CHAPTER 5

GENETIC NEURO BASED DIRECT TORQUE CONTROL

5.1 INTRODUCTION

In the present scenario, the combination of intelligent control with adaptive and robust control appears to be the most promising research accomplishment in the control area of drive. Artificial neural network is an important data mimic tool used for classification and clustering. Sahoo et al (2005) developed the iterative control algorithm for indirect control of torque in switched reluctance motor. It is an attempt to build a machine that will mimic brain activities and be able to learn. Kalaivani et al. (2013) discussed the speed control of switched reluctance motor along with the torque reduction using non dominated sorting genetic algorithm. The architecture of a simple neural network is composed of three layers, namely input layer, hidden layer and the output layer. Each layer has a number of nodes and the nodes are interconnected to each other. There is some weight usually associated with every connection. Input layer represents the raw information that is fed into the network.

Every single input to the network is duplicated and sent down to the nodes in hidden layer. Hidden layer receives the data from the input layer and modifies them by using some weight value and then this new value is sent to the output layer. The data value will also be modified by the weight from the connection between the hidden and the output layer. Different types of
algorithm are used to train the neural network which will improve the performance of the neural net by reducing its error along its gradient. The error is expressed by the root-mean-square error. The error is the half sum of the geometric averages of the difference between the projected target and the actual output vector over all patterns. One major limitation or the drawback with the neural network in the non linear control is the accuracy of the output which depends on the updating of the weight at each layer and on the training process. This limitation in control can be overcome by integrating Genetic Algorithm with the neural network for improving the performance of the drive.

The major steps involved in genetic algorithm optimization are the generation of population of solution, finding the objective functions and fitness function. GAs can be viewed as trying to maximize the fitness function by evaluating several solution vectors. The purpose of these operators is to create new solution vectors by selection, combination or alteration of the current solution vectors that have shown good tempo ray solutions. The new population is further evaluated and tested till termination. In this chapter the proposed controller is implemented by the integration of neural network with the direct torque control (DTC) and optimized by using GA for SRM drive.

5.2 GENETIC NEURO ON TORQUE RIPPLE REDUCTION

The concept of GANN is the training of neural network by the genetic algorithm for improving the performance of the machine by means of reducing the torque ripple. Neural network has the inherent property of identification. In this control the error torque is fed as the input to the neural network controller. In this network supervised learning algorithm is utilized for training the neural network. Due to considerable non-linearity in the
torque characteristics, and the extensive requirement for lower torque ripple, good dynamic performance and cost sensitivity of SRM, a feed-forward Back Propagation Neural Network (BPNN) based Direct torque control is proposed to minimize the torque ripple at different loads making it simple, easy to implement and fast dynamics. By splitting the training data into several contiguous sets and designing a bank of two-hidden-layer neural network controllers for the whole torque range, the appropriate switching profile to reduce the torque ripple is obtained. Computed results show that the proposed scheme can reduce the torque ripple and provide good dynamic performance with respect to changes in the torque commands. The genetic algorithm is used to determine the weights and the threshold values in the neural network.

The three main operators for implementing GA are fitness evaluation, selector and breeding. The population size depends on the nature of the problem, but typically contains several hundreds or thousands of possible solutions. Often, the initial population is generated randomly, allowing the entire range of possible solutions. The proper selection of population, crossover and mutation rate will determine the weight and the threshold value. These optimized values are summed with the processing data resulting in the reduction of torque error. The reduced torque error along with flux error and sector is used to select the proper voltage vectors which in turn reduces the torque ripple.

5.3 MODELING OF GENETIC NEURO CONTROLLER

The proposed Genetic Neuro controller architecture shown in Figure 5.1 consist of one input layer, one output layer and two hidden layers. As the single hidden layer is not sufficient to determine the stability of the nonlinear system, two hidden layers are preferred. The torque error is the
input that is fed to the input layer. The weights that are optimized by the genetic algorithm are summed with the data and fed as the input to the first hidden layer. The output from the first hidden layer is again added with the weight and is fed as the input to the second hidden layer. The output of the hidden layer is fed as the input to the output layer after the summation of weights with the hidden layer data. The genetic algorithm is used to optimize or update the weights and the threshold values of the neural network.

The proposed controller is modeled with the population size of 50, Crossover probability (c) is set as 0.8, Mutation rate (w) is set as 0.09 and the $R_1$ and $R_2$ are the variable used in the objective and fitness function. The number of data used for testing and training the network is selected as 100. The feed forward back propagation algorithm is used to train the network. The learning rate is selected as 0.45 as the network structure is very simple in nature. Setting the right training rate could be difficult, if the learning rate is too small or if the algorithm takes longer time to converge. Similarly choosing a large learning rate could have opposite effect and the algorithm could diverge.

Initially, the bias is taken as 1 and the values are added along with the optimized weights which in turn reduce the error in the output of the network which is the torque error. The network provides its best performance at 11th epoch with the value of 3.986e-009 which is very accurate and the error is termed to be zero. The gradient and the Mu value at the 11th epoch are 1.214e-008 and 1e-008. Here the error is reduced at the early iteration which proves that the selection of voltage vector from the vector table is precise and it results in the reduction of torque ripple over a wide range of speed. As the better performance is obtained at the earlier iteration the computational time is also improved.
The threshold and the weight are normally represented as \( th \) and \( W \). The genetic algorithm used for training the neural network is implemented by mentioning the total number of thresholds and weights of the neural network are packed in \( n \)-dimensional vector ‘\( M \)’ which is given by the Equation (5.1).

\[
M = [th_1w_{01}, th_2w_{11}, \ldots \ldots \ldots ,th_{16}w_{221}] = [m_1,m_2,\ldots,m_{16}]
\]  

(5.1)

5.4 GENETIC NEURO BASED DIRECT TORQUE CONTROL

Direct torque control is an optimized AC variable frequency drive control principle where converter switching angle directly converts the motor variable, namely torque and flux. The block diagram of the proposed controller based DTC depicts the same as classical DTC. The only difference is that the hysteresis torque controller is replaced by the Genetic Neuro controller. In this proposed technique the actual flux and the torque are estimated from the stator voltage and the resistance. The speed error is fed into the conventional PI controller whose gain values \( K_p \) and \( K_i \) are maintained at 0.1 and 0.01 respectively. The speed error is converted into
reference torque by the PI controller. The reference torque is compared with the actual torque that is measured and the resultant error is fed as input to the proposed controller.

The proposed controller consists of one input layer, one output layer and two hidden layers. As the single hidden layer is not sufficient to determine the stability of the nonlinear system, two hidden layers are preferred. The weights that are optimized by the genetic algorithm are summed with the torque error data and fed as the input to the first hidden layer. The output from the first hidden layer is again added with the weight and is fed as the input to the second hidden layer. The output of the hidden layer is fed as the input to the output layer after the summation of weights with the hidden layer data. The genetic algorithm is used to optimize or update the weights and the threshold values of the neural network.

Table 5.1  Genetic Neuro based Switching Voltage Vector

<table>
<thead>
<tr>
<th>Controller</th>
<th>Voltage Vector Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ</td>
<td>T</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>U6</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>U7</td>
</tr>
</tbody>
</table>

The output from the genetic neuro controller is the reduced torque error. The selection of voltage switching vector for the converter is depicted in Table 5.1. U1, U2, U3, U4, U5, U6, U7 and U8 are termed as active voltage vectors and U0 and U9 are called as Null Vectors. Based on the selection of
the eight switching vectors the power converter switched is fired on and on which in turn reduces the torque and the flux error in the switched reluctance motor drive.

The selection of appropriate voltage vectors results in the proper sequence of turning on and off the power electronic converters resulting in proper excitation of the stator and the rotor poles. The proper excitation between the aligned and the unaligned inductance minimizes the torque ripple and also improve the motor response over a wide speed range both in the static and dynamic condition.

5.5 GANN BASED DTC RESULTS

The simulation is carried out in MATLAB/Simulink environment. The four phase 8/6 switched reluctance motor with the power output of 1.5kW is considered for testing purpose. The aligned and unaligned inductances are made as 10mH and 49mH respectively. The rated speed of the drive is set as 3800rpm, rated torque is calculated as 4Nm and the rated current 8A/phase is considered for the drive. The simulation is carried out both in the static mode as well as in the dynamic mode over a wide speed range.

Initially, the motor speed is set at rated speed and the load torque is varied based on which the torque ripple is calculated. Similarly, the test is carried out with 50% and 25% of the rated speed with reference to the variation in the rated load torque. Here the bandwidth of the hysteresis controller is maintained as -1 to 1. The performance of the proposed controller both in static and dynamic condition are shown in the following Figures.
1. **Performance at rated load Condition**

The SRM drive is initially stimulated with rated load torque, say 4Nm over a wide speed range. The torque and current response are observed and tabulated to know the efficacy of the drive under various operating range of speed. The performance characteristics of the SRM drive are observed on the respective scopes.

The drive is initially tested under the rated load condition by setting the reference speed as the rated one. The corresponding torque and current response are shown in Figure 5.2. For clarity over the responses, the time scale variation for 4 phase currents and total torque is taken as 0.71 –0.76 second. From the curve, it is observed that a maximum current of 8A is reached during the rated condition.

![Figure 5.32](image-url)  
**Figure 5.32**  Current and Torque response at rated load condition
The torque error is minimized by the proposed controller which in turn selects the proper switching vector which results in reduction of torque ripple as shown in the above mentioned figure. The figure is further enlarged to specify the variation of the torque ripple accurately and is shown in Figure 5.3.

![Figure 5.3 Torque ripple at rated torque](image)

(a) Rated speed (b) half rated speed (c) 10% of rated speed

The response curve (a) shown above states that the torque varies with a maximum value ($T_{max}$) of 4.05Nm and a minimum value ($T_{min}$) of 3.98Nm and having the average torque ($T_{avg}$) of 4.01Nm reaches at 0.03sec. The torque output and the torque ripple in percentage can be calculated as 1.7%.

Torque response curve (b) depicts above shows that the torque output ($T_{out}$) reaches the rated torque in 0.03 s and, after that, the output torque varies between a maximum torque ($T_{max}$) of 4.07 Nm and a minimum torque ($T_{min}$) of 3.97Nm. The average torque output ($T_{avg}$) has been found to be 4.03 Nm. The torque output in ripple is calculated in percentage as 2.5%.
The torque curve (c) mentioned above reveals that the torque output ($T_{out}$) reaches the rated torque in 0.03s and after that, the output torque varies between a maximum torque ($T_{max}$) of 4.09 Nm and a minimum torque ($T_{min}$) of 3.96Nm. The average torque output ($T_{avg}$) has been found to be 4.0 Nm. The percentage torque ripple is calculated as 3.3%.

2. **Performance at 75% of the rated Load Torque**

The performance characteristics of the SRM drive are observed on the respective output terminals. The drive is tested with 75% of the rated load torque keeping the speed constant at the rated condition.

The corresponding current and torque response are shown in Figure 5.4. From the curve, it is observed that maximum phase current of 6A is reached during the specified condition.

![Figure 5.4 Phase Current and torque response at 75% of the rated load with rated speed](image-url)
The above shown torque response curve is enlarged to show the accurate variation of torque under specified load condition with respect to wide variation of speed. The variation is observed and shown in Figure 5.5.

![Torque response curves](image)

**Figure 5.5  Torque response at 75% of the rated load torque**

(a) Rated speed (b) half rated speed (c) 10% of rated speed

The curve (a) depicts above shows that the torque output \(T_{out}\) reaches the 75% rated torque in 0.03 s and, after that, the output torque varies between a maximum torque \(T_{max}\) of 3.03 Nm and a minimum torque \(T_{min}\) of 2.98Nm. The average torque output \(T_{avg}\) has been found to be 3.0 Nm. The torque ripple output is calculated in percentage as 1.6%. Torque response curve (b) specified above reveals that the torque output \(T_{out}\) reaches the 75% rated torque in 0.03 s and, after that, the output torque varies between a maximum torque \(T_{max}\) of 3.04 Nm and a minimum torque \(T_{min}\) of 2.97Nm.

The average torque output \(T_{avg}\) has been found to be 3.0 Nm. The ripple torque output is calculated as 2.3%. The torque output curve (c) shown above states that the torque output \(T_{out}\) reaches the 75% rated torque in 0.03 s and, after that, the output torque varies between a maximum torque \(T_{max}\) of
3.045 Nm and a minimum torque ($T_{\text{min}}$) of 2.955Nm. The average torque output ($T_{\text{avg}}$) has been found to be 3.01 Nm. The torque output in terms of ripple is calculated in percentage as 2.9%.

3. **Performance at 50% of the rated Load Torque**

The characteristics performance of the SRM drive is observed on the respective scopes. The torque, speed and current response are observed and tabulated to know the effectiveness of the controller. The drive is simulated with 50% of the rated load condition keeping the speed at the rated condition. The corresponding torque and current response is shown in Figure 5.6. From the curve it is observed that maximum current of 3A is reached during the rated condition.

![Figure 5.6 Current and Torque response at 50% of the load torque with rated speed](image)
The torque response curve is enlarged to show the accurate variation of torque under specified rated load condition with respect to wide range of speed. The variation is observed and shown in Figure 5.7.

![Figure 5.7 Torque response at 50% of the rated load torque](image)

(a) Rated speed (b) half rated speed (c) 10% of rated speed

The torque output curve (a) specified above shows that the torque output ($T_{out}$) reaches the 50% rated torque in 0.03 s and, after that, the output torque varies between a maximum torque ($T_{max}$) of 2.015 Nm and a minimum torque ($T_{min}$) of 1.985Nm. The average torque output ($T_{avg}$) has been found to be 2.00 Nm. The torque ripple output in percentage is calculated as 1.5%.

The response curve (b) depicts above defines that the torque output ($T_{out}$) reaches the 50% rated torque in 0.03 s and, after that, the output torque varies between a maximum torque ($T_{max}$) of 2.025 Nm and a minimum torque ($T_{min}$) of 1.98Nm. The average torque output ($T_{avg}$) has been found to be 2.00 Nm. The torque ripple output is calculated in terms of percentage as 2.2.
The Torque ripple curve (c) portrayed above states that the torque output ($T_{out}$) reaches the 50% rated torque in 0.03 s and, after that, the output torque varies between a maximum torque ($T_{\text{max}}$) of 2.025 Nm and a minimum torque ($T_{\text{min}}$) of 1.975 Nm. The average torque output ($T_{\text{avg}}$) has been found to be 2.01 Nm. The torque output in terms of ripple is calculated as 2.48%.

4. **Performance at 25% of the rated load torque**

The SRM dive is stimulated with 25% load torque and at different rated speed. The torque and current response are observed and tabulated to know the efficacy of the proposed controller. The drive is initially tested with 25% of the rated load condition keeping the speed at the rated condition.

![Figure 5.8](image.png)

**Figure 5.8** Current and torque profile for 25% of the load torque at rated speed
The corresponding torque and current response is shown in Figure 5.8. From the curve it is observed that maximum current of 2A is reached during the rated condition. The above shown torque response curve is made clear to show the accurate variation of torque under 25% of the rated load condition with respect to different speed condition. The variation is observed and shown in Figure 5.9.

The response curve (a) shown above defines that the torque output \((T_{\text{out}})\) reaches the specified rated torque in 0.03 s and, after that, the output torque varies between a maximum torque \((T_{\text{max}})\) of 1.006 Nm and a minimum torque \((T_{\text{min}})\) of 0.995Nm. The average torque output \((T_{\text{avg}})\) has been found to be 1.00Nm. The torque ripple output in percentage is calculated as 1.1%.

![Torque Profile](image)

**Figure 5.9  Torque profile for 25% of the load torque**
(a) Rated speed (b) half rated speed (c) 10% of rated speed

The ripple output (b) depicts above defines that the torque output \((T_{\text{out}})\) reaches the 25% rated torque in 0.03 s and, after that, the output torque varies between a maximum torque \((T_{\text{max}})\) of 1.008 Nm and a minimum torque \((T_{\text{min}})\) of 0.993Nm. The average torque output \((T_{\text{avg}})\) has been found to be
1.0Nm. The percentage ripple torque is calculated as 1.5%. The curve (c) defines above specifies that the torque output ($T_{out}$) reaches the 25% rated torque in 0.03 s and, after that, the output torque varies between a maximum torque ($T_{max}$) of 1.019 Nm and a minimum torque ($T_{min}$) of 0.991Nm. The average torque output ($T_{avg}$) has been found to be 1.0Nm. The torque ripple in percentage is calculated as 1.8.

5. Performance under Dynamic Load condition

In the simulation carried out under dynamic condition, the speed was kept at rated condition and it is made constant. Three cases were considered: in the first case, as shown in Figure 5.10, the command torque, $T_{com}$ was changed from 0 Nm to 1 Nm at 0.15s whereas, in the second case, $T_{com}$ was changed from 1 Nm to 2Nm at 0.53s. From the figure it shows that the dynamic performance of the controller is very good. $T_{out}$ reaches to 2 Nm at 0.03 s.

![Figure 5.10 Torque profile under dynamic load condition](image.png)

However, at the time of starting, the torque ripple is quite higher compared with those in the steady-state. At this period, the phase current is also higher compared to the rated current. This is due to the fact that at the time of start the motor needs large power to accelerate. The high starting
output torque and current demonstrate that the motor should have short duration overload ability.

#### 5.6 COMPARATIVE STUDY

An analysis is made on the genetic neuro controller and the revealed observations are compared with the ANFIS controllers based DTC is arranged in Table 5.2. In this table, the statistical parameters such as torque

<table>
<thead>
<tr>
<th>S.No</th>
<th>Proposed Controller based DTC</th>
<th>Rated Speed in%</th>
<th>Torque ripple in % with respect to the % Applied load torque</th>
<th>Computational Time(sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hysteresis Controller</td>
<td>100</td>
<td>6.0 5.0 4.9 2.0</td>
<td>Equal to run time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>6.48 6.4 6 2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>7.4 7.2 6.9 3.0</td>
<td></td>
</tr>
<tr>
<td>2</td>
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<td>6.6 6.2 5.9 2.4</td>
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<tr>
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<td>5.6 5.2 5.0 2.2</td>
<td></td>
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<tr>
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<td>6.37</td>
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<td></td>
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<td>4.7 4.6 4.47 2.1</td>
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<td>3.75 3.6 3.46 1.9</td>
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<tr>
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ripple and settling time \( (T_s) \) for the proposed controller and the ANFIS controllers are specified. From the results it is revealed that torque ripple is marginally minimized in the proposed controller compared with the ANFIS controller. The Test is conducted with different loads and speed conditions. The load torque is defined as 100% of the rated, 75% of the rated, 50% of the rated and 25% of the rated. Similarly the speed is varied with respect to rated speed, 50% of the rated speed and 10% of the rated speed. The torque ripple is measured at different instant in DTC method using the proposed controllers. The measured torque ripple is compared with the hybrid intelligent controller based DTC for the same operating conditions. From the comparison it seems clear that the torque ripple obtained in the proposed controller based DTC is comparatively less both in static and dynamic mode of operation which in turn improves the efficiency of the drive.

5.8 SUMMARY

In this chapter the minimisation of torque ripple along with torque response is carried out with the proposed controller based DTC. The drive is simulated under variable torque and speed both in static and dynamic condition. The results above reveal that there is good percentage of torque ripple that is reduced in the proposed controller compared with hybrid intelligent controller. Here for the rated load torque the torque ripple is in the range of 1.7% to 3.25% and for 75% of the load torque the torque ripple varies between 1.6% to 2.9% which is minimum compared with the other proposed controllers. Similarly for 50% of the load torque the variation of the torque ripple is in the range of 1.5% to 2.48% and for 25% of the rated load torque the bandwidth of the torque ripple lies between 1.1% to 1.8% which is much superior over the wide speed range compared with the proposed controller techniques.

Similarly the settling time of the torque and the response time of
the speed is also improved in the proposed controller compared to the ANFIS controller which in turn improves the performance characteristics of the motor drive. The Simulation time or the computation time is also compared with the ANFIS controller based DTC and the results shows that it is also better in real time control. The proposed controller approaches of torque-ripple minimization attempt smooth motor torque over a wide speed range. Although the speed progressively varies the torque ripple, these new approaches are highly preferable for applications where the range of speed variation is very wide.