Multiobjective Optimisation by PSO for Switched Reluctance Motor (SRM) Drive

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Abstract: Switched Reluctance Motor (SRM), which has many advantages like Induction machine exhibits very nonlinear characteristics and high torque ripple, the only disadvantages of this machine. Its torque ripple is dependent on the current profile and also on the turn on and turns off angle of phase excitation and the speed is dependent on the current command. This work presents one of the Heuristic approaches like Particle Swarm optimization (PSO) to determine the optimum proportional-integral (PI) controller parameters and turn on and turn off angles, for minimum torque ripple with optimum torque profile SRM drive. These offline tuning methods are implemented for the model of a SRM in MATLAB. It has been observed that by optimizing the controller parameters of a SRM drive with PSO the performance of the controller is improved.

1 INTRODUCTION

Switched Reluctance Motors (SRM) are fast becoming a popular alternative to Induction Motors (IM) in the variable speed drive market. Though the first SRM was built in 1838, it did not find widespread use until the late 1970's. This was due to the difficulty in controlling the machine. Since the 1960's, with the advent of power electronics and high power semiconductor switches, control of the SRM has become much easier and there has been a renewed interest in SRM drives. In different industries, wide range of speed control with fast torque response regardless of load variation is required. This can be achieved very efficiently for SRM (Miller, 2004). SRM exhibits certain advantages like simple structure, high speed operation, wide range of speed control, robustness, high torque per volume, low rotor inertia, highly fault tolerant structure etc. but despite of all these advantages one incipient disadvantage makes this motor inefficient for industrial application. This is due to the high torque ripple that exists in the SRM characteristics. In case of other industrial motors the torque ripple can be minimised by profiling the motor driving current. This profiling is done by proper design of the PI (proportional-Integral) controller. The driving current is forced to follow the reference current either by Pulse Width Modulation (PWM) controller or Hysteresis Controller. In case of SRM current profiling is not the only solution.

The problem with SRM is due to its higher degree of nonlinearity in the characteristics compared to conventional industrial induction motor or DC motor. It exhibits high torque as well as speed ripple due to the typical torque characteristics. This characteristics is due to nonlinear inductance profile with respect to position and torque is dependent not only on current but also on inductance profile. Hence proper design of the controller for SRM drives is itself an optimisation task.

In this present work a novel optimal design of the controller for SRM drives has been proposed. Here the tuning of the controller parameters and also the position of current firing for every particular phase are required. Hence the optimisation problem lies for current shaping so that torque ripple is minimised. This problem of nonlinearity in its characteristics and torque ripple increases in case of variable speed applications. To find out the optimum parameters of the controller to obtain a good closed loop response at different operating conditions is a hard task. The PI controller parameters can be optimized by conventional tuning methods, such as Ziegler-Nicholson (ZN) method. Other tuning methods like pole placement optimization technique are also done

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(George, 1994). Now-a-days Evolutionary methods like Genetic Algorithm (GA), biologically inspired methods like Particle Swarm Optimization (PSO), Ant Colony optimisation (ACO) etc. are used for tuning the parameters of the controllers. These new tuning techniques can efficiently solve complex problems like nonlinearity in the plant, variable speed problems, where the conventional methods may not optimize the controller parameter so accurately. PSO is another Heuristic approach which is inspired by the ability of flock of birds or herd of animals to adapt to their environment. It was developed in 1995 by James Kennedy and Russ Eberhart while attempting to simulate the choreographed, graceful motion of the swarm of birds as a part of socio-cognitive study investigating the motion of collective intelligence in biological population. In PSO, a set of randomly generated solutions propagates in the designed space towards the optimal solution over a number of iteration based on large amount of information about the designed space (Kennedy, 1995). Both GA and PSO are similar in the sense that these two techniques are population based heuristic search methods and they approach for the optimal solution by updating generations. Since these approaches are supposed to find a solution to a given objective function but employ different strategies and computation effort, it is appropriate to compare their performance.

In citation (Hameyer, 2008) the authors perform a multiobjective optimization in a SRM aiming both to maximize the mitigation of the torque ripple and to minimize the degradations of the starting and mean torques. The technique was applied on the optimization of some rotor geometrical parameters with the aid of finite element simulations to evaluate the approximation points for the Kriging model. In (Owatchaiphong, 2009), a design methodology is presented for sizing a SRM. The proposed method combines the use of genetic and fuzzy algorithms together to simplify the design method. In (Balaji, 2011) Particle Swarm Optimization (PSO) based design optimization of SRM has been presented. Here The SRM design is formulated as multi objective constrained optimization problem. The objective functions for obtaining desired design are maximization of average torque and minimization of torque ripple with stator and rotor pole arc as design variables. But all these optimisation are aimed to optimise motors' structural design.

Many researchers have applied both GA and PSO in different fields of engineering e.g. In (Panda, 2007), the authors have compared GA with PSO for designing a TCSC based controller for power system stability improvement.

In this present work we have applied PSO to search for the optimal PI controller parameters as well as firing angle and commutation angle of SRM drive The performance of this optimization techniques in terms of convergence rate, error minimization and time complexity is good.

2 MATERIALS AND METHODS

2.1 Switched Reluctance Motor

The Reluctance Motor is an electric motor in which torque is produced by the tendency of its moveable part to move to a position where the inductance of the excited winding is maximized or reluctance of the winding is minimum. This motor has field coils as of a DC Motor field winding for its Stator and no coils or magnets in the Rotor. The rotor is aligned whenever the diametrically opposite stator poles are excited. In a magnetic circuit the rotating parts prefer to come in minimum reluctance (maximum inductance) position at the instance of excitation. When two rotor poles are aligned with two stator poles, another set of rotor poles will be out of alignment with respect to another set of stator poles. Hence by switching stator currents in a sequence, the rotor is rotated.

$$V = Ri + L(\theta,i)\frac{di}{dt} + i(\theta,t)\frac{dL(\theta,i)}{dt} \tag{1}$$

$$T_e = \frac{1}{2}\sum_N i^2 . \frac{dL(\theta,i)}{dt} \tag{2}$$

$$T_e - T_L = J\frac{d\omega}{dt} + B\omega \tag{3}$$

The SRM can be modeled using the following system equations [(1)-(3)], where V, T_e, T_L are applied voltage, electromagnetic torque and load torque respectively. R and L are the resistance and inductance of the stator per phase winding. J and B are inertia constant and damping constants of the machine. i is the current through the winding and ω is the speed of the machine. $L(\theta,i)$ is the Stator Inductance, which depends upon the rotor position (fig 1) and also current in stator winding is a function of both position and time, it is non-linear and thus a simple equivalent circuit of SRM is not possible. The inductance profile is curved at the top; which causes high Torque ripples, speed oscillations, increased audible noise and fatigue of the shaft.

The currents are forced to each phase at an advance angle θ_{on} and commutated at commutation angle θ_{off} (Fig1). Again depending upon the magnetic saturation inductance varies for different current level or it may be said that non linearity is introduced both in current and inductance profile. The magnitude of the current is dependent on load. But the nonlinearity in inductance profile gives rise to the torque ripple (Fig .2), as torque is a function of both the current and the angular position. Hence smooth control of speed and torque is problem area for SRM drive. Controller can be designed to mitigate these problems. In addition to this inherent motor problem if the input voltage and frequency fluctuates then this torque ripple problem is aggregated.

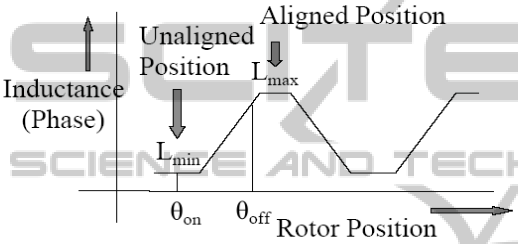

Figure 1: Inductance profile vs. Rotor position.

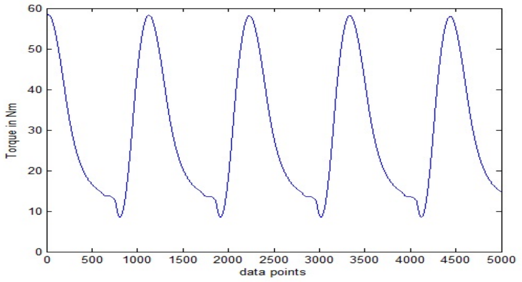

Figure 2: Torque profile vs. Rotor position (as data points).

2.2 Basic Plan of the Work

In this work, optimization of the parameters of PI controller for current control and turn on and turn off angle control of the controller of a SRM has been done using PSO. The design has been considered for a SRM (6/4 pole, 1 HP, 110V) in MATLAB SIMULINK environment. This tuning has been done to the model of SRM in offline. The gain parameters for the current controller for a step input are initially calculated by Ziegler-Nicholson's optimization technique which serves as the parent parameters for current controller. From the design specification an initial set for turn-on angle and turn off angle have been randomly chosen within the permissible range. For optimization, two different criteria for smoothening of torque profile have been chosen which serve as the fitness function of the algorithms.

The current applied to the machine has is feedback control, which provides current reference according to the error in torque.

The model of the test SRM is considered as the Plant model (Fig 3). This model is nonlinear in nature as the equation (1-3) and as described earlier.

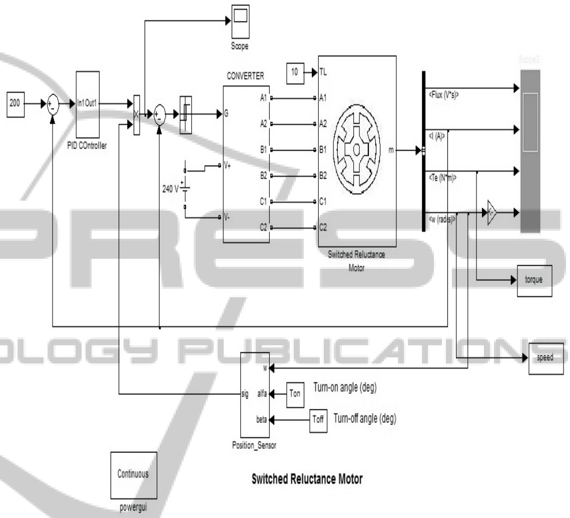

Figure 3: Block diagram of the overall system.

In this wok the objective functions are represented by eqn 4 and eqn 5. First objective is to minimise the speed error by PI controller. Second objective is to minimise of Total Torque Distortion (TTD) by controlling the gain of the controller and as well the turn on and turn off angle.

$$e(i) = i_{ref} - i_{act} \tag{4}$$

$$TTD = \frac{T_{\max} - T_{\min}}{T_{avg}} \tag{5}$$

Where e(i) represents the error in current from reference current to actual current. *TTD* is the total n phase torque distortion which is considered as the fitness function. *TTD* is calculated as the ratio between the maximum and minimum torque difference to average torque for a particular phase.

The output of the PI controller is described by the following eqn 6 , where M_n is the output of the controller at n^{th} instant which is derived from the (n-1)th error and k^{th} sum of previous errors. k_p is the proportional constant and k_i is the integral constant. The constrains of these multi objective problem are eqn 7 and eqn 8.

$$M_n = k_p e(n-1) + k_i \sum_k e(n-k) \tag{6}$$

$$\begin{Bmatrix} k_{p\min} < k_p < k_{p\max} \\ k_{i\min} < k_i < k_{i\max} \end{Bmatrix} \tag{7}$$

$$\begin{Bmatrix} T_{onmim} < T_{on} < T_{on\max} \\ T_{offmim} < T_{off} < T_{offm\text{ax}} \end{Bmatrix} \tag{8}$$

The controller gains like proportional constants (k_p) and integral constant (k_i) are limited by their minimum and maximum limit beyond which the controller will lose its stability.

For turn on (T_{on}) angle and turn off (T_{off}) angle there are also minimum and maximum limit beyond which per phase current control will not be applicable.

2.3 Particle Swarm Optimisation

Particle Swarm Optimization (PSO) is a population based stochastic optimization technique. It shares many similarities with evolutionary computation techniques such as genetic algorithm but the features of PSO, like easy way of implementation, stable convergence characteristics and computational efficiency has made it much superior than others (Mehdi, 2007), (Gaing, 2004) (Banerjee 2010). PSO is initialized with a group of random particles (solutions) and then searches for optima by updating generations. In every iteration, each particle is updated by following two "best" values. The first one is the best solution (fitness) it has achieved so far. (The fitness value is also stored.) This value is called p_{best}. Another "best" value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the population. This best value is a global best and called g_{best}. When a particle takes part of the population as its topological neighbours, the best value is a local best and is called p_{best} . After finding the two best values, the particle update sits velocity and positions.

$$\begin{Bmatrix} V_{id}\left[n+1\right] = V_{id}\left[n\right] + \\ c_1 * rand() * (pbest_{id}\left[n\right] - present_{id}\left[n\right]) + \\ c_2 * rand() * (gbest_{id}\left[n\right] - present_{id}\left[n\right]) \\ present_{id}\left[n+1\right] = present_{id}\left[n\right] + V_{id}\left[n+1\right] \end{Bmatrix} \tag{9}$$

Where $V_{id}[n]$ is the particle velocity of the current particle (n). $p_{best}[n]$ and g_{best} [n] are defined as state before. rand(n) is a random number between (0,1). c1 and c2 are learning factors. The values of c1 and c2 can be calculated as in eqn 10.

$$\begin{Bmatrix} c_1 = (c_{1f} - c_{1i}) * (\frac{i_{ter}}{m_{axiter}}) + c_{1i} \\ c_2 = (c_{2f} - c_{2i}) * (\frac{i_{ter}}{m_{axiter}}) + c_{2i} \end{Bmatrix} \tag{10}$$

Where c_{1i} , c_{1f}, c_{2i} and c_{2f} are constants, iter is the current iteration number and m_{axiter} is the number of maximum allowable iteration. The objective of such modification is to boost up the global search over the entire search space.

3 IMPLEMENTATION

In this section how the program has been implemented in MATLAB is described.

3.1 Optimization of PI Controller using Ziegler-Nichol's Method

From all the methods designed to optimize PID controller, Ziegler and Nichols' method is mostly used (Ogata, 2010). The methods are based on characterization of process dynamics by a few parameters and simple equations for the controller parameters. The first method is applied to plants with step responses. This type of response is typical of a first order system with transportation delays. The second method targets plants that can be rendered unstable under proportional control. The technique is designed to result in a closed loop system with 25% overshoot. This is rarely achieved as Ziegler and Nichols determined the adjustments based on a specific plant model. Here the second methods have been used, Kcr is the gain at critical oscillation and Pcr is the time period. The controller gains are specified in according to a rule (Table 1).

Table 1: PID Controller parameters.

PID Type	Kp	Ki	Kd
P	0.5 Kcr	Infinite	0
PI	0.45 Kcr	Pcr/1.2	
PID	0.6 Kcr	Pcr/2	Pcr/8

3.2 Optimisation of the Plant by PSO

Algorithm for PSO:

- Initialise k_p, k_i values using Z-N method
- Initialisation of T_{on} and T_{off} for a particular range for which the reluctance is minimum and reluctance is approaching maximum
- Generate the initial k_p, k_i, T_{on} and T_{off} for a number of population size in the vicinity of the initial values as real number.
- Set generation =1
- Simulate the SRM model by setting the parameters of k_p, k_i, T_{on} and T_{off} of the PI controller for this set of population size.
- Calculate the error in torque ripple for a particular period of time for which the current of that phase reaches speed for each set of population size for a particular speed demand
- While(!maximum iteration number is achieved)
- calculate fitness functions
- Select the fittest individual according to the fitness function
- Calculate p_{best} of each individual and g_{best} of the population
- Update the velocity and position of the best fitted individual with pbest and gbest
- Increase the generation by number 1
- Compute k_p, k_i, T_{on} and T_{off} for the i^{th} string
- Simulate the plant with this set of values
- Evaluate fitness (i^{th}) of the simulation output
- Perform selection mechanism to generate sub-generation
- Check the convergence criteria.

4 RESUTS

Here a current demand is given. The problem is started with a particular T_{on} and T_{off} angle and PI controller parameters. The current profile and torque profile is shown in fig4 with this initial sets of parameters. Here TTD= 1.75

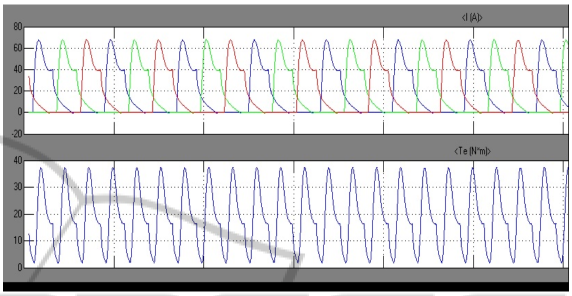

Figure 4: The current profile (upper) and the torque developed (lower) before tuning the parameters.

After 20 iteration it has been found that the current profile as well as the torque profile has been improved (Fig 5).

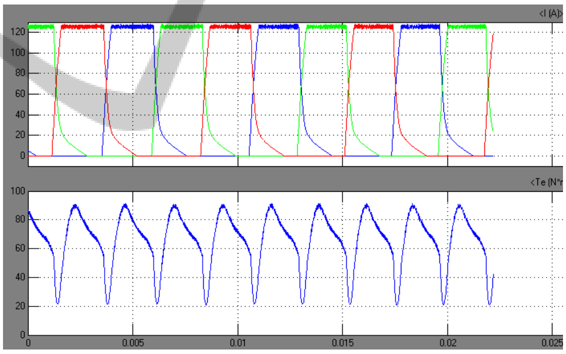

Figure 5: The current profile (upper) and the torque developed (lower) during tuning (after 20 iteration), TTD=1.3.

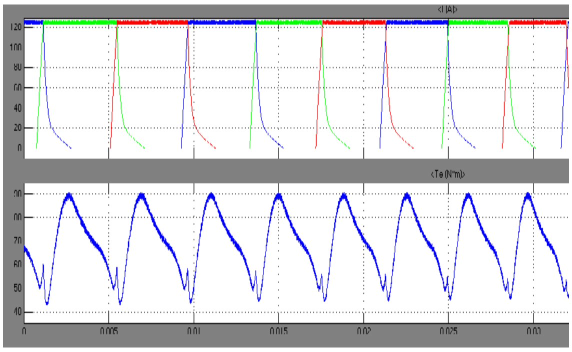

Figure 6: The current profile (upper) and the torque developed (lower) during tuning (after 50 iteration) with TTD=0.78.

After 50 iteration the torque profile has further been improved. So far optimized value of the controller coefficients are $K_p = 2.97$, $K_i = 1.23$, $T_{on} = 44.5^o$ and $T_{off} = 77.6^o$ obtained after 50 generations.

The present work provides immense research possibilities for the future. This optimisation problem is very much suitable since the SRM exhibits very non linear characteristics. GA based optimization will also be carried out and relative comparison will be made between PSO and GA. The stability considerations for controller design can be augmented with the present scheme, which would be regarded as a further constraint while computing the fitness function. This work can be utilized to solve optimization problems involving design of controllers for more complex and non-linear electromagnetic machines. This method as described can be extended for SRM in online and time complexity will be studied.

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