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Application of many optimizing liaisons technique for speed control with torque ripple minimization of switched reluctance motor

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***Abstract* – A comparison in the performance of Many Optimizing Liaisons (MOL) and Gravitational Search Algorithm (GSA) techniques are utilised in the present work for speed control with torque ripple minimization of Switched Reluctance Motor (SRM). The control mechanism consists of two control loop (PI controller) and turn on/ turn off angle control of the 75 KW, 4-phase 8/6 SRM. The problem considered here is to obtain the operating parameter of speed controller, current controller and turn on/ turn off angle is regarded as multi objective problem for optimization with the goal of reducing torque ripple and integral square error of speed. The simulation and analysis is executed in MATLAB/SIMULINK environment. The execution evaluation of MOL and GSA is done by evaluating different statistical parameter. It is noticed that the torque ripple coefficient, ISE of speed & current are significantly reduced by MOL approach**

***Index Terms - Switch reluctance motor (SRM); Proportional integral (PI) controller; Torque ripple; Many optimizing liaison (MOL); Gravitational search algorithm (GSA*)**

I. INTRODUCTION

A Switched Reluctance Motor (SRM) is characterized by many attractive features, such as inherent simplicity in construction, high torque to mass ratio, low maintenance cost makes it a strong competitor to induction machine [1, 2]. In hybrid electrical vehicles, SRM offers better performance than induction motor and permanent magnet motor [3, 4]. The high torque ripples are produced in SRM because of its nonlinear electromechanical characteristics caused by non-linear magnetic characteristics after saturation [5]. But, when SRM is used in high power servo system, it is desired that torque ripple should be minimum[6]. The performance of SRM can be enhanced by improved mechanical design or by electronic operation of sophisticated control system. Improved mechanical design aspect requires variations in the structure and design of stator and rotor pole, which increases the cost of motor [7]. Alternatively, a sophisticated control system could be designed taking into consideration the non-linear electro-mechanical characteristics of SRM. This is possible by proper choice of various operating parameter values such as turn on and turn off angle, voltage and current [8]. Numerous methods have been proposed in literature for minimization of ripple in the output torque by controlling the profile of output torque, thus the current waveform [9-13]. These methods include fuzzy logic [9], neural network [14] to control current waveform in electrical drives. But, application of these advanced techniques requires skilled user. At the same time, optimization approaches, use profound information of systems problem by well-developed models and have enormous potential for application. Heuristic optimization technique based methods have been proposed recently for designing of a controller. In industries, Proportional Integral (PI) controller is the most favored controller because of its effectiveness and simplicity in use. In light of above, PI controllers are opted for performance improvement of SRM. The SRM performance can be improved by minimizing ripple in the output torque, fast and accurate tracking of speed with reference speed & and also fast and accurate tracking of current to their reference value. By implementing the optimal values for control parameter of SRM, its performance significantly improved. Keeping this point in view, various optimization techniques [15-17] have been applied in a number of literature so as to modulate current waveform in electrical drives. Application of various heuristic optimization techniques for tuning the PI controller has been reported in literature [18-20]. Gravitational Search Algorithm (GSA) is a recently proposed algorithm inspired by Newtonian gravity law [21]. From the literature[21] it is reported that GSA provides better performance than Real Genetic Algorithm (RGA) and also Particle Swarm Optimization (PSO) for standard benchmark functions [21]. A plainer PSO which is called "social only" was proposed [27, 28]. Chipperfield and Pedersen [29] undergone further studies and given a name to it as Many Optimizing Liaisons (MOL). They also reported that MOL gives somewhat improved performance compared to PSO. Keeping in view the above points, MOL method is practised in the present paper for obtaining different optimal parameter values required for speed control with torque ripple minimization of switched reluctance motor. The superior performance of MOL is depicted by making comparison of the results obtained with the recently proposed Gravitational Search Algorithm. It is shown that many approaches have been suggested for the objective of speed control of SRM [30, 31]. Many others have proposed minimization of ripple in output torque by adjusting torque profile [6, 11, 15]. The SRM performance become better by the proper selection of commutation angle control [9, 10]. In the present work, control scheme for controlling SRM speed with minimization of torque ripple as well as optimal selection of turn on /turn off angle is suggested..

II. MODELING OF SRM DRIVE

The mathematical modeling illustrating the behavior of a 8/6, 75 KW SRM involving the electrical equation for each phase and the mechanical equation governing are reported in literature [32, 33]. The nonlinear magnetic characteristics of SRM is observed because of saturation and changeable air gap with rotor position which makes the magnetic flux linkage a nonlinear function of stator current (i) and rotor position(θ) The magnetic flux linkage is expressed by

$$\psi_s(t) = \psi_s(i, \theta)$$

(1)

The magnetic flux linkage function is simplified by analytical non-linear function [29, 30].

The stator phase voltages are expressed as the time integral of the difference of stator phase voltage and voltage drop in the stator resistance.

$$\psi_s(t) = \int_0^t (V_s - R_s I_s) dt$$

where $\psi_s(t)$ is the flux linkage vector, V_s is the stator voltage vector, R_s is the stator winding resistance, θ is the rotor position and I_s is the stator current vector. Stator current is found from magnetization characteristics $\psi(i,\theta)$. Expression for flux linkage (ψ) is nonlinear in nature. The expression for non-linear stator current $i(\psi,\theta)$ is derived from the magnetization characteristics $\psi_s(i,\theta)$. The magnetization characteristics are plotted from analytical expressions as

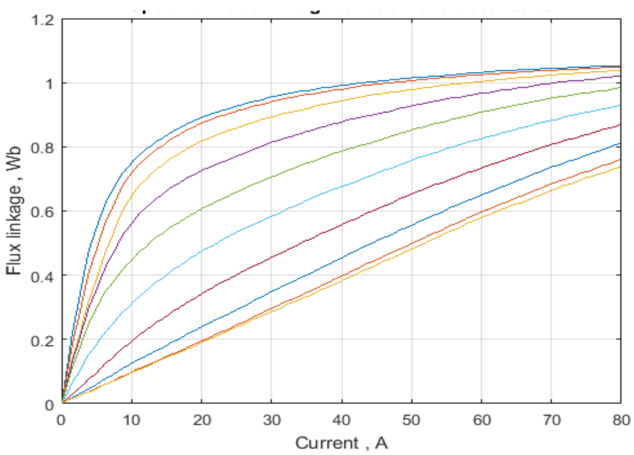

Fig. 1. Magnetization characteristic of the proposed machine

displayed in Fig. 1. In Fig. 1, theta (θ) represents different position of rotor in degree during its rotation.The electromagnetic torque of one phase of SRM are found by taking the derivative of machine co-energy $w^{'}(i.\theta)$ as

$$T_e(i,\theta) = \frac{\partial}{\partial \theta} w^{'}(i,\theta)$$

(3)

where $w^{'}$ is given by:

$$w^{'}(i,\theta) = \int_0^i \psi(i,\theta) di \qquad (4)$$

The electromagnetic torque T_e developed by the machine is calculated by addition of all the individual developed torques of each phase. Equation of mechanical system is given by:

$$T_e = J \frac{d\omega_m}{dt} + B\omega_m + T_L$$

(5)

where, ω_m is angular velocity, J is moment of inertia and load torque respectively, B is the friction coefficient.

III. Speed control with minimization of torque ripple of SRM drive

The torque and flux linkage inductance of SRM are strongly coupled and hence nonlinear variation in torque is observed with the changes in rotor position including phase current. Therefore, by regulating profile of stator current and appropriate selection of turn on angle and turn off angle ripple in output torque can be minimized. In view of the above, speed control including the torque ripple minimization of SRM is proposed with turn on control, turn off angle control, θ_{on} & θ_{off} respectively. For controlling speed and current, conventional PI controllers are used. Optimal combinations of PI controller parameter values and turn on angle & turn off angle are obtained for improvement in performance of SRM drive. With the optimum selection of these six parameters the performance of SRM drive can be enhanced and torque ripple can be decreased greatly.

To measure speed error and current error, Integral Squared Error (ISE) criteria are used. These error criteria are given by

$$ISE_{speed} = \int (\omega_{ref} - \omega_m)^2 dt$$

(6)

$$ISE_{current} = \int (I_{ref} - I_{phase})^2 dt$$

(7)

To measure torque ripple T_{ripple} , torque ripple coefficient as proposed in [15] is employed. The expression for ripple coefficient is given by Eq. (8)

$$T_{ripple} = \frac{T_{\max} - T_{\min}}{T_{mean}} \tag{8}$$

where $T_{\min}$, $T_{\max}$ and T_{mean} are the minimum, maximum and mean torque values of the total output torque.

IV. Objective function formulation

A multi-objective optimization problem formulation is done by combining torque ripple coefficient and integral square error of speed subject to constraints. The constraint considered in the problem formulation is integral square error of current that is computed from the performance of inner loop.
The objectives can be formulated as:
Minimization of ISE of speed as:

$$f_1 = \min(ISE\_speed) \tag{9}$$

Minimization of T_{ripple} as:

$$f_2 = \min(T_{ripple}) \tag{10}$$

The maximum value of stator phase current in steady state should be less than a specified value. Hence, the constraint is specified as:

stator phase current < 10 ampere (11)

The optimization problem can now be stated as:

$$\min\ f = f_1 + \alpha f_2 \tag{12}$$

subject to the constraint given by Eq. (11).

V. Overview of MOL and GSA

A. Many Optimising Liaison(MOL)

Many Optimizing Liaison (MOL) is a simpler version of Particle Swarm Optimization (PSO) suggested in [27]. Later an amended form of original PSO was proposed [28] and subsequently, Pederson, Chipperfield [29] made extensive investigation and and given a name to it as MOL. It is observed in literature that MOL provides better performance with easier tunable algorithm parameters

In this algorithm first a number of particle are initialized in the search space which fly around to find the best solution. During this process all the particles are looking for best particle (best solution) in their search path considering their own best solution as well as best solution that has been found so far. The velocity update in PSO is given by:

$$v_j^{k+1} = wv_j^k + \kappa_P \times \Re_P(pbest_j - x_j^k) + \kappa_G \times \Re_G \times (gbest - x_j^k) \tag{13}$$

Where x_j^k and v_j^k are the position and velocity of j^{th} particle at iteration k respectively. The initial velocity and position are chosen randomly and updated for each iteration. In the above equation, $pbest_j$ is the best position of agent j and $gbest$ is the best position of swarm, κ_P and κ_G are cognitive and social parameter, $\Re_P$ and $\Re_G$ are the random numbers generated between 0 and 1. The inertia weight 'w' preserve an equilibrium between global and local search and hence PSO rapidly searches the optimum result with fewer iterations. The inertia weight 'w' decreases linearly in the course of iterations as given below.

Where

$$w = w_{\max} - \left(\frac{w_{\max} - w_{\min}}{k_{\max}}\right)k \tag{14}$$

where $w_{\max}$ and $w_{\min}$ are the maximum and minimum values of inertia weight respectively. The new position occupied by the particle is calculated by adding a velocity component its present position. After that boundaries are levied on the distance travelled by the particle in single step movement. By which the particle can travel from one search space to another search space in a single step movement.

This exploration process of changing particle position continues until an optimum solution is reached.

In MOL algorithm is a plainer form of PSO, the particle best position is excluded by setting $\Re_P$ to zero. The velocity updated formula for MOL is given by:

$$v_j^{k+1} = wv_j^k + \kappa_G \times \Re_G \times (gbest - x_j^k) \quad (15)$$

A. Gravitational Search Algorithm(GSA)

Gravitational Search Algorithm (GSA) was suggested recently by Rashedi *et al.* [21]. In GSA, a search space is started with *N* number of candidate solutions which are created randomly. The gravitational force acting by candidate *m* on candidate *n* at a specific time *t* is expressed as:

$$F_{nm}^d(t) = G(t)\frac{M_{pn}(t) \times M_{am}(t)}{R_{nm}(t) + \Psi}(x_n^d(t) - x_m^d(t)) \quad (16)$$

where, M_{am} is the active mass of body m, M_{pn} is the passive mass of body n, $G(t)$ is the gravitational constant at time t, $R_{nm}(t)$ is the Euclidian distance between the two bodies m & n and Ψ is a constant.

The gravitational constant is determined as:

$$G(t) = G_0 \times (\exp^{(-\alpha \frac{Iter}{Iter_{\max}})}) \quad (17)$$

where, G_0 is the initial gravitational constant, α is the descending coefficient, $Iter_{\max}$ is the maximum number of iteration taken in the search process and $Iter$ is the current iteration.

The all total force acting on candidate n is

$$F_n^d(t) = \sum_{m=1, m\neq 1}^{N} \rho(F_{nm}^t(t)) \quad (18)$$

where, ρ is a randomly generated number in the range [0, 1]

The force experienced by a body is determined by the product of mass and acceleration of that body as per Newton's law of motion.

Therefore, the acceleration of a candidate n having a mass M_i at any time t, in the search space of dimension d can be determined as:

$$\mathrm{A}_n^d(t) = \frac{F_n^d(t)}{M_i(t)} \quad (19)$$

The velocity of candidate n is expressed by

$$v_n^d(t+1) = \Re_n \times (v_n^d(t) + \mathrm{A}_n^d(t)) \quad (20)$$

whwre, $\Re_n$ is a random number generated in the interval 0 to 1.

The position of candidate n can be determined by:

$$x_n^d(t+1) = x_n^d(t) + v_n^d(t+1) \quad (21)$$

VI. APPLICATION OF MOL AND GSA FOR SPEED CONTROL AND TORQUE RIPPLE MINIMIZATION OF SRM

The system for controlling the speed consists of two PI controllers, one for speed and other for current control. It also consists of a Pulse Width Modulation (PWM)/ hysteresis controller regulator and commutation angle controller. These gains(PI speed controller and PI current controller) are obtained by MOL and GSA algorithm as explained earlier. The commutation period of phase winding is found by the commutation angle control. The information from rotor position feedback is used to choose the turn on angle (θ_{on}) & turn off angle (θ_{off}) of power switches. The current control for an activated phase winding is realized by using a current hysteresis controller.

A. Speed Controller

The structure of speed controller employed in the present study is a standard PI controller. The input to the speed controller is the error signal which is difference of reference speed and actual speed. The speed controller output is the current command for the current controller. The control action provided by proportional controller is proportional to its gain factor K_{P_speed}. The purpose of integral controller is to remove steady state error by providing low frequency compensation. The transfer function for PI speed controller expressed in S-domain is given below

$$T_{speed}(s) = K_{P\_speed} + \frac{K_{I\_speed}}{s} \quad (18)$$

where, K_{P_speed} and K_{I_speed} are the proportional gain and integral gain respectively of PI speed controller.

A. Current Controller

The structure of current controller is similar to PI structure speed controller. In this study, similar PI controllers are used for each phase of 3-phase SRM. The transfer function of PI controller connected to any one of the phase is expressed as:

$$T_{current}(s) = K_{P\_current} + \frac{K_{I\_current}}{s} \quad (19)$$

where $K_{P\_current}$ and $K_{I\_current}$ are the proportional gain and integral gain of PI current controller. The information given by PI speed controller is then feed as an input to PWM as shown in Fig. 2 to generate the gating pulse sequence for the voltage to be applied to each phase windings.

C. Control of turn on and turn off angle

The turn on angle and turn off angle controller controls the position of rotor in accordance with the stator. Fig. 2 demonstrates the per phase inductance characteristics of stator with progress of rotor in degrees. As a SRM is not intended to operate during heavy saturation period [32].

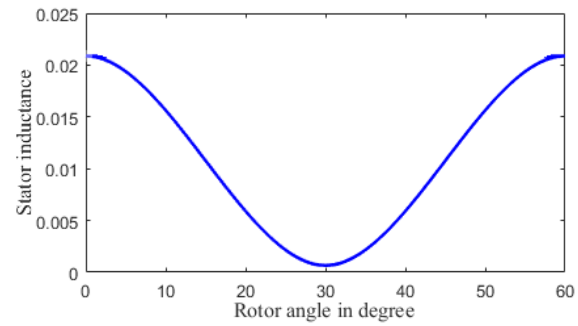

Fig. 2. Variation of stator inductance as rotor position varies during 60-degree rotation of rotor

To get a motoring torque, a none-zero positive current is be applied during the positive slope of inductance i.e. $\frac{dL}{d\theta}$ because a generating action occurs with the action of unipolar current applied during the negative slope of inductance profile [33]. To avoid the operation of the SRM drive with negative torque, the flux is permitted to decay before the rotor enters into negative torque area. Therefore, turn off time is selected near the maximum inductance position. The maximum aligned position occurs when there is complete alignment of stator and rotor poles. The inductance offered by SRM at this position is maximum. Hence it is necessary to turn off the current slightly before then maximum inductance position is reached.

VII. Application of MOL and GSA technique

The range for proportional controller gain and integral controller gain used for speed controller / current controller are as provided in Table I. The lower and upper bounds for turn on and turn off angle are taken in consideration from the single phase inductance profile with respect to rotor position as shown in Fig. 2, so as to avoid the operation of SRM during saturated condition.

Model of SRM and its speed control mechanism based on MOL and GSA technique is devised in MATLAB/SIMULINK environment.

Optimal combination of gain parameter of current controller, speed controller, turn on angle and turn off angles are got by applying MOL and GSA optimization technique by minimizing the combined objective of minimizing ISE of speed along with torque ripple coefficient with ISE of current as a constraint. To evaluate the performance of each algorithm, 30 independent trials are executed for MOL and GSA algorithms.It is obtained that the settling time obtained by GSA technique is 0.65 whereas settling time obtained by MOL is 0.39. The torque ripple for best Integral square of speed is obtained by GSA is 22.6459 where as torque ripple obtained by MOL is 20.2480 .

Hence it can be concluded that the speed controller designed using MOL algorithm provides improved performance in term of providing lesser torque ripple coefficient, integral square error of speed as compared to GSA algorithm.

Table I. Bounds of PI speed controller, PI current controller, turn on angle and turn off angle

Design criteria for controller	Lower limit	Upper limit
$K_{I\_current}$	-500	500
$K_{P\_current}$	0	5000
K_{I_speed}	0	5000
K_{P_speed}	0	300
Turn on angle	32	36
Turn off angle	54	58

The values obtained by GSA algorithm for speed tracking with the reference speed for the proportional constant, integral constant of speed controller, proportional constant, integral constant of current controller, turn on and turn off angle control are 30.0627, 258.6744, 2520.1, -433.3830, 35.29, 54.54 respectively. Whereas the valuse obtained by MOL algorithm for speed tracking with the reference speed for the proportional constant, integral constant of speed controller, proportional constant, integral constant of current controller, turn on and turn off angle control are 300, 317.5, 2087.8, -500, 35.0632, 54respectively.

VIII. Time domain analysis

Time domain simulations are performed to get a better insight into the performance of SRM control.. Total torque and tracking of speed with the reference speed in Fig. 3 and Fig. 4 for by MOL and GSA based controllers.

Fig. 3(a)

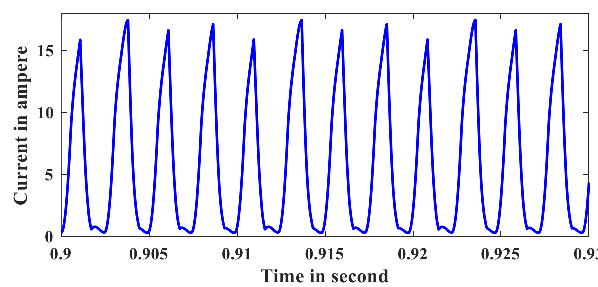

Fig. 3(a)

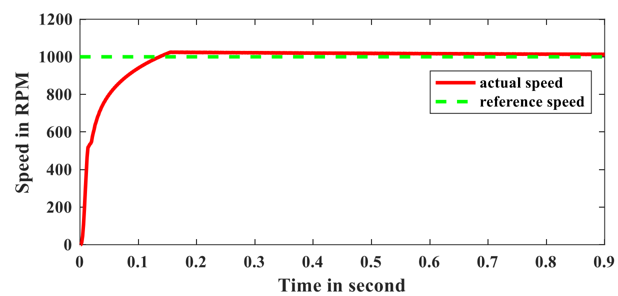

Fig. 3(b)

Fig. 3. Performance analysis of speed control of 4-phase SRM using MOL algorithm, Fig. 3(a).

Torque in Nm Vs time in seconds, Fig. 3(b). Speed in RPM Vs time in second

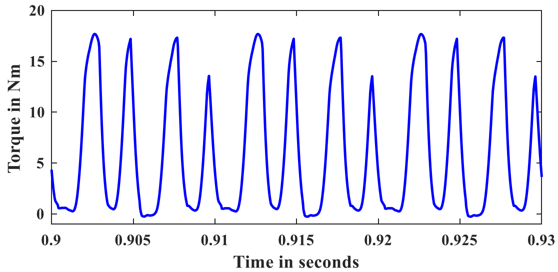

Fig. 4(a)

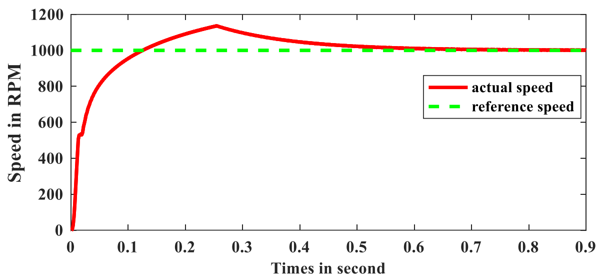

Fig. 4(b)

Fig. 4. Performance analysis of speed control of 4-phase SRM using GSA algorithm, Fig. 4(a). Torque in Nm Vs time in seconds, Fig. 4(b). Speed in RPM Vs time in second

IX. Conclusion

In the present study, MOL and GSA technique is proposed for speed control of SRM. Optimal parameter of speed controller, current controller, along with turn on and turn off angle are obtained by MOL. Performance of MOL and GSA optimized controllers is compared by computing the integral square error of speed, torque coefficient along with computing the best, worst, mean and standard deviation of integral square error of speed and torque ripple. It is concluded from the obtained result that MOL based speed controller give better performance for SRM drives by minimizing the torque ripple and settling times as well as provides better current profile due to its robust exploitation and exploration capability.

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