Comparison of ANN- and GA-based DTC eCAR

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Received: 5 March 2021 / Revised: 27 May 2021 / Accepted: 28 May 2021 / Published online: 9 June 2021
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Abstract
In this paper, an artificial intelligence (AI)-integrated direct torque control (DTC) scheme is developed for an electric vehicle (EV or eCAR) propulsion motor drive. In addition, a comparison is made between adaptive neural network (ANN) and genetic algorithm (GA)-based torque controllers. The integration of AI into EVs has attracted the attention of many researchers in terms if drive control, dynamic stability, speed estimation, and energy management strategies. Amidst the various motor drive control strategies, DTC schemes with space vector pulse width modulation (SVPWM) have gained prominence due to its fast torque (speed) control capability. The smooth control of a DTC-eCAR propulsion motor is accomplished by the use of AI algorithms. The applications of ANN and GA algorithms for tuning the torque controller are tested and the behavior of an eCAR in terms of drive range, percentage of state of charge (SOC), and energy consumption for different driving conditions is observed using MATLAB simulations.

Keywords Adaptive neural network · Artificial intelligence · Direct torque control · Electric vehicle · Genetic algorithm · Powertrain · Vehicle dynamics

1 Introduction
Nowadays, human survival is being adversely affected due to environmental perils. Globally, the Coronavirus (COVID-19) pandemic has pushed down the GDP and caused the loss of many human lives. The majority of auto-manufacturers have put off the production of vehicles due to the COVID-19 crisis and there is a drastic decrease in the auto market growth rate. After this pandemic, there will be a huge demand for EVs in view of their eco-friendly nature. In EVs, the choice of a propulsion motor and its control strategy play a vital role, especially for battery-powered vehicles (eCAR). EVs are gaining popularity due to their silent, smooth, and zero emission operation, as well as their portable charging and higher fuel economy. In addition, the cost of fuel/unit charge is less when compared to combustion vehicles. However, these vehicles have challenges such as excessive charging time and poor energy density, which provide areas of possible research for their improvement. These limitations can be overcome by implementing an efficient control strategy.

In modern research, the integration of artificial intelligence (AI)-based motor control schemes has gained prominence due to the need for most suitable parameter selection. The grey wolf optimization (GWO) algorithm is a recently developed algorithm that imitates the grey wolf community hierarchy and hunting mechanisms. It has the major advantage of reducing the number of the search parameters. The authors of [1] proposed an optimal control strategy for a bearing less permanent-magnet synchronous machine (BPMSM) drive. The weighting matrices $K_3$ are obtained by employing the GWO algorithm. In [2], an optimal control strategy for a permanent-magnet synchronous hub motor (PMSHM) drive using the state feedback control method plus the GWO algorithm was proposed. The GWO algorithm is employed to acquire the weighting matrices $Q$ and $R$ in the linear quadratic regulator optimization process. In [3], the parameters of a PI are tuned using an ANN and a GA for a DTC scheme. The DTC can increase the dynamic stability, mitigate torque and flux

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ripples, and increase the energy efficiency of the induction motor drive under different operating conditions. In [4], an improved direct instantaneous torque control (DITC) based on adaptive terminal sliding mode control (ATSMC) was proposed. It is a novel DTC for motors. The authors of [5] proposed an improved direct torque control (DTC) with a sliding mode controller and an observer to reduce the torque ripples of a four-phase SRM. In [6], the appropriateness of a DTC scheme for a typical EV propulsion system was predicted. In addition, a search control method for a precise flux and torque estimator, and an efficiency optimizer using offline loss model for EV parameter optimization were derived. In [7], a review of DTC schemes integrated with intelligent algorithms was given and a comparative analysis was made with respect to algorithm intricacy, speed tracking, parameter variations, switching losses, and ripples reduction. In [8], a stator flux optimization algorithm-based DTC scheme to increase the drive range of an EV in terms of the full charge driving of a 3 kW induction motor is tested by considering the effect of core loss and leakage inductance. In [9], a DTC scheme for battery and fuel cell powered front wheel drive (FWD) EV with an ANN speed PI controller, tracks the reference speed accurately when compared to traditional PI controllers in terms of the U.S. Environmental Protection Agency (EPA) and the New European Driving Cycle (NEDC). In [10], a GA-based DTC-IM drive, to regulate PI controller parameters was discussed. In [11], a DTC space vector-modulated (SVM) control strategy for the speed control of a three-phase IM using a GA to optimize the speed PI controller parameters was discussed, and the behaviors of GA-PI and traditional PI were compared.

In this paper, an AI-integrated DTC scheme is developed for an eCAR propulsion motor drive, and a comparison is made between ANN- and GA-tuned torque controllers. The responses of the two intelligent algorithms are observed in terms of torque ripple, battery SOC, and drive range under different driving conditions. The remainder of this paper is organized as follows. In Sect. 2, the DTC scheme for an eCAR propulsion system is explained. In Sect. 3, the integration of an ANN torque controller for the DTC scheme is discussed. In Sect. 4, the integration of a GA torque controller for the DTC scheme is discussed. In Sect. 5, a comparative simulation study is made among the conventional PI-, ANN- and GA-based controllers to validate their performances. Section 6 recapitulates the conclusions of the work done.

2 Direct torque-controlled eCAR propulsion

In the 1980s, Takahashi Isao and Depenbrock Manfred published an article with the title Direct Torque Control (DTC), to contest with traditional vector controls. The DTC scheme has good dynamic stability and robustness in the presence of induction motor parameter variations. In DTC, the control pulses generated for the switches of the voltage source inverter are resolved directly. In modern studies, a great deal of research has been carried out on DTC schemes [12–14]. The classical DTC scheme using hysteresis controllers is widely used for the torque and flux control of an induction motor. However, at lower speeds and operating at a low switching frequency, they produce high flux and torque ripples, which cause acoustic noise and reduce the control performance. Later, a number of DTC schemes came into existence to overcome the impediments of the classical DTC scheme. Most of these schemes concentrated on torque and flux ripple minimization. An optimal advanced discontinuous PWM (ADPWM) algorithm for a DTC-controlled induction motor drive is used to depict the actual value of gamma (γ) given a set policy frequency. The space vector PWM (SVPWM) technique provides solutions to a few of the hardships found in traditional PWM schemes. The sequence of three switching states yields eight output voltage vectors. At any given instance, the inverter has to drive one of these voltage vectors. Of the eight voltage vectors, V0 and V7 are zero-voltage vectors, and V1, V2, V3, V4, V5, and V6 are active voltage vectors, and they are presented in the space vector plane in Fig. 1, [15]. In this approach, the overall time interval of the zero-voltage vector is uniformly distributed between V0 and V7. In addition, the zero-voltage vector time is distributed proportionally at the initial and final parts of a sub-cycle in a symmetrical way. The frontier for the modulation index is 0.866, while 0127–7210 is utilized in the first sector, 0327–7230 is utilized in the second sector, and so on [16].

A VSI is used to develop a three-phase voltage vector with a regulated amplitude and frequency. A block diagram of the VSI, and the output voltage, switching pulses, and sectors are shown in Figs. 2, 3, respectively. In Fig. 4, a block diagram of a direct torque control scheme integrated with intelligent control algorithms (ANN and GA) for the torque control of an eCAR propulsion motor is shown. Initially, the size and rating of

![Fig. 1 Two-level space vector representation](image-url)
the propulsion motor are determined based on the vehicle mass, acceleration rate, and maximum speed limit. Later, the induction machine is modeled in a synchronously rotating reference frame using Clark’s and Park’s transformations. The d–q axis voltage and current magnitudes are measured to estimate the actual speed, torque, and flux of the motor using an adaptive motor model [17].

The set speed $\omega_{s}^{*}$ is compared with the estimated speed $\omega_{s}$, and the speed error is regulated by a speed PI controller also termed as a driver model since it gives the percentage of the accelerator pedal position (APP) or reference torque magnitude $T_{e}^{*}$. The speed controller output $T_{e}^{*}$ is then compared with the torque $T_{e}$, which is computed by an adaptive motor model. Then, the torque error is processed through the proposed intelligent torque controller (ANN and GA) to obtain the synchronously rotating reference slip speed $\omega_{sl}^{*}$. The summation of $\omega_{sl}^{*}$, $\omega_{s}$ and its integration denotes theta $\theta_{e}^{*}$. Then, the reference input d–q axis voltage vectors are manipulated by the reference voltage vector calculator (RVVC) block using the following equation, and the output is fed to SVPWM [18–20]:

$$F_{ref} = \frac{2\pi f}{V_{ref}} \sqrt{\int_{0}^{\frac{2}{3}\pi} F_{seq}^{2} d \alpha},$$

where $F_{seq}^{2}$ is the RMS stator flux ripple of a specific sequence, and $V_{ref}$ is the reference voltage vector at the angle $\alpha$.

### 3 Artificial intelligence-based torque controller

**i. ANN-tuned torque controller**

The integration of an AI-based DTC scheme is introduced for the enrichment of eCAR performance in view of a higher acceleration rate, maximum speed, drive range, and fuel economy. The ANN algorithm has a simple structure, simple learning practices, and can resolve higher order nonlinear function. However, it is ineffective for motor parameter variations. The feed forward multilayer neural network and the recursive neural network are two typical ANN networks. In the literature, ANN-based DTC schemes have been used for control parameter identification, state estimation, tuning speed controllers, torque controllers, sensorless speed estimation, and voltage vector selection. An online ANN speed estimator that keeps V/f constant for a DTC-controlled IM drive is discussed and observed. It is observed that the steady-state operation of the ANN speed estimator...
provides a fast-dynamic response, but is not effective during transient operation [21]. The pros and cons of the ANN-based DTC scheme are described. It has been shown that the ANN controller experiences reductions in the settling time at starting and in speed reversal [22]. An ANN-based speed controller for a SVM-DTC-controlled IM was developed to mitigate steady-state speed errors as well as transient torque and flux ripples [23]. In this paper, an ANN-based torque controller for a DTC-controlled eCAR is implemented to minimize the torque ripple and to enhance the performance of the eCAR. First, the ANN network is constructed by the input data, output data, target data, and error data attained by the response of a step-input signal. The network is selected in a 2, 40, 1 manner, with two neurons in the input layer, 40 neurons in the hidden layer, and one neuron in the output layer. The input data are the torque error and the change in torque error, and the output is the steady-state torque error. The process of the ANN network is shown in Fig. 5.

Once the ANN is constructed with the available data, it is trained using the Levenberg–Marquardt back propagation algorithm [24]. In Simulink, the ANN network is designed by typing “nntool” in the MATLAB command window, and the ANN structure is depicted in Fig. 6. In addition, the Simulink model of the ANN is originated by the command “genism(network)”, as shown in Fig. 7.

The subsystems of the ANN network are shown in Fig. 8.

### ii. GA-tuned torque controller

Genetic algorithms (GA) make up a branch of the AI tree that has great prominence in global parameter optimization procedures. The first GA was brought into existence by John Holland in 1970 and it is one of the most robust optimization algorithms. The integration of a GA into drive control made it possible to easily solve complex control systems by searching a set of possible solutions in parallel using a fitness function as a mean of selective among different sets of possible solutions and using randomize operators instead of derivative information. A GA create new generations to increase the population of the former population. Crossover and mutation are the two major elements for generating a new solution. In the crossover process, the chromosomes are split into two new chromosomes and swapped in the mutation process. This occurs during natural selection and natural evaluations to produce new generations. A GA is more robust to parametric variations, yields better solutions in a shorter period of time, and requires less computing power. The drawback of a GA is the selection of parameters
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since they are strongly subject to user knowledge and the investigation process. Recently, with the introduction of GA-based DTC control schemes, the dynamic stability of induction motor drives has improved, and the GA is adapted to optimize the torque controller gain values to achieve accurate speed tracking as well as significant reductions in the torque, flux, and current ripples. In this paper, a GA is employed to optimize the parameters of the torque controller to attain minimal torque ripples. A GA is a global search method utilized for computing the best or near solutions from a group of complex solutions. The process of a GA is described as follows.

Step 1: Build up a set of chromosomes (arbitrarily). The generated chromosomes are the present nominated solutions of the problem.

Step 2: Compute fitness values (integral time absolute error (ITAE)) for all of the chromosomes.

Step 3: Assemble the chromosomes starting from the better solution (i.e., the least fitness value).

Step 4: Clone the best chromosomes to obtain better attributes in the population.

Step 5: Perform a crossover process for the parent chromosomes to obtain a new population.

Step 6: Mutate chromosomes with a small predetermined value.

Step 7: Compute the new fitness values for all of the chromosomes.

Step 8: Restart Step 3 through Step 7 until the minimum error criterion is met.

A basic block diagram of a GA for the tuning of torque controller parameters is show in Fig. 9. In addition, the properties involved in this GA are represented in Table 1.

The optimized best output values of the GA-based PI controller are shown in Fig. 10. It can be seen that the values of $K_p$ and $K_i$ are 0.5 and 1.8, respectively.
4 Simulation analysis

An intelligent ANN- and GA-based DTC-controlled front wheel drive (FWD) eCAR propulsion system was designed to analyze the behavior of an eCAR with vehicle dynamics under different driving conditions. The propulsion system of the eCAR incorporates several apparatuses such as a 35 kW, 100 Ah, 400 V Lithium-ion (Li-ion) battery stack, a 4 kW, 400 V AC/DC/AC bidirectional on-board charger, a 90 kW three-phase squirrel-cage induction motor, an intelligent ANN- and GA-integrated SVPWM-based microcontroller, a two-level IGBT-based three-phase VSI, a simple gear with a gear ratio of 10.8, a differential transmission, and a drive axel. The mass of the vehicle is 1680 kg, with a frontal area of 1.2 square meters and a wheel radius of 0.2794 m. A parametric analysis is performed for pre-sizing the components of the eCAR powertrain to increase the acceleration rate and driving range [25]. The components of the eCAR are modeled with the help of mathematical equations, and the vehicle dynamics are considered by adding force due to inertia, aerodynamic drag, rolling friction, and hill climbing or a gradient slope, where all these forces are represented in terms eCAR parameters [26]. The road load is determined by means of a quadratic equation relating to the eCAR speed. This equation is given by the following equation:

\[ F_{rl} = A_1 + B_1 V + C_1 V^2. \]  \hfill (2)

The environmental protection agency (EPA) constants \( A_1, B_1, \) and \( C_1 \) correspond to inertial force, gradient force, and aerodynamics, respectively. These constraints are definite for each eCAR configuration. All these forces add to the total tractive effort given by the following equation:

\[ F_{tr} = F_{rl} + m \times a, \]  \hfill (3)
where \( F_{\text{tr}} \) is the tractive force, \( m \) is the mass, and \( a \) is the acceleration. The acceleration value is given by the following equation:

\[
\alpha = \frac{dv}{dt} = \frac{F_{\text{tr}} - (F_{\text{fr}})}{m}.
\]

(4)

The proposed ANN- and GA-based DTC eCAR propulsion system is modeled using R2019b MATLAB simulation software, and is shown in Fig. 11.

Simulation results obtained for both the ANN and GA intelligent torque controllers are analyzed and compared with the conventional PI controller as follows. Initially, the response of the developed AI-integrated DTC eCAR Simulink model was analyzed with the step input as a set speed. In Fig. 12a, it is observed that the time taken to reach a vehicle speed of 25 m/s or 90 km/h is 5.2 s, which is one of the customer desires. This can be achieved with an acceleration rate of 4.8 m/s², a motor angular speed of 314 rad/s at a maximum output power of 90 kW, and a torque of 290 N-m. Figure 12b represents the torque response of the PI-, ANN- and GA-based DTC schemes for a step input. It is seen that the GA torque controller has smoother and lower torque ripple. Figure 13a represents speed

![Fig. 11 Model-based design of an intelligent ANN- and GA-based direct torque-controlled eCAR](image1)

![Fig. 12 Step input: a motor speed characteristics; b motor torque characteristics](image2)

![Fig. 13 Step change input: a motor speed characteristics; b motor torque characteristics](image3)
responses of the PI-, ANN- and GA-based DTC schemes for a step change input. The step change input represents rural, urban, and highway-driving conditions with the speeds of 40 km/h, 80 km/h, and 120 km/h. Figure 13b represents the torque response of the PI-, ANN- and GA-based DTC schemes for a step change input. It is seen that the GA torque controller has a low torque ripple. Figure 14a represents the speed response of an eCAR in terms of the European Cycle (ECE-R15). Figure 14b represents the torque response of the PI, ANN and GA. It is seen that the GA torque controller has accurate speed tracking and low torque ripple. Figure 15a represents the energy consumption of an eCAR over one European Cycle. It is seen that the GA has a low energy consumption of about 210 W-s while the PI and ANN have 255 W-s and 260 W-s, respectively. Figure 15b represents the percentage state of charge (SOC) of a Lithium-ion battery over one European Cycle. It is seen that the GA has a higher %SOC of about 95.5% when compared to those of the PI and ANN. A comparative analysis is made among the PI-, ANN- and GA-tuned torque controllers. This comparison is tabulated in Table 2 in terms of maximum torque ripple.

Thus, from the above simulation analysis, it is clear that the proposed GA-tuned torque controller is best suited

| Table 2 Maximum torque ripple for different controllers |
|------------------------------------------------------|
| **Ref. input** | **Step** | **Step change** | **European cycle** |
|               | PI   | ANN | GA | PI   | ANN | GA | PI   | ANN | GA |
| Torque ripple | 100  | 20  | 8  | 120  | 40  | 20 | 60   | 10  | 5  |
for DTC eCAR since it provides a low torque ripple, an increased drive range, and low fuel consumption.

5 Conclusion

An AI-integrated DTC scheme was proposed for an eCAR propulsion system. A comparative analysis is made among PI-, ANN-, and GA-tuned torque controllers under different driving conditions. Each component of the eCAR propulsion system is modeled using mathematical relations. In this paper, a 90 kW three-phase cage IM is used to attain a maximum speed of 90 km/h in 5.2 s, which is a desirable characteristic for an eCAR. The proposed AI-integrated DTC scheme was designed in simulation software and the behaviors of the PI-, ANN-, and GA-tuned torque controllers where analyzed. From the obtained simulation results, it is observed that the performance of the GA torque controller is much better than those of the PI and ANN controllers, since it offers a low torque ripple at higher speeds, while consuming less power. Thus, the performance of an eCAR in view of fuel economy, energy efficiency, and driving range is improved with the integration of a GA torque controller into its DTC scheme.

References

1. Sun, X., Jin, Z., Cai, Y., Yang, Z., Chen, L.: Grey wolf optimization algorithm based state feedback control for a bearingless permanent magnet synchronous machine. IEEE Trans. Power Electron. 35(12), 13631–13640 (2020)
2. Sun, X., Hu, C., Lei, G., Guo, Y., Zhu, J.: State feedback control for a pm hub motor based on gray wolf optimization algorithm. IEEE Trans. Power Electron. 35(1), 1136–1146 (2020)
3. Reza, C.M.F.S., Islam, M.D., Mekhilef, S.: A review of reliable and energy efficient direct torque-controlled induction motor drives. Renew. Sustain. Energy Rev. 37, 919–932 (2014)
4. X. Sun, L. Feng, K. Diao and Z. Yang: An improved direct instantaneous torque controller based on adaptive terminal sliding mode for a segmented-rotor SRM. IEEE Trans. Ind. Elec. (2020)
5. X. Sun, J. Wu, G. Lei, Y. Guo and J. Zhu: Torque ripple reduction of srm drive using improved direct torque control with sliding mode controller and observer. IEEE Trans. Ind. Elec. (2020)
6. Rehman, H., Xu, L.: Alternative energy vehicles drive system: control, flux and torque estimation, and efficiency optimization. IEEE Trans. Veh. Tech. 60(8), 3625–3634 (2011)
7. El Ouanjli, N., Derouch, A., El Ghizilal, A.: Modern improvement techniques of direct torque control for induction motor drives - a review. Prot. Control Mod. Power Syst. 4, 11 (2019)
8. Hilmi, A., Mustafa, A.: A novel DTC method with efficiency improvement of IM for EV applications. Eng. Technol. Appl. Sci. Res. 8, 3456–3462 (2018)
9. Araria, R., Negadi, K., Marignetti, F.: Design and analysis of the speed and torque control of IM with DTC based ANN strategy for electric vehicle application. Tecnica Ital J Eng Sci 63, 181–188 (2019)
10. Prof Al-Shaikhli, Saadi Khudair, Kanaan Jalal, & Luay Ibrahim.: Direct torque control of induction motor based on genetic algorithm. Internat. J. Scientif. Eng. Res. (2014)
11. Mohammad, K.A., Sakran, R.K.: Speed control of DTC_SIMV for induction motor by using genetic algorithm-based PI controller. Thi Qar Univ J Eng Sci 9(2), 17–28 (2018)
12. Bramananda Reddy, T., Amarnath, J., Subba Rayudu, D., Haseeb, K.M.: Generalized discontinuous PWM based direct torque-controlled induction motor drive with a sliding mode speed controller. IEEE Proc Power Electron Drives Energy Syst Indu Growth, PEDES’06 (2006)
13. Bramananda Reddy, T., Amarnath, J., Subba Rayudu, D.: New hybrid SVPWM methods for direct torque controlled induction motor drive for reduced current ripple. IEEE Proc Power Electron Drives Energy Syst Ind Growth (2006)
14. Habeter, T.G.: Direct torque control of induction machines using space vector modulation. IEEE Trans. Ind. Appl. 28(5), 1045–1053 (1992)
15. Sri Gowri, K., Reddy, T.B., Sai Babu, C.: Direct torque control of induction motor based on advanced discontinuous PWM algorithm for reduced current ripple. Electr. Eng. 92, 245–255 (2010)
16. Sri Gowri, K., Bramananda Reddy, T., Babu, C.S.: High-performance generalized ADPWM algorithm for VSI fed IM drives for reduced switching losses. Internat. J. Recent Trend Eng. 2(5), 96 (2009)
17. Zhenyu, J., Byeongwoo, K.: Direct torque control with adaptive PI speed controller based on neural network for PMSM drives. MATEC Web Conf 160, 02011 (2018)
18. Chintu Sagar, Y., Sri Gowri, K., Kumaraswamy, G.: Implementation of dSPACE controlled CSVPWM based induction motor drive. Internat J Eng Res Technol (IJERT) 2(11), 1070–1075 (2013)
19. Kumar, A.S., Gowri, K.S., Kumar, M.V.: Performance study of various discontinuous PWM strategies for multilevel inverters using generalized space vector algorithm. J. Power Electron. 20, 100–108 (2020)
20. Kumar, A.S., Gowri, K.S., Kumar, M.: New generalized SVPWM algorithm for multilevel inverters. J. Power Elect. 18(4), 1027–1036 (2018)
21. Narongrit, P., Ming-Shyan, W.: Online speed estimation using artificial neural network for speed sensorless direct torque control of induction motor based on constant V/F control technique. Energies 11(8), 2176 (2018)
22. Verma B Singh, D Yadav: Investigation of ANN tuned PI speed controller of a modified DTC induction motor drive. IEEE international conference on power electronics, drives and energy systems (PEDES), Mumbai. 1–6. (2014)
23. S. V. Jadhav, J. Kirankumar, B. N. Chaudhari: ANN based intelligent control of Induction Motor drive with Space Vector Modulated DTC. IEEE international conference on power electronics, drives and energy systems (PEDES), Bengaluru, 1–6 (2012)
24. Djeriri, Y., Meroufel, A., Massoum, A.: Artificial neural network based direct torque control of doubly fed induction generator. J. Electr. Eng. 14, 71–79 (2014)
25. Gururaj, B., Gowri, K.S.: Performance optimization of an eCAR by parametric analysis. Eng. Technol. Appl. Sci. Res 9(6), 4968–4973 (2019)
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