International Journal of Power Electronics and Drive System (IJPEDS)
Vol.3, No.3, September 2013, pp. 311~320
ISSN: 2088-8694

Neural Network Controllers in Direct Torque Controlled Synchronous Motor

A Sudhakar[1], M Vijaya Kumar[2]
[1]Department of Electrical and Electronics Engineering, SVIT Engineering College, Anantapuram, A.P, India
[2]Department of Electrical Engineering, JNT University, Anantapuram, A.P, India

Article Info

Article history:

Received July 28, 2013
Revised Aug 23, 2013
Accepted Sep 3, 2013

Keyword:

Artificial Neural Network
Proportional Integral controllers
Direct torque control
Permanent Magnet
Synchronous Motor
Torque ripple

ABSTRACT

In recent times, permanent magnet synchronous motors (PMSM) have gained numerous industrial applications, because of simple structure, high efficiency and ease of maintenance. But these motors have a nonlinear mathematical model. To resolve this problem several studies have suggested the application of vector control (VC) and direct torque control (DTC) with soft-computing (SC) techniques. This paper presents neuro direct torque control (NDTC) of PMSM. Hence this paper aims to present a technique to control torque with reduced ripple compared to previous techniques. The outputs of Artificial Neural Network (ANN) controller mechanism is compared with that of classical DTC and the results demonstrate the influence of ANN is improved compared to classical DTC topology. The system is also verified and proved to be operated stably with reduced torque ripple, sudden speed reversals, at low torque and at high torque. The proposed method validity and effectiveness has been verified by computer simulations using Matlab/Simulink®. These results are compared with the ones obtained with a classical DTC using PI speed controller.

Corresponding Author:

A.Sudhakar,
HOD, Department of Electrical and Electronics Engineering,
S.V.I.T Engineering College,
Anantapuram A.P, India.
Email : ambarapu_sudhakar@yahoo.co.in

1. INTRODUCTION

In the past, DC motors were used extensively in areas where variable speed operation was required, since their flux and torque could be controlled easily by the field and armature current. However, DC motors have certain disadvantages, which are due to the existence of the commutator and the brushes, that is, they require periodic maintenance, and they have limited commutation capability under high-speed, high-voltage operational conditions.

These problems can be overcome by the combination of rapid development of semiconductors, microprocessors and control technology of alternative current (AC) motor. Now PMSM has become a leading machine in the industrial applications because it has simple and rugged structure, high maintainability and economy, it is also robust and immune to heavy overloading, etc [1]. Its small dimension compared with DC motors allows PMSM motor to be used widely in industrial applications. Direct torque control method is one of the newest control systems for PMSM based on vector control of electric motors [2]. This method was invented originally for induction motor (IM) by Takahashi [3] and Depenbrock [4] in 1986 and 1988 respectively, and then a lot of improvements over the proposed method have been made by other researchers for PMSM. The DTC of a PMSM motor involves the direct and independent control of the flux linkage and electromagnetic torque, by applying optimum current or voltage switching vectors to the converter.

It is also known that DTC drive is less sensitive to parameters de-tuning (only stator resistor is used to estimate the stator flux) and provides a high dynamic performance than the classical vector control (fastest response of torque and flux).This method allows a decoupled control of flux and torque without using speed or position sensors. This type of command involves nonlinear controller type hysteresis, for both stator flux magnitude and electromagnetic torque, which introduces limitations such as a high and uncontrollable switching frequency [5]-[7]. This controller produces a variable switching frequency and consequently large torque and flux ripples and high current distortion. The DTC is mostly used in the objective to improve the reduction of the undulations or the flux distortion, and to have good dynamic performance. It is essentially based on a localization table which allows selecting the vector to apply to the inverter according to the position of the stator flux vector and of the direct control of the stator flux and the electromagnetic torque. Several studies are planned to decrease the swings on the level of the flux and torque. For that, we developed an intelligent technique to improve the dynamic performances of the DTC of a synchronous machine by a controller based on the artificial neural network in order to lead the error caused by flux and the torque towards an optimal values during a fixed time period. In recent years, much interest is focused on the use of artificial intelligence techniques (fuzzy logic, neural networks, genetic algorithms…) in identification and non linear control systems [8]. This is mainly due to their ability learning and generalization.

In this paper, neural network controllers are implemented in sector selection and switching vector selection scheme, to reduce the torque ripple by regulating the flux and torque errors, are proposed. Direct Torque Control describes the way to control torque, directly based on the electromagnetic state of the machine. DTC can be pertinent to asynchronous machines, permanent magnet machines etc. For a DC machine, field or armature currents are controlled to adjust the speed or torque, but to adjust these parameters for an induction machine, either input frequency and/ or voltage have to be controlled by using PWM, SPWM or SVPWM techniques [9]-[11]. DTC is the first technology to control the motor variables of torque and flux [12]. Because torque and flux are motor parameters that are being directly controlled, there is no need for a modulator, as used in PWM drives, to control the frequency and voltage. A modified DTC scheme that utilizes space vector modulation (SVM)was reported in [13]. Stability problems occur especially in the field weakening range, where a large load angle is necessary to produce a high torque in such systems. The benefit of DTC technology includes exceptional dynamic performance features, many of which are obtained without the need for an encoder or tachometer to monitors shaft position or speed [13, 10]:When compared to the classical DTC scheme, the proposed technique can suppress torque and flux ripples significantly.

The organization of this paper departed as, Section 2 will present the mathematical representation of PMSM and the concept of conventional DTC and Section 3 describes the implementation of DTC-ANN technique. The simulation and experimental results will be presented in Sections 4 and conclusions are stated in Section 5.

2. MATHEMATICAL MODEL OF PMSM AND CONVENTIONAL DTC METHOD

The electrical and mechanical equations of the PMSM in the rotor d-q reference frame can be expressed as:

$$v_d = R_s i_d + \frac{d\psi_d}{dt} - \omega_e \psi_q \quad (1)$$

$$v_q = R_s i_q + \frac{d\psi_q}{dt} - \omega_e \psi_d \quad (2)$$

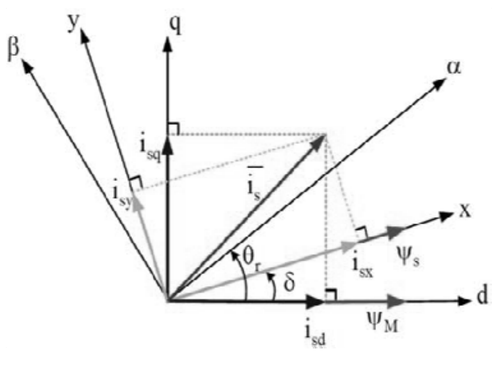


Figure 1. Stator and Rotor Magnetic Fluxes in Various Reference Frames

Where $\psi_d = L_d i_d + \psi_m$, $\psi_q = L_q i_q$ and the stator flux linkage is $\psi_s = \left(\psi_d + \psi_q\right)^2$. It has been shown that the electromagnetic torque in a PMSM can be regulated by controlling the magnitude and angle of the stator flux linkage or load angle δ that is seen in Figure 1. This can be performed by applying the proper output voltage vectors of an inverter to the machine. There are six nonzero voltage vectors and two zero voltage vectors for a three level inverter as depicted in Figure 2.

$$v_s = \frac{2}{3} V_{DC} \left(S_a + S_b e^{j\frac{2\pi}{3}} + S_c e^{j\frac{4\pi}{3}} \right)$$

S_a,S_b and S_c are used to show the state of each leg in the inverter, which is either 0 or 1. They are 0 when the leg is connected to 0 or 1 when it is connected to the DC bus voltage V_{DC} . It has also been proved that the torque dynamics is dependent on the speed of rotation of the stator flux linkage with regard to the magnetic flux linkage. In other words to get a fast torque response one should increase the load angle δ.

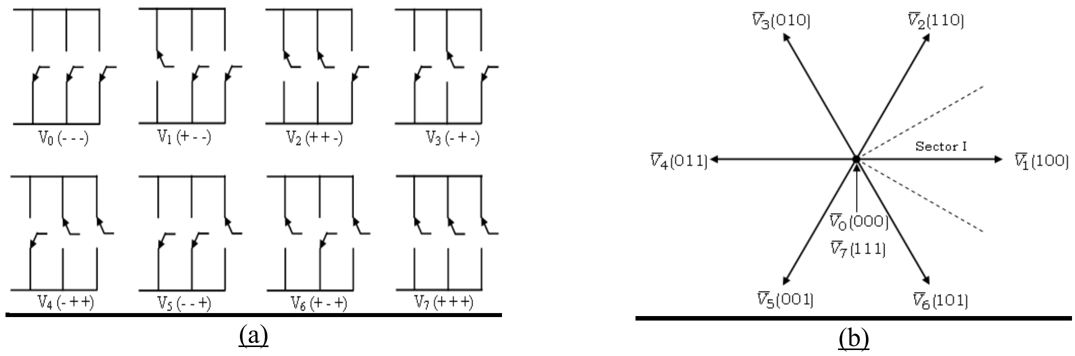


Figure 2. (a) Switching states of 2-level Inverter, (b) Voltage vectors applied to Inverter

After sampling the motor voltages and currents, the stator flux magnitude and machine torque are estimated as:

$$\psi_s = \int \left(v_s - R_s i_s \right) dt \qquad (3)$$

$$T_e = \frac{3}{2} P \left[\psi_D i_Q - \psi_Q i_D \right] \qquad (4)$$

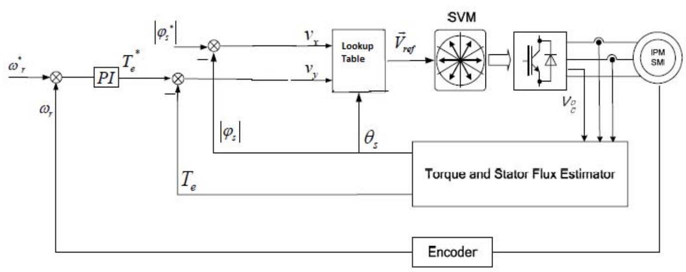


Figure 3. Conventional DTC Applied to PMSM

The D and Q subscripts are used to represent the quantities in the stationary reference frame. Based on the estimated torque and flux errors and the stator flux region the switching table generates the proper switching commands for the inverter.

Stator magnetic flux vector ψ_s and rotor magnetic flux vector ψ_m, can be represented on rotor flux(dq), stator flux(xy) reference system as shown in figure. The angle between the stator and rotor magnetic fluxes δ is the load angle. It is constant for a constant load torque [7], [2], [11].

$$\psi_d = L_d i_d + \psi_m \quad (5)$$

$$\psi_q = L_q i_q \quad (6)$$

$$v_q = R_s i_q + \frac{d}{dt}\psi_q + \omega_r \psi_d \quad (7)$$

$$v_d = R_s i_d + \frac{d}{dt}\psi_d - \omega_r \psi_q \quad (8)$$

$$T_e = \frac{3}{2} p \left(\psi_d i_q - \psi_q i_d\right) \quad (9)$$

$$T_e = \frac{3}{2} p \left[\psi_m i_q - \left(L_q - L_d\right) i_d i_q\right] \quad (10)$$

Where the symbols of parameters are as follows:

ψ_d -D axis stator magnetic flux,
ψ_q -Q axis stator magnetic flux,
ψ_m -Rotor magnetic flux,
L_d -D axis stator leakage inductance,
L_q -Q axis stator leakage inductance,
R_s -Stator winding resistance,
T_e -Electromagnetic torque,
p -pole number.

Using Equation (3) and (4) and Figure 1-2 the expressions (5)-(9) are obtained, and it can be transformed into Equation (10)

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} \cos\delta & -\sin\delta \\ \sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} f_x \\ f_y \end{bmatrix} \quad (11)$$

Here *f* represents the voltage, current and magnetic flux. Using Figure 1;

$$\sin\delta = \frac{\psi_q}{\psi_s} \quad (12)$$

$$\cos\delta = \frac{\psi_d}{\psi_s} \quad (13)$$

The expression ψ_s represents the stator magnetic flux amplitude. When the necessary terms are placed using Figure 1 the following equation is obtained. It is clear that electromagnetic torque is directly proportional to the y-axis component of the stator current. Controlling directly y-axis component of the stator current provides appropriate selection of the voltage switching vectors. Depending on parameters is less is the main advantage of stator current control. It is possible to say that in a practical application the estimation technique shown in Equation (6) requires saturation-dependent inductances. Therefore in Equation (9) direct torque control over the stator current control is more convenient.

The electromagnetic torque can be estimated from the below expression:

$$T_e = \frac{3}{2} P \left(\psi_d i_q - \psi_q i_d\right) \quad (14)$$

Where the load angle can be determined by:

$$\delta = \tan^{-1} \frac{\psi_q}{\psi_d}. \quad (15)$$

The conventional DTC is considered as two position control technique, it depends on the torque and flux levels, so the torque margins permit the torque ripples. The good estimation and fast controller response are used to overcome this problem and the conventional DTC method applied to PMSM is shown in Figure 3. The Figure 3 shows the general structure of the Direct Torque Control DTC of the PMSM in the reference mark dq. The currents isd, isq, Vsd and Vsq are subjected to the transformation of Clark in order to obtain the components isα, isβ, Vsα and Vsβ. Its applied components have a block of estimator of torque and flux as well as the detector of sector. By applying a set level (ψsref = 1.3797wb) to the reference flux and a set square to the reference electromagnetic torque obtained from error between reference speed and actual speed. Changing system parameters is: These values estimated thereafter are compared with values of reference to be included in correctors of hysteresis to 2 and has 3 levels, to introduce its errors into a table of commutation which functions by report sector to generate the impulses of the inverter. This will generate the tension three-phase current thereafter which will be transformed into coordinates d-q, the output voltages Vsd and Vsq are applied in average values at the boundaries of the phases stator of the PMSM. In the performed simulation, certain stator flux and torque references are compared to the values calculated in the driver and errors are sent to the hysteresis comparators. Based on the error between reference torque and estimated torque, error between constant flux value selected and estimated flux value and the load angle δ between rotor flux and stator flux the corresponding voltage vector is selected as input to the inverter to achieve control of torque parameter of PMSM.

3. IMPLEMENTATION OF NEURAL CONTROLLERS IN DTC OF PMSM

A neural network is a machine like human brain with properties of learning capability and generalization. They require a lot of training to understand the model of the plant. The basic property of this network is that it is capable of approximating complicated nonlinear functions Due to its parallel treatment of the formation, it infers emergent properties able to resolve problems qualified in the past as complex [12]-[14], [23]. The structure of the direct neuronal torque control of a permanent magnet synchronous machine is illustrated below in Figure 4.

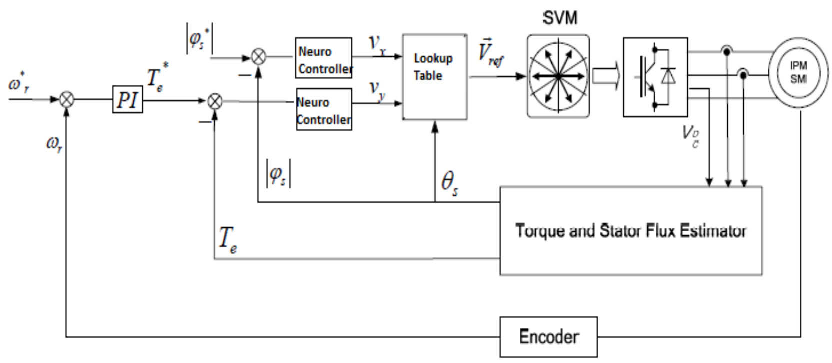


Figure 4. Implementation of Neuro Controllers in DTC of PMSM

The network taken is a 1-5-1 feed forward network with first layer of log sigmoid transfer function, second layer of hyperbolic tangent sigmoid transfer function and third layer of linear transfer function. Training method used was again back-propagation. All the three neural networks were trained to performance 0.001 msec. The back-propagation algorithm is used to train the neural networks. The training function used is Levenberg-Marquardt back propagation, it updates weights and bias values according to Levenberg-Marquardt optimization. As soon as the training procedure is over, the neural network gives almost the same output pattern for the same or nearby values of input. Figure 5-8 represent the design of Neural network architecture. Figure 5 gives the overview of Neural network with respective inputs and outputs. Figure 6 and 7 represents the different weight and bias based on which the relative output will be generated. Figure 8 represents the 1-5-1 design of Neural network. This tendency of the neural networks which approximates the output for new input data is the reason for which they are used as intelligent systems.

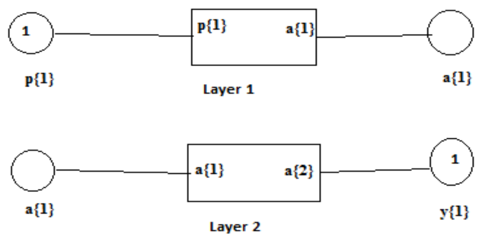


Figure 5. Neural Network Block

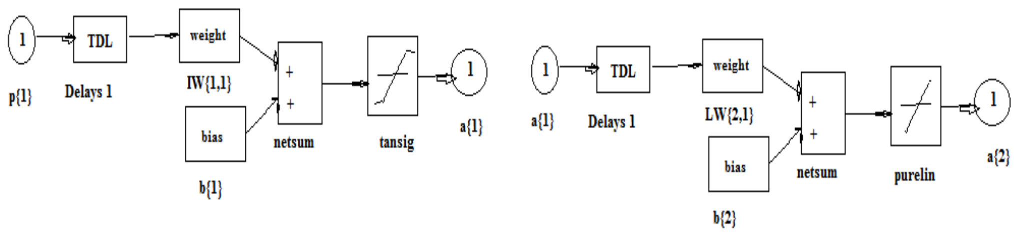


Figure 6. Block Layer 1 and Layer 2

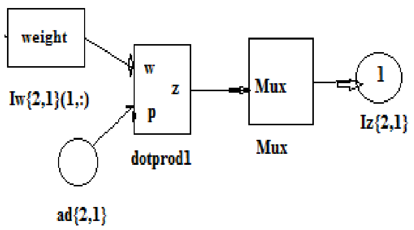


Figure 7. Block Weights

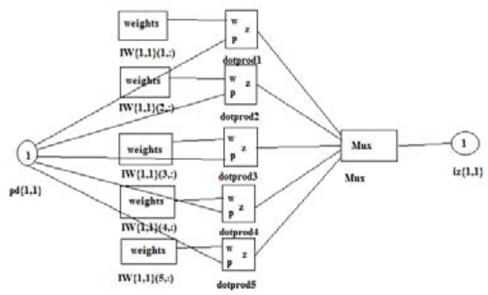


Figure 8. Block Weights

The simulink code for neural network controller with flux error and torque error as inputs and inverter switching states as output is given below.

Simulink code for neuro-controller with flux error as input

```
%P inputs
(E_FLUX)
p=[0 0 0 0 0 0 1 1 1 1 1 1 0 0 0 0 0 0 1 1 1 1 1 1];
% vector output of state
Sa,Sb,Sc.
t=[0 1 0 1 0 1 0 0 0 1 1 1 1 0 1 0 1 0 1 0 0 0 1 1;0
1 0 1 0 1 1 1 0 0 0 1 1 0 1 0 1 0 1 1 1 0 0 0;0 1 0 1
0 1 0 1 1 1 0 0 1 0 1 0 1 0 0 0 1 1 1 0];
net10 = newff([0 1],[10 3],{'tansig' 'purelin'});
net10.trainParam.epochs = 1000;
net10.trainParam.goal=0;
net10 = train(net10,p,t);
Y = sim(net10,p); e=t-Y; plot(p,t,p,Y,'o')
```

Simulink code for neuro-controller with torque error as input

```
%P inputs
(E_TORQUE)
p=[0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1];
% vector output of state
Sa,Sb,Sc.
t=[0 1 0 1 0 1 0 0 0 1 1 1 1 0 1 0 1 0 1 0 0 0 1 1;0
1 0 1 0 1 1 1 0 0 0 1 1 0 1 0 1 0 1 1 1 0 0 0;0 1 0 1
0 1 0 1 1 1 0 0 1 0 1 0 1 0 0 0 1 1 1 0];
net10 = newff([0 1],[10 3],{'tansig' 'purelin'});
net10.trainParam.epochs = 1000;
net10.trainParam.goal=0;
net10 = train(net10,p,t);
Y = sim(net10,p); e=t-Y; plot(p,t,p,Y,'o')
```

The neuro controllers implemented in DTC of PMSM in Figure 4 considers the error between constant flux value and estimated flux, error between reference torque and estimated torque as inputs individually, which play a key role along with load angle δ in the selection of switching state of inverter in DTC of PMSM.

4. RESULTS AND DISCUSSION

Simulation results for a DTC system when controlling the permanent magnet synchronous machine for following parameters:

Table 1. PMSM Parameters

Parameter	Values
Max voltage	280
Speed	150 rad/sec
Load Torque	±2 Nm
Stator resistance Rs	19.4 Ω
Number of poles p	4
d-axis inductance Lsd	388.5mH
q-axis inductance Lsq	475.5mH
Moment of inertia J	0.00129

Simulations were performed to show the performances of the technique used in this section and based on neural controller for the control of the PMSM. Figure 9 and 10 represent the stator flux locus for conventional and Neural controllers based DTC methods. Comparatively the stator flux ripple in Figure 10 is reduced compared to conventional DTC method in Figure 9. In Figure 11 and Figure 12 no-load starting transients in Conventional and Neural controllers based DTC methods are represented. The torque ripple and stator current Total Harmonic Distortion (THD)% value in steady state for conventional and proposed methods is represented in Figure 13 and Figure 14. The torque ripple content in proposed method is reduced compared to conventional DTC method. The THD values obtained for stator currents meet the IEEE 519 standards. The THD % value of proposed method is reduced compared to conventional DTC method. The transients during speed reversal for conventional and proposed DTC methods are presented in Figure 15 and Figure 16. The load torque 2N.m is applied at 0.7 second removed at 1.4 second. The parameters responses in conventional and proposed methods are represented in Figure 17 and Figure 18.The simulation results shows that the stator current ripples with direct torque neural networks control in steady state is significantly reduced compared to classical DTC and illustrates the response of stator flux magnitude of the neural network DTC. The stator flux of the DTC_ANN has the fast response time in transient state.

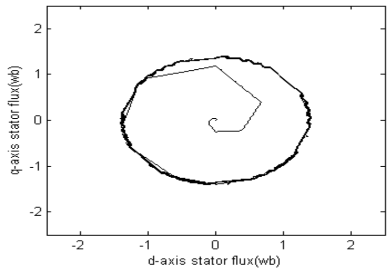


Figure 9. Conventional DTC: Locus of Stator Flux

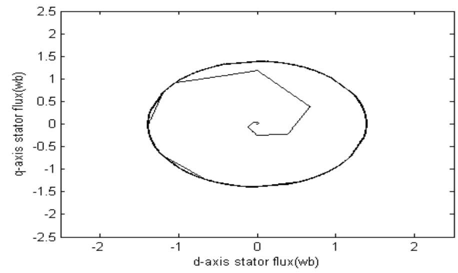


Figure 10. Proposed DTC: Locus of Stator Flux

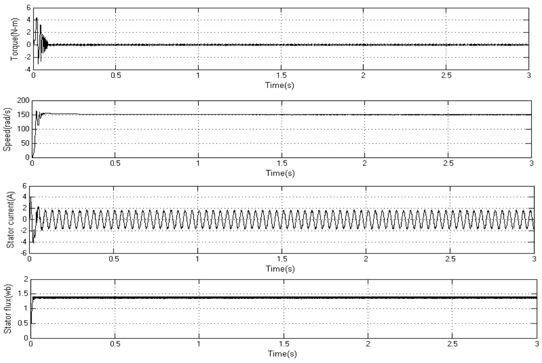


Figure 11. Conventional DTC: No Load Starting Transients

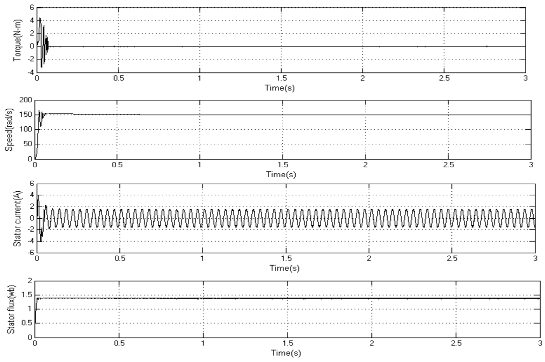
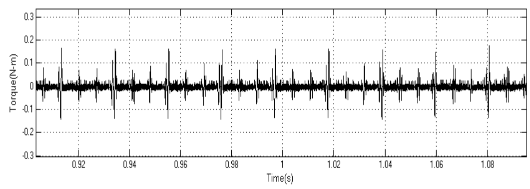
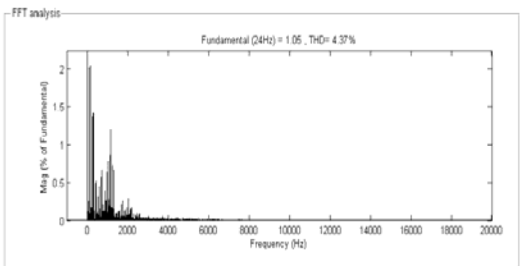
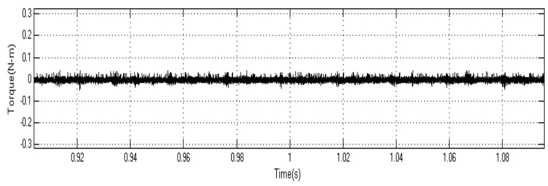


Figure 12. Proposed DTC: No Load Starting Transients







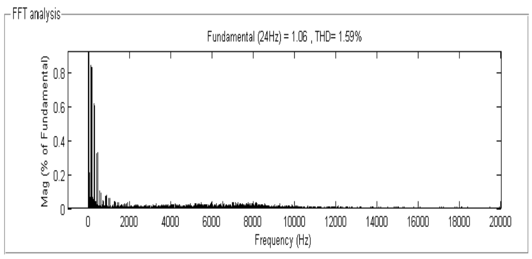


Figure 13. Conventional DTC: Torque Ripple and Stator Current

Figure 14. Proposed DTC: Torque Ripple and Stator Current

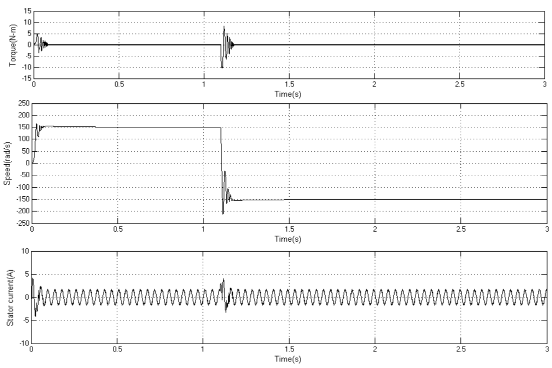


Figure 15. Conventional DTC: Transients during Speed Reversal

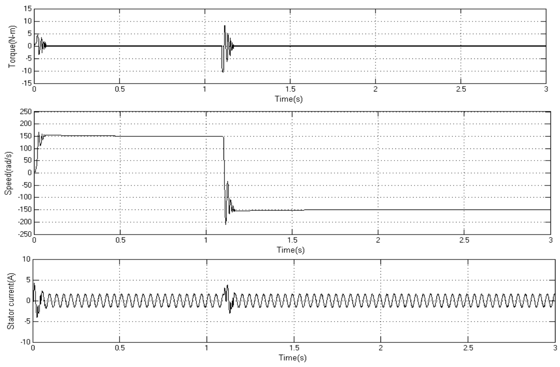


Figure 16. Proposed DTC: Transients during Speed Reversal

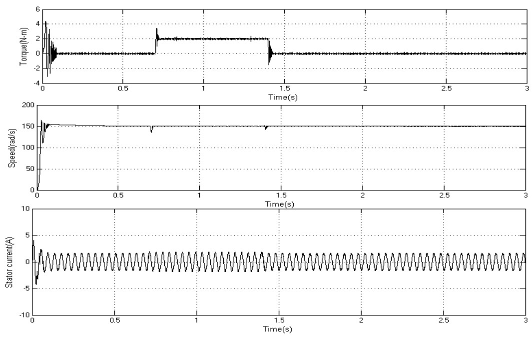


Figure 17. Conventional DTC: Load Torque of 2 Nm Applied at 0.7 sec and Removed at 1.4 sec

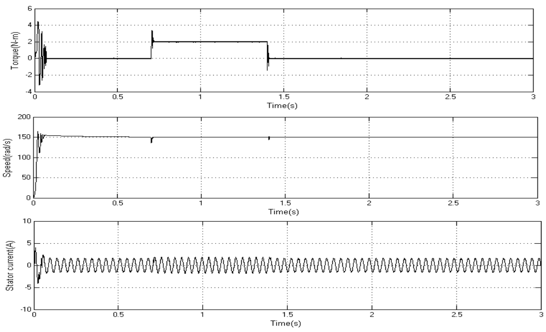


Figure 18. Proposed DTC: Load Torque of 2 Nm Applied at 0.7 sec and Removed at 1.4 sec

From Figure 13 and Figure 14 for conventional and proposed DTC methods the torque ripple (peak-peak) and stator current THD values are represented in Table 2.

Table 2. Comparison of Conventional and Neural Controller based DTC Methods

Method	Torque ripple	% THD value
Conventional DTC method	35.2%	4.37%
Neural controller based DTC method	7.6%	1.59%

5. CONCLUSION

The Direct Torque Control (DTC) is an important alternative method for the PMSM motor drive, with its high performance and simplicity. The DTC applied to PMSM machine fed by a 3-level inverter presents good performance and undulations reduction. In this case, intelligent techniques were developed in order to replace the conventional DTC topology.

In this paper, neural network controllers are proposed for DTC. The proposed method gives efficient response with reduced torque ripple and smoother stator flux trajectory. From the simulation results, it can be observed that the at various operating conditions like no-load starting transients, sudden speed reversals and application of removal of load torque at specified time instants. The stator current THD% value at steady state is improved by implementing Neural network controllers in DTC of PMSM. The performance of the neural network DTC scheme shows the stability and learning capability of neural networks, the proposed method can be considered as better technique.

REFERENCES

[1] Peter Vas. Sensorless Vector and Direct Torque Control. *Monographs in Electrical and Electronic Engineering*. Oxford University Press. 1998; 42.

[2] NP Quang, JA Dittrich. Vector Control of Three-Phase AC Machines. *Power Systems, Springer*. 2008: 1612-1287.
[3] Hany M Hasanien. Torque ripple minimization of permanent magnet synchronous motor using digital observer controller. *Energy Conversion and Management*. 2010; 51: 98-104.
[4] Suman Maiti, Chandan Chakraborty, Sabyasachi Sengupta. Simulation studies on model reference adaptive controller based speed estimation technique for the vector controlled permanent magnet synchronous motor drive. *Simulation Modelling Practice and Theory.* 2009; 17: 585-596.
[5] B Bossoufi, M Karim, S Ionita, A Lagrioui. Performance Analysis of Direct Torque Control (DTC) for Synchronous Machine Permanent Magnet (PMSM). *Proc. IEEE-SIITME' Pitesti, Romania.* 2010: 275-280.
[6] R Kumar, RA Gupta, SV Bhangale, H Gothwal. Artificial neural network based direct torque control of induction motor drives. *IETECH Journal of Electrical Analysis, IETECH Publications.* 2008; 2(3): 159- 165.
[7] R Toufouti, S Meziane, H Benalla. Direct torque control for induction motor using intelligent techniques. *Journal of Theoretical and Applied Information Technology.* 2007; 35-44.
[8] B Bossoufi, M Karim, S Ionita, A Lagrioui, G Iana. Matlab & Simulink Simulation with FPGA-Based Implementation Sliding Mode Control of a Permanent Magnet Synchronous Machine Drive. *WSEAS transactions on systems and control*. 2011; 3(6): 92-103.
[9] G Foo, S Sayeef, MF Rahman. Wide Speed Sensorless SVM Direct Torque Controlled Interior Permanent Magnet Synchronous Motor Drive. *IEEE Transactions on Industrial Applications.* 2008; 1439-1444.
[10] TB Reddy, BK Reddy, J Amarnath, DS Rayudu, MdH Khan. Sensorless Direct Torque Control of Induction Motor based on Hybrid Space Vector Pulsewidth Modulation to Reduce Ripples and Switching Losses – A Variable Structure Controller Approach. *IEEE Power India Conference*. 2006.
[11] GS Buja, MP Kazmierkowski. Direct Torque Control of PWM Inverter-Fed AC Motors – A survey. *IEEE Transactions on Industrial Applications.* 2004; 51: 744–757.
[12] L Tang, L Zhong, MF Rahman, YH. A Novel Direct Torque Control for Interior Permanent Magnet Synchronous Machine Drive System with Low Ripple in Flux and Torque and Fixed Switching Frequency. *IEEE Trans. Power Electro.* 2004; 19: 346-354.
[13] KL Shi, TF Chan, YK Wong, SL Ho. Estimation of an Induction Motor Drive Using an Optimized Extended Kalman Filter. *IEEE Transaction on Industrial Electronics*. 2002; 49(1).
[14] DV Naga Ananth. Artificial Neural Network Based Direct Torque Control for Variable Speed Wind Turbine Driven Induction Generator. *International Journal of Computer and Electrical Engineering*. 2011; 3(6): 880-889.
[15] Badre Bossoufi, Mohammed Karim, Silviu Ionita, Ahmed Lagrioui. DTC Control Based Artificial Neural Network For High Performance PMSM Drive. *Journal of Theoretical and Applied Information Technology.* 2011; 33(2): 165-176.
[16] Ahmed A Mahfouz. IntelligenT DTC For PMSM Drive Using Anfis Technique. *International Journal of Engineering Science and Technology (IJEST).* 2012; 4(3): 1208-1222.
[17] A El Janati El Idrissi, N Zahid M Jedra. Neuro Direct Torque Control of Permanent Magnet Synchronous Motor with Genetic Algorithm Speed Controller. *Journal of Theoretical and Applied Information Technology.* 2012; 35(1): 1-6.

BIOGRAPHIES OF AUTHORS

A. Sudhakar is currently working as Assistant Professor/HOD in Electrical and Electronics Engineering Department, SVIT College of Engineering and Technology, Anantapuram,A.P, India. He graduated from Intell Engineering College, Anantapur, A.P, India in 2004. He obtained M.Tech degree from Jawaharlal Nehru Technological University, Anantapur,A.P, India. in 2007. He is pursuing Doctoral degree from JNTU, Anantapuram, A.P, India.His research area include Power Electronics and Electrical Drives. He has published Research papers in various National and International journals.

Dr. M. Vijaya Kumar is currently working as a Professor in Electrical and Electronics Engineering Department, JNT University, Anantapuram,A.P, India. He is rendering services as Director of Foreign Affairs and Alumni for JNTU Anantapuram. He graduated from NBKR Institute of Science and Technology, Vidyanagar, A.P. India in 1988. He obtained M.Tech degree from Regional Engineering College, Warangal, India in 1990. He received Doctoral degree from JNTUniversity, Hyderabad, India in 2000. He has published over150 research papers. He received two research awards from the Institution of Engineers (India). His areas of interests include Electrical Machines, Electrical Drives, Microprocessors and Instrumentation.