Review on different control techniques for induction motor drive in electric vehicle

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Abstract. Now a day Electric vehicles (EV) are called future vehicles in place of internal combustion engines because of their working with pollution free and more efficient. This paper reviews various control strategies of induction motor drives (IMD) for EV applications. Efficiency and performance are the major considerations in selecting control algorithms for induction motor drives. Basically there are scalar control and vector control methods for IMDs. Scalar control technique has drawback of low performance. Conventional direct torque control (DTC) technique is one of the most preferable control technique for controlling torque and flux independently. But due to the lower switching frequency in direct torque control leads to more flux ripple and torque ripples and it leads lower performance of induction motor drives.

Keywords. Electric vehicle, Induction motor drive, direct torque control.

1. Introduction

In present days environment concerned research is going in a rapid manner to solve our environment issues such as increase of carbon dioxide level, depletion of ozone layer. Year by year there is rapid increase in production of Internal Combustion (IC) engine vehicles which increases pollution in the environment, so that there is increase in design and development of electric vehicle in automotive industries to replace IC engine vehicles.

In addition to reduced pollution in the environment, electric vehicle gives good performance in terms of its efficiency & torque [1]. The only disadvantage of EV is its cost [2]. Due to the environment concern and less fuel consumption EV are attractive than conventional IC engines [3]. For better efficiency of EV, it is necessary to choose motor drive and its control techniques properly. This means electric motor drive system is very much important and it is like heart of the entire electric vehicle system. The following figure 1 represents the block diagram of various parts of electric vehicle system [4].

![Block diagram representation of electrical vehicle system](image)

In the above fig (1), controller part, power converter part and electric motor part represents core of the drive of the EV. It consists of electric vehicle control system and battery management system works together to reduce power consumption [1, 5]. The motor that we choose must have following basic requirements which are [1].
i. High power density and high torque density
ii. Low losses
iii. Good controlling property
iv. Better dynamic performance
v. Rugged and simple in structure
vi. Low cost
In earlier research DC motor are preferably used in EV applications due to simple in controller design and their characteristics are well matched for electric vehicle motor. With the increase in the research advancement of controlling technique, induction motor comes into the main frame for choosing as drive motor for electric vehicle applications [6]. It is commutator less motor, it is highly reliable, rugged and maintenance free [7]. Even though it has more advantages than dc motors, it has some drawbacks like nonlinear characteristics due to this, analysis becomes complex [8, 9] and flux in the induction motor is not measurable [10].To overcome these drawbacks, few control strategies are presented [11] and it compares among conventional controllers and intelligent controllers with respect to torque ripples. Simultaneously to reduce the torque and flux ripples and to improve the dynamic response Field Oriented Control (FOC) is established [8]. This technique decouples the torque and flux to get fast dynamic torque response [12-14] and it improves the performance of the drive system. FOC algorithm is very much sensitive to parameter variation with respect to temperature variation, which leads to reduced performance [15].
To overcome the limitations of FOC, DTC was explained by TAKANASHI [16] & DEPENBROCK [17]. In DTC control signals are calculated directly for the inverter [18-20]. But this conventional DTC has drawbacks like more torque ripple and flux ripples in low speed region and various switching frequency, due to this torque and flux are not fully controllable [21-23].Many modern control techniques are invented for controlling the two main parameters; those are torque and flux of IM for electric vehicle applications. In this paper section II deals with modelling of induction motor, section III explain about basic design concept of DTC, section IV deals with different control algorithm and section V ends with conclusion.

2. Modelling of induction motor
Analysis of induction motor is little complex due to its nonlinear characteristics. The better way to analyse the three phase induction motor is 2-phase model expressed by \( \Psi_{sa}, \Psi_{sb} \) and \( \psi_{sa}, \psi_{sb} \). The equations that represents the induction motor are along \( \alpha \) and \( \beta \) axis are [24][25]

\[
\frac{d}{dt} \begin{bmatrix} i_{sa} \\ i_{sb} \\ \psi_{sa} \\ \psi_{sb} \end{bmatrix} = \begin{bmatrix}
-\frac{1}{\tau_s} (\frac{1}{\tau_s} + \frac{1}{\tau_r}) & \frac{1}{\sigma_l \tau_r} & \frac{\omega_r}{\sigma_l \tau_r} & \frac{1}{\sigma_l \tau_r} \\
-\frac{1}{\sigma_l \tau_r} & -\frac{1}{\sigma_l (\tau_r + \tau_s)} & \frac{\omega_r}{\sigma_l \tau_r} & \frac{1}{\sigma_l \tau_r} \\
-R_s & 0 & 0 & 0 \\
0 & -R_s & 0 & 0 \\
\end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ \psi_{sa} \\ \psi_{sb} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \end{bmatrix} 
\]

(1)

Here \( \alpha, \varsigma \), and \( \sigma \) are called +ve constants

\[
\sigma = \frac{M^2}{L_y L_y} = \frac{R_s}{L_s} \approx \frac{R}{L}
\]

The following are the equations for torque and moment of inertia

\[
T_{em} = (\psi_{sa} i_{sa} - \psi_{sb} i_{sb}) 
\]

\[
j \frac{d\alpha}{dt} + f\Omega = T_{em} - Tr
\]

(2)

(3)
The transformation from three phases to two phases can be done by

$$\begin{bmatrix} x_a \\ x_b \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/\sqrt{3} & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

(4)

3. Direct Torque Control

Direct torque control of induction motor is initially proposed by Takahashi and Depenbrock in 1980s decade. It works on principle of direct use of control signals for power semiconductor switches of voltage source inverter. As pulse width modulation is absent in DTC, so that control strategy is simple. Figure 2 shows electromagnetic torque and stator flux are independently controlled by hysteresis comparators. The outcomes of these two comparator decide the switching signals from switching table. It gets its attention because of its simplicity. The basic block diagram [1] which represents DTC is shown in figure 2.

![Figure 2. Basic representation of Direct Torque Control](image)

The design of control technique (DTC) is mainly depending on determination of torque and stator flux linkages depend on these equations. The equation for electromagnetic torque $T_e$ is given by

$$T_e = \frac{3}{2} p (\psi_{sq} - \psi_{sd})$$

(5)

$$\psi_{sd} = \int (v_{sd} - R_s i_{sd}) dt$$

(6)

$$\psi_{sq} = \int (v_{sq} - R_s i_{sq}) dt$$

(7)

Where

- $p$=number of poles
- $\psi$=flux linkage
- $i_{sq}$=quadrature axis stator current
- $i_{sd}$=direct axis stator current
- $R_s$=stator resistance
- $v_{sd}$=Quadrature axis stator voltage
- $v_{sq}$=Direct axis stator voltage

The following equations (8) & (9) used to determine the magnitude and angle of stator flux linkage
\[ \psi_s = \sqrt{(\psi_{sQ}^2 + \psi_{sq}^2)} \]  

\[ \theta = \tan^{-1}\left(\frac{\psi_{sq}}{\psi_{sQ}}\right) \]  

(8)  

(9)  

It can be selected directly the stator voltage vector based on comparison between reference and actual values of torque and flux linkages according to the conventional switching table [1]. Even though DTC has more advantages over other control techniques, it has some drawbacks like it generates more torque and flux ripples. To reduce or avoid these ripples many control algorithms are introduced for induction motor drives.

4. Control Algorithms

There are various control techniques for induction motor drives in electric vehicle applications. They are i) Proportional Integral (PI) controller ii) PID controller iii) Sliding mode controller (SMC) iv) Fuzzy logic controller (FLC) v) Neural network controller vi) Model predictive controller vii) Hybrid controllers., and more. Few important algorithms are reviewed here. One can choose the better algorithm for controlling of induction motor drives. This paper [1] concludes that sliding mode control is well suited for electric vehicle compared to conventional proportional integral and fuzzy logic controller. This paper explains how efficiency and performance can be improved by using sliding mode controller. This paper also compares the two torque control techniques they are indirect FOC and Direct torque control. [26-29] proposes SMC which will increase the performance of the IM drive as compared to PI controllers [30,31] explains combination of SMC and FLC gives better dynamic characteristics compared to PI and FLC controller alone. In this paper [32] he proposes new controller called neural network based DTC to reduce the settling time and improve the performance of switched reluctance motor where he reduced the torque ripple of margin of 1%. This paper [33] explains the online optimization technique to vanish the flux and torque hysteresis band. It is better performance than conventional DTC as it uses the predefined switching table. This paper explains how torque ripple can be educed using Predictive torque control (PTC) and analysis of speed response and torque ripple in the induction motor which is used in electric vehicles. Due to the complexity in calculation, settling time is more in PTC as compared to conventional DTC. He explained with result that percentage of torque ripple and current total harmonic distortion (THD) are less in PTC compared to conventional DTC.

This paper gives increase in torque and speed response of switched reluctance motor by choosing voltage vector using look up table based DTC [34]. The authors [35] proposed DTC for induction motor drives based on lookup table. By proper selection of switching table values, it is possible to improve the performance and dynamic behaviour of induction motor based electric vehicles. This paper also utilizes the regenerative braking where partial energy from the motor is used to charge the battery. This paper [36] proposes Artificial Neural Network (ANN) controller to reduce both torque and flux ripples by considering proper values for input and feedback through online mode. By using both simulation and practical it explains that proposed controller is more efficient than conventional controller. This paper [37] improvises the transient analysis by using ANN controller but no changes in torque and flux ripples. This paper [38] replaces neural controller instead of switching table and hysteresis controller to reduce the torque and flux ripples.

In this paper [39] authors explains the three different control strategies for induction motor drive based EV applications which are DTC space vector modulation (DTC-SVM), conventional DTC and FOC algorithms. By using DTC-SVM it has been noted that stator current ripples considerably decreasing hence it improves the dynamic performance of induction motor drives. [40] In this paper fast dynamic response of induction motor drive for electric vehicle is achieved by DTC-SVM in the place of voltage source inverter. This[41] paper explains on intelligent controller which is called an
better controlling technique for switched reluctance motor which reduces the overshoot time and also improves torque response of the drive system. The following Table 1 gives comparison between five different controllers by considering different parameters.

Table 1. Comparison among different controllers.[1, 2, 42-49]

| Parameter/technique | Conventional DTC | SMC based DTC | DTC-MPC | Fuzzy based DTC | ANN based DTC |
|---------------------|------------------|---------------|---------|-----------------|---------------|
| Torque & flux Ripple| high             | medium        | less    | Very less       | Very less     |
| Torque response     | high             | high          | high    | Very high       | Very high     |
| Current THD         | high             | less          | less    | less            | less          |
| Switching loss      | high             | average       | less    | less            | less          |

By considering above table we can say that conventional direct torque control algorithm has more torque and flux ripples compared to other algorithms. Depending upon parameter selection and application it is feasible to select particular algorithm for induction motor drives.

5. Conclusion
This paper reviews various control strategies available for IM based electric vehicle applications. The major objective of the review was to lower the flux ripple and torque ripples of induction motor drive and intern enhancing the performance of electric vehicle. The control techniques like conventional DTC, SVM-DTC, SMC-DTC, Fuzzy based DTC and ANN DTC are compared for dynamic response, torque ripple and flux ripple, total harmonic distortion and switching frequency. These algorithms have their own advantages and drawbacks. The table 1 gives comparison among various algorithms. Therefore selection of these algorithms for induction motor is based on cost, accuracy and application. Fuzzy logic controller is used where the system behaviour is more complicated and semantic rules are necessary to explain the system. Compared to FLC artificial neural network is good for modelling in this conditions as ANN is more suitable for controlling nonlinear devices. As induction motor has a nonlinear model and therefore ANN is highly suitable for controlling induction motor drive in electrical vehicle.

6. References
[1] Aktas, M., Awaili, K., Ehsani, M., and Arisoy, A. (2020). Direct torque control versus indirect field-oriented control of induction motors for electric vehicle applications. *Engineering Science and Technology, an International Journal, 23*, Pages 1134-1143
[2] Chau, K. T. (2015). Electric vehicle machines and drives: design, analysis and application. *John Wiley & Sons.*
[3] Ehsani, Mehrdad, Yimin Gao, and Ali Emadi. Modern Electric, Modern Hybrid, and Fuel Cell Vehicles. *Book* (2010).
[4] Chan, C. C. (2002). The state of the art of electric and hybrid vehicles. *Proceedings of the IEEE, 90*(2), 247-275.
[5] Hu, Changjian, Yimin Gao, and Q. Huang Alex (2015). Power management strategy of hybrid electric vehicles based on particle swarm optimization. *IEEE Transportation Electrification Conference and Expo (ITEC)*, pp. 1-6. IEEE, 2015.
[6] Tabbache, B., Kheloui, A., and Benbouzid, M. E. H. (2010, September). Design and control of the induction motor propulsion of an electric vehicle. *IEEE Vehicle Power and Propulsion Conference* (pp. 1-6). IEEE.

[7] Butler, Karen L., Mehrdad Ehsani, and Preyas Kamath. (1999) A Matlab-based modeling and simulation package for electric and hybrid electric vehicle design. *IEEE Transactions on Vehicular Technology* 48, no. 6: 1770-1778.

[8] Karagiannis, Dimitrios, Alessandro Astolfi, Romeo Ortega, and Mickaël Hilairet (2009). A nonlinear tracking controller for voltage-fed induction motors with uncertain load torque. *IEEE Transactions on Control Systems Technology* 17, no. 3: 608-619.

[9] Sen, P. C. (1990). Electric motor drives and control-past, present, and future. *IEEE Transactions on Industrial Electronics*, 37(6), 562-575.

[10] Trabelsi, R., Khedher, A., Mimouni, M. F., & M'sahli, F. (2012). Backstepping control for an induction motor using an adaptive sliding rotor-flux observer. *Electric Power Systems Research*, 93, 1-15.

[11] Pushparajesh Viswanathan and Manigandan Thathan (2016) Torque ripple minimization of direct torque controlled four phases witched reluctance motor using artificial intelligent controller *World Journal of Modelling and Simulation*, Vol. 12, pp. 163-174

[12] Amezquita-Brooks, L., Liceaga-Castro, E., Liceaga-Castro, J., & Ugalde-Loo, C. E. (2015). Flux-torque cross-coupling analysis of FOC schemes: Novel perturbation rejection characteristics. *ISA transactions*, 58, 446-461.

[13] El Ouanjli, N., Derouich, A., El Ghzizal, A., Chebahbi, A., & Taoussi, M. (2017, November). A comparative study between FOC and DTC control of the Doubly Fed Induction Motor (DFIM). *International Conference on Electrical and Information Technologies (ICEIT)* (pp. 1-6). IEEE.

[14] Mehazzem, F., Nemmour, A. L., & Reama, A. (2017). Real time implementation of backstepping-multiscalar control to induction motor fed by voltage source inverter. *International Journal of Hydrogen Energy*, 42(28), 17965-17975.

[15] Novotny, D. W., & Lipo, T. A. (1996). Vector control and dynamics of AC drives *Oxford university press*. (Vol. 41)

[16] Takahashi, I., & Noguchi, T. (1986). A new quick-response and high-efficiency control strategy of an induction motor. *IEEE Transactions on Industry Applications*, (5), 820-827.

[17] Depenbrock, M. (1988). Direct self-control (DSC) of inverter-fed induction machine. *IEEE Transactions on Power Electronics*, 3, 420–429.

[18] Vaez-Zadeh, S., & Jalali, E. (2007). Combined vector control and direct torque control method for high performance induction motor drives. *Energy conversion and management*, 48(12), 3095-3101.

[19] El Ouanjli, N., Derouich, A., El Ghzizal, A., El Mourabit, Y., & Taoussi, M. (2017). Contribution to the improvement of the performances of doubly fed induction machine functioning in motor mode by the DTC control. *International Journal of Power Electronics and Drive Systems*, 8(3), 1117.

[20] Khedher, A., & Mimouni, M. F. (2010). Sensorless-adaptive DTC of double star induction motor. *Energy Conversion and Management*, 51(12), 2878-2892.

[21] Reza, C. M. F. S., Islam, M. D., & Mekhilef, S. (2014). A review of reliable and energy efficient direct torque controlled induction motor drives. *Renewable and Sustainable Energy Reviews*, 37, 919-932.

[22] Kadir, M. A., Mekhilef, S., & Ping, H. W. (2007, October). Direct torque control permanent magnet synchronous motor drive with asymmetrical multilevel inverter supply. In 2007 7th *International Conference on Power Electronics* (pp. 1196-1201). IEEE.

[23] Naik, N. V., Panda, A., & Singh, S. P. (2015). A three-level fuzzy-2 DTC of induction motor drive using SVPWM. *IEEE Transactions on Industrial Electronics*, 63(3), 1467-1479.
[24] Buja, G., Casadei, D., & Serra, G. (1997, July). Direct torque control of induction motor drives. In ISIE '97 Proceeding of the IEEE International Symposium on Industrial Electronics (Vol. 1, pp. TU2-TU8).IEEE.

[25] Slemon, G. R. (1989). Modelling of induction machines for electric drives. IEEE Transactions on Industry Applications, 25, 1126–1131.

[26] Abdelfatah, N., Abdeldjebar, H., Bousserhane, I. K., Hadjeri, S., & Sicard, P. (2008). Two wheel speed robust sliding mode control for electric vehicle drive. Serbian journal of electrical engineering, 5(2), 199-216.

[27] Alagna, S., Cipriani, G., Corpora, M., Di Dio, V., & Miceli, R. (2016, November). Sliding mode torque control of an induction motor for automotive application with sliding mode flux observer. IEEE International Conference on Renewable Energy Research and Applications (ICRERA) (pp. 1207-1212).IEEE.

[28] Ltifi, A., Ghariani, M., & Neji, R. (2014, December). Performance comparison of PI, SMC and PI-Sliding Mode Controller for EV. In 2014 15th InternationalConference on Sciences and Techniques of Automatic Control and Computer Engineering (STA) (pp. 291-297). IEEE.

[29] Nasri, A., Gasbaoui, B., & Fayssal, B. M. (2016). Sliding mode control for four wheels electric vehicle drive. Procedia Technology, 22, 518-526.

[30] Bounemedène, A., & Abdellah, L. (2012). A novel sliding mode fuzzy control based on SVM for electric vehicles propulsion system. ECTI Transactions on Electrical Engineering, Electronics, and Communications, 10(2), 153–163.

[31] Nasri, A., Hazzab, A., Bousserhane, I. K., Hadjeri, S., & Sicard, P. (2009). Fuzzy-sliding mode speed control for two wheels electric vehicle drive. Journal of Electrical Engineering & Technology, 4(4), 499-509.

[32] Viswanathan, Pushparajesh, and Manigandan Thathan (2016). Minimization of Torque Ripple in Direct Torque Controlled Switched Reluctance Drive Using Neural Network. Asian Journal of Research in Social Sciences and Humanities 6, no. 8:65-80.

[33] Kousalya, V., Rai, R., & Singh, B. (2020, June). Predictive Torque Control of Induction Motor for Electric Vehicle. IEEE Transportation Electrification Conference & Expo (ITEC) (pp. 890-895). IEEE.

[34] Pushparajesh, V., Balamurugan, M., & Ramaiah, N. S. (2019). Artificial Neural Network Based Direct Torque Control of Four Phase Switched Reluctance Motor. Available at SSRN 3371369.

[35] Singh, B., Jain, P., Mittal, A. P., & Gupta, J. R. P. (2006, April). Direct torque control: a practical approach to electric vehicle. IEEE Power India Conference (pp. 4-pp). IEEE.

[36] Bouhoune, K., Yazid, K., Boucherit, M. S., & Nahid-Mobarakeh, B. (2018, November). Simple and Efficient Direct Torque Control of Induction Motor Based on Artificial Neural Networks. IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC) (pp. 1-7).

[37] Zegai, M. L., Bendjebbar, K. Belhadri, M. L. Doumbia, B. Hamane, and P. M. Koumba (2015). Direct torque control of Induction Motor based on artificial neural networks speed control using MRAS and neural PID controller. IEEE Electrical Power and Energy Conference (EPEC), pp. 320-325.

[38] Sayouti, Y., A. Abbou, M. Akherraz, and H. Mahmoudi (2010). Real-time DSP implementation of DTC neural network-based for induction motor drive. :pp 233-233.

[39] Prabudha, B. V., Aparna Balamurugan, T. Selvathai, Rajaseeli Reginald, and Jayashree Varadan (2019). Evaluation of different Vector Control methds for Electric Vehicle Application. 2nd International Conference on Power and Embedded Drive Control (ICPEDC), pp. 273-278. IEEE, 2019.
[40] Ellabban, Omar, Joeri Van Mierlo, and Philippe Lataire (2011). Direct torque controlled space vector modulated induction motor fed by a Z-source inverter for electric vehicles. *International Conference on Power Engineering, Energy and Electrical Drives*. IEEE.

[41] Pushparajeshviswanathan, Manigandan Thatan (2015) Hybrid Controller Based Instantaneous Torque Control of Four Phase Switched Reluctance Motor *Middle-East Journal of Scientific Research* **23** (**11**): 2736-2747.

[42] Reza, C. M. F. S., Islam, M. D., & Mekhilef, S. (2014). A review of reliable and energy efficient direct torque controlled induction motor drives. *Renewable and Sustainable Energy Reviews*, **37**, 919-932.

[43] Sutikno, T., Idris, N. R. N., & Jidin, A. (2014). A review of direct torque control of induction motors for sustainable reliability and energy efficient drives. *Renewable and sustainable energy reviews*, **32**, 548-558.

[44] Ammar, A., Benakcha, A., & Bourek, A. (2017). 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**(28), 17940-17952.

[45] Gadoue, S. M., Giaouris, D., & Finch, J. W. (2009). Artificial intelligence-based speed control of DTC induction motor drives—A comparative study. *Electric Power Systems Research*, **79**(1), 210-219.

[46] Gdaim, S., Mtibaa, A., & Mimouni, M. F. (2010). Direct torque control of induction machine based on intelligent techniques. *International Journal of Computer Applications*, **10**(8), 29-35.

[47] Lascu, C., Boldea, I., & Blaabjerg, F. (2004). Direct torque control of sensorless induction motor drives: a sliding-mode approach. *IEEE Transactions on Industry Applications*, **40**(2), 582-590.

[48] Kumar, R. H., Iqbal, A., & Lenin, N. C. (2017). Review of recent advancements of direct torque control in induction motor drives—a decade of progress. *IET Power Electronics*, **11**(1), 1-15.

[49] Niu, F., Wang, B., Babel, A. S., Li, K., & Strangas, E. G. (2015). Comparative evaluation of direct torque control strategies for permanent magnet synchronous machines. *IEEE Transactions on Power Electronics*, **31**(2), 1408-1424.