Speed control of PMSM with Different Control Methods

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***Abstract*:**

PMSM are widely used in home appliances as well as industraial applications.This paper proposes the speed control of PMSM using LQR, Fuzzy LQR and ANN based LQR controllers. The linear quadratic regulator (LQR) is used as an optimal speed controller for PMSM drives. To confirm, which is the effective speed control technique, all the control techniques are simulated in MATLAB/ Simulink environment. From the experimental results it is clear that the the ANN based LQR method gives better performance compared to the other two techniques .it is validated that the ANN based LQR has the advantages of robustness, easy implementation and adequate performance in the face of uncertainties.

Keywords : *PMSM, LQR, FUZZY LQR,* and ANN *based LQR.*

I. INTRODUCTION

Nowadays Permanent magnet synchronous motors (PMSM) are widely used , because of its high performance, clear functionality and effectiveness. PMSM have very popularity in wide array of applications. Compared with DC motor and AC induction motor, the PMSM have the advantages, so it generates the rotor magnetic flux with rotor magnets, therefore it achieves higher efficiency. Therefore PMSM are used in electric and hybrid vehicles, high-end white goods like refrigerators, washing machines, dishwashers, high-end pumps, fans and in other appliances. In spite of , the PMSM system is not easy to control because it is a nonlinear multivariable system and its performance can be highly affected by parameters variations in the run time.

The proportional-integral-derivative (PID) controllers are the common choice of controlling the PMSM systems in industrial applications. Moreover., the big problem of the traditional PID controller is its sensitivity to the system parameter uncertainties. So adaptive control technique like variable structure control are introduced. Thus, speed controller is designed using LQR, fuzzy LQR and ANN based LQR controller. The theory of LQR controller is concerned with operating a dynamic system at minimum cost. The case where the system dynamics are described by a set of linear differential equation and the cost is described by a linear quadratic function is called the LQ problem. Fuzzy logic is based on human reasoning, providing algorithms which can convert a set of linguistic rules based on expert knowledge into an automatic control strategy.An artificial neural network is a massively parallel distributed processor made up of simple processing units, which has a natural propensity for storing experimental knowledge and making it available for use.

In recent years, for achieving high performance control in the non linear system LQR along with the soft computing techniques like Fuzzy and ANN are employed.The unknown non linear dynamics and load are captured by ANN.LQR ANN, which is the combination of both of two, so give improved performance. In this work ANN based LQR is proposed for the speed control of PMSM. The performance is compared with LQR and Fuzzy LQR, te result are analysed. The effectiveness of both the controllers are verified using the responses obtained from MATLAB/Simulink.

The organization of the rest of this paper can be summarized as follows.The modeling of PMSM is represented in Section II .SectionIII represents the LQR and ANN based LQR control of PMSM. SectionIV representthe simulation results. Conclusion based on the experimental work is given in Section V.

II. SYSTEM MODEL DESCRIPTION

The modeling of PMSM drive system is required for proper simulation of the system. The d-q model has been developed on rotor reference frame. Stator mmf rotates at the same speed as that of the rotor.

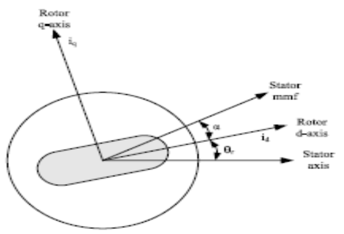

Fig 1 : Motor Axis

The assumptions made for the modelling of PMSM is given by,

1) Saturation is neglected.
2) The induced EMF is sinusoidal.
3) Eddy currents and hysteresis losses are negligible.
4) There are no field current dynamics.

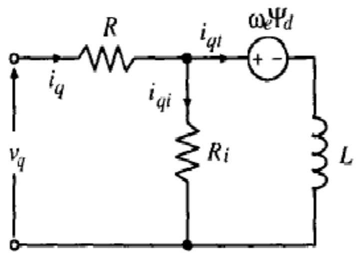

Fig 2 : Equivalent Circuit Along D Axis

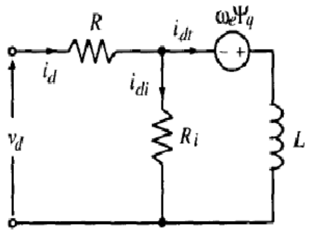

Fig 3 : Equivalent Circuit Along Q Axis

The voltage equations are given by,

$$V_d = R_d i_d + \frac{d\lambda_d}{dt} - \omega_r \lambda_q \quad (1)$$

Where λ_d and λ_q are the flux linkages. The electromagnetic torque developed is given by,

$$T_e = \frac{3}{2}\frac{p}{2}(\varphi_m i_q + (L_q - L_d) i_d i_q) \quad (2)$$

From the above equations the dq frame model is obtained as,

$$\frac{di_d}{dt} = \frac{v_d}{L_q} - \frac{R}{L_d} i_d + \omega_r \frac{L_q}{L_d} i_q$$

$$\frac{di_q}{dt} = \frac{v_q}{L_q} - \frac{R}{L_q} i_q - \omega_r \frac{L_d}{L_q} i_d - \omega_r \frac{\varphi_m}{L_q} \quad (3)$$

$$\frac{d\omega_r}{dt} = \frac{3p\,\varphi_m}{2J} i_q + \frac{3p}{2J}(L_q - L_d)\, i_d i_q - \frac{\beta}{J}\omega_r - \frac{T_L}{J}$$

Where i_d , i_q are direct and quadrature axis current, L_d , L_q are direct and quadrature axis inductances, R is the stator resistance and P number of poles.

The above PMSM is represented in state space form as,

$$\dot{x} = Ax + BU$$

$$y = Cx + Du$$

So the equation is in the form of,

$$\begin{bmatrix} \dot{\omega} \\ \dot{i}_{qs} \\ \dot{i}_{ds} \end{bmatrix} = \begin{bmatrix} \frac{-B}{J} & \frac{3}{2J}\frac{P^2}{4}\psi_m & 0 \\ \frac{\psi_m}{L_s} & \frac{-R_s}{L_s} & -\omega_0 \\ 0 & \omega_0 & \frac{-R_s}{L_s} \end{bmatrix} \begin{bmatrix} \omega \\ i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} \frac{-P}{2J} & 0 & 0 \\ 0 & \frac{1}{L_S} & 0 \\ 0 & 0 & \frac{1}{L_S} \end{bmatrix} \begin{bmatrix} T_L \\ V_{qs} \\ V_{ds} \end{bmatrix} \quad (4)$$

$$y = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \omega \\ i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_L \\ V_{qs} \\ V_{ds} \end{bmatrix}$$

where Vds, Vqs,&TL are the inputs and ω ,iqs & ids are the states to be measured.

III. LQR AND ANN BASEDLQR CONTROLLER DESIGN

A. LQR Controller Design

Linear quadratic regulator or LQR is the popularly used control technique to find the state feedback gain for a closed loop system. In LQR control the open-loop poles can be relocated to get a stable system with optimal control and minimum cost for given weighting matrices of the cost function.It is the optimal theory of pole placement method. To get the optimal gains, one should describe the optimal performance index and then solve algebraic Riccati equation.

Linear Quadratic Regulator, the Algebraic Ricatti Equation (ARE) given in the form of

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \quad (5)$$

where P is the symmetric positive-definite matrix. The regulator gain K is given by,

$$K = T^{-1}(T)^{-1}BP = R^{-1}B^{T}P \quad (6)$$

Then the cost function is,

$$J = \int x(t)^{T} Qx(t) + u(t)^{T} Ru(t)dt \quad (7)$$

where Q and R are the matrices, they are commonly tuned by trial and error method.The choice of the values of Q and R, the cost function is minimised.

1) Matlab Script file

```
A=[-1.111 4533.333 0 ;
   -26.5625   -134.375  -251.3;
       0  -251.3 -134.375];
B=[2222.222 0 0;
   0 312.5 0;
   0 0  312.5;
    ];
C=[0 1  0;
    0 0 0 ;
    0 0 0];

D=[ 0 0 0;0 0 0 ;0 0 0];
speed_ss=ss(A,B,C,D)
[NUM,DEN] = ss2tf(A,B,C,D,3)
NUM =1.0e+004 *[0    -0.0000    -
7.8531    -8.7248];
DEN =1.0e+007 *[0.0000    0.0000
0.0076    1.6131];
sys=tf(NUM,DEN)
Q = diag([20 100 10 ]);
R = [10 0 1;0 2 1;1 1 2];
K = lqr(A,B,Q,R)
sisotool(sys)
pole(sys)
zero(sys)
```

The output obtained by above program is ,

Gain, k = -1.1110

B. Fuzzy LQR

Fuzzy logic is a form of many-valued logic in which the truth values of variables may be any real number between 0 and 1, considered to be "fuzzy". The Fuzzy controller performance was equivalent to the LQR controller and sometimes it violated due to system uncertinities. Here Fuzzy supervisory controller of the gain matrix of the LQR control is employed.so the Fuzzy LQR gives better results by designing a Fuzzy Controller for each mode to be controlled and gain matrix estimated in the modal space. Since it is not necessary to solve the Ricatti equation and the number of variables is reduced. The suggestion of designing a supervisory Fuzzy controller for the LQR control showed little improvement in performance when compared to the simple LQR controller. Regarding the performance of Fuzzy controllers compared to LQR controller, as the gain matrix is fixed then the variations of the parameters of the system expected poor performance.Since the Fuzzy controller with estimated gain matrix added to the inertia forces, may increase vibration, in the event of changes in system parameters.

C. ANN based LQR Controller Design

In machines artificial neural network (ANN**)** are inspired by biological neural networks that is the central nervous systems(brain) of a human,which are used to estimate or approximate functions that can depend on a large number of inputs and they are generally unknown**.**

ANN based LQR is used to improve the gain matrix. ANN baesd LQR design approach can be effectively used for plants characterized by a non-stationary state matrix. A set of controllers is designed for different working points and an FFNN is employed to store this knowledge. The gain matrix K is then adjusted on the fly if the state matrix A changes. In the case of synchronous motors, some entries of the state matrix A are functions of stator inductance and load torque variations. It cange during the operating time due system parameter uncertinities.The combination of LQR and ANN based LQR gives good performance than the LQR controller used alone.

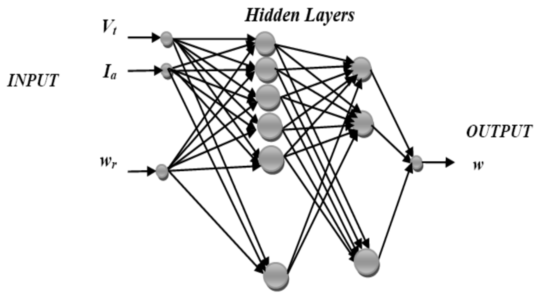

Fig 4.Artificial Neural Network

1) Training the NARMA-L2

NARMA-L2 (Nonlinear Autoregressive-Moving Average) neural controller requires very least computation and it's simply a rearrangement of the neural network plant model, which is trained off-line namely in batch form. The only online computation is a forward pass through the neural network controller [2].NARMA-L2 controller, a multilayer neural network has been successfully applied in the identification and control of dynamic systems[3]. Training is the process of the modifying the connection weights in some orderly fashion using a suitable learning method. The network uses a learning model, in which input is presented to the network along desired output. The weights after training contain meaningful information whereas before training they are random and no meaning

It is important that all the information, the network needs to learn is supplied to the network as a data set. When each pattern is read, the network uses the input data to produce an output, which is then compared to the training pattern, if there is difference, the connection weights are altered in such a direction that the error is still greater than the maximum desired tolerance, the ANN runs again through all the input patterns repeatedly until all the errors are within the required tolerance. The trained network can then be used to make decisions, identify patterns, or define associations in new input data sets which are not trained.

IV. SIMULATION RESULTS

Simulations have been carried out for the speed control of PMSM with LQR, Fuzzy LQR and ANN based LQG controllers. The motor parameters used for simulation purpose are given in table 1.

Table 1 PMSM Parameters

Parameters	Values
Trated	2.4Nm
N	8
Rs	0.43 ohm
Ls	3.2mH
φ_m	0.085V-s/rad
J	0.0018kg-m2
B	0.0002 N-m-s/rad

First section discuss about the speed control of pmsm with ordinary LQR controller. The simulation block is shown in Fig 5. The desired speed is choosen as 251.3 rad per seconds.

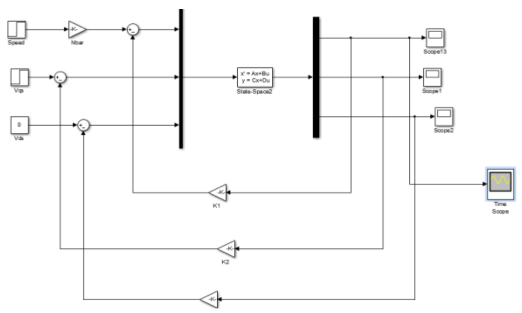

Fig.5. Simulink Model of PMSM with LQR Controller

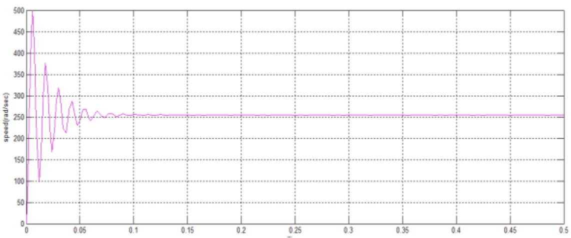

Fig.6 **Simulation** Result of PMSM with LQR Controller

In fig 6 ,it can be shows that the motor speed settles down at the reference value of 251.3 rad/sec in 20.670 ms with a high oscillation or overshoot. From the plot for the output of the speed controller it is observed that there exist sudden spikes and dips around the instant when the motor speed has reached its reference value. The maximum peak overshoot is about 251.016.

fig 7 shows the Fuzzy LQR based system.From the simulation result shown fig8 says that, its behaviour such as rise time , peak overshoot and settiling time are improved than previous controller.

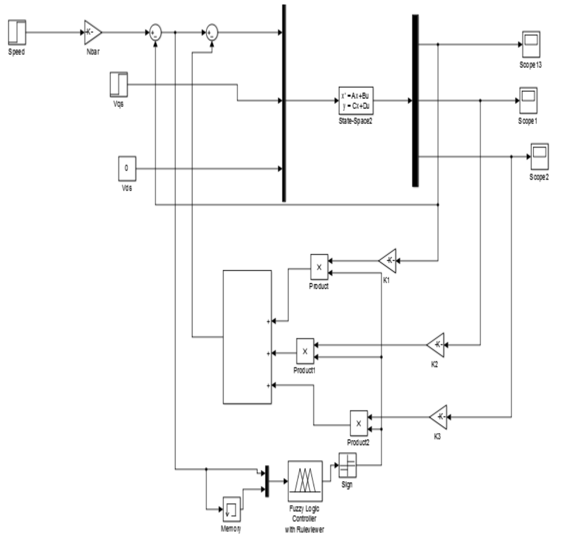

Fig.7. Simulink Model of PMSM with Fuzzy LQR Controller

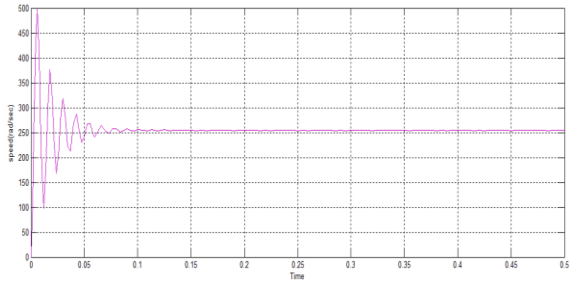

Fig.8 Simulation Result of PMSM with Fuzzy LQR Controller

Fig.9 shows the fis editor. Here the learning method used are Mamdani method.

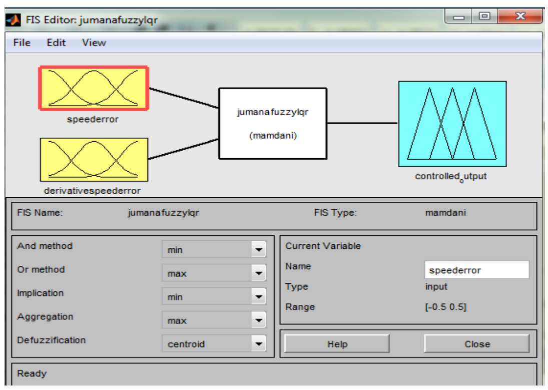

Fig.9 Fis Editor.

Control methods	Maximum Peakovershoot (%)	Settling time (ms)	Rise time (ms)
LQR Controller	98.66	335.331	1.213
Fuzzy LQR Controller	160.040	303.212	1.165
ANN LQR Controller	99	145.014	1.841

Table 2 Comparison of Parameters with Different Controllers

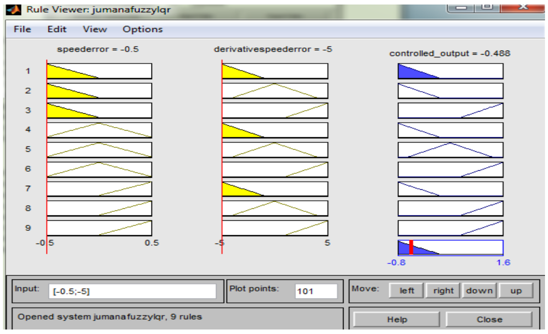

Fig.10 Rule Base

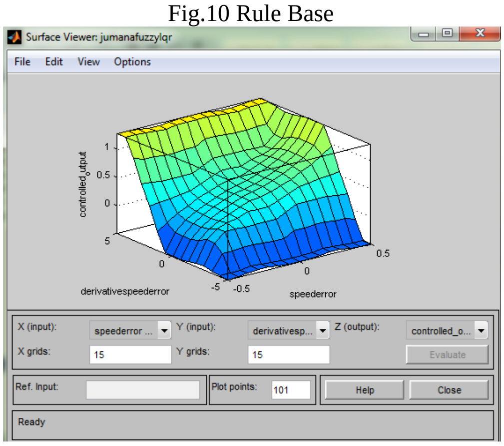

Fig.11 Surface Viewer

Fig 10 & 11 shows the rule base and surface viewer accordingly. Based on these rules Fuzzy woeks properly.

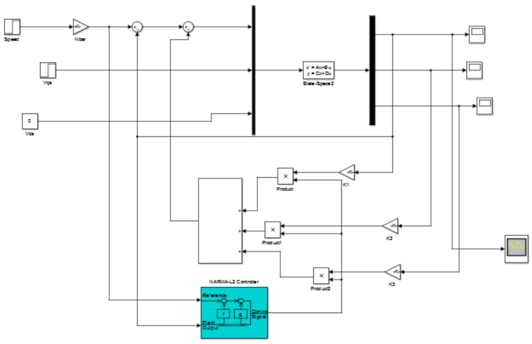

Fig.12 Simulink model of PMSM with ANN based LQR Controller

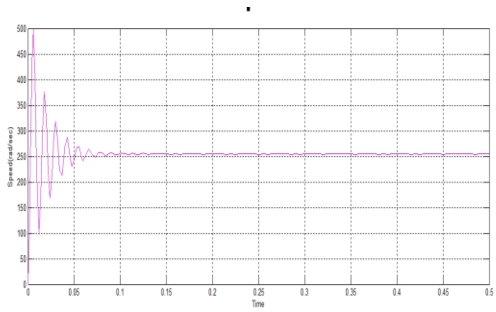

Fig.13 Simulation result of PMSM with ANN based LQR

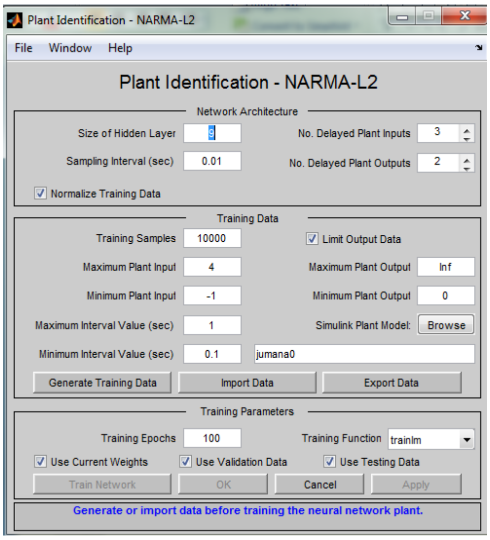

Fig.14 NARMA-L2 Controller

Fig 6, 8 and 13 show the simulation results of the LQR, Fuzzy LQR and ANN LQR Controller. All of them are accurately tracked to the desired value. Fig 14 shows the Narma-L2 ,which acurately control the ANN based LQR sysyem.

The parameters obtained from the speed response curve are given in Table 2. It is clear that peak overshoot and settling time is less for ANN based LQR whereas rise time is less for Fuzzy LQR controller.

V. CONCLUSION

From the simulation results, it is clear that ANN based LQR achieves good performance in the speed response of the PMSM. Here the state feedback gain matrix is formulated and modification of gain done by using fuzzy and ANN networks. To improve the transient response of PMSM in terms of rise time, overshoot, settling time and steady-state error,the adaptation gains are tuned properly.

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