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IMPLEMENTATION OF NEURO-FUZZY CONTROLLER FOR PMSM DRIVE FOR WATER PUMPING APPLICATION

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Abstract **– This paper presents the design and development of a Neuro-Fuzzy controlled PMSM (Permanent Magnet Synchronous Motor) drive used to drive a Centrifugal pump. A new approach to speed control of PMSM using space vector pulse width modulation (SVPWM) technique is presented using MATLAB/Simulink platform to implement a neuro-fuzzy logic control.**

Keywords **– PMSM, Centrifugal Pump, Neuro-Fuzzy Control, SVPWM.**

I. INTRODUCTION

According to recent information within the European Union, electric drives consume about 70 percent of the total power produced. Pump systems are one of the major sectors of the chemical industries, gasoline, irrigation networks, and water distribution system. The Pump and pumping systems consume from 10 to 40 percent of total power generated [1]. Using variable speed drive in such applications is an energy efficient solution to achieve an optimal flow rate for these applications. PMSM (Permanent Magnet Synchronous Motor) is broadly used in industries, EV (Electrical Vehicles), robots etc. Its requirement is increasing incessantly from the few decades. The main reason is due to its higher efficiency, large torque to volume ratio, reliability in action, and simple construction. Due to massive available saving opportunities of energy in the pump system, different study results are suggestive for increasing performance of the controller in the pump system.

Present days, the flow rates of the pumps are controlled through PMSM motor for desired flow requirement. Various control techniques are available for PMSM to control flow rate of pump system. Among them, the conventional control schemes are proportional Integral Derivative(PID), proportional Integral (PI) and proportional Derivative (PD), adaptive PI needs more time to stabilize the controller action and also very sensitivity to parameter variations [2]. Other controls shift operator control and delta for higher speeds [3]. So in 1993 Jang developed an unique control methodology which is combination of fuzzy logic and neural network. Neuro-Fuzzy may be a fuzzy structure that uses culture data developed from or encouraged by neural network hypothesis to regulate as its parameters (fuzzy sets and fuzzy rules) by dealing with samples of data. A Neuro-fuzzy structure can be out looked at as a three-layer feed forward neural network. Such controllers are examined as potential candidates for such an application.

II. METHODOLOGY

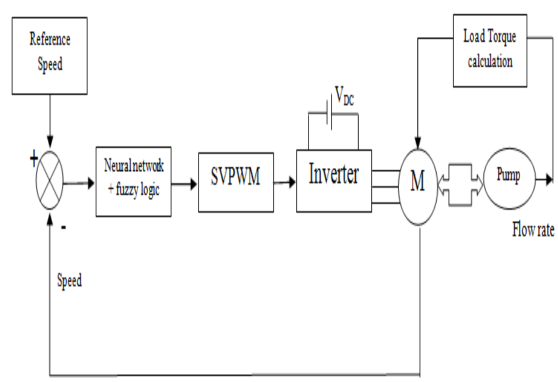

Figure 1: Block Diagram for proposed System

The DC voltage is fed to the inverter and the output of the inverter is three-phase AC and is supplied to PMSM motor. The Centrifugal pumping system is coupled with motor and flow rate is fed back the value to get the desired load torque. By using a speed control loop the Neuro-Fuzzy control system the

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necessary voltage space vector generation is achieved for the inverter.

III. MATHEMATICAL MODELLING OF PMSM

PMSM is broadly used in industries, EV (Electrical Vehicles), robots etc. Its requirement is increasing incessantly from the few decades. The main reason is due to its higher efficiency, large torque to volume ratio, reliability in action, and simple construction.

Assumptions made:

1. Neglect the Magnetic Saturations.
2. The induced EMF is sinusoidal.
3. Hysteresis losses and circulation of Eddy currents are neglected.

The stator q-axis and d-axis voltages for PMSM is written as,

$$V_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q \quad (1)$$

$$V_d = R_s i_d - \omega_r \lambda_q + \rho \lambda_d \quad (2)$$

Flux linkages are given by,

$$\lambda_d = L_d i_d + \lambda_f \quad (3)$$

$$\lambda_q = L_q i_q \quad (4)$$

Electromagnetic Torque and Speeds are expressed as,

$$T_e = \frac{3}{2} * \frac{P}{2} * (\lambda_d i_q - \lambda_q i_d) \quad (5)$$

$$\omega_m = \frac{1}{J} * \int (Te - Tl - B\omega r) \quad (6)$$

Where, Voltages V_q and V_d are q and d reference frame voltages (V),Currents i_q and i_d are q and d reference frame currents (A),Inductance L_q and d_q are q and d reference inductances (H) ,R_s= Stator resistance (Ω) ,ρ=d/dt, J=Rotational inertia (Kg.m^2) Te= Electromagnetic Torque (N-m) , ω_m= Rotor Speed (rpm), B= Friction coefficient (N-m-s).

IV. NEURAL NETWORK AND FUZZY LOGIC CONTROL TECHNIQUE

Neural Network Controller

A network which is composed of chemically connected group or groups of neurons. The network's processing capability is stored within the strengths, or weights inter-unit association, obtained through a process of adoption or learning from a gaggle of instructing sequences. Figure.2 shows a multi-input neuron .A neurons with M inputs and individual inputs N_1, N_2,……..$N_{1, M}$ of the neuron bias b, the load matrix W which is summed up with weighted inputs to effectively obtain input n. n= WM + b.

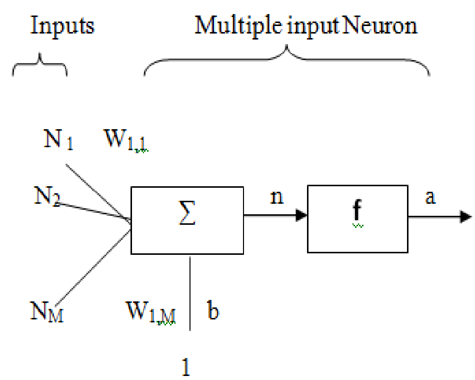

Figure 2: Multi Input Neuron Network

Where, there is just one row matrix W for the neuron case. Now often the output is written as,

a= f (WN + b).

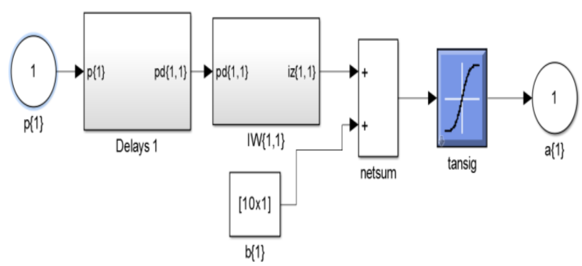

Figure 3: Proposed Neural Network

The input layer is an error in speed; the neural network built to monitor the speed of this drive with input layers, hidden layers and one output layer. Either tansig or logsig functions can be used for the hidden layers. Neural network output is fed as error and delta error (change in error) for fuzzy logic to get multiplication factor of desired voltage level.

Fuzzy Logic Controller

Fuzzy logic control (FLC) is a technique of linguistic control based on information that the system is controlled automatically. The FLC does not need significant mathematical model equations, in contrast to other control techniques. Using the FLC complex model can be regulated without understanding the specific mathematical model. The FLC module is composed of the following process control units.

• Converting Crisp value into fuzzy set (Fuzzification)

• Knowledgebase

• Converting fuzzy set crisp value (Defuzzification)

In fuzzification, the fuzzy reasoning utilizes fuzzy sets, and the control action is performed according to the fuzzy inputs. In the knowledge base, the "if-then" control rules are patterned to support fuzzy logic to achieve control action. The significant process is the design of membership functions for input and output in the fuzzy reasoning module.

In defuzzification, transforms the fuzzy set into crisp values. The output of the neural networks are the inputs for the FLC i.e, error and delta error (change in error) with the five and three membership functions respectively as shown. The error and delta error are the inputs, and the voltage reference multiplication factor is the FLC output.

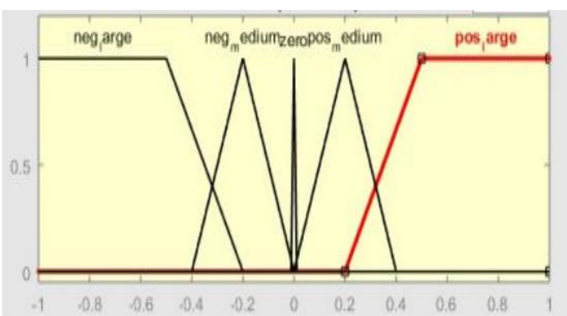

Figure 4: Error membership functions

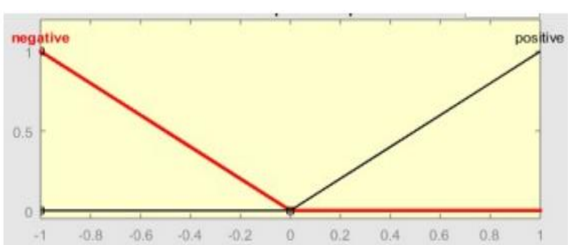

Figure 5: Delta error membership functions

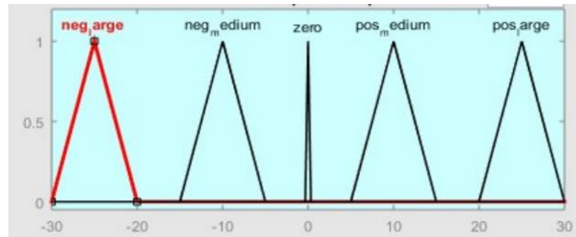

Figure 6: Control membership functions

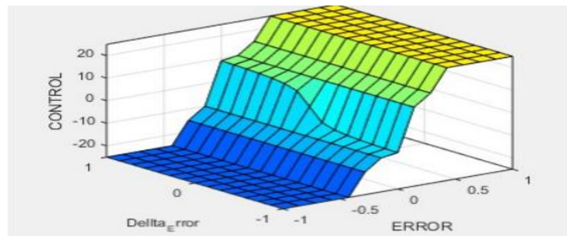

Figure 7: Fuzzy Logic Surface

V. SPACE VECTOR PULSE WIDTH MODULATION

A typical 3-phase VSI is shown below for PMSM drive control by SVPWM. The methodology behind SVPWM is to take as the standard ideal flux and response it from the actual flux generated by the 8 switching states of the inverter. It is achieved by the switching of 6 IGBT switches. The inverter can have 8 output vector spaces, depending upon the 8 switching combinations. 6 out of 8 produce a non-zero state, remaining two produce zero state output. Thus there are six sectors from 1-6.

The maximum RMS line to line voltage is 0.707Vdc and phase voltage is 0.408Vdc these values are 1.15 times are higher than what a standard SPWM technique can generate.

In the SVPWM approach reference or desired voltage space vector V_{ref} is generated with the necessary switching time from zero vectors and adjacent space vectors. The steps for implementing the SVPWM algorithm are explained below:

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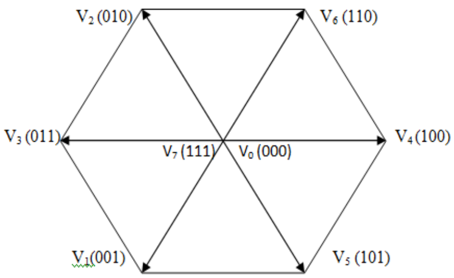

Figure 8: Space Vector Trajectory

Step 1: Judgment of sector

Vref sector can be determined based on the relationship between Vα, Vβ in each sectors decided as follows:

If $V_\beta > 0$, Then X=1, else X=0

$\sqrt{3}\, V_\alpha - V_\beta > 0$, Then Y=1, else Y=0

$-\sqrt{3}\, V_\alpha - V_\beta > 0$, Then Z=1, else Z=0

Now, N= X+2Y+4Z

1-D input value as [1 2 3 4 5 6] and output value as [2 6 1 4 3 5] lookup table can be used to find the sector number N.

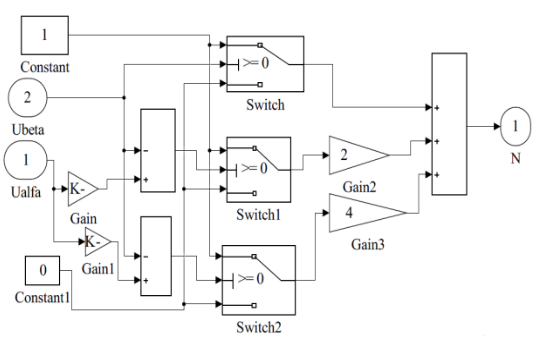

Figure 9: Judgment of Sector

Step 2: Determination of Switching time for Vectors calculation T_k and T_{k+1} . T_k and T_{k+1} represents the operating time of the corresponding voltage vector in the sector, k. The operating time can be determined as in the following step:

$$A=\sqrt{3}\,\frac{T}{V_{dc}}V_\beta$$

$$B=\frac{3}{2}\frac{T}{V_{dc}}\left(V\alpha+\frac{1}{\sqrt{3}}V_\beta\right.$$

$$C=\frac{3}{2}\frac{T}{V_{dc}}\left(\frac{1}{\sqrt{3}}V_\beta - V_\alpha\right)$$

Here, T represents the total switching period. Mean while the operating time could be observed in table.

Table 1: Determination of T_k and T_{k+1}

Sector No.	**1**	**2**	**3**	**4**	**5**	**6**
T_k	**-C**	**B**	**A**	**C**	**-B**	**-A**
T_{K+1}	**A**	**C**	**-B**	**-A**	**-C**	**B**

It must be interpreted that the total sum of T_k and T_{k+1} should be less than T. There are some modifications to be made if the summation is greater than zero, then modifications are: $T_k = T_k T/(T_k+T_{k+1})$, and $T_{k+1} = T_{k+1} T/(T_k+T_{k+1})$. The Simulink model is in figure10.

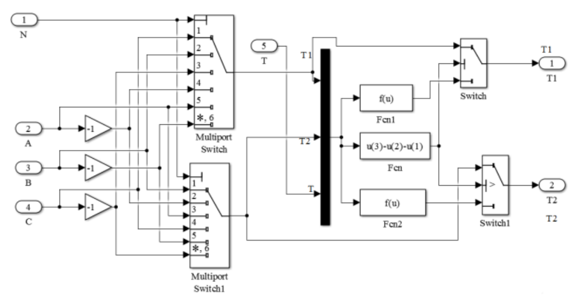

Figure 10 : Determination of Operating Time for Vectors

Step 3: There is need for finding out the switching points for symmetrical PWM sequence. The switching points for vectors will be computed as in the following step:

$$T_a = \frac{1}{4}(T - T_k - T_{k+1})$$

$$T_b = T_a + \frac{1}{2}T_k$$

$$T_c = T_b + \frac{1}{2}T_{k+1}$$

Table 2 shows the switching points for vectors for the T_{cm1}, T_{cm2} and T_{cm3}.

Table 2: Switching Points for Vectors

Vector Switching Points	Sectors 1	2	3	4	5	6
T_{cm1}	T_a	T_b	T_c	T_c	T_b	T_a
T_{cm2}	T_b	T_a	T_a	T_b	T_c	T_c
T_{cm3}	T_c	T_c	T_b	T_a	T_a	T_b

The figure.11 Shows the simulink module to determine switching points.

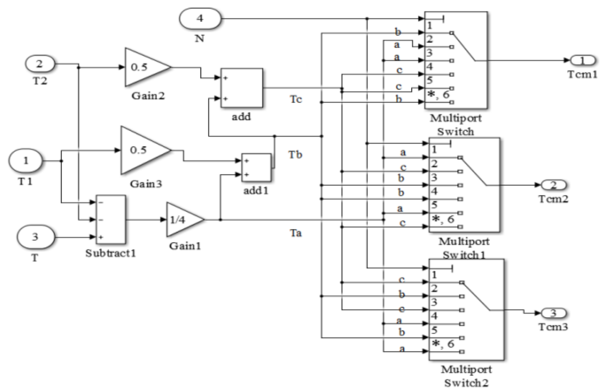

Figure 11: Switching points for vectors.

Step 4: PWM switching pulse generation now, T_{cm1}, T_{cm2} and T_{cm3} and triangular wave are compared to generate PWM pulses. PWM1, PWM3, PWM5 are the pulses and PWM2, PWM4, PWM6 are the complementary pulses. This is done by NOT logic gate operation. The symmetrical space vector PWM waveform is now generated and is employed in three phase voltage source inverter.

VI. RESULTS AND DISCUSSION

Table 3 lists the parameter values taken for simulation of PMSM.

Table 3: PMSM and Pump parameters

Parameter	Value	Units
DC Voltage	440	V
Stator Resistance(R_s)	13	Ω
d-axis Inductance(L_d)	3	mH
q-axis Inductance(L_q)	3	mH
Rotational Inertia (J)	40e-6	Kg-m^2
Number of Pole pairs(P)	2	
Damping co-efficient(B)	0.00124	N-m-s
Head level(H)	30	M
Pump efficiency(η)	0.75	

The pumping system simulations were carried out in MATLAB to verify results and its effectiveness. The speed and flow rates are for plotted for different cases.

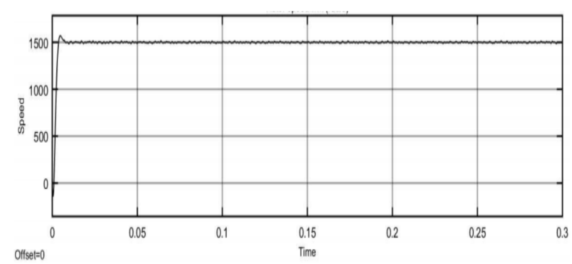

Figure 12.a: Speed 1500rpm

The above figure shows the speed (1500rpm) response of using Neuro-Fuzzy controller with rising time of 0.005s, settling time of 0.012s and peak overshoot of 3.93%.

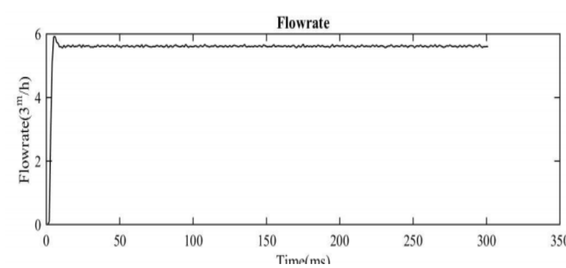

Figure 12.b: Flowrate of 5.88m^3/h for 1500rpm

The above figure shows the water flowrate from the centrifugal pump is 5.88m^3/h for the speed of (1500rpm).

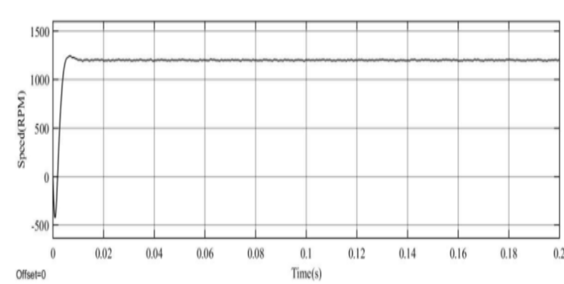

Figure 12.c: Speed 1200rpm

The above figure shows the speed (1200rpm) response of using Neuro-Fuzzy controller with rising time of 0.007s, settling time of 0.012s and peak overshoot of 3.6%.

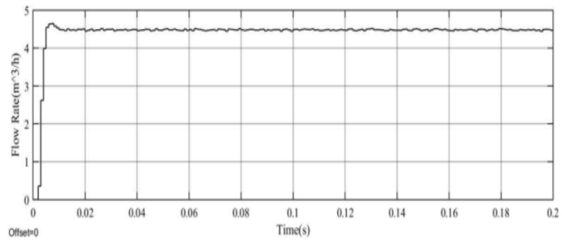

Figure 12.d: Flowrate of 4.5m^3/h for 1200rpm

The above figure shows the water flowrate from the centrifugal pump is 5.88m^3/h for the speed of (1500rpm). It can be seen that, the speed and flowrates are directly proportional as speed increases, flowrate also increases.

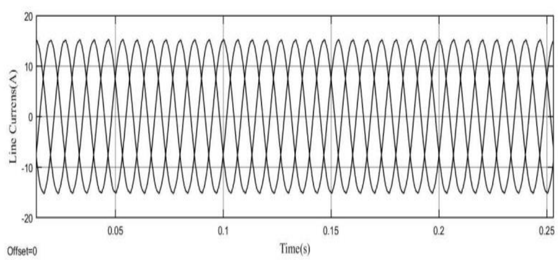

Figure 13: Three phase stator currents

The figure.13 shows the three phase sinusoidal stator currents for the PMSM drive and that the currents are free from harmonics.

From reference [5], comparison is done on PID based PMSM control system and proposed control system. In PID controller only for one particular speed is controlled but in case of Neuro-Fuzzy control system can be used for wide range of speed application. From the literature [5], the speed response using FO-PID (Fractional Order PID) controller is achieved with the rising time (t_r) of 0.172s, settling time (t_s) of 0.237s and peak overshoot of 4.71% and the speed response with the IO-PID (Integer Order PID) is achieved with the rising time (t_r) of 0.167s, settling time(t_s) of 0.332s and peak overshoot of 8.16%. By Neuro-Fuzzy controller the speed response is achieved with the rising time (t_r) of 0.005s, settling time of 0.012s and the peak overshoot of 3.93%.

VII. CONCLUSION

The controller for the centrifugal pumping system's flow rate control was successfully. Farmers need to concentrate on sustainability, which involves energy efficiency and efficient use of water supplies, to keep production up and stay competitive in the market. Pumping systems are crucial in the provision of optimized electricity and water solutions.

This paper mainly focuses on performance analysis of neuro-fuzzy controlled PMSM for pumping systems for which improved performance is found when compared to the performance of conventional controllers. This method reduces the computational time, fast learning, and less error. It is considered as a set of rules capable of being modified through learning and with the possibility to construct the process from scratch. It can be updated in the form of fuzzy inference and based on prior knowledge. Thus a proper design of the neuro-fuzzy can controller replaces other conventional controllers.

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