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Design of Speed Controller for Permananent Magnet Synchronous Motor Drive Using Genetic Algorithm Based Lower Order System Modelling

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Abstract: Problem statement: In this study, a Model Order Reduction (MOR) method is proposed for reducing higher order system into lower order system. Speed controller design is carried out to the lower order system by Genetic Algorithm (GA) approach and this controller is used to higher order system. **Approach:** This study is used to find a solution to a given objective function employing different procedures and computational techniques. The problem area chosen is that of lower order system modelling used in design of speed controller for Permananent Magnet Synchronous Motor (PMSM) drive. **Results:** Genetic Algorithm obtains a better controller values that reflects the characteristics of the original higher order system and the performance evaluated using this method are compared with the existing approximation method. **Conclusion:** Performance of this Speed controller has been verified through Simulation using MATLAB package.

Keywords: Permananent Magnet Synchronous Motor (PMSM), drive, genetic algorithm, lower order system modelling, speed controller

INTRODUCTION

During the early 1950s researchers studied evolutionary systems as an optimisation tool, with an introduction to the basics of evolutionary computing (Sivanandam and Deepa, 2009). Until 1960s evolutionary systems was working in parallel with Genetic Algorithm (GA) research. At this stage, evolutionary programming was developed with the concepts of evolution, selection and mutation. Holland (1992) introduced the concept of Genetic Algorithm as a principle of Charles Darwinian theory of evolution to natural biology. The working of genetic algorithm starts with a population of random chromosomes. The algorithm then evaluates these structures and allocates reproductive opportunities such that chromosomes, which have a better solution to the problem, are give more chance to reproduce. While selecting the best candidates, new fitter offspring are produced and reinserted and the less fit is removed. The exchange of characteristics of chromosomes takes place-using operators like crossover and mutation. The solution is defined with respect to the current population. GA operation basically depends on the Schema theorem. GAs are recognized as best function optimisers and is used broadly in pattern discovery, image processing, signal processing and in training Neural Networks.

Many control system applications, such as satellite altitude control, fighter aircraft control, model-based predictive control, control of fuel injectors, automobile spark timer, possess a mathematical model of the process with higher order, due to which the system defined becomes complex. These higher order models are cumbersome to handle (Sivanandam and Deepa, 2009). As a result, lower order system modelling can be performed, which helps in alleviating computational complexity and implementation difficulties involved in the design of controllers and compensators for higher order systems. Further, the development and usage of micro controllers and microprocessors in the design and implementation of control system components has increased the importance of lower order system modeling (Prasad, 2000; 2003a; 2003b). Thus, in this study, Genetic Algorithm is used independently to higher order systems and a suitable lower order system is modelled (Sivanandam and Deepa, 2009).

The availability of modern Permanent Magnets (PM) with considerable energy density led to the development of dc machines with PM field excitation in the 1950's. Introduction of PM to replace electromagnets, which have windings and require an external electric energy source, resulted in compact dc machines (Islam *et al*., 2011). The synchronous machine, with its conventional field excitation in the

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rotor, is replaced by the PM excitation; the slip rings and brush assembly are dispensed with. With the advent of switching power transistor and silicon-controlled rectifier devices in later part of 1950s, the replacement of the mechanical commutator with an electronic commutator in the form of an inverter was achieved. These two developments contributed to the development of PM synchronous and brushless dc machines (Islam *et al*., 2011). The armature of the dc machine need not be on the rotor if the mechanical commutator is replaced by its electronic version. Therefore, the armature of the machine can be on the stator, enabling better cooling and allowing higher voltages to be achieved: significant clearance space is avilable for insulation in the stator. The excitation field that used to be on the stator is transferred to the rotr with the PM poles. These machines are nothing but 'an inside out dc machine' with the field and armature interchanged from the stator to rotor and rotor to stator respectively (Pillay and Krishnan, 1989). In this study contains design of speed controller for permanant magnet synchronous machines using Genetic algorithm based lower order modelling.

Speed controller design: The design of the speed-controller is important from the point of view of imparting desired transient and steady state characteristics to the speed-controlled PMSM drive systems (Islam *et al*., 2011). A proportional-plus-integral controller is sufficient for many industrial applications; hence, it is considered in this work. Selection of the gain and time constants of such a controller (Talebi *et al*., 2007) by using the symmetric-optimum principle is straightforward if the d axis stator current is assumed to be zero (Wallace, 1994). In the presence of a d axis stator current, the d and q current channels are cross-coupled and the model is non-linear, as a result of the torque term . Under the assumption that the d axis current being zero (i.e., i_{ds}^{r} =0), then the system becomes linear and resembles that of a separately-excited dc motor with constant excitation (Sharma *et al*., 2008). From then on, the block-diagram derivation, current loop approximation, speed-loop approximation and derivation of the speed controller by using symmetric optimum are identical to those for a dc motor drive speed controller design.

Block diagram derivation: The motor q axis voltage equation with the d axis current being zero becomes (Sharma *et al*., 2008):

$$V_{qs}^{r} = (R_s + L_q p)i_{qs}^{r} + \omega_r \lambda_{af} \quad (1)$$

And the electromechanical Eq. 2 is:

$$\frac{P}{2}(T_e - T_l) = Jp\omega_r + B_1\omega_r \quad (2)$$

where, the electromagnetic torque is given by Eq. 3:

$$T_e = \frac{3}{2}.\frac{P}{2}\lambda_{af} i_{qs}^{r} \quad (3)$$

And if the load is assumed to be frictional, then Eq. 4:

$$T_l = B_l \omega_m \quad (4)$$

Which, upon substitution, gives the electromechanical Eq. 5 as:

$$(Jp + B_t)\omega_r = \left\{\frac{3}{2}\left(\frac{P}{2}\right)^2 .\lambda_{af}\right\} i_{qs}^{r} = K_t . i_{qs}^{r} \quad (5)$$

The frictional torque coefficient is Eq. 6:

$$B_t = \frac{P}{2}B_l + B_1 \quad (6)$$

And torque consatnt is Eq. 7:

$$K_t = \frac{3}{2}\left(\frac{P}{2}\right)^2 .\lambda_{af} \quad (7)$$

The Eq. 1 and 5, when combined into a block diagram with the current-and speed-feedback loops added (Sharma *et al*., 2008) are shown in Fig. 1.

The inverter is modeled as a gain with a time lag (Talebi *et al*., 2007) by Eq. 8-10:

$$G_r(s) = \frac{K_{in}}{1 + sT_{in}} \quad (8)$$

Where:

$$K_{in} = 0.65\frac{V_{dc}}{V_{cm}} \quad (9)$$

$$T_{in} = \frac{1}{2f_c} \quad (10)$$

where, V_{dc} is the dc-link voltage input to the inverter (Islam *et al*., 2011), V_{cm} is the maximum control voltage and f_c is the switching (carrier) frequency of the inverter.

The induced emf due to rotor flux linkages, e_a, is Eq. 11:

$$e_a = \lambda_{af}\omega_r (V) \quad (11)$$

Current loop: This induced-emf loop crosses the q axis current loop and it could be simplified by moving the pick-off point for the induced-emf loop from speed to current output point. This gives the currnt-loop transfer function (Sharma *et al*., 2008) from Fig. 2.

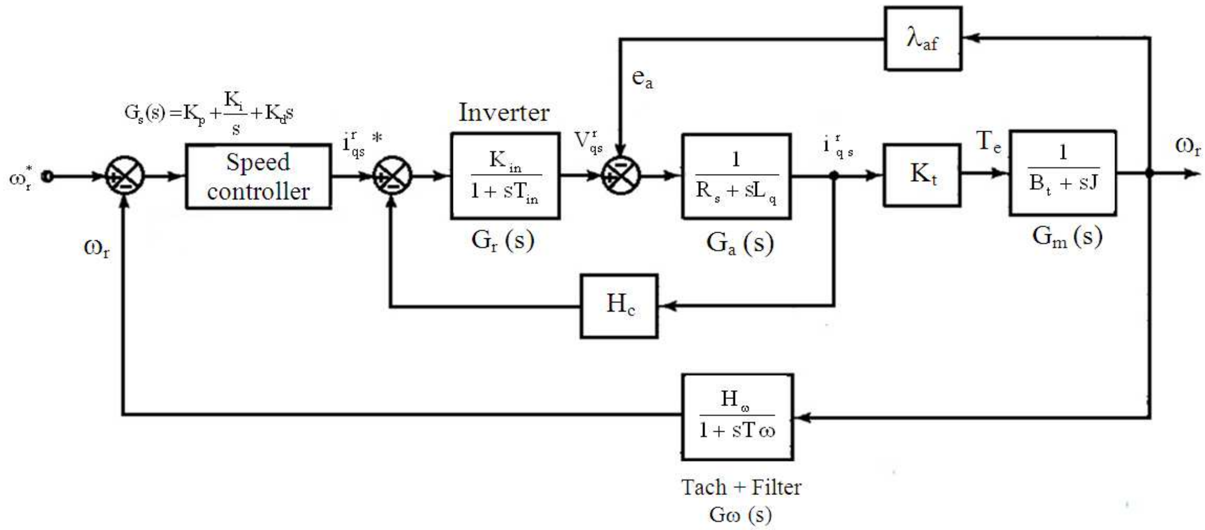

Fig. 1: Block diagram of the spped-controlled PMSM drive

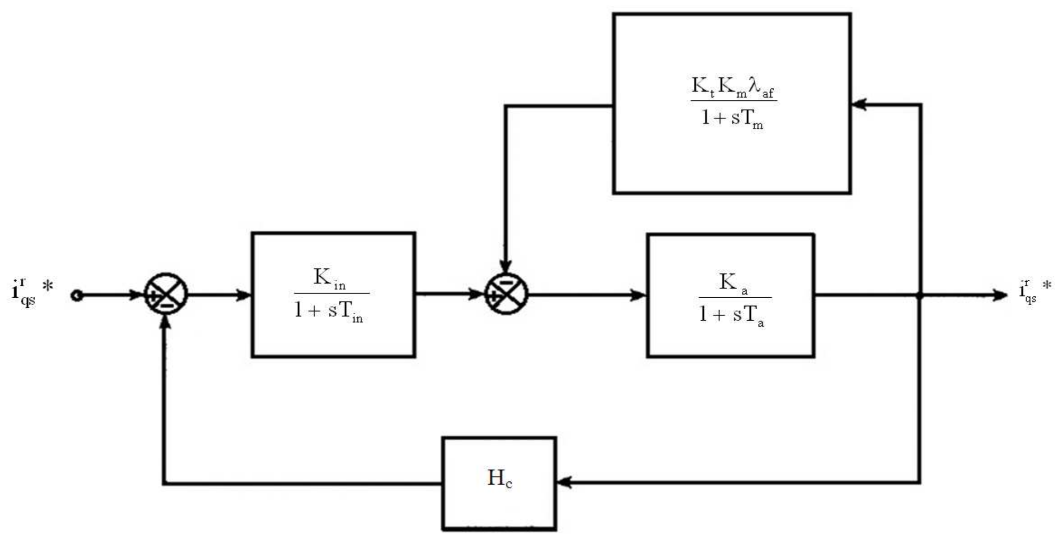

Fig. 2: Current controller

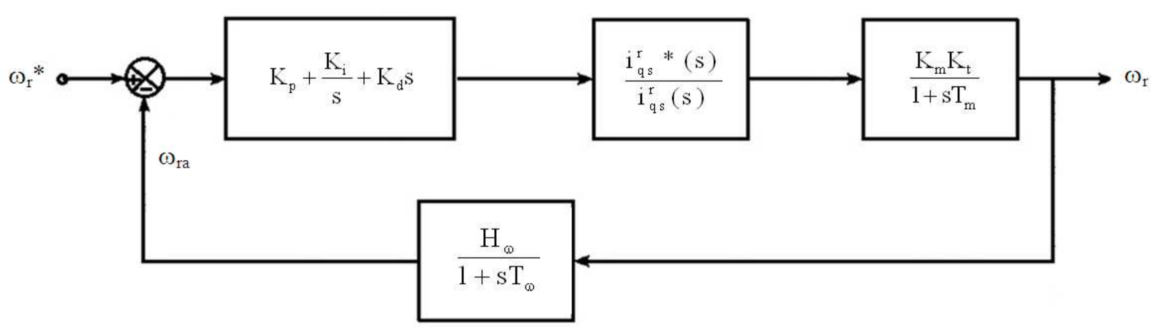

Fig. 3: Speed-control loop

This induced emf loop crosses the q axis current loop and it could be simplified by moving the pick-off point for the induced-emf loop from speed to current output point. This gives the current-loop transfer function from Fig. 2 as Eq. 12 and 13:

$$\frac{i_{qs}^{r}(s)}{i_{qs}^{r}*(s)}=\frac{K_{in}K_{a}(1+sT_{m})}{H_{c}K_{a}K_{in}(1+sT_{m})+(1+sT_{in})\left\{K_{a}K_{b}+(1+sT_{a})(1+sT_{m})\right\}} \quad (12)$$

Where:

$$K_a=\frac{1}{R_s};T_a=\frac{L_q}{R_s};K_m=\frac{1}{B_t};T_m=\frac{J}{B_t};K_b=K_tK_m\lambda_{af} \quad (13)$$

This current-loop transfer function (Krishnan and Ramaswami, 1974) is substituted in the design of the speed controller as follows.

Speed controller: The speed-control loop is shown in Fig. 3.

Drive parameters: The PMSM drive system parameters are as follows:

$R_s = 1.4\Omega$, $L_d = 0.0056$H, $L_q= 0.009$H, $\lambda_{af} = 0.1546$ Wb-Turn, $B_t = 0.01$ N-m/rad/sec, $J = 0.006$ kg-m^2, $P = 6$, $f_c = 2$kHz, $V_{cm} = 10$V, $H_\omega = 0.05$ V/V, $T_\omega = 0.002$ sec, $H_c = 0.8$ V/A, V_{dc}=285V.

From the above drive parameters the following values are obtained:

Inverter: Gain,K_{in} = 18.525 V/V; Time constant, T_{in} = 0.00025 sec.
Motor (electrical): Gain, K_a = 0.7143; Time constant, T_a = 0.0064 sec.
Induced emf loop: Torque constant, K_t = 2.087 N.m/A
Mechanical gain, K_m = 100 rad/s/Nm; Mechanical Time constant, T_m = 0.6 sec.
$K_b = K_tK_m\lambda_{af} = 32.26$.

Proposed method of model reduction: The proposed method of model reduction is Cross Multiplication of Polynomials Model order reduction method. It consists of the following steps in the system approximation process.

Step-1: The denominator and numerator polynomial constant terms in the reduced order model are obtained through Pade approximation: The transfer function of higher order (n^{th}) is considered as Eq. 14:

$$G(s)=\frac{a_0+a_1s+a_2s^2+\ldots+a_{n-1}s^{n-1}}{b_0+b_1s+b_2s^2+\ldots+b_{n-1}s^{n-1}+b_ns^n} \quad (14)$$

G (S) can be expanded into a power series about S = 0 of the form Eq. 15-17 (Shamash, 1975):

$$G(s)=c_0+c_1s+c_2s^2+\cdots \quad (15)$$

Where:

$$c_0=\frac{a_0}{b_0} \quad (16)$$

And:

$$c_k=\frac{1}{b_0}\left[a_k-\sum_{j=1}^{k}b_jc_{k-j}\right],\quad k>0 \quad (17)$$

With:

$$d_k=0 \qquad \forall\, k>n-1$$

The d_i are directly proportional to the time moments of the system, assuming the system is stable Eq. 18 (Shamash, 1975):

$$G_r(s)=\frac{d_0+d_1s+d_2s^2+\ldots+d_{r-1}s^{r-1}}{e_0+e_1s+e_2s^2+\ldots+e_{r-1}s^{r-1}+e_rs^r} \quad (18)$$

Then for R (s) to be Pade approximant of G (S), the following Eq. 19 and 20 are obtained:

$$d_0=e_0\cdot c_0 \quad (19)$$

$$\begin{aligned} d_1&=e_0\cdot c_1+e_1\cdot c_0\\ &\vdots\\ 0&=e_0\cdot c_{2r-2}+e_1\cdot c_{2r-1}+\cdots c_{r-1}\\ 0&=e_0\cdot c_{2r-1}+\cdots c_r \end{aligned} \quad (20)$$

From the Eq. 16 and 20:

$$c_0=\frac{a_0}{b_0}=\frac{d_0}{e_0} \quad (21)$$

From the Eq. 21, let Eq. 22:

$$\left.\frac{a_0}{b_0}=\frac{d_0}{e_0}\right\} \quad (22)$$

Step-2: The unknown coefficients of different powers of 's' remaining in reduced order model are determined: The given higher order system transfer function is equated and cross multiplied with k^{th} order general transfer function. This process yields (n+2) equations with (2r-1) unknown reduced order transfer function coefficients. This step is similar to the model order reduction method proposed in Manigandan *et al*. (2005), where the values of e_0 or d_0 are kept as equal to '1' irrespective of the system condition to obtain the values of unknown coefficients in the reduced order model transfer function. But in this proposed method, the values of e_0 and d_0 are obtained through Pade approximation method as detailed in step-1. This leads to better system approximation as compared to the model order reduction method proposed by Eq. 23 and 24 Manigandan *et al*. (2005):

$$\frac{a_0 + a_1 s + a_2 s^2 + \ldots + a_{n-1}s^{n-1}}{b_0 + b_1 s + b_2 s^2 + \ldots + b_{n-1}s^{n-1} + b_n s^n} = \frac{d_0 + d_1 s + d_2 s^2 + \ldots + d_{r-1}s^{r-1}}{e_0 + e_1 s + e_2 s^2 + \ldots + e_{r-1}s^{r-1} + e_r s^r} \quad (23)$$

$$\begin{aligned}&\left(a_0 + a_1 s + a_2 s^2 + \ldots + a_{n-1}s^{n-1}\right)\\ &\left(e_0 + e_1 s + e_2 s^2 + \ldots + e_{r-1}s^{r-1} + e_r s^r\right)\\ &= \left(b_0 + b_1 s + b_2 s^2 + \ldots + b_{n-1}s^{n-1} + b_n s^n\right)\\ &\left(d_0 + d_1 s + d_2 s^2 + \ldots + d_{r-1}s^{r-1}\right)\end{aligned} \quad (24)$$

The coefficients of same power of 's' on both side of the Eq. 24 equated with each other (Ramesh *et al*., 2008) and is given by Eq. 25:

$$\begin{gathered} a_{n-1}\cdot e_r = b_n \cdot d_{r-1}\\ a_{n-1}\cdot e_{r-1} + a_{n-2}\cdot e_r = b_{n-1}\cdot d_{r-1} + b_n \cdot d_{r-2}\\ \vdots\\ a_2\cdot e_0 + a_1\cdot e_1 + a_0 \cdot e_2 = b_0\cdot d_2 + b_1\cdot d_1 + b_2\cdot d_0\\ a_1\cdot e_0 + a_0\cdot e_1 = b_1\cdot d_0 + b_0\cdot d_1\\ a_0\cdot e_0 = b_0 \cdot d_0 \end{gathered} \quad (25)$$

The (n+2) set of Eq. 25 is solved with the values of d_0, e_0 obtained in (22). This leads to have different set equations for solving the remaining unknown parameters. Based on the optimal ISE value, the unknown values are selected and the resultant reduced order model is obtained as Eq. 26 and 27:

$$G_r(s) = \frac{d_0 + d_1 s + d_2 s^2 + \ldots + d_{r-1}s^{r-1}}{e_0 + e_1 s + e_2 s^2 + \ldots + e_{r-1}s^{r-1} + e_r s^r} \quad (26)$$

If $r = 2 \Rightarrow$

$$G_2(s) = \frac{d_0 + d_1 s}{e_2 s^2 + e_1 s + e_0} \quad (27)$$

Step-3: The cumulative error index (J) for initial reduced order model is calculated (Sivanandam and Deepa, 2009): Consider, the transfer function of higher order (n^{th}) as:

$$G(s) = \frac{a_0 + a_1 s + a_2 s^2 + \ldots + a_{n-1}s^{n-1}}{b_0 + b_1 s + b_2 s^2 + \ldots + b_{n-1}s^{n-1} + b_n s^n}$$

The general form of the transfer function of a second order system in the *s*-domain can be represented as:

$$G_{ri}(s) = \frac{T_1 + T_2 S}{s^2 + 2\zeta\omega_n S + \omega_n{}^2} \quad (28)$$

where, ζ is the damping ratio and ω_n is the undamped natural frequency of oscillation in rad/sec. The values of T_1 and T_2 corresponding to Eq. 28 can be computed as $T_1 = T_g$ and $T_2 = S_g / \omega_n^2$. Where, the transient gain (T_g) and steady state gain (S_g) are computed as:

$$Tg = \frac{a_{n-1}}{b_n} \text{ and } Sg = \frac{a_0}{b_0}$$

By using proposed scenario-1, the reduced order model obtained in step-2/step-3 is modified in to an initial form as Eq. 29:

$$G_{ri}(s) = \frac{\frac{d_0}{e_2} + \frac{d_1}{e_2}s}{\frac{e_0}{e_2} + \frac{e_1}{e_2}s + s^2} = \frac{A_0 + A_1 s}{B_0 + B_1 s + s^2} \quad (29)$$

Where:

$$A_0 = \frac{d_0}{e_2} = T_1, A_1 = \frac{d_1}{e_2} = T_2,$$
$$B_0 = \frac{e_0}{e_2} \text{ and } B_1 = \frac{e_1}{e_2}$$

The unit step input time response of the initial second order approximant G_{ri} (S) is analyzed with a computer program and its characteristics are noted. The cumulative error index J using the integral square error of the unit step time responses of the given higher order system G(s) represented by Eq. 15 and the initial second order approximant G_{ri} (S) represented by Eq. 29 is calculated. The cumulative error index J is calculated using the formula Eq. 30:

$$J = \sum_{t=0}^{N}[y(t) - y_r(t)]^2 \quad (30)$$

where, y(t) *is* the output response of the higher order system at the N^{th} instant of time, $y_r(t)$ is the output response of the second order model at the N^{th} instant of time and N is the time interval in seconds over which the error index is computed.

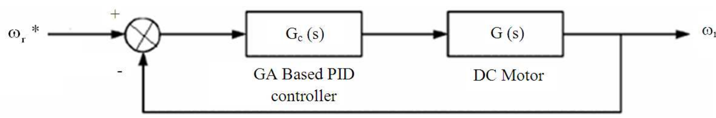

Fig. 4: Block diagram of the GA based PID controller of the system

Table 1: Parameters of GA

GA property	Value/method
Population size	60
Maximum Number of generations	20
Performance index/fitness function	Mean square error
Selection Method	Normalized Geometric selection
Probability of selection	0.05
Crossover method	Arithmetic crossover
Number of crossover points	3
Mutation method	Uniform mutation
Mutation probability	0.1

Table 2: GA based PID controller gain values

Gain parameters	K_p	K_i	K_d
Gain values	17.70713	31.7933	0.00407

After giving the above parameters to GA the PID controllers can be easily tuned and thus system performance can be improved (Thomas and Poongodi, 2009).

Step-4: Find the PID Controller Constants using GA: GA can be applied to the tuning of PID controller gains to ensure optimal control performance at nominal operating conditions. The block diagram for the entire system is given below in Fig. 4 and also the genetic algorithm parameters chosen (Thomas and Poongodi, 2009) for the tuning purpose are shown below in Table 1.The constants K_p, K_i and K_d are determined using Genetic Algorithm (GA) approach (Mahony *et al*., 2000). The Controller design for resultant reduced order model will closely match with the corresponding higher order model.

After giving the above parameters to GA the PID controllers can be easily tuned and thus system performance can be improved.

Speed controller design by proposed method:

Transfer function Approach:

Original Higher order system without speed controller and filter: Let G(s) be the transfer function of the original higher order system. The transfer function of PMSM drive system without speed controller and filter is as follows Eq. 31:

$$G(s) = \frac{1657.078s + 2763.2}{0.000000576s^4 + 0.0024s^3 + 4.2s^2 + 27.778s + 34.63} \quad (31)$$

Reduced order system: Let $G_r(s)$ be the transfer function of the reduced order system (Portone, 1997). The transfer function of the reduced order system of PMSM drive by the application of proposed method is as follows Eq. 32:

$$G_r(s) = \frac{3237.95s + 2763.2}{8.21s^2 + 47.59s + 34.63} \quad (32)$$

From Eq. 29, the reduced order model is obtained as Eq. 33 (Ravichandran, 2007):

$$G_r(s) = \frac{394.4s + 336.56}{s^2 + 5.796s + 4.22} \quad (33)$$

Speed controller: To obtain an optimum transient response of the system, a PID controller is chosen with transfer function Eq. 34 (Kuo and Golnaraghi, 2003; Ogata, 2010):

$$G_c(s) = K_p + \frac{K_i}{s} K_d s \quad (34)$$

Where:

K_p = Proportional gain
K_i = Integral gain
K_d = Derivative gain

The Values of K_p, K_i and K_d are obtained by Genetic Algorithm (GA) approach. The resultant K_p, K_i and K_d values are tabulated as shown in Table 2.

Speed controller design for reduced system: The block diagram of reduced system with speed controller is shown in Fig. 5.

where, K_p, K_i and K_d values are 17.70713, 31.7933 and 0.00407 respectively.

Speed controller design for original system: The K_p, K_i and K_d values of speed controller of Original system is same as that of reduced system. Using this value the speed controller of original system is done. Fig. 6 shows the block diagram of original system with speed controller.

Design specifications: The system is tested with unit step input and the design procedure is followed based on the following design specifications:

Maximum peak overshoot = less than 3%
Settling time = less than 3 sec
Steady state error = 2% (assumed for optimum response) Before proceeding on to the simulation, the starting values of the parameters of controller are deduced using newly proposed procedures

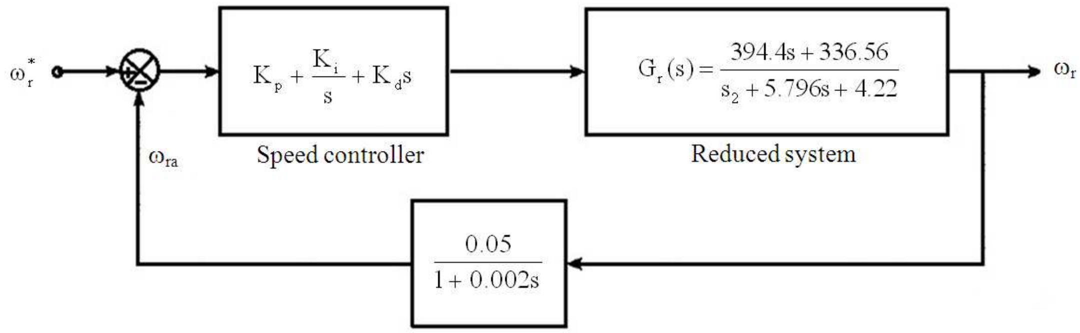

Fig. 5: Block diagram of reduced system with speed controller

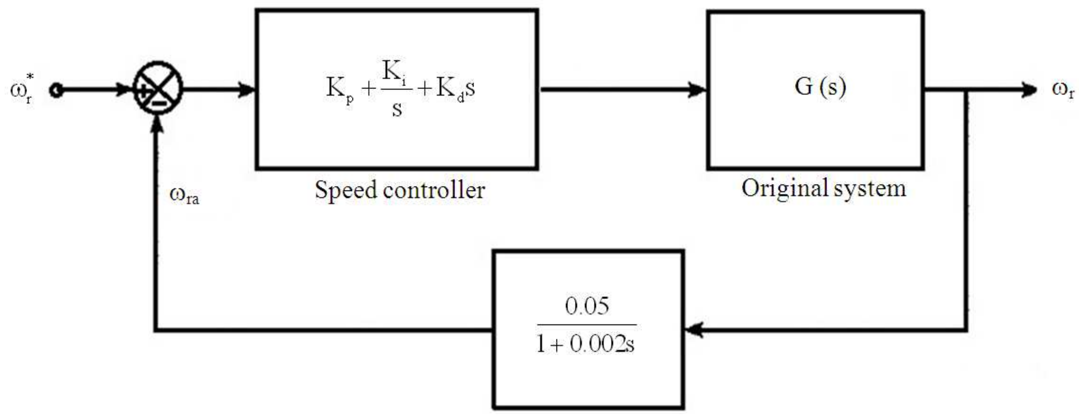

Fig. 6: Block diagram of original system with speed controller

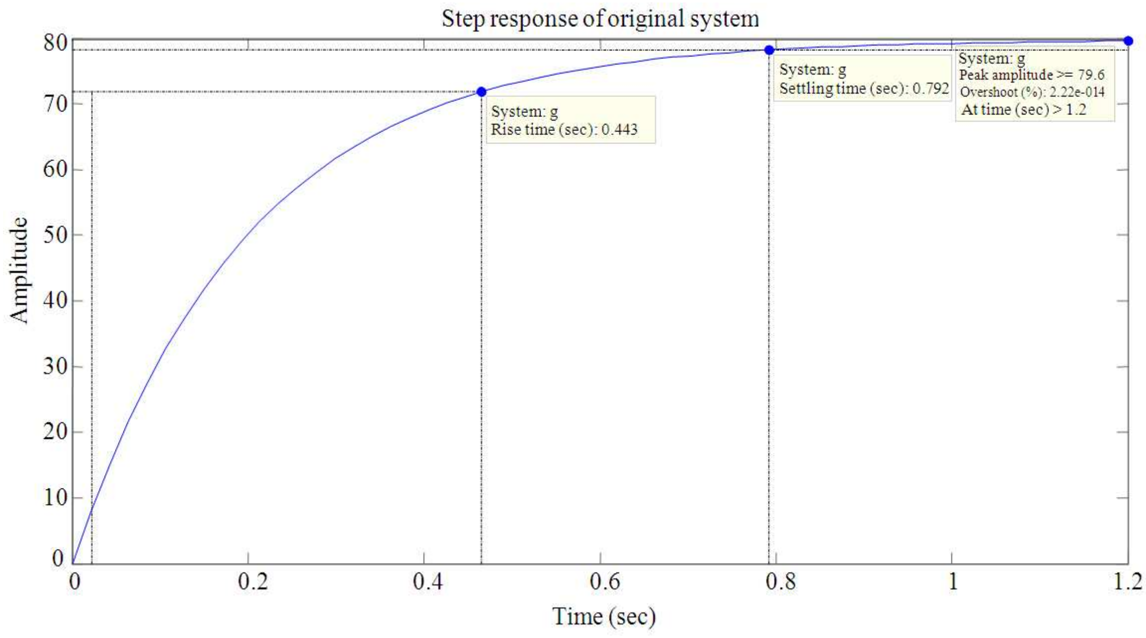

Fig. 7: Step response of original system without speed controller

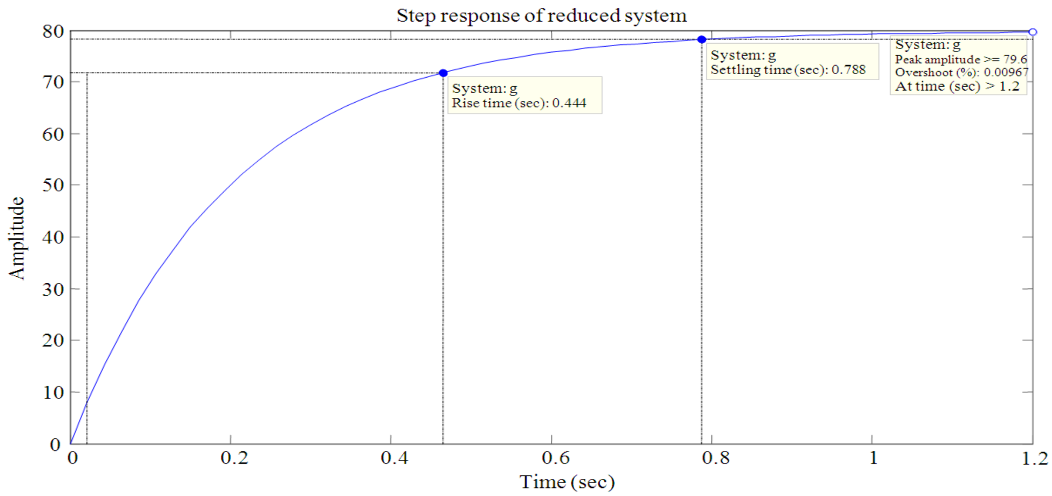

Fig. 8: Step response of reduced system without speed controller

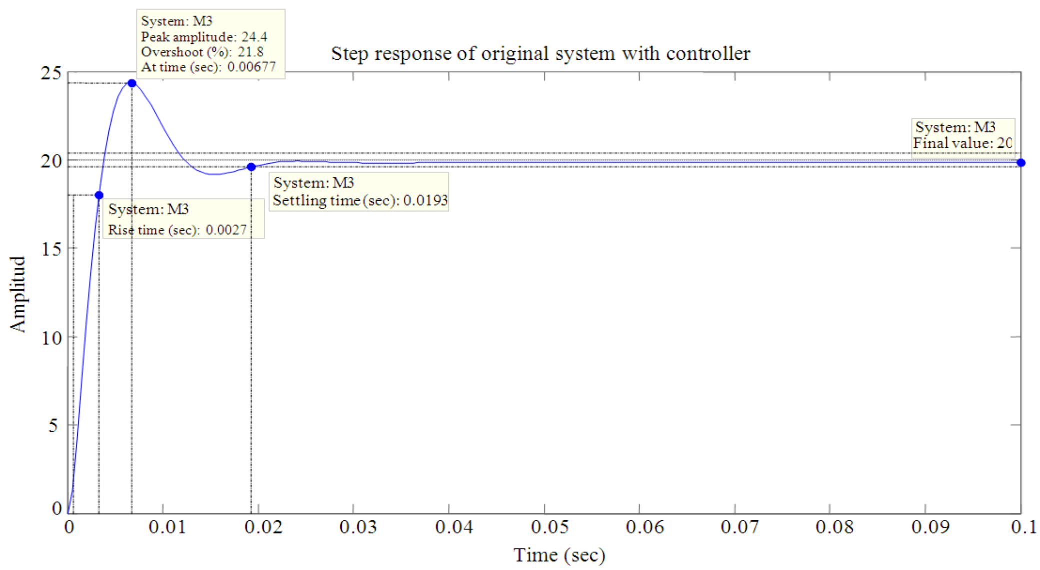

Fig. 9: Step response of original system with speed controller

Simulation results: The effectiveness of the newly proposed scheme for the design of PID Speed controller for PMSM drives are demonstrated using computer simulations. The system is simulated for step input using MATLAB-SIMULINK software with and without controllers (Chapman, 2002). The output responses of the above simulation studies are given in the following Figures.

Step response of original system: The step response of the PMSM drive system is shown in Fig. 7.

Step response of reduced system: The step response of the reduced order PMSM drive system is shown in Fig. 8.

Step response of original system with controller: The step response of the PMSM drive system with Speed controller by proposed method is shown in Fig. 9. Compared with PMSM drive with conventional speed controller it gives better performance as listed in Table 3.

Step response of reduced system with controller: The step response of the reduced order PMSM drive system with Speed controller by proposed method is shown in Fig. 10.

Step response of original system with conventional controller: Step response of original system with conventional speed controller of PMSM drive is shown in Fig. 11.

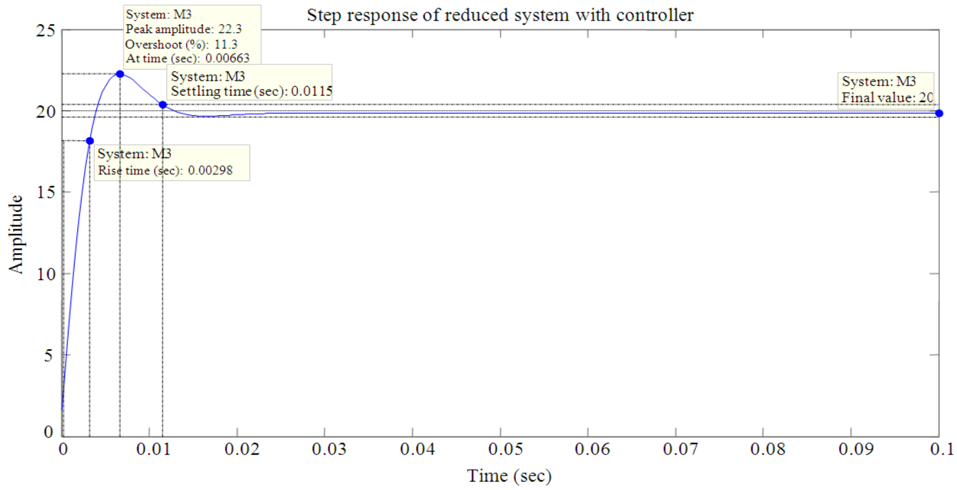

Fig. 10: Step response of reduced system with speed controller

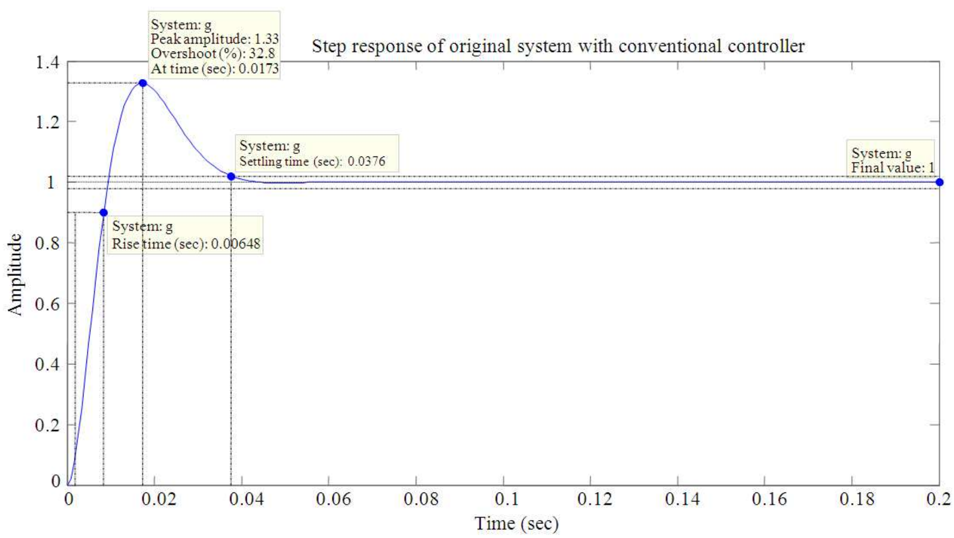

Fig. 11: Step response of original system with conventional speed controller

MATERIALS AND METHODS

For an ideal control performance by the PID controller, an appropriate PID parameter tunning is necessary (Oi *et al*., 2008). Mostly used PID controller tunning methods for drive controls are Zigler-Nichols method and symmetric optimum tunning method.These tunning methods are very simple, but cannot guarantee to be always effective. To surmount this inconvenience, optimization procedure may be used for the better design of controllers.

Genetic algorithm (GA) methods have been widely used in control applications.The GA method have been employed successfully to solve complex problems.The use of GA methods in the determination of the different controller parameters is effective due to their fast convergence and reasonable accuracy.This work the parameters of the PID speed controller is tuned using Genetic algorithm.

RESULTS

In this study, the performance of a PMSM drive with MOR based speed controller is evaluated on the basis of rise time, settling time and maximum overshoot. The performance of the drive system with MOR based controller has been improved as compared with the conventional PI speed controller (Singh, 2006). Table 3 gives the response of the drive system.

Table 3: Comparision of step responses of the system with and without controller for both proposed and conventional method of speed controller

Cases	Rise time (t_r) sec	Settling time (t_s) sec	Maximum overshoot (%)
Original system without controller	0.4430	0.7920	2.22×10^{-14}
Reduced system without controller	0.4440	0.7880	0.00967
Original system with proposed controller	0.0027	0.0193	0.00677
Reduced system with proposed controller	0.00298	0.0115	0.00663
Original system with conventional controller	0.00648	0.0376	32.80000

The simulation result (Fig. 9) shows that the response of the PMSM drive system with MOR based speed controller is better as compared to conventional method (Table 3). The speed control loop of the drive is simulated with a Conventional controller; in order to compare the performances to those obtained from the respective MOR based drive system (Rahman, 2003).

DISCUSSION

The dynamic and steady state performance of the MOR based speed controller for permanent magnet synchronous motor drive is much better than the Conventional PI speed controller. All the comparisons for the different cases are tabulated in Table 3.

CONCLUSION

The model order reduction method proposed in this study gives better approximated reduced order model for the given PMSM drive system. Because of this we get the reduced order system performance as close as possible to the higher order system response. This will result in reduction in design cost and system complexity. The method proposed in this study are applied for the Speed controller design of PMSM drive. This study focuses on the reduction of models it minimizes the complexity involved in direct design of PID Speed Controller. The approximate values for PID Controller parameters are calculated from the Genetic algorithm approach and suitably tuned to meet the required performance specifications. The tuned values of these controller parameters are attached with the original system and its closed loop response for a unit step input is found to be in good accord with the response of reduced order model.

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