Improved direct torque control strategy performances of electric vehicles induction motor

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ABSTRACT

A three-wheeled electric scooter (3WES) with two control techniques is modeled and simulated in this study. The conventional direct torque control (C-DTC) and the DTC based on a neural network artificial multi layers (ANN-DTC). The objective is to assess the traction system’s response to the control approach. by 3WES taking into account the dynamics of the scooter, the range and the energy consumption of the battery. The 3WES was simulated numerically using the MATLAB/Simulink environment, which is powered 1.5 kW by two induction motors integrated into the rear wheels. Where the reference speeds of the rear wheels detected using a differential electronic. This can possibly cause it to synchronize the wheel speed in any curve. Each wheel's speed was controlled by two types of regulators, PI and ANN, to increase stability and reaction time (in terms of set point tracking, disturbance rejection and rise time). The proposed ANN-DTC control technique reduces torque, stator flux, and current ripple by roughly 35%. While the range of 3WES has increased by approximately 8.062 m, the battery power consumption has decreased by nearly 0.25%.

Keywords: 3WES Artificial neural network ANN Direct torque control DTC Induction motor IM Speed control PI

1. INTRODUCTION

Air pollution is a major problem in modern society. All contributes to health concerns, while CO2 emissions have an adverse effect on the ecosystem [1]. The transport industry is a significant source of greenhouse gases. The European Union (EU) has developed a plan to increase use of electric vehicles on the continent. in order to minimize pollution produced by passenger transport. In the EU, the emissions associated with the additional power generation necessary for electric transmission are less than those associated with fossil-fueled types of transportation are currently in use. Compared to ICE vehicles, electric vehicles are currently unreasonably expensive., according to studies. Electrification using two-wheel electric technology is a possibility, particularly in metropolitan areas [2]. Within the last year, electric scooters have gained popularity as a more environmentally friendly alternative to regular scooters.

For the most part, industrial applications use the squirrel cage induction machine as their primary electric actuator. the latter is distinguished by its resilience, dependability, low cost, and low maintenance needs. However, as a result of its modeling, a nonlinear, closely coupled system is created. and multivariate equations, its dynamic behavior is frequently rather complicated. Additionally, many state variables, such as flows, are not quantifiable. These restrictions necessitate the development of increasingly sophisticated control algorithms for real-time torque and flow control in these devices. Numerous control techniques for achieving this goal have been presented in the literature. Traditional controls were put to the test in the mid-
1980s by a new asynchronous machine control approach known as direct torque control (DTC) [3], [4]. Its operation is based on direct determination of the control pulses supplied to the voltage inverter switches in order to keep the electromagnetic torque and stator flux within two predetermined hysteresis bands. This use of the technique enables the decoupling of torque control and flux to be achieved without the need of pulse width modulation (PWM) or coordinate transformation.

Additionally, the main benefits of DTC are the rapid dynamic torque response, the minimum of dependence on rotor parameters, and the absence of coordinate transformations [5], [6]. However, this technique has two significant disadvantages: on the one hand, the switching frequency is highly variable; on the other side, the amplitude of the torque and stator flux ripples is poorly controlled across the whole working speed range. It should be observed that torque ripples add to the noise and vibration generated by the rotating shaft, resulting in fatigue. To further mitigate the impact of these phenomena on the service life of electric actuators, intelligent strategies are regarded to be beneficial.

Currently, artificial intelligence techniques are known for their power to solve problems related to the automation of industrial processes, such as the control, command, identification and estimation of parameters of electrical systems. The intelligent technique based on fuzzy logic belongs to the class of knowledge model-based systems. It is applied more and more in the control of the induction machine and the adaptation of its command [7]-[9]. Fuzzy logic-based approaches are considered to be a very powerful solution for controlling nonlinear systems or systems for which there are no mathematical models. Neural networks are distinguished by their capacity for processing, learning and approximation which is another technique of artificial intelligence. They are considered to be a completely different class from classical computers [10]-[12].

In this study, we propose to propose a DTC control using intelligent strategies. We are interested in the DTC control of an induction machine that propels an electric scooter's two-wheel drive via artificial neural networks. This effort will conclude with a comparison of the results obtained using ANN-DTC and conventional DTC control.

2. MODEL OF THE ELECTRIC MOTORIZATION BY IN-WHEEL IM

An artificial neural network-direct torque control (ANN-DTC) is used to execute direct control of the coupling based on knowledge of stator flux amplitude and location, and as a result, a balance must be struck between modeling complexity and precision when developing control techniques. Based in another on the knowledge of the amplitude and the position of the stator flux, one presents the complete model of the machine in the reference of park linked to the stator reference frame (α-β) is put in the form of following state as shown Figure 1.

\[
\dot{x} = Ax + Bu \tag{1}
\]

Such as: \(x = [i_{s\alpha} i_{s\beta} \varphi_{s\alpha} \varphi_{s\beta}]^T\), \(u = [u_{s\alpha} u_{s\beta}]^T\)

\[
A = \begin{bmatrix}
-\eta & \omega_r & K & 0 \\
\omega_r & -\eta & -\omega_r & K \\
0 & 0 & 0 & 0 \\
0 & R_s & \sigma L_s & 0
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
0 \\
0 \\
1 \\
0
\end{bmatrix}
\tag{3}
\]

With: \(\sigma = 1 - \frac{M^2}{l_s l_r}, T_s = \frac{l_s}{R_s}, T_r = \frac{l_r}{R_r}, \omega_r = \frac{p \Omega_r}{\sigma l_s T_r}, \eta = -\frac{1}{\sigma} \left( \frac{1}{T_r} + \frac{1}{T_s} \right)\)

Figure 1. The configuration of 3WDES three-wheel drive electric scooter

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3. WHEEL INDUCTION MOTOR DRIVE BASED ON CONVENTIONAL DTC

A technique for controlling induction motor torque directly was developed in the mid-1980s by I. Takahashi and T. Noguchi [13], [14], as well as DeBembrok. DTC stands for direct-to-consumer (direct torque control). The DTC works by measuring the control pulses sent to the voltage inverter’s switches directly. This is done to keep the stator flux and electromagnetic torque within predetermined hysteresis zones. This method’s implementation allows the flow and torque control to be separated. At its output, the voltage inverter reaches seven phase plane positions, which correspond to eight voltage vector sequences: [15]-[19]. Figure 2 illustrates a three-wheeled electric scooter's induction motor's DTC block diagram incorporated within the wheels. The flux may be estimated using measurements of the induction machine's stator current and voltage magnitudes [20].

\[
\varphi_{sa} = \int_0^t (v_{sa} - R_s i_{sa}) \, dt
\]

\[
\varphi_{sb} = \int_0^t (v_{sb} - R_s i_{sb}) \, dt
\]

The stator flux modulus is written:

\[
\varphi_s = \sqrt{\varphi_{sa}^2 + \varphi_{sb}^2}
\]

The area \(N_i\) it determines the location of the vector \(\varphi_s\) based on the components \(\varphi_{sa}\) and \(\varphi_{sb}\). The angle \(\theta_s\) between the frame of reference \((\alpha - \beta)\) and the vector \(\varphi_s\), is equal to [21].

\[
\theta_s = \arctan \left( \frac{\varphi_{sb}}{\varphi_{sa}} \right)
\]

Once the two components of the flux have been determined, the electromagnetic torque may be calculated using the [22]:

\[
T_{em} = \frac{3}{2} p [\varphi_{sa} i_{sb} - \varphi_{sb} i_{sa}]
\]

Table 1 illustrates the DTC control truth table [18].

<table>
<thead>
<tr>
<th>Sector (N_i)</th>
<th>(\Delta \varphi_s = 1)</th>
<th>(\Delta T_{em} = 1)</th>
<th>(S_1)</th>
<th>(S_2)</th>
<th>(S_3)</th>
<th>(S_4)</th>
<th>(S_5)</th>
<th>(S_6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta \varphi_s = 0)</td>
<td>(\Delta T_{em} = 1)</td>
<td>(V_2)</td>
<td>(V_3)</td>
<td>(V_4)</td>
<td>(V_5)</td>
<td>(V_6)</td>
<td>(V_1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\Delta T_{em} = 0)</td>
<td>(V_5)</td>
<td>(V_6)</td>
<td>(V_7)</td>
<td>(V_8)</td>
<td>(V_9)</td>
<td>(V_1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\Delta T_{em} = -1)</td>
<td>(V_9)</td>
<td>(V_0)</td>
<td>(V_1)</td>
<td>(V_2)</td>
<td>(V_3)</td>
<td>(V_4)</td>
<td></td>
</tr>
<tr>
<td>(\Delta \varphi_s = 1)</td>
<td>(\Delta T_{em} = 0)</td>
<td>(V_0)</td>
<td>(V_7)</td>
<td>(V_8)</td>
<td>(V_9)</td>
<td>(V_1)</td>
<td>(V_4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\Delta T_{em} = -1)</td>
<td>(V_4)</td>
<td>(V_5)</td>
<td>(V_6)</td>
<td>(V_7)</td>
<td>(V_8)</td>
<td>(V_9)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. 3WES conventional direct torque control for in-wheel induction motor drive
4. WHEEL INDUCTION MOTOR DRIVE BASED ON NEURONE ARTIFICIEL ANN

To enhance the speed reference tracking performance of the ANN-DTC control method, the PI controller has been replaced by ANN artificial neuron network type controller as shown in Figure 3. The neural network that we used is a multilayer network with local connection which uses the back-propagation algorithm [22] for their learning [23]-[26]. The figure illustrates the neural network, we used to be a multilayer network with local connection which uses the back-propagation algorithm for their learning [27]. The structure of the neural network used is shown in the Figure 4.

4.1. Design of ANN-DTC controller

The PI controller has been combined by an ANN artificial neuron network type controller to increase the performance of the ANN-DTC control strategy in terms of speed reference tracking. The neural network that we utilized is a multilayer network with local connections that learns using the back-propagation technique [28]. The structure of the neural network used is shown in the Figure 4. To generate the ANN controller by Matlab/Simulink where we have chosen 64 hidden layers and 03 output layers with activation functions of type 'Tansig' and 'Purelin' respectively [29]. This network weights and biases are updated using a back-propagation technique called the Levenberg-Marquardt (LM) algorithm.

5. SPEED CYCLE PROPOSED FOR THE 4WD ELECTRIC VEHICLE

We recommended a ten-second speed cycle. The cycle speed profile is seen in Figure 5. This trajectory is comprised of seven distinct stages. The first phase involves rolling along a straight road at a speed of 30 km / h; the second phase involves imposing a right turn on the scooter via a set point of the steering angle (δ=25 °); as it is illustrated in Figure 6 the third phase involves rolling along a straight road at the same speed; and the fourth phase

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involves imposing a left turn on the scooter via a steering angle (δ = 15°). The sixth step involves the scooter rolling along a straight road at a speed of 30 kilometers per hour. In the sixth phase, the 3WES accelerates to 50Km / h while it climbs a road inclined at a 10° inclination (slope). Finally, (07) depicts the deceleration phase, with the scooter traveling at a speed of 5Km / h. The road limitations are listed in Table 2.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Time (Sec)</th>
<th>Event information</th>
<th>Scooter speed Km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>0s &lt; t &lt;1.5s</td>
<td>Straight road</td>
<td>30 km/h</td>
</tr>
<tr>
<td>02</td>
<td>1.5s &lt; t &lt;2.5s</td>
<td>Curved road side right</td>
<td>30 km/h</td>
</tr>
<tr>
<td>03</td>
<td>2.5s &lt; t &lt;4s</td>
<td>Straight road</td>
<td>30 km/h</td>
</tr>
<tr>
<td>04</td>
<td>4s &lt; t &lt;5s</td>
<td>Curved road side left</td>
<td>30 km/h</td>
</tr>
<tr>
<td>05</td>
<td>5s &lt; t &lt;6s</td>
<td>Straight road</td>
<td>30 km/h</td>
</tr>
<tr>
<td>06</td>
<td>6s &lt; t &lt;8s</td>
<td>Climbing slope 10%</td>
<td>50 km/h</td>
</tr>
<tr>
<td>07</td>
<td>8s &lt; t &lt;10s</td>
<td>Straight road</td>
<td>5 km/h</td>
</tr>
</tbody>
</table>

The driver has control over the steering angle of the front wheel, while the electronic differential has control over the speeds of the wheels that are really driving the car. Turn phase 2 involves the right driving wheel rotating faster than turn phase 1. The Figure 9 present the variation in wheel speed throughout various phases Figure 9(a) with CDTC, and Figure 9(b) with ANN-DTC, you can see how these patterns play out. A
second left turn (phase 4) is taking place on the scooter, and the electronic differential is doing its thing to help it stay stable as it makes this turn.

The evolution of the electromagnetic torque generated by the three-wheeled electric scooter two propulsion motor (IM) is depicted in Figure 10(a) using the conventional DTC and Figure 10(b) using ANN-DTC control methods. The obtained findings demonstrate the proposed ANN-DTC control excellent dynamic performance in terms of torque response. Additionally, torque ripples are significantly reduced as compared to conventional direct torque control (C-DTC). This improvement is summarized in Table 3.

![Figure 9. Variation in wheel speed throughout various phases (a) with CDTC (b) with ANN-DTC](image)

![Figure 10. Torque response developed by the two motors using (a) conventional DTC (b) ANN-DTC](image)

Table 3. Electromagnetic torque value of each motor during the whole driving cycle

<table>
<thead>
<tr>
<th>Electromagnetic Torque</th>
<th>Phase 01</th>
<th>Phase 02</th>
<th>Phase 03</th>
<th>Phase 04</th>
<th>Phase 05</th>
<th>Phase 06</th>
<th>Phase 07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Rear IM C-DTC</td>
<td>2.62</td>
<td>0.74</td>
<td>2.61</td>
<td>2.72</td>
<td>4.43</td>
<td>11.42</td>
<td>1.72</td>
</tr>
<tr>
<td>ANN-DTC</td>
<td>2.06</td>
<td>1.18</td>
<td>2.04</td>
<td>1.67</td>
<td>3.94</td>
<td>10.72</td>
<td>1.74</td>
</tr>
<tr>
<td>Right Rear IM C-DTC</td>
<td>2.62</td>
<td>3.24</td>
<td>2.61</td>
<td>1.14</td>
<td>4.43</td>
<td>11.42</td>
<td>1.72</td>
</tr>
<tr>
<td>ANN-DTC</td>
<td>2.06</td>
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<td>2.04</td>
<td>2.17</td>
<td>3.94</td>
<td>10.72</td>
<td>1.74</td>
</tr>
</tbody>
</table>

7. CONCLUSION

In this work, a comparative study of two control strategies which are made to improve the dynamics of a three-wheeled electric vehicle 3WES: namely by the classic direct torque control C-DTC and DTC based on the artificial neuron network ANN-DTC, where the switch table and hysteresis regulators have been removed and replaced by artificial neuron network type regulators. Analysis of simulation results show a significant reduction in torque ripple and stator flux, low stator current distortion, thus the dynamic performance of 3WES has been improved. This improvement is clearly visible in the resistive torque responses, aerodynamic torque, distance traveled and SOC of 3WES compared to the conventional C-DTC control method.
REFERENCES


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