

## Impact of sensorless neural direct torque control in a fuel cell traction system

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### ABSTRACT

Due to the reliability and relatively low cost and modest maintenance requirement of the induction machine make it one of the most widely used machines in industrial applications. The speed control is one of many problems in the traction system, researchers went to new paths instead the classical controllers as PI controller, they integrated the artificial intelligent for its yield. The classical DTC is a method of speed control by using speed sensor and PI controller, it achieves a decoupled control of the electromagnetic torque and the stator flux in the stationary frame, besides, the use of speed sensors has several drawbacks such as the fragility and the high cost, for this reason, the specialists went to propose an estimators as Kalman filter. The fuel cell is a new renewable energy, it has many applications in the traction systems as train, bus. This paper presents an improved control using DTC by integrate the neural network strategy without use speed sensor (sensorless control) to reduce overtaking and current ripple and static error in the system because the PI controller has some problems like this; and reduce the cost with use a renewable energy as fuel cell.

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## 1. INTRODUCTION

From the new technology of energy sources is fuel cell because hydrogen cycle is a good environmentally energy cycle and enabled type [1]. The burning of hydrogen and oxygen is an electrochemical combustion, this combustion products the electricity, water, and heat this is the fuel cell principle [2-4]. The high performance of direct torque control strategy (DTC) driving technologies for AC motors is the first factor to be a favorite strategy for a fuel cell traction systems. The pi controller has some problems in its control [5, 6]. The uses of Kalman filters as estimate states based on linear dynamical systems in state space format To avoid the sensor speed problems [7]. This problem led to the research on artificial intelligent controllers designed to solve this problem and improved the strategie results [8]. In this work a proposed direct torque neural network strategy, we suggest to put neural network controller in the place of traditional PI controller that generates the reference torque and cancelate the use of the speed sensor by introducing of Kalman filter, consequently we can release the speed sensor and obtain on the system without overtaking in the speed and more reduction of currents ripple.

**2. FUEL CELL DEVICES**

After World War II the development of fuel cells started. Alkaline fuel cells (AFC) and proton exchange membrane fuel cells (PEMFC) were developed for space programs. In the end 1960s, the world start to do many developments in this way as the development of phosphoric acid fuel cells (PAFC), high temperature molten carbonate (MCFC), and solid oxide fuel cells (SOFC). Fuel cells are classified as power generators because they can operate continuously, or for as long as fuel and oxidant are supplied. The values of the typical operation temperature and efficiency are the main conditions of fuel cells application, Figure 1 presents the fuel cells topology [9-11]. There are many applications of fuel cell and in different domain as train bus gas stations [12, 13].

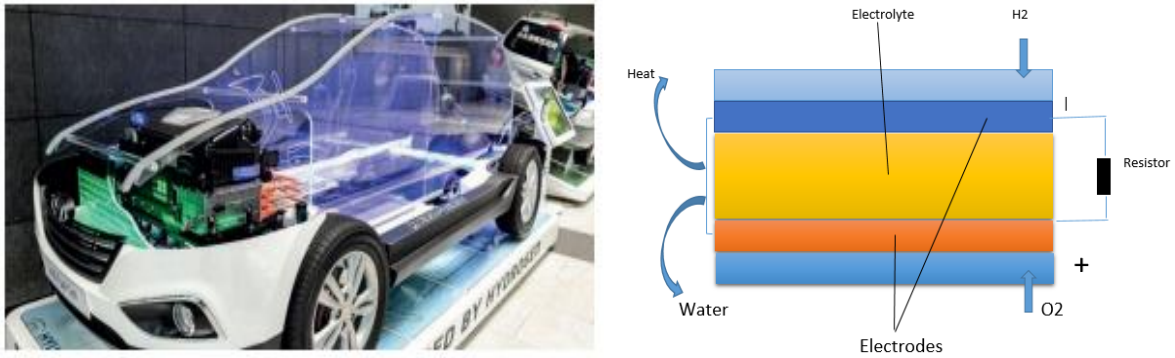


Figure 1. Fuel cell topologies and its application in traction vehicle

**3. THE CLASSICAL DIRECT TORQUE CONTROL DTC**

By using the DTC scheme [14], there are two hysteresis comparators receive the error of the electromagnetic torque and flux signals. The corresponding output variables and the stator flux position sector are used to select the appropriate voltage vector from a switching table that generates pulses to control the inverter power switches [15, 16]. The three phase inverter controlled with six power switches, this switches are the responsible to create the voltage vector  $V_s$ . The Boolean states expression of it is  $S_j (j = a, b, c)$ . Where:  $S_j = 1$  means up switch is closed and down switch is opened, then  $S_j = 0$  means up switch is opened and down switch is closed. The output voltage vector can be calculated by using this three Boolean variables and dc voltage, as (1). The next cycle shows the possible positions of voltage vector  $V_s (S_a, S_b, S_c)$  [17-19] as shown in Figure 2.

$$V_s = \sqrt{\frac{2}{3}} v_{dc} [S_a + S_b e^{j2\pi/3} + S_c e^{j4\pi/3}] \tag{1}$$

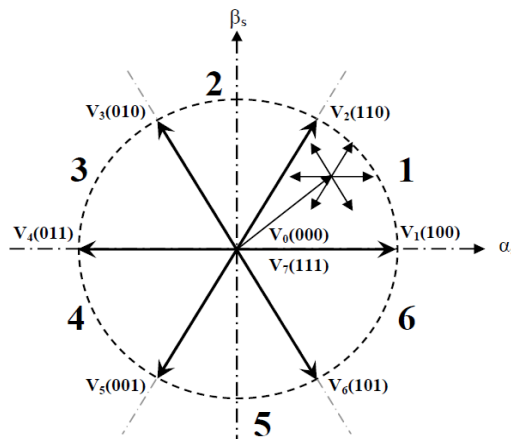


Figure 2. The possible positions voltage  $V_s$

**3.1. Stator flux control**

After modeling the induction machine, the stator flux is estimated by (2).

$$\phi_s = \int (V_s - R_s i_s) dt \tag{2}$$

We consider that  $R_s$  is negligible relative to the voltage  $V_s$ , on a time interval between  $T_k$  and  $T_{k+1}$ , corresponding to a sampling period  $T_e$ , ( $S_a, S_b, S_c$ ) are fixed, we can say:

$$\phi_s(T_{k+1}) = \phi_s(T_k) + V_s \cdot T_e \tag{3}$$

$$\Delta\phi_s = \phi_s(T_{k+1}) - \phi_s(T_k) = V_s \cdot T_e \tag{4}$$

**3.2. Electromagnetic torque control**

Equation (5) shows how to control the value of the torque by the angle between stator and rotor fluxes vectors [20, 21]. The increasing of the load requires an increase in the angle  $\theta_{sr}$  for obtained the acceptable results.

$$C_{em} = p \frac{M}{\sigma L_s L_r} \phi_s \cdot \phi_r \cdot \sin(\theta_{sr}) \tag{5}$$

**3.3. DTC switching table**

look-up table proposed by Takahashi shows that the Boolean output values of the two hysteresis comparators of the flux torque and the angle of the vector (sector) are determine the position vector to choose the appropriate voltage vector to save the reference speed value presented in Table 1 [18-22].

Table 1. DTC switching table

N		1	2	3	4	5	6
$\Delta\phi_s$	$\Delta T_{em}$						
1	1	V <sub>2</sub>	V <sub>3</sub>	V <sub>4</sub>	V <sub>5</sub>	V <sub>6</sub>	V <sub>1</sub>
	0	V <sub>7</sub>	V <sub>0</sub>	V <sub>7</sub>	V <sub>0</sub>	V <sub>7</sub>	V <sub>0</sub>
0	1	V <sub>3</sub>	V <sub>4</sub>	V <sub>5</sub>	V <sub>6</sub>	V <sub>1</sub>	V <sub>2</sub>
	0	V <sub>0</sub>	V <sub>7</sub>	V <sub>0</sub>	V <sub>7</sub>	V <sub>0</sub>	V <sub>7</sub>

**4. KALMAN FILTER AND ITS ALGORITHM**

The simple form and require small computational power are some characteristics of Kalman filter [23], it consists of two stages in its algorithm prediction and update. ‘Correction’, respectively, has the same uses of ‘prediction’ and ‘update’ in different literature [24]. The Kalman filter algorithm as (6)-(11).

Prediction:

$$\hat{x}_k^- = F \hat{x}_{k-1}^+ + B u_{k-1} \tag{6}$$

$$p_k^- = F p_{k-1}^+ F^T + Q \tag{7}$$

Update:

$$\hat{y}_k = z_k - H \hat{x}_k^- \tag{8}$$

$$k_k = p_k^- H^T (R + H p_k^- H^T)^{-1} \tag{9}$$

$$\hat{x}_k^+ = \hat{x}_k^- + k_k \hat{y} \tag{10}$$

$$p_k^+ = (1 - k_k H) p_k^- \tag{11}$$

**5. NEURAL NETWORKS PRINCIPLE**

Artificial neural networks (ANN) is one of many important features of artificial intellegent [25, 26]. The neuron is the basic element of an artificial neural network which has a summer and an activation function [26] as shown in Figure 3 The model of a neuron is given by:

$$y = \phi \left( \sum_{i=1}^N w_i \cdot x_i + b \right) \quad (12)$$

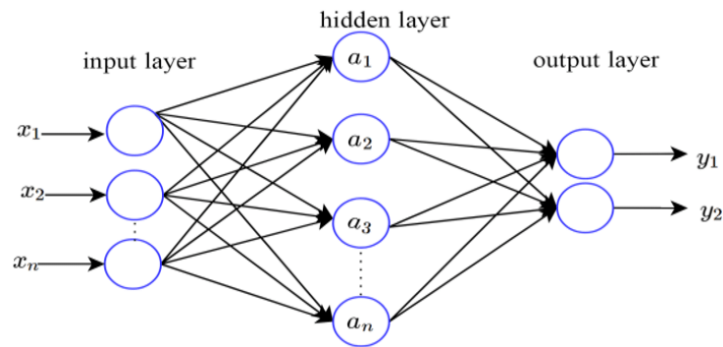


Figure 3. Neural network structure

For ensure best result and fast convergence it must to use the algorithm equation [27]. The main algorithm equations of the neural network as (13), (14).

$$E(k) = \frac{1}{N} \sum_{i=1}^N d_i(k) - y_i(k))^2 \quad (13)$$

$$w_{ji}(k+1) = w_{ji}(k) - \eta \frac{\partial E(k)}{\partial w_{ji}(k)} + \alpha \Delta w_{ji}(k) \quad (14)$$

## 6. NEURAL NETWORK DIRECT TORQUE CONTROL

The basic structure of neural direct torque control (NDTC) method for traction system is presented in Figure 4. The artificial neural network replaces the PI controller; the inputs of neural network controller are the error between the speed reference and the speed from Kalman filter, the derivative error, and electromagnetic torque. The neural network controller output layer has one neuron. This neuron gives the electromagnetic torque reference. The use of Kalman filter for estimate the speed of the traction system to avoid the sensor speed problems. The DC/AC inverter is connected by fuel cell system that receives its impulses from switching table that is connected by two hysteresis and sector flux calculation, in this work there is a comparison between classical DTC based on these PI controller with direct torque neural network based on ANN in the traction system connected by fuel cell source.

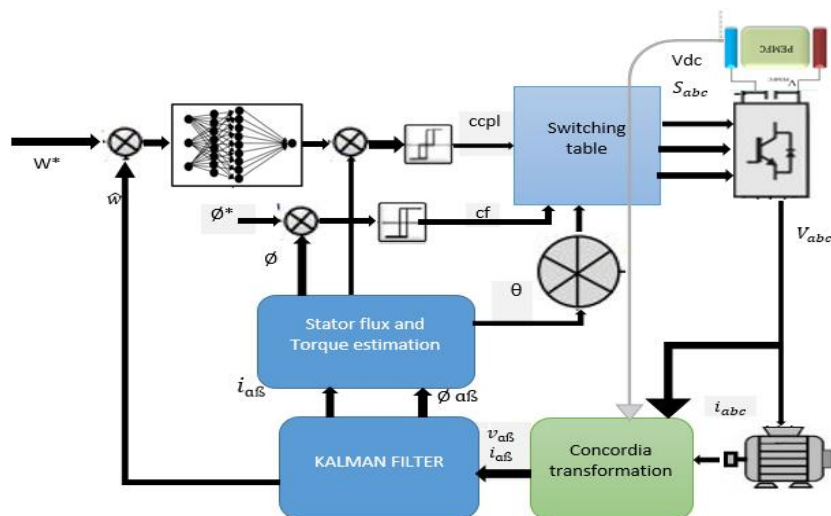


Figure 4. Direct torque neural network control model

**7. RESULTS AND DISCUSSION**

To show the performances of direct torque control with neural networks control we use the MATLAB Simulink to take the simulation results of the NDTC model Figures 5, a comparison between classical DTC, and NDTC without speed sensor (sensor less) and the speed error in Figure 6. Figures 7 and 8 and present current and torque of each control type. The the fuel cell characteristics for obtain 330 V in the input of inverter are mentioned in Figure 9.

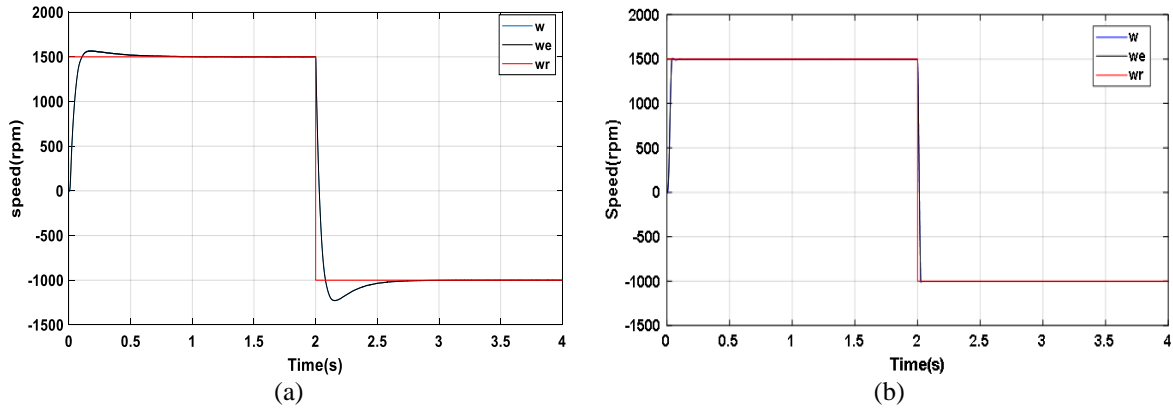


Figure 5. Sensorless speed control performances; (a) DTC, (b) NDTC

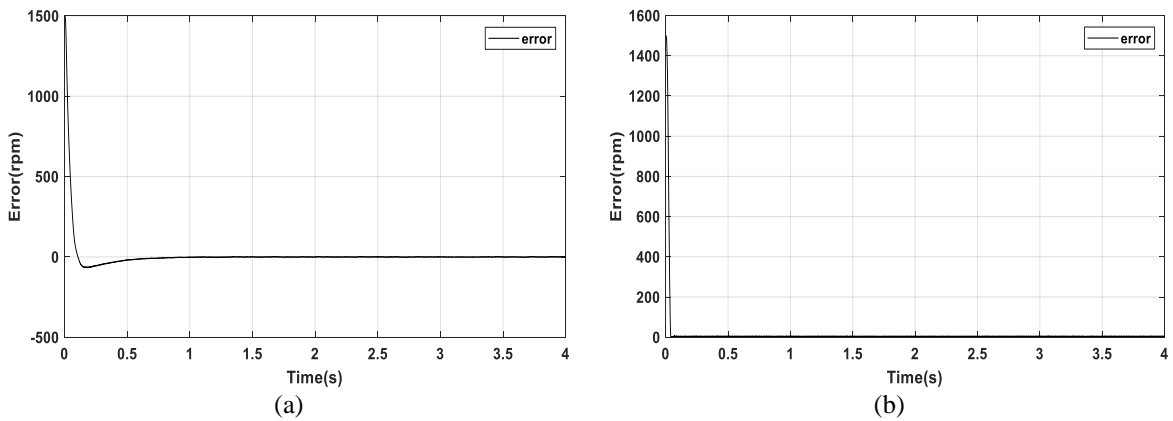


Figure 6. Speed error; (a) DTC, (b) NDTC

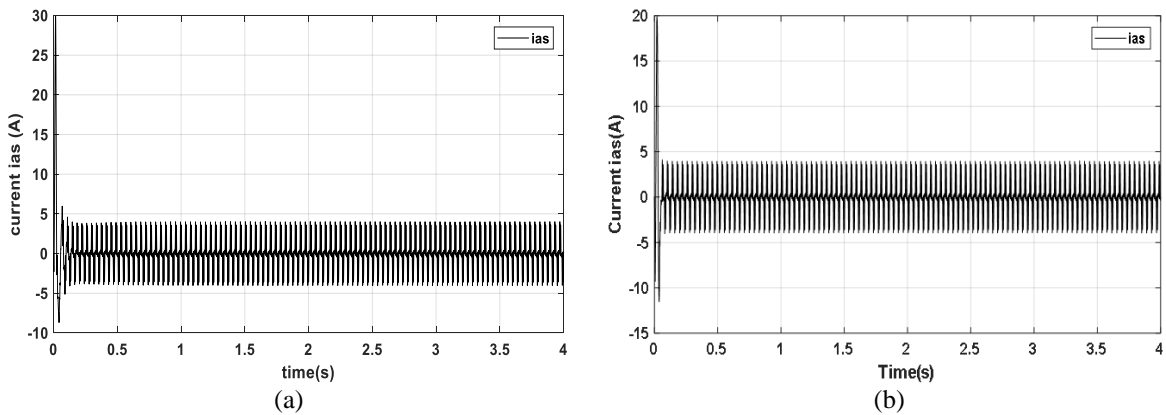


Figure 7. Current of induction motor; (a) DTC, (b) NDTC

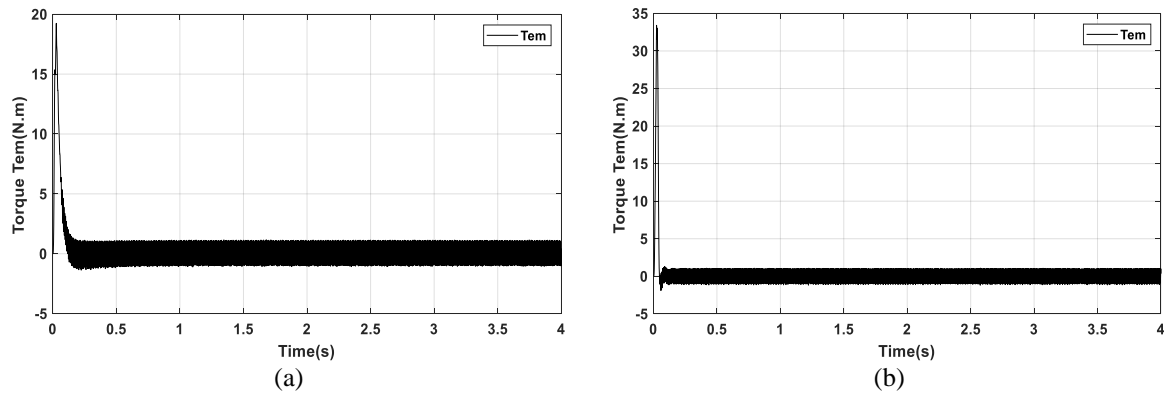


Figure 8. Electromagnetic torque; (a) DTC, (b) NDTC

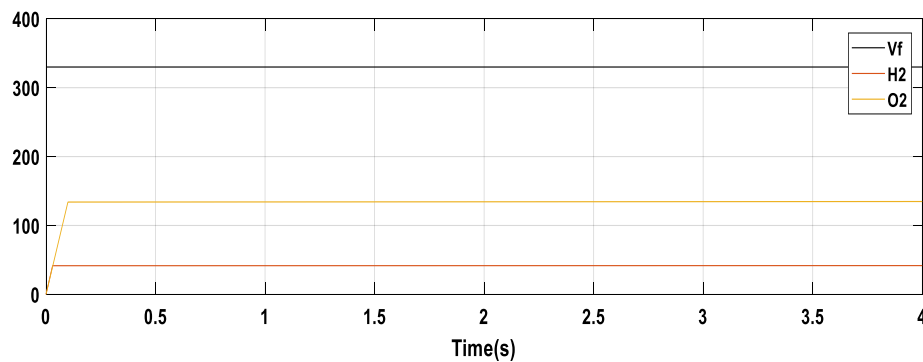


Figure 9. Fuel cell performances

The speed and flux references that used in the simulation are the same. We applied a resisting torque of 2 N.m at 0 sec. The Figure 5 shows the speed results, the speed applied in positive trend between the time of 0 sec and 2 sec is about 1500 rpm, at the time of 2 sec the speed value is reduced to 1000 rpm in the opposite trend for test the system and Kalman filter estimator. The responses time in DTC and NDTC are 0.5 sec, 0.05 sec respectively it means that NDTC has the smallest responses time.

In the current results, the starting current in DTC arrive to 30 A and NDTC has 20 A. In the simulation results of the electromagnetic torque it can notice that the torque's ripples with NDTC direct is reduced compared to classical DTC and the trajectory of torque is established quickly in NDTC. The neural network controller receive the deference. The last simulation results shows the input of PI controller and neural network controller (speed controller) there is visual error in DTC in the first second and invisual in NDTC. All results of simulation were without speed sensor it means that Kalman filter is used in this type of sytem, and it can also notice that it can use feul cell as source of inverter.

## 8. CONCLUSION

The last part of this paper shows the comparison results between classical control and modern one applied on the traction system connected by fuel cell without speed sensor. The best result of the Kalman filter indicates that it can solve the problems of speed sensor in this type of system, after the visual defference between DTC and NDTC, the results show that the direct torque neural network control has better performance than DTC, especially with the advantage of reducing current ripple which can reverse and degrade the functioning of the fuel cell.

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