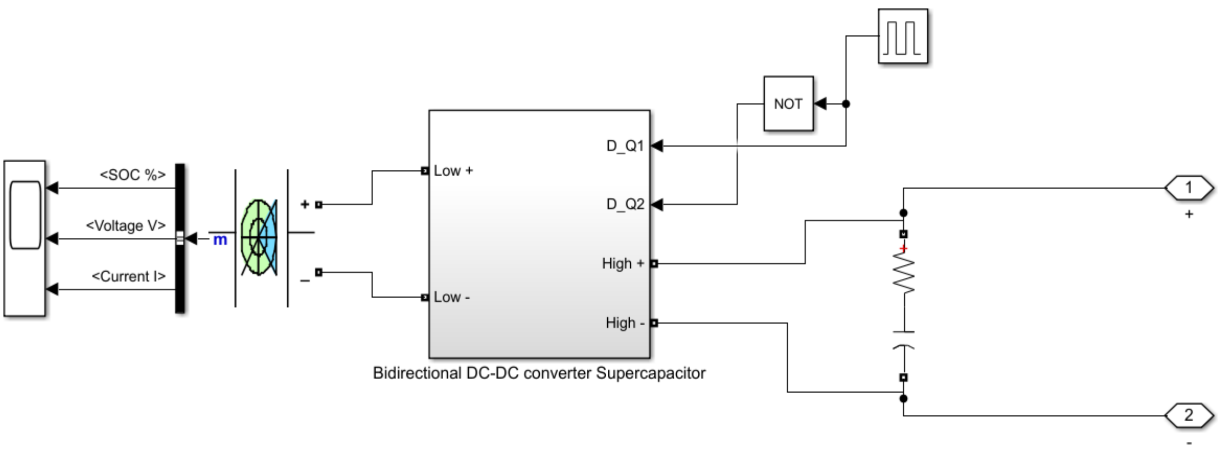

Fig. 5. System of a supercapacitor as main storage in MATLAB model

2.3 Model DC Battery as Main Storage

Figure 6 shows that the system of a DC battery as main storage using MATLAB. It consists of a DC battery and bidirectional DC-DC converter. A boost bidirectional DC-DC converter is used to convert a fixed DC battery voltage into a higher DC voltage, and the output DC voltage can be varied to control the speed of the motor. For testing the uses of the DC battery to supply for the variable frequency drive, the input supply would be around 400V supply to the variable frequency drive.

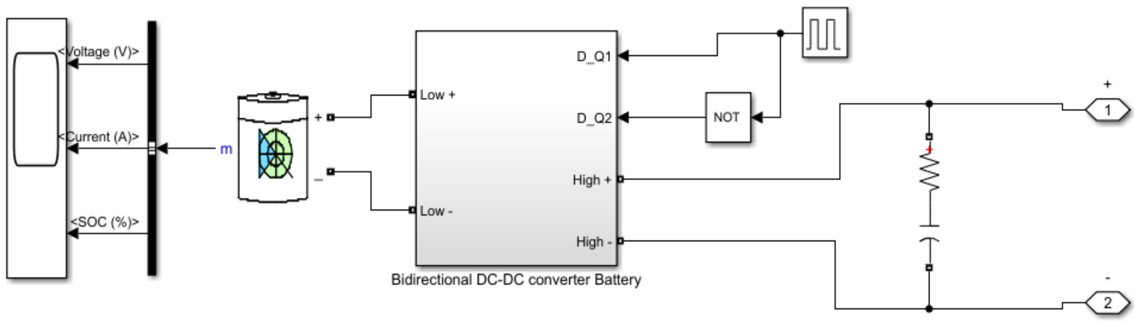

Fig. 6. System of a DC battery as main storage in MATLAB model

3. Results

3.1 Speed comparison of Different Sector Method for Supercapacitor and DC Battery

The simulation has been conducted for a three-phase 2.2 kW induction motor. The starting up and the steady states of the controlled motor with load introduction according to speed step reference of 1100 rpm are presented. For DTC, the chosen bandwidths of the hysteresis controller are 0.005 Wb for flux and 0.01 Nm for torque. A load of 10 Nm has suddenly appeared after 0.2 seconds. Based on Figure 6 to Figure 7 the speed for all models is following the desired path until the motor is step torque loaded in 0.2 second. When the motor is loaded, the speed variation owing to the load is minor, and the speed recovers to the required speed in 0.06 second, with a deviation of 1103 rpm using the six-sector approach. As demonstrated, the implementation of twelve sector can achieve more faster speed response as compare to six sector method. Besides that, the accelerating speed response to achieve steady speed in using battery faster than using supercapacitor. In Figure 6 and Figure 8, the accelerating speed to achieve steady speed in using battery only needed about 0.03 seconds while in Figure 7 and Figure 9 needed that 0.1 second for accelerating speed to achieve steady speed by using supercapacitor.

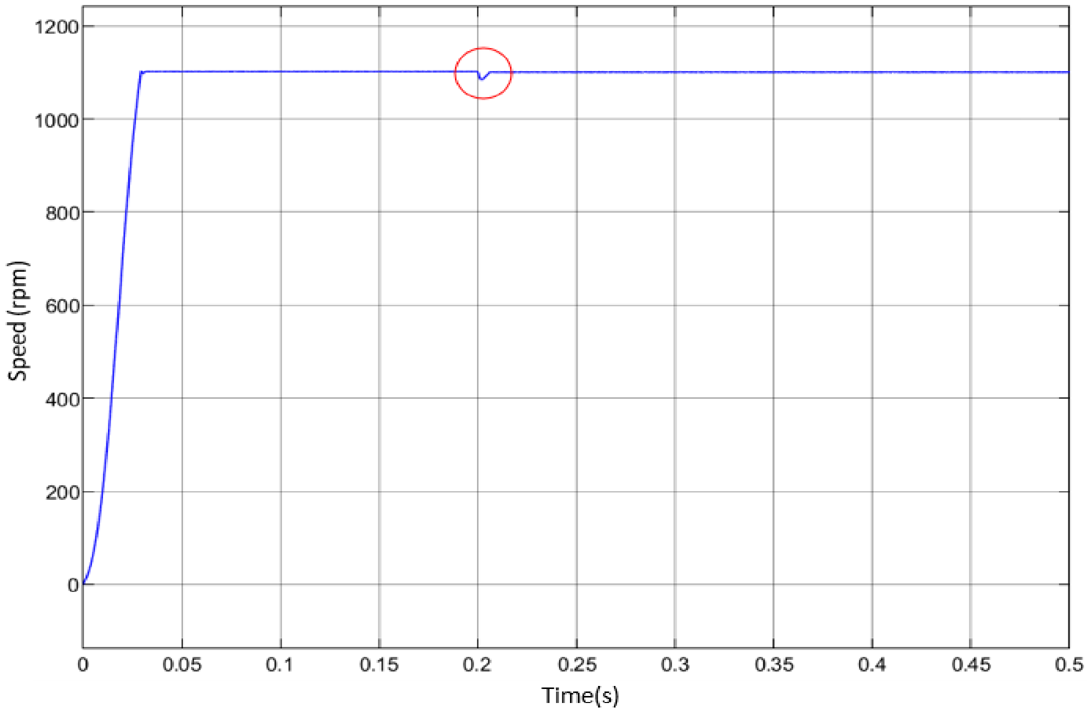

Fig. 6. Rotor speed response of six sector method using DC battery

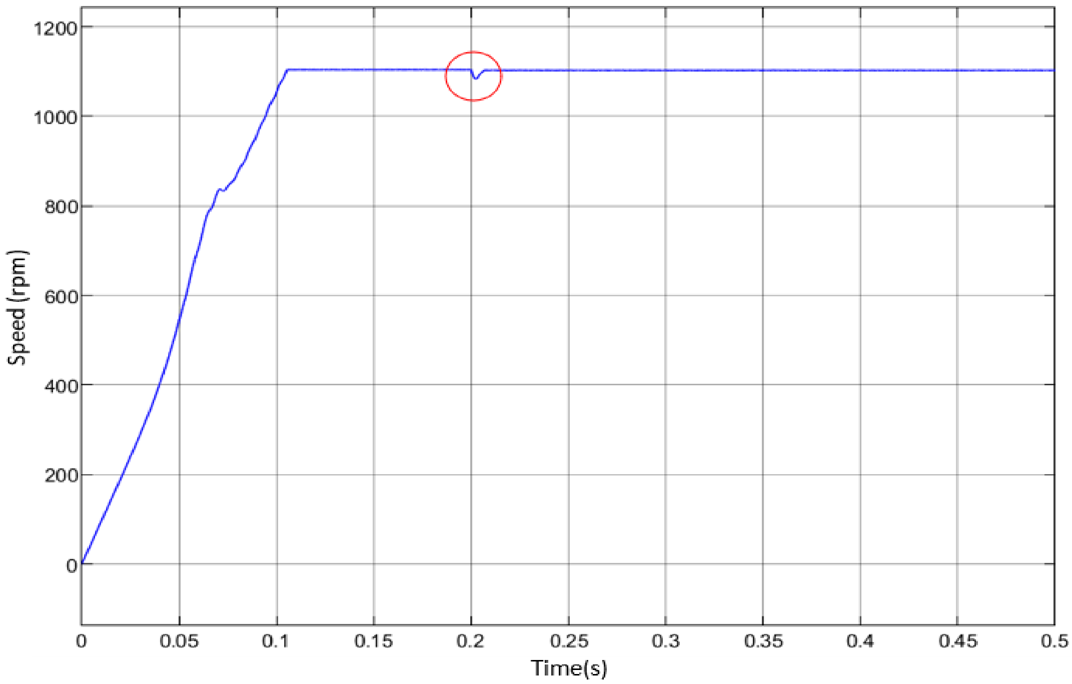

Fig. 7. Rotor speed response of six sector method using supercapacitor

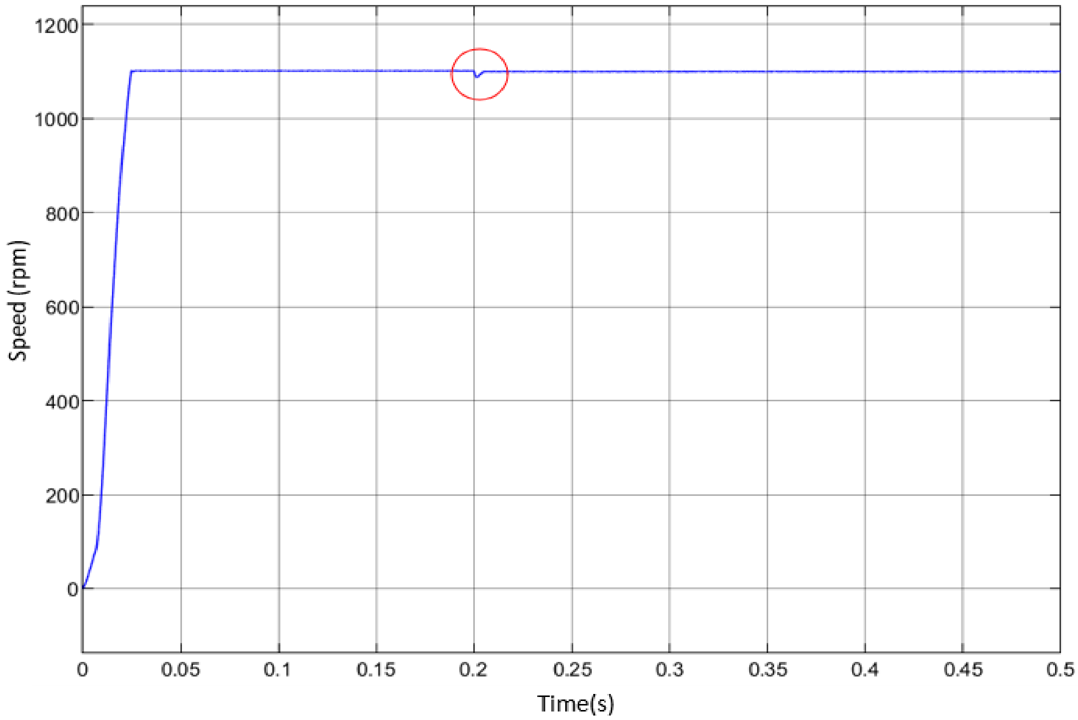

Fig. 8. Rotor speed response of twelve sector method using DC battery

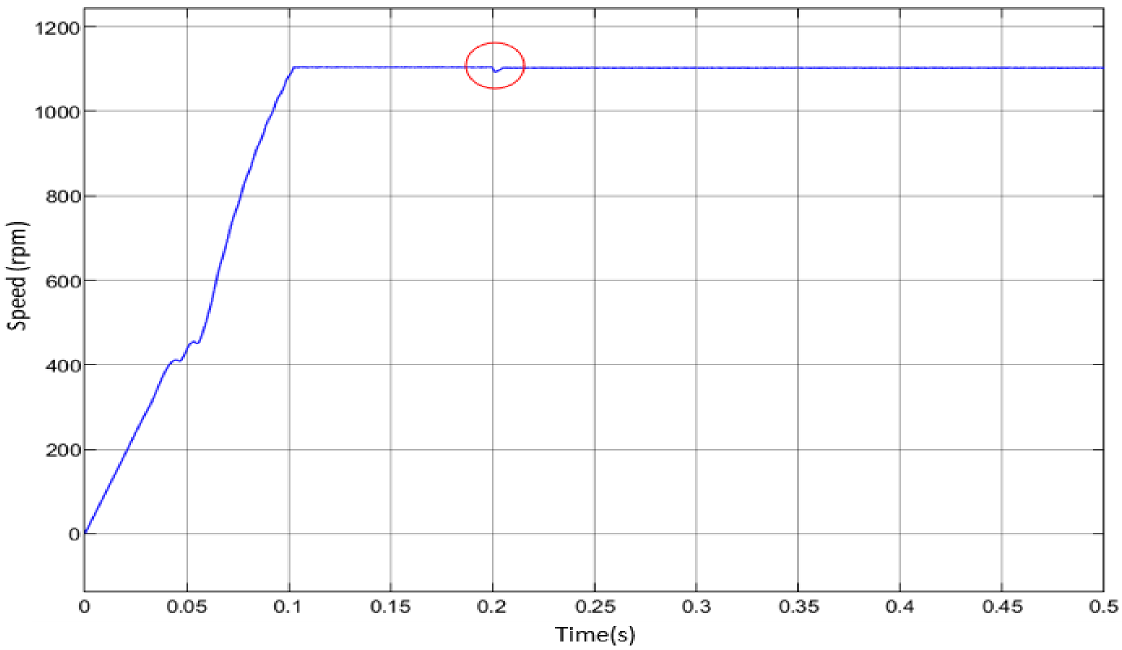

Fig. 9. Rotor speed response of twelve sector method using supercapacitor

3.2 Electromagnetic Torque Comparison of Different Sector Method for Supercapacitor and DC Battery

The torque response for the both DTC method (six sector and twelve sector) is shown in Figure 10 to Figure 13. A change in torque level is applied from -10Nm to 10Nm at 0.2 second. The DTC with twelve sector method shows better performance compared to the six sector DTC method due to reducing ripples and the faster response after the changes. Besides that, in Figure 10 and Figure 11 which is the uses six sector method give more spiky torque which about 18Nm by using supercapacitor and DC battery as compared to twelve sector method. In other hand, the torque in Figure 12 and Figure 13 which is the uses of twelve sector method more smoothly following the load torque by using supercapacitor and DC battery and also when changes torque applied which the spiky torque about 15.5Nm. The disadvantage of spiky torque is that it forces the motor to draw more current, especially when load torque is given for a certain period, and if the motor is overloaded (even for a short period of time), the protective mechanism may step in and disconnect the unit. Starting torque ranges from 50 to 70 Nm when a DC battery is used for six sector and twelve sector method, but it only takes 0.03 second to establish consistent torque, as shown in Figure 10 and Figure 12. On the other hand, in Figure 11 and Figure 13, the uses of supercapacitor as main storage give starting torque about $\pm 15Nm$ but to achieve steady torque need 0.1 second. The starting torque of using battery as main storage give higher starting torque compare to supercapacitor due to behaviour of direct torque control which direct torque control produce a non-uniform amount of low frequency noise that gives in torque distortion at low speed.

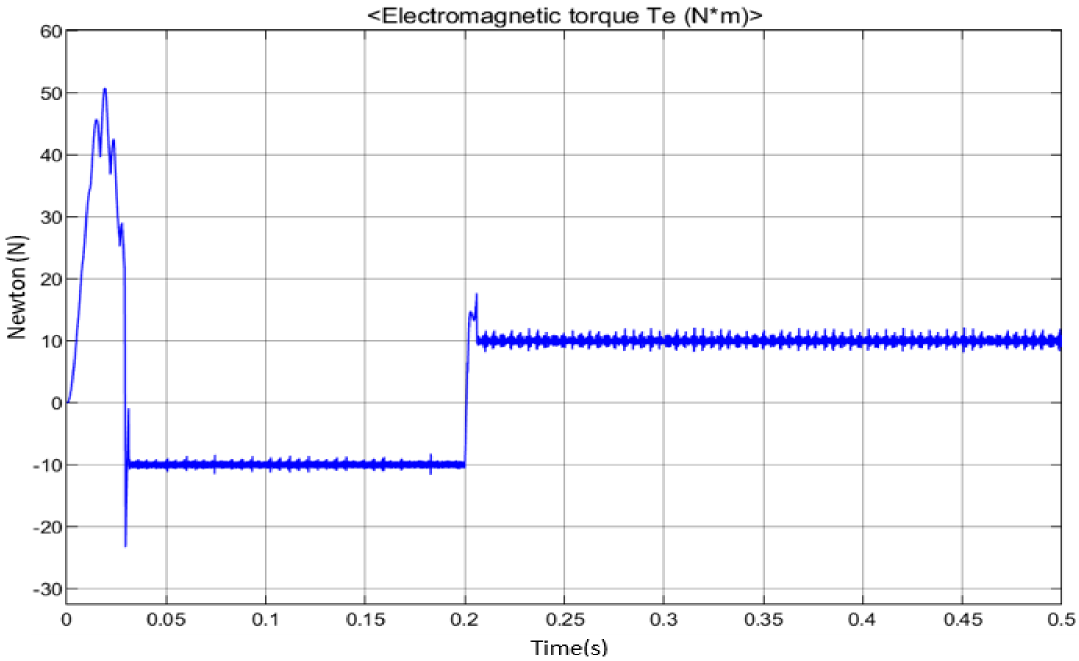

Fig. 10. Electromagnetic torque of six sector method using DC battery

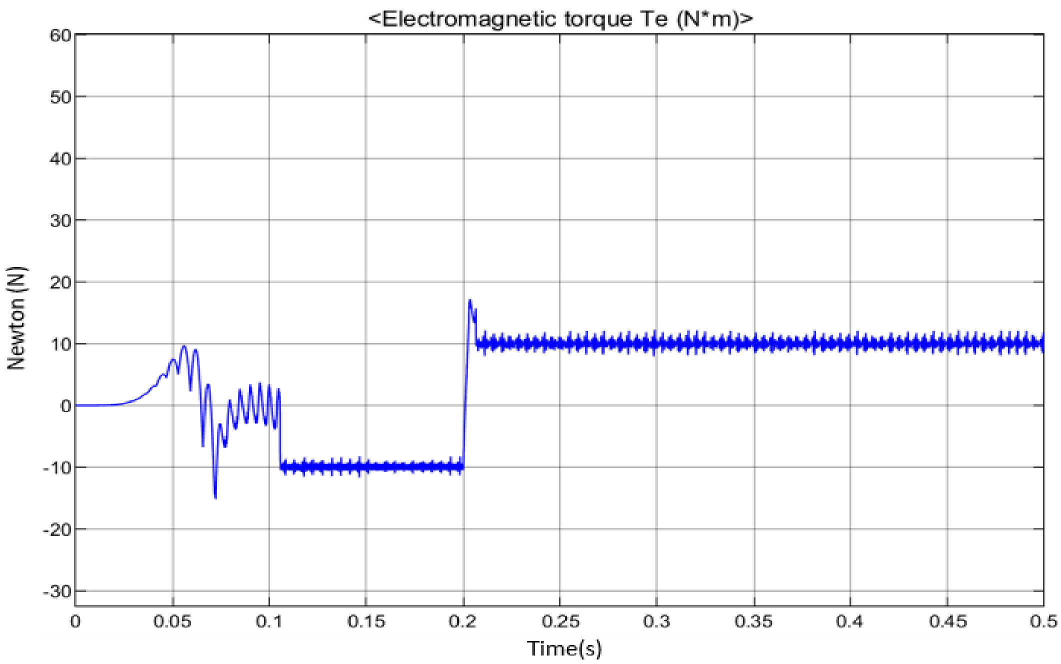

Fig. 11. Electromagnetic torque of six sector method using supercapacitor

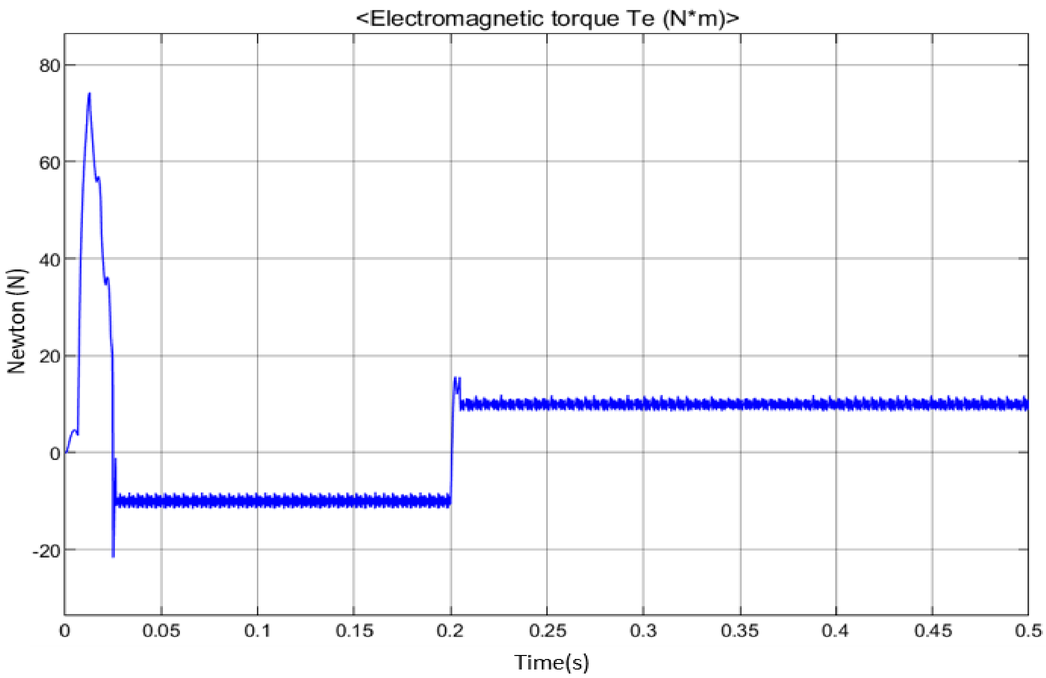

Fig. 12. Electromagnetic torque of twelve sector method using DC battery

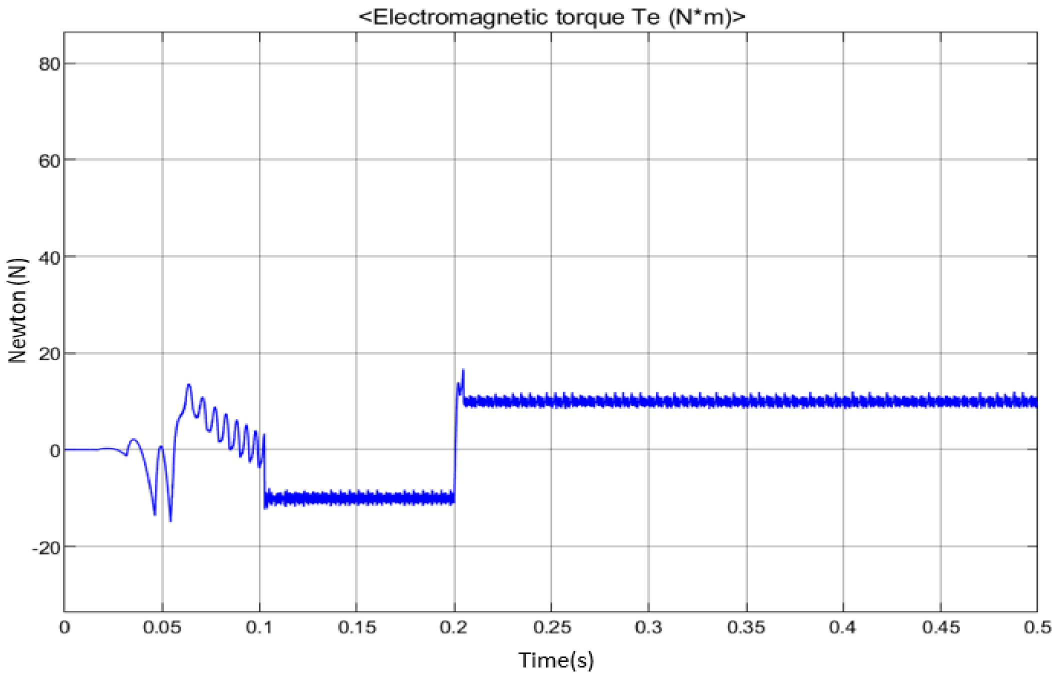

Fig. 13. Electromagnetic torque of twelve sector method using supercapacitor

4. Conclusions

This research aimed to develop direct torque control for induction motor. Based on the specification of induction motor, the system been developed in MATLAB Simulink has presented. The system also been developed used supercapacitor and DC battery as main storage. The uses of supercapacitor gave less at starting motor of the system compared to using DC battery. Based on the aspect, the used of supercapacitor as main storage gave safety to the induction motor to withstand starting current and torque. The objective of analyzing the implementation of the direct torque control technique for induction motor using supercapacitor and DC battery is presented. From the analysis, the direct torque control technique still has a high torque ripple which exceeded the hysteresis boundary. The DTC with twelve sector method shows better performance compared to the six sector DTC method due to reducing ripples and the faster response after applied 10Nm at 0.2 seconds. The use of supercapacitor is better when at motor start-up compared to DC battery. The implementation of twelve sector method give more smoothly to achieve steady waveform as compared to six sector method. The typical DTC system creates a large torque ripple because the specified voltage space vector is utilised for the whole switching period, regardless of the severity of the torque error. The duty ratio of the voltage vector used at each switching instance can be modified based on the size and position of the stator flux and torsion error to reduce torque ripple and improve drive performance. The direct torque control needs to be progressed further for this method to provide an efficient controller for the induction motor by optimizing this method with partial swarm optimization (PSO).

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References

[1] Aazmi, M. A., M. I. Fahmi, M. Z. Aihsan, H. F. Liew, and M. Saifizi. "Direct torque control of induction motor with different energy storage for electrical vehicle (EV) application." In *Journal of Physics: Conference Series*, vol. 2107,

no. 1, p. 012052. IOP Publishing, 2021. https://doi.org/10.1088/1742-6596/2107/1/012052.

[2] Van Rhyn, Pierre, and Jan Harm C. Pretorius. "Increasing Water Pump Station Throughput by Introducing VFD-Based IE4 Class Synchronous Reluctance Motors with Improved Pump Control." In *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)*, pp. 1-6. IEEE, 2018. https://doi.org/10.1109/EEEIC.2018.8494393

[3] Schibuola, Luigi, Massimiliano Scarpa, and Chiara Tambani. "Variable speed drive (VSD) technology applied to HVAC systems for energy saving: an experimental investigation." *Energy Procedia* 148 (2018): 806-813. https://doi.org/10.1016/j.egypro.2018.08.117.

[4] Ram, Sita, O. P. Rahi, and Veena Sharma. "A comprehensive literature review on slip power recovery drives." *Renewable and Sustainable Energy Reviews* 73 (2017): 922-934. https://doi.org/10.1016/j.rser.2016.11.154.

[5] Liu, Huan, and Hui Zhang. "A novel direct torque control method for brushless DC motors based on duty ratio control." *Journal of the Franklin Institute* 354, no. 10 (2017): 4055-4072. https://doi.org/10.1016/j.jfranklin.2017.03.017.

[6] Kumar, M. Satyendra, and Shripad T. Revankar. "Development scheme and key technology of an electric vehicle: An overview." *Renewable and Sustainable Energy Reviews* 70 (2017): 1266-1285. https://doi.org/10.1016/j.rser.2016.12.027.

[7] Douiri, M. R., M. Cherkaoui, T. Nasser, and A. Essadki. "A neuro fuzzy PI controller used for speed control of a direct torque to twelve sectors controlled induction machine drive." In *2011 International Conference on Multimedia Computing and Systems*, pp. 1-6. IEEE, 2011. https://doi.org/10.1109/ICMCS.2011.5945686

[8] Noroozi, M. A., J. S. Moghani, J. Mili Monfared, and H. Givi. "An improved direct torque control of brushless DC motors using twelve voltage space vectors." In *2012 3rd Power Electronics and Drive Systems Technology (PEDSTC)*, pp. 133-138. IEEE, 2012. https://doi.org/10.1109/PEDSTC.2012.6183312.

[9] Aktas, Mustafa, Khaled Awaili, Mehrdad Ehsani, and Aydemir Arisoy. "Direct torque control versus indirect field-oriented control of induction motors for electric vehicle applications." *Engineering Science and Technology, an International Journal* 23, no. 5 (2020): 1134-1143. https://doi.org/10.1016/j.jestch.2020.04.002.

[10] Patil, Mayuri S., Rameshwari Medhane, and S. S. Dhamal. "Comparative analysis of various DTC control techniques on BLDC motor for electric vehicle." In *2020 7th International Conference on Smart Structures and Systems (ICSSS)*, pp. 1-6. IEEE, 2020. https://doi.org/10.1109/ICSSS49621.2020.9201982.

[11] Gasbaoui, Brahim, Abdelfatah Nasri, and Othmane Abdelkhalek. "An efficiency PI speed controller for future electric vehicle in several topology." *Procedia Technology* 22 (2016): 501-508. https://doi.org/10.1016/j.protcy.2016.01.109

[12] Sontakke[1], Kaushal B., and Ramchandra P. Hasabe. "Real Time Simulation of Direct Torque Control of BLDC Motor Drive using Opal-RT Simulator." https://doi.org/10.17577/ijertv9is080055

[13] Hannan, M. A., Jamal A. Ali, Azah Mohamed, and Aini Hussain. "Optimization techniques to enhance the performance of induction motor drives: A review." *Renewable and Sustainable Energy Reviews* 81 (2018): 1611-1626. https://doi.org/10.1016/j.rser.2017.05.240.

[14] Costa, Bruno Leandro Galvão, Clayton Luiz Graciola, Bruno Augusto Angélico, Alessandro Goedtel, Marcelo Favoretto Castoldi, and William Cesar de Andrade Pereira. "A practical framework for tuning DTC-SVM drive of three-phase induction motors." *Control Engineering Practice* 88 (2019): 119-127. https://doi.org/10.1016/j.conengprac.2019.05.003

[15] Arpit, Gahlawat, H. P. Singh, and Kamlesh Pandey. "Advance speed control of three phase induction motor using field oriented control method." *Materials Today: Proceedings* 80 (2023): 1981-1985. https://doi.org/10.1016/j.matpr.2021.06.020

[16] Sutikno, Tole, Nik Rumzi Nik Idris, and Auzani Jidin. "A review of direct torque control of induction motors for sustainable reliability and energy efficient drives." *Renewable and sustainable energy reviews* 32 (2014): 548-558.https://doi.org/10.1016/j.rser.2014.01.040

[17] Ammar, Abdelkarim, Abdelhamid Benakcha, and Amor Bourek. "Closed loop torque SVM-DTC based on robust super twisting speed controller for induction motor drive with efficiency optimization." *international journal of hydrogen energy* 42, no. 28 (2017): 17940-17952.https://doi.org/10.1016/j.ijhydene.2017.04.034