CHAPTER 3

GA-PI BASED DIRECT TORQUE CONTROL

3.1 INTRODUCTION

Soft computing is an innovative approach for constructing intelligent systems computationally which has just come into the limelight. It is now realized that complex real world problems require intelligent systems that has knowledge, techniques and methodology for various sources. These intelligent systems are supposed to possess human link expertise within a specific domain to adapt them and learn to do better in changing environment.

The Genetic Algorithm (GA) is an optimization routing based on the principles of natural genetics. Since the inception of the GA concept, it has been useful in solving a variety of problems. One of the major advantages of GA methods compared to other methods is that it needs little problem specific knowledge and it can be applied on a broad range of problems. GA methods only need the target (fitness) function for a given problem, which is to be optimised. Additional problem specific knowledge can easily be brought into the GA heuristic to improve performance.

Genetic Algorithm does have negligible demands on the nature of the problem space and they even can be applied on complex problems with discontinuous, non-differentiable and possibly noisy target functions. Additionally, the system behaves robust to external GA process parameters.
and therefore it is easy to use on very different problems without the need for special tuning or expert knowledge. Because of the diversity of GA methods it is easy to select an appropriate method that is especially suited for a given problem, regarding the data types that are to be processed, the representation of the solution and the search space topology.

- They are payoff-driven. Payoffs may mean improvements in predictive power or return over a benchmark and such payoffs can be easily translated to a fitness function for an GA.
- GA methods are inherently quantitative therefore they are better suited for parameter optimization.
- GA methods allow a wide variety of extensions and constraints that cannot be provided in traditional methods. They are robust, revealing a remarkable balance between efficiency and efficacy.
- GA methods are easily combined with other optimization techniques by the use of Memetic Algorithms (MA) and it can seamlessly scale between a pure GA approach and any other optimization technique as long as both algorithms use the same representation as possible solution
- GA methods can also be extended to Multiobjective optimization, which is of special interest in most financial applications

3.2 GENETIC-PI ON TORQUE RIPPLE REDUCTION

GAs is adaptive search algorithm based on the evolutionary ideas of natural selection and genetics. It represents an intelligent exploitation of a random search used to solve optimization problems. Although randomized
GAs are by no means random instead they exploit historical information to 
direct the search into the region of better performance within the space 
research. The GA maintains a population of n chromosomes with associated 
fitness values. Parents are selected to mate on the basis of their fitness, 
producing offspring via a reproductive plan. Sequentially highly fit solutions 
are given more opportunities to reproduce, so that offspring inherits 
characteristics from each parent.

In the proposed method a closed loop Genetic Algorithm based 
direct torque control model was constructed for the SRM drive. The motor 
parameters such as torque, phase flux and the rotor position are obtained from 
the four phase SRM drive. Conventional PI controller is used to reduce to 
reduce the torque error and the two level hysteresis controllers is used to 
minimize the flux error. The $K_p$ and $K_i$ are optimized by the genetic algorithm 
and is used to reduce the torque error.

The steps for torque control are summarized as follows:

- Sample the torque and the flux of the SRM
- Calculate change in torque and flux by comparing with the reference value
- The torque error is minimized by the proposed controller and the flux magnitude error by hysteresis controller.
- In PI controller the gain values are tuned by the genetic algorithm and the algorithm procedure for tuning the gain values are as follows
  
a. Choose the number of digits to represent each controller parameter $K_p$ and $K_i$. 
b. Choose crossover probability (Pc) and Mutation Probability (Pm)

c. Generate an initial population of $K_p$ and $K_i$ (random selection). Initialize sample time $T$ and set time $t$.

d. Generate $K_p$ and $K_i$ gain values for the torque error and the signal is referred to the switching table for the sector selection.

e. With the proper sector selection and switching table the SRM drive torque ripple is reduced effectively.

Based on the torque error, flux error and the position of the rotor, the optimal selection of the voltage space vector is done which decides the switching sequence of the power electronic switches. The converter switches are fired in sequence results in the reduction of torque ripple and increase in the motor performance under different operating condition.

### 3.3 MODELLING OF GENETIC-PI CONTROLLER

GA handles a population of possible solutions. Each solution is represented through a chromosome which is just an abstract representation. Coding all possible solutions into a chromosome is the first step, but certainly not the most straightforward one of a GA. A set of reproduction operators has to be determined too. Reproduction operators are applied directly on the chromosomes, and are used to perform mutations and recombination over solutions of the problem.

The genetic algorithm is executed to fine tune the PI controller by selecting the best chromosomes from the total population. The parent selection is prominent in order to select the best chromosomes. The parent with high fitness value is selected for reproduction using the Roulette wheel.
The Roulette wheel has slots which are sized according to the fitness of each chromosome. The selection process is carried out to spin the roulette wheel.

The steps for control are summarized as follows:

**Step 1**: Sample the signal of the SRM.

**Step 2**: Calculate change in error.

**Step 3**: Choose the number of digits to represent each controller parameter $K_p$ and $K_i$.

**Step 4**: Choose crossover probability ($p_c$) and mutation probability ($p_m$).

**Step 5**: Generate an initial population of $K_p$ and $K_i$ gains.

**Step 6**: Initialize sample time $T$ and set time $t$.

**Step 7**: Generate $K_p$ and $K_i$ gain values for the error.

**Step 8**: With the proper gain values the desired output is achieved.

The sequential flowchart explaining the operation of genetic algorithm is shown in Figure 3.1.
Figure 3.1 Flowchart of the proposed Process

In the proposed controller, the objective function and the fitness function are specified in the Equation (3.1) to (3.4) as

Objective Function

\[ K_p = 10^*R1(1,1); \quad K_p \text{ value range 1 to 20} \]  

(3.1)
\( K_i = R2(1,2); \quad K_i \text{ value range 0 to 2} \quad (3.2) \)

**Fitness Function**

\[
\text{current}_x = \text{current}_x + v_o \quad (3.3)
\]

\[
v_o = w v_o + c1(R1.*(\text{local}_best_x - \text{current}_x)) + c2(R2.*(\text{globl}_best_x - \text{current}_x)) \quad (3.4)
\]

\( w = 0.09 \) (Mutation Rate)

The Local fitness and the global fitness are specified as

**Local Fitness**

\[
\text{current}_\text{fitness}(i) < \text{local}_\text{best}_\text{fitness}(i) \quad \text{[for } i = 1 \text{ to } n \text{ ]}
\]

\[
\text{local}_\text{best}_\text{fitness}(i) = \text{current}_\text{fitness}(i);
\]

\[
\text{local}_\text{best}_x(:,i) = \text{current}_x(:,i)
\]

**Global Fitness**

\[
\text{current}_\text{global}_\text{best}_\text{fitness} < \text{global}_\text{best}_\text{fitness} \quad \text{[for } g = 1 \text{ to } n \text{ ]}
\]

\[
\text{global}_\text{best}_\text{fitness} = \text{current}_\text{global}_\text{best}_\text{fitness};
\]

\[
\text{globl}_\text{best}_x(:,i) = \text{local}_\text{best}_x(:,g);
\]

### 3.4 GENETIC-PI BASED DIRECT TORQUE CONTROL

In the proposed closed loop control method the GA-PI controller replace the Hysteresis controller and PI controller in the DTC block is tuned to reduce the error in the torque. The three level hysteresis controller and
Conventional PI controller used in classical DTC suffer from the varying switching frequency and high torque ripple results in poor drive performance and those results are depicted in chapter 2. Similarly, the system is forced to the edge of instability and it may take a while to iteratively adjust the controller to obtain a continuous oscillation.

The closed loop control using conventional controller consumes more time and it can venture into unstable regions, which could cause the system to get highly uncontrollable. These major drawbacks can be overwhelmed by replacing the conventional hysteresis controller with proportion integral controller which is used for controlling the torque. The block diagram for the proposed controller based DTC is similar to the Figure 2.1 depicted in chapter 2 where the hysteresis torque controller is replaced with GA-PI controller.

In the proposed block diagram the reference speed is initially set and then it is compared with the actual speed of the Drive using comparator. The resultant speed error is converted into torque reference by using PI controller. In the speed PI controller the gain values $K_p$ and $K_i$ are determined by trial and error method. Here $K_p$ is set as 0.1 and $K_i$ is made as 0.01 for converting the speed error into the torque reference. The resultant reference torque is then compared with the actual torque using the torque comparator and the resultant error is fed as the Input to the GA-PI controller. Genetic Algorithm (GA) is a derivative-free optimization technique which makes it more attractive for applications that involve non smooth or noisy signals. GA when compared with other optimization techniques such as stimulated annealing and random search technique is termed to be superior as it avoids a local minimum which is a major issue particularly in the non linear system.
In the proposed GA the population size \( n \) is selected as 50, Crossover probability \( c \) is set as 0.8, Mutation rate \( w \) is set as 0.09 and \( R_1 \) and \( R_2 \) are the variable used in the objective and fitness function. The tuned controller values are used to select the switching vectors from the switching vector table.

The selection of voltage switching vector for the converter is depicted in Table 3.1. \( U_1, U_2, U_3, U_4, U_5, U_6, U_7 \) and \( U_8 \) are termed as active voltage vectors and \( U_0 \) and \( U_9 \) 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.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Voltage Vector Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S(1)</td>
</tr>
<tr>
<td>( \Phi )</td>
<td>( T )</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>( U_5 )</td>
</tr>
<tr>
<td>1</td>
<td>( U_3 )</td>
</tr>
<tr>
<td>0</td>
<td>( U_4 )</td>
</tr>
</tbody>
</table>

The selected vectors are used to turn on and turn off the switching devices which in turn minimize the torque ripple, improve the speed and torque performance results in the increase of drive efficiency over a wide speed range.
3.5 GA-PI CONTROLLER BASED DTC RESULTS

This chapter presented the simulation results of the SRM Drive based on direct torque control technique with Genetic PI controller. The simulink model of the SRM drive based on the DTC is developed in MATLAB which comprises Torque and Flux Hysteresis, Switching table, Power Converter, Physical model of SRM drive(8/6) and α-β transformation block. Various results expressing the performance using the proposed controller for DTC based SRM drives are illustrated and the performances are observed for the torque and the speed reference with respect to time.

These results are compared with the results obtained from other controller and it is established that DTC with evolutionary computing has better scope in SRM control design. The test is conducted with the SRM drive having the power output of 1.5kW, rated RPM as 3800 rpm, rated torque as 4Nm and the drive is applied a dc voltage of 120V. The aligned Inductance and the unaligned Inductance are set as 10mH and 49mH. The stator flux is set as 0.3wb and the inertia and friction are set as 0.008 and 0.01. In the proposed method the performance of the controller is analyzed both in steady state as well as in dynamic conditions.

During the static condition the drive is initially tested with rated load condition for wide range of speed. The motor performance in terms of current, flux, speed and torque are observed. The drive is further stimulated under variable load torque condition and it proves that the proposed controller based DTC increase the efficiency of the machine. The performance of the proposed controller under various operating conditions is observed as follows.
1. **Performance at rated load Condition**

The drive is tested initially with constant load torque and wide range of speed using the proposed controller. The drive is simulated under the rated load condition with respect to rated speed. The corresponding torque and current response is shown in figure 3.2. From the curve it is observed that maximum current of 8A is reached during the rated condition.

![Graph showing torque and current response at rated load condition](image)

**Figure 3.2  Current and Torque response at rated load condition**

The torque varies within the specified bandwidth of 4Nm. The proposed controller reduces the torque error results in proper selection of switching vectors from the vectors table along with the stator flux and the sector angle. The proper selection of voltage vectors switches the power electronics devices in a proper sequence results in the reduction of torque ripple over a wider range. The torque response shown above is further
enlarged to specify the variation of the torque ripple accurately over the wide range of speed is shown in Figure 3.3.

![Figure 3.3: Torque ripple at rated torque](image)

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

From the response curve (a) the torque varies with a maximum value ($T_{\text{max}}$) of 4.12Nm and a minimum value ($T_{\text{min}}$) of 3.99Nm and having the average torque ($T_{\text{avg}}$) of 4.0Nm reaches at 0.05sec. The percentage torque is calculated as 3.25%.

The torque response curve (b) shows that the torque output ($T_{\text{out}}$) reaches the rated torque in 0.05 s and, after that, the output torque varies between a maximum torque ($T_{\text{max}}$) of 4.12 Nm and a minimum torque ($T_{\text{min}}$) of 3.96Nm. The average torque output ($T_{\text{avg}}$) has been found to be 4.02Nm. The torque ripple in percentage is calculated as 3.9%.

The response curve (c ) depicts that the torque output($T_{\text{out}}$) reaches the rated torque in 0.05s and, after that, the output torque varies between a
maximum torque ($T_{\text{max}}$) of 4.13 Nm and a minimum torque ($T_{\text{min}}$) of 3.94Nm. The average torque output ($T_{\text{avg}}$) has been found to be 4.04 Nm. The torque output in terms of ripple is calculated in percentage as 4.7%.

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

The drive is initially stimulated with 75% load torque and with various speed conditions. The drive is simulated with the specified load condition keeping the speed at the rated condition. The corresponding torque and current response is shown in Figure 3.4. From the curve it is observed that a maximum current of 6A is reached during the rated condition.

![Figure 3.4](image_url)  
**Figure 3.4** Phase Current and torque response at 75% of the rated load with rated speed

The torque response and the current response under the specified condition are superior with the proposed controller compared with the other proposed controller. The torque response curve is enlarged to show the clear variation of torque under specified load condition with respect to wide range of speed. The variation is observed and shown in Figure 3.5.
Figure 3.5  Torque response at 75% of the rated load torque

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

Torque response curve (a) shows that the torque output ($T_{out}$) reaches the required rated torque in 0.05 s and, after that, the output torque varies between a maximum torque ($T_{max}$) of 3.08 Nm and a minimum torque ($T_{min}$) of 2.99 Nm. The average torque output ($T_{avg}$) has been found to be 3.0 Nm. The percentage torque ripple is calculated as 3.0%.

The response curve (b) reveals that the torque output ($T_{out}$) reaches the specified rated torque in 0.05 s and, after that, the output torque varies between a maximum torque ($T_{max}$) of 3.10 Nm and a minimum torque ($T_{min}$) of 2.99 Nm. The average torque output ($T_{avg}$) has been found to be 3.0 Nm. The net torque ripple in percentage is observed as 3.66%.

Torque ripple curve (c ) defines that the torque output ($T_{out}$) reaches the 75% rated torque in 0.04 s and, after that, the output torque varies between a maximum torque ($T_{max}$) of 3.12 Nm and a minimum torque ($T_{min}$) of 2.98 Nm. The average torque output ($T_{avg}$) has been found to be 3.02 Nm. The
torque output and the torque ripple in percentage can be calculated by employing the above mentioned equation which is 4.6%.

3. Performance at 50% of the rated Load Torque

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 3.6. From the curve it is observed that maximum current of 3A is reached during the rated condition.

![Figure 3.6 Current and Torque response at 50% of the load torque with rated speed](image)

The above shown torque response curve is enlarged to show the accurate variation of torque under 50% of the rated load condition with respect to the different speed condition. The variation is observed and shown in Figure 3.7.
Figure 3.7  Torque response at 50% of the rated load torque

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

Torque response curve (a) shows that the torque output ($T_{out}$) reaches the specified torque in 0.05 s and, after that, the output torque varies between a maximum torque ($T_{max}$) of 2.03 Nm and a minimum torque ($T_{min}$) of 1.99Nm. The average torque output ($T_{avg}$) has been found to be 2.0 Nm. The torque ripple with the specified condition is calculated in percentage as 2.0%.

The torque ripple curve (b) reveals that the torque output ($T_{out}$) reaches the required rated torque in 0.05 s and, after that, the output torque varies between a maximum torque ($T_{max}$) of 2.04 Nm and a minimum torque ($T_{min}$) of 1.98Nm. The average torque output ($T_{avg}$) has been found to be 2.01 Nm. The torque ripple in percentage is calculated as 2.9%.

The response curve (c) denotes that the torque output ($T_{out}$) reaches the 50% rated torque in 0.04 s and, after that, the output torque varies between a maximum torque ($T_{max}$) of 2.05 Nm and a minimum torque ($T_{min}$) of 1.96Nm. The average torque output ($T_{avg}$) has been found to be 2.01Nm. The
torque output in terms of ripple is measured and calculated in percentage as 4.47%.

4. Performance at 25% of the rated load torque

The simulation is carried out with 25% of the rated load condition keeping the speed at the rated condition. The corresponding torque and current response is shown in Figure 3.8. From the response curve it was observed that a maximum current of 2A is reached during the rated condition.

![Torque and Current Response](image)

**Figure 3.8** Current and torque profile for 25% of the load torque at rated speed

The accurate variation of torque under 25% of the rated load with respect to variable speed condition is analyzed in the below mentioned figure to show the clarity of variation. The variation is observed and shown in Figure 3.9.
Figure 3.9  Torque profile for 25% of the load torque
(a) Rated speed (b) half rated speed (c) 10% of rated speed

The response curve (a) specifies that the torque output \( (T_{\text{out}}) \) reaches the required rated torque in 0.05 s and after that, the output torque varies between a maximum torque \( (T_{\text{max}}) \) of 1.009 Nm and a minimum torque \( (T_{\text{min}}) \) of 0.997Nm. The average torque output \( (T_{\text{avg}}) \) has been found to be 1.00N.m. The torque ripple in percentage is calculated as 1.2%.

Similarly the response curve (b) defines that the torque output \( (T_{\text{out}}) \) reaches the specified rated torque in 0.05 s and, after that, the output torque varies between a maximum torque \( (T_{\text{max}}) \) of 1.013 Nm and a minimum torque \( (T_{\text{min}}) \) of 0.996Nm. The average torque output \( (T_{\text{avg}}) \) has been found to be 1.0Nm. The percentage torque ripple is observed and calculated as 1.7%.

The ripple curve (c) denotes that the torque output \( (T_{\text{out}}) \) reaches the 25% rated torque in 0.04 s and, after that, the output torque varies between a maximum torque \( (T_{\text{max}}) \) of 1.016 Nm and a minimum torque \( (T_{\text{min}}) \) of 0.995Nm. The average torque output \( (T_{\text{avg}}) \) has been found to be 1.0Nm. The net torque ripple in calculated percentage under this condition is 2.1%.
5. **Performance under Dynamic Load condition**

In the simulation carried under dynamic condition, the speed was kept at rated condition and it is made constant. In the first case, as shown in Figure 3.10, the command torque, $T_{com}$, was changed from 0.5 Nm to 2 Nm at 0.45s, 2 Nm to 1 Nm at 0.8s and so on. From the figure it shows that the dynamic performance of the controller is very far better as $T_{out}$ reaches 2 Nm at 0.03 s.

![Torque profile under dynamic load condition](image)

**Figure 3.10** Torque profile under dynamic load condition

3.6 **PERFORMANCE COMPARISON**

The Simulation was carried out and the observations at various conditions are observed and tabulated in the Table 3.2. In this table, the motor parameters such as torque ripple and settling time ($T_s$) for different controllers including the proposed controller are mentioned for variable torque and variable speed condition. Results proves that the variation of torque ripple lies in the band of 3.25%-4.7% for rated load 3.0%-4.6% for 75% of the load, 2%-4.47% for 50% of the rated load and 1.2%-2.1% for 25% of the rated load over a wide speed range. From the comparison it seems clear that the torque ripple over a wide range of speed is fairly less in the proposed controller based DTC technique compared to the other controller. The reduction of torque ripple in turn reduces the mechanical vibration and
acoustic noises over a wide range making the drive highly efficient even under nonlinear conditions.

Table 3.2 Performance Comparison between different controllers

<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>
<td>Fuzzy Controller</td>
<td>100</td>
<td>4.7 4.0 3.5 1.5</td>
<td>4.34</td>
</tr>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>10</td>
<td>6.6 6.2 5.9 2.4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Neural Network Controller</td>
<td>100</td>
<td>3.5 3.3 2.5 1.3</td>
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</tr>
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<td></td>
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<td>4.4 4.0 3.5 1.8</td>
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<td>10</td>
<td>5.6 5.2 5.0 2.2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Genetic-PI Controller</td>
<td>100</td>
<td>3.25 3.0 2.0 1.2</td>
<td>6.37</td>
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<td></td>
<td>10</td>
<td>4.7 4.6 4.47 2.1</td>
<td></td>
</tr>
</tbody>
</table>

3.7 SUMMARY

The torque ripple minimisation using GA based DTC is elaborated in this chapter where the proposed controller is used to minimize the torque ripple and to provide better torque response. The simulation test was also conducted for different load torques both in constant mode as well as in variable mode and the results are shown here. Simulation results prove that
the Evolutionary computing based direct torque control technique is able to minimize the ripple content in the motor torque output at different operating conditions compared to Intelligent Controller based DTC and the Classical DTC technique. Compared to the Intelligent controller, the torque ripple is almost minimized in the range of about 0.1% to 1.5% for a fixed speed with variable torque. The settling time of the torque and the response time of the speed can be reduced in the proposed technique compared to the other controller which in turn increases the efficiency of the machine. The Simulation time or the computation time is also measured and compared with the other controller which illustrates that the processing time in proposed method is considerably a little bit higher for real time control. Although the torque ripple will progressively reduced in the proposed controller, selecting the boundaries appropriately is a major issues and these new approaches are highly desirable for applications where the speed range varies widely which in turn decides the efficacy of the machine. This limitation is overcome by going for hybrid controller based DTC which will be discussed in the forthcoming chapter. The performance of the proposed technique is comparatively evaluated and compared with the Intelligent controller based DTC and the classical DTC along with the existing literatures.