IJCSE International Journal of Computer Sciences and Engineering Open Access
Research Paper **Volume-3, Issue-12** **E-ISSN: 2347-2693**

Response Based Tunning of Proportional and Integral Constants in PI Controlled Six Phase PMSM Drive

[1*]Anurag Singh Tomer, [2]S.P.Dubey

[1]Department of Electrical Engineering. IGKV, RAIPUR(C.G.)*
[2]Department of Electrical Engineering, RCET, BHILAI(C.G.)

www.ijcseonline.org

Received: 22/Nov/2015 Revised: 05/Dec/2015 Accepted: 22/Dec/2015 Published: 31/Dec/21015

***Abstract*—** This paper deals with the modeling of six phase Permanent Magnet Synchronous Motor (PMSM) which has been done with the aid of Matlab and then the complete drive system is designed which consists primarily of two inverter and a Proportional integral controller. Proportional-Integral controller is most commonly used in drives system. The combination of proportional and integral is important to increase the speed of response and also to eliminate the steady state error.It also gives the reason of choosing six phase over three phase and superiority of PMSM with other motors like DC motors and Induction motor. Performance analysis with Manual tunning of proportional (Kp) and integral (Ki) constant is studied which shows the best suited value of Kp and Ki in the drive system by of these values.

***Keywords*—** Multiphase, Permanent magnet synchronous motor (PMSM), PI controller, Proportional constant (Kp) and Integral constant (Ki)

I. INTRODUCTION

Multiphase variable speed drive has received growing interest because of several advantages of multiphase and superiority of PMSM drive system over other drive system. This growing interest is due to the fact that this machine can provide significant improvements in various facets of performance as compared to traditional three phase motor and multi phase induction Motors.Historical technical reasons that required adopting the multiphase drive solution instead of three-phase are listed below [1,2,3,4,5,6]:-

1) Reduces the stator current per phase.
2) Improved reliability.
3) Reduced pulsating toques produced by time harmonic components in the excitation waveform.
4) Fault tolerant drives.
5) Higher degree of freedom.

The main application areas of multiphase machines specially motor drives are ship propulsion, traction (including Electric and hybrid electric vehicles) and the concept of More-electric "aircraft. In addition the other suitable applications are Locomotive traction, aerospace and high power Applications.

The commonly used controller to control the operation of a drive system is a proportional and integral cotroller, it improves steady state accuracy by decreasing the steady state errors, reduces the offsets produced in the system, Maximum overshoot of the system can be easily controlled, Slow response of the over damped system can be made faster with the help of these controllers.

II. THREE PHASE DRIVES VS. SIX PHASE DRIVES

As stated above at point no.1, related to high-power applications with current limited devices. For a given motor power, an increase in phase number determines a reduction in Power per phase, enabling the use of smaller power electronic devices in each inverter leg, without increasing the voltage per phase.

The improved reliability features, listed at point no.2, enable their use also in faulty conditions; in fact if one phase of a multiphase machine becomes open circuit, the machine is able to self-start and to run with only a de-rating.

Finally, the advantages derived from statement at point no.3 Time-harmonic of voltages and currents introduced by this operation-mode produced low frequency torque ripple, leading to difficulties on speed control and noise production. Since in a n-phase machine torque pulsations are caused by supply time-harmonics of the order $2n\pm1$, which result in torque ripple harmonic $2n$ times higher than the supply frequency, an increase in the number of phases seem the best solution to the problem.

As stated at point no.4.The increased number of phases in multiphase drives offers considerable benefits because of the capability to continue operation when a single or multiple phase loss occurs [1,2,3].

Three-phase drive is sensitive to different kinds of faults, both in motor phase and in inverter leg. When one of these faults does occur in one phase, the drive operation has to be stopped for a non-programmed maintenance schedule. The motor in faulty conditions is able to run but it is not still self-starting. The cost of this schedule can be high, thus justifying the development of fault tolerant motor drive systems. On the other hand, multiphase machines in post-fault condition can continue to be operated with an asymmetrical winding structure and unbalanced excitation, producing a higher fraction of their rated torques with little pulsations when compared to the three phase machines.

III. SUPERIORITY OF PMSM MOTOR

Two types of permanent-magnet ac motor drives are available in the drives industry. These are Permanent Magnet Synchronous Motor (PMSM) drives with sinusoidal flux distribution and the brushless DC Motor (BLDC) drive with trapezoidal flux distribution [1-2]. Availability and competitive prices of high energy-density permanent magnet (PM) materials accompanied by powerful fast digital signal processors and micro-controllers with the outstanding advances in semiconductor switches and modern control technologies have opened up new possibilities for permanent magnet /brushless motor drives in order to meet competitive worldwide market demands. In addition to this PMSM have several advantages over the DC brush motor and induction motor for low power application. (Listed below)

PMSM have the following advantages over DC Motors:-
Less audible noise, longer life, Spark less (no fire hazard)
Higher speed, higher power density and smaller size, Better heat transfer [3,7,8,9,10,11]
PMSM have the following advantages over Induction Motors:-
Higher efficiency, Higher power factor, Higher power density for lower than 10 KW applications, resulting in smaller size
Better heat transfer [4-10].

IV. MODELLING OF SIX PHASE PMSM

In developing the mathematical model the following assumptions are made[11]:

- The set of stator windings are symmetrical.
- The capacitance can be neglected.
- Each distributed windings may be represented by a concentrated winding.
- The change in the inductance of the stator windings is sinusoidal and free from higher harmonics.
- Hysteresis loss and eddy current losses are neglectwd.
- The magnetic circuits are linear (not saturated) and the inductance values do not depend on the current.

In this study, a six-phase PMSM with two three-phase Windings is adopted where *ABC* winding is spatially 30 electrical degrees phase led to *XYZ* winding [12,13].

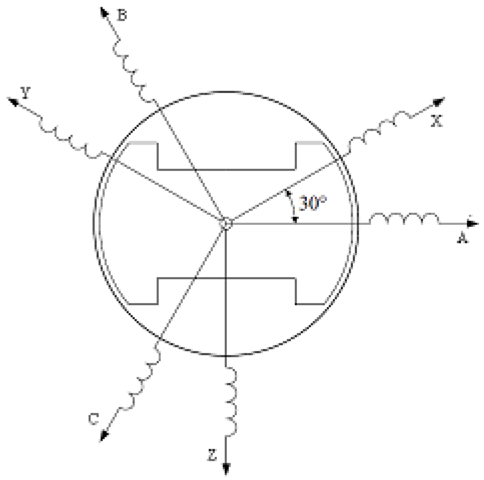

Figure-1 Six- Phase PMSM Motor (Stator winding)

The phase voltage and flux linkage equations in the stationary reference frame for *ABC* winding and *XYZ*winding of six-phase PMSM are shown as:

$$V_{ABC} = R_S I_{ABC} + \frac{d\phi_{ABC}}{dt} \tag{1}$$

$$\phi_{ABC} = L_{11} I_{ABC} + L_{12} I_{XYZ} + \phi'_{MABC} \tag{2}$$

$$V_{XYZ} = R_S I_{XYZ} + \frac{d\phi_{XYZ}}{dt} \tag{3}$$

$$\phi_{XYZ} = L_{22} I_{XYZ} + L_{21} I_{ABC} + \phi'_{MXYZ} \tag{4}$$

Where Rs = diag [Rs, Rs, Rs]^T is the stator resistance vector; $V_{ABC}=[V_A\ V_B\ V_C]^T$ is the phase voltage vector of abc winding; $I_{ABC}= [i_A\ i_B\ i_C]^T$ is the current vector of ABC winding; Vxyz=[Vx Vy Vz]^T is the phase voltage vector of winding; $i_{XYZ}= [i_x\ i_y\ i_z]^T$ is the current vector of XYZ winding;$Ø_{ABC}=[Ø_A\ Ø_B\ Ø_C]^T$ is the stator flux linkage vector of win ABC ding; $Ø_{XYZ}=[Ø_X\ Ø_Y\ Ø_Z]^T$ is the stator flux linkage vector of *xyz* winding; $\mathbf{L_{11}}$ is the stator inductance vector of win ABC winding;L_{22} is the stator inductance vector of *XYZ* winding; $\mathbf{L_{11}}$ and $\mathbf{L_{22}}$ are the mutual inductance vectors; $Ø'_{MABC}$' is the permanent-magnet flux linkage vector of ABC winding; $Ø'_{MXYZ}$ is the permanent-magnet flux linkage vector of *XYZ* winding[14,15,16].
In order to control the six-phase PMSM, the following Transformation matrixes have been used to transfer the above equations into the synchronous rotating reference frame:

$$Tqd\ 1 = \frac{2}{3}\begin{bmatrix} \cos\ \theta_e & \cos(\ \theta_e - 120\ ^0) & \cos(\ \theta_e + 120\ ^0) \\ \sin\ \theta_e & \sin(\ \theta_e - 120\ ^0) & \sin(\ \theta_e + 120\ ^0) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (5)$$

$$Tqd\ 2 = \frac{2}{3}\begin{bmatrix} \cos(\ \theta_e - 30^0) & \cos(\ \theta_e - 150^0) & \cos(\ \theta_e + 90^0) \\ \sin(\ \theta_e - 30^0) & \sin(\ \theta_e - 150^0) & \sin(\ \theta_e + 90^0) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (6)$$

where T_{qd1} is the transformation matrix for *ABC* winding; $T_{qd\,2}$ is the transformation matrix for *XYZ* winding; θ*e* is the rotor flux angle[15]. Moreover, the machine model of a six-phase PMSM can be described in synchronous rotating reference frame as follows

$$v_{q1} = R_s I_{q1} + L_{q11}\frac{dI_{q1}}{dt} + \omega_e(L_{d11}I_{d1} + \phi_{PM}) \qquad (7)$$

$$v_{d1} = R_s I_{d1} + L_{d11}\frac{dI_{d1}}{dt} - \omega_e L_{q11} I_{q1} \qquad (8)$$

$$v_{q2} = R_s I_{q2} + L_{q22}\frac{dI_{q2}}{dt} + \omega_e(L_{d22}I_{d2} + \phi_{PM}) \qquad (9)$$

$$v_{d2} = R_s I_{d2} + L_{d22}\frac{dI_{d2}}{dt} - \omega_e L_{q22} I_{q2} \qquad (10)$$

$$\omega_e = \frac{P}{2}\omega_r \qquad (11)$$

where v_{d1} and v_{q1} are the *d-q* axis voltages of *ABC* winding; $v_{d\,2}$ and v_{q2} are the *d-q* axis voltages of *XYZ* winding; i_{d1} and i_{q1} are the *d-q* axis currents of *ABC* winding; i_{d2} and i_{q2} are the *d-q* axis currents of *XYZ* winding; L_{d11} and L_{q11} are the *d-q* axis inductances of *ABC* winding; $L_{d\,22}$ and L_{q22} are the *d-q* axis inductances of *XYZ* winding; ω_r is the rotor angular velocity; ω_e is the electrical angular velocity;$Ø_{PM}$ is the permanent magnet flux linkage; p is the no.of pole pairs of six phase PMSM. As assumed that winding sets are identical (L_{q11}=L_{q22}= L_q and L_{d11}=L_{d22}= L_d). Furthermore, the developed electric torque *e Te* can be represented by the following equation:

$$T_e = \frac{3}{2}\frac{P}{2}\left[\phi_{PM}\left(I_{q1} + I_{q2}\right) + \left(L_d - L_q\right)\left(I_{d1}I_{q1} + I_{d2}I_{q2}\right)\right] \qquad (12)$$

However, the electromagnetic torque cannot be estimated accurately in a general case without knowledge of the currents of both winding sets and the inductance parameters that describe the magnetic coupling between them.

In addition, the mechanical dynamic equation of the six-phase PMSM is:

$$T_e = J\frac{d\omega_r}{dt} + B\omega_r + T_L \qquad (13)$$

Where *J* is the inertia of six-phase PMSM; *B* is the damping Coefficient; *L T* is the load torque.[14,15,16].

V. MACHINE PARAMETER AND MODEL

The Six phase PMSM parameter and model is given in following table:1 and diagram for simulation purpose [14,15,17].

Table:1

S.No.	Name	Rating
1.	Nominal voltage *Vn*	380 volts
2.	Nominal speed *nn*	350RPM(36.5rad/s)
3.	No.of Poles	8
4.	Stator Resistance Rs	0.64 ohm
5.	PM flux Linkage $Ø_{PM}$	2.04 wb
6.	Ld,Lq	24mH,31.4mH
7.	Inertia J	.014Nm/(rad/sec^2)
8.	Damping coefficient B	.0124Nm/(rad/sec)

(a) Machine Parameter

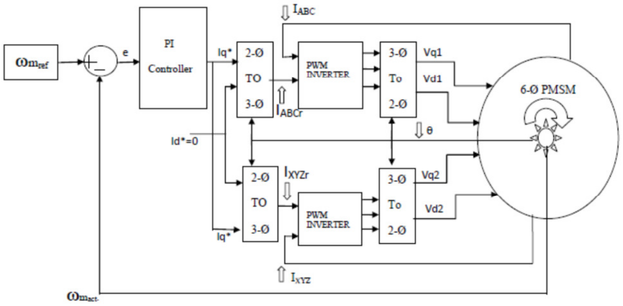

Figure-2 Six-Phase PMSM model

VI. PROPORTIONAL-INTEGRAL CONTROLLER

The PI controller produces an output signal consisting of two terms-one proportional to input signal and the other proportional to the integral of input signal. The concerns of PI controller in the system are to reduce the steady state error and increased the order and type of the system by one which is shown in Fig.3.

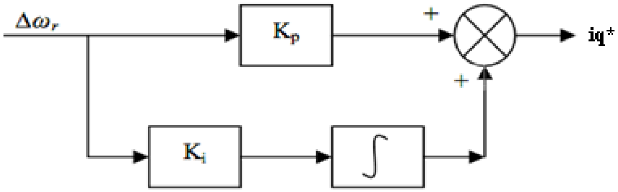

Figure 3: PI controller

Transfer function $PI = K_p + \frac{K_i}{S}$ (14)

$$i_{q*} = K_p \Delta\omega_r + K_i \int \Delta\omega_r\, dt \qquad (15)$$

This iq* which is than sent ahead in the system to control the operation of Six Phase PMSM drive system as shown in block diagram in Fig:2 For tunning of PI controller Closed Loop Ziegler-Nichols Method is used. Since it is trial and error method it is time consuming. After seeing the improvements in response of the model, the most suitable value of Kp and Ki is chosen [18, 19]

VII. SIMULATION RESULTS

The above model of six phase PMSM drive system has been simulated for 0.2s ,the load Torque and speed is fix at 0 N-M and 36.5 rps respectively.

The value of Kp and Ki is taken random i.e. Ki=20 and Kp=0.1and after seeing the response in first case the value of Ki is chosen random by keeping the Ki=20 (fix).afterthat when got the value of Kp for which the response is good we will fix the Kp to that value and chose the randome values of Ki.

The following table shows the results that which value of Kp and Ki suits for the given drive system.

Table:2

S.No.	Ki	Kp	Setling time Ts(sec)	Overshoot (rps)
1	20	0.1	0.16	40.68
2	20	0.15	0.155	40.675
3	20	0.2	0.143	37.687
4	20	0.25	0.129	36.872
5	20	0.3	0.09	Nil
6	20	0.4	0.18	Nil
7	20	0.5	delayed	Nil
8	15	0.3	delayed	Nil
9	25	0.3	0.103	37.135
10	30	0.3	0.111	38.5
11	40	0.3	0.115	39.79
12	50	0.3	0.118	41.33
13	75	0.3	0.12	44.46
14	100	0.3	0.13	46.92

(a) Different Values of Kp and Ki

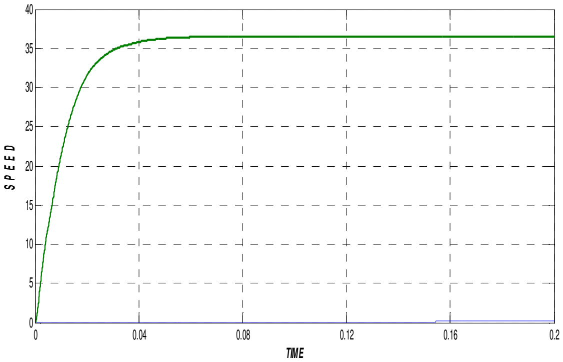

Figure-4 Speed at Ki=20 and Kp= 0.3

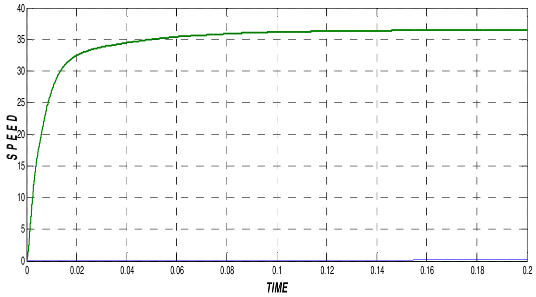

Figure-5 Speed at Ki=20 Kp=0.5

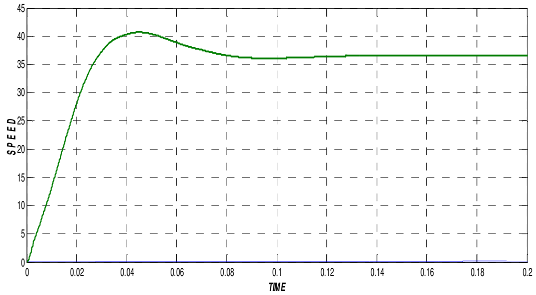

Figure-6 Speed at Ki=20 and Kp=0.1

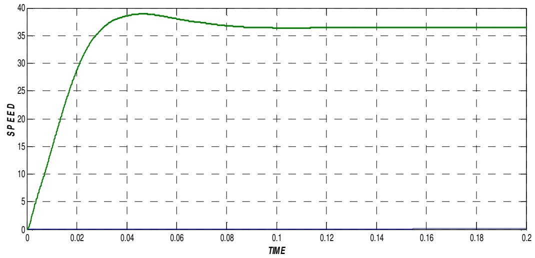

Figure-7 Speed at Ki=20 and Kp=0.15

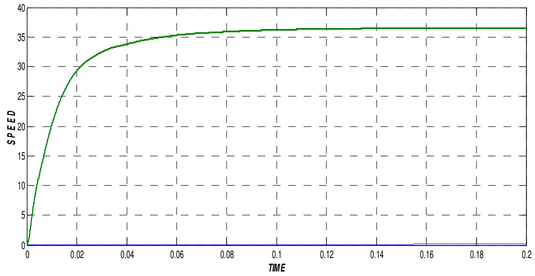

Figure-8 Speed at Ki=15 and Kp=0.3

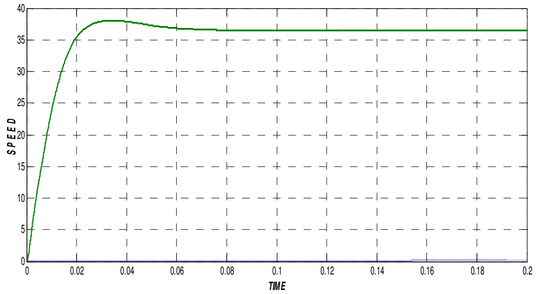

Figure-9 Speed at Ki=30 and Kp=0.3

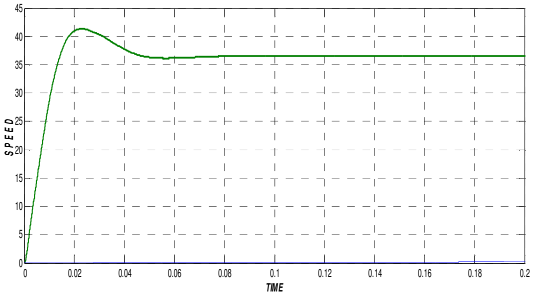

Figure-10 Speed at Ki=50 and Kp=0.3

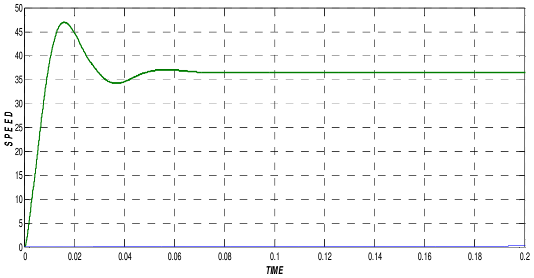

Figure-11 Speed at Ki=100 and Kp=0.3

VIII. CONCLUSION

Mathematical and computer model of multiphase motor with six-phase stator winding and Permanent magnet rotor is presented. The simulation results of the proposed drive scheme are obtained under reference speed condition and the tunning of constants for PI controller has been done manually by hit and trial method. From The response obtained in fig.4 which demonstrate that for the proposed PI controller the value of Kp=0.3 and Ki=20 are well suited because it has fast settling time and zero overshoot as compared to other values of PI constants . Overall it can be said that the performance of the proposed scheme is satisfactory for the tunned value of Kp and Ki.

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AUTHORS PROFILE

Er.Anurag Singh Tomer is presently working as scientist (Electrical Engineering) at Indira Gandhi Krishi Vishwavidyalaya, Raipur (C.G.). He is M.Tech in Electrical Engineering. His area of reasearch are Artificial Intelligent, Drivecontrol, Modeling/ Simuation, Multiphase Machines. He is having an experience of around fifteen years in the field of teaching and research.

Dr.Satya Prakash Dubey is Presently working as Dean Research and Development at RCET, Bhilai (C.G.). He is Ph.D. in Electrical. He has many reseacrh projects under his belt.His area of research are filters, power electronics, Drives, Artificial intelligent, Multiphase machine analysis, Control System etc.