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ISSN (Online) 2321-2004
ISSN (Print) 2321- 5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

NFTPCOS-18

National Conference on Future Technologies in Power Control and Communication Systems

College of Engineering Perumon, Kollam, Kerala

Vol. 1, Special Issue 2, March 2018

Minimisation of Torque Ripple in PMSM Using a Proportional Resonant Control Technique

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Abstract: Permanent magnet synchronous motors (PMSM) are extensively used in many applications including robotics, precision machining etc. because of their good features such as, high efficiency, light weight, better accuracy, and low maintenance requirements compared to induction motors. Because of the increasing demand for energy efficiency, PMSM replaces the traditional induction motors. The main problem with this motor is the formation of torque ripples at low-speed which may cause mechanical vibrations and induces oscillations in speed. So low-speed applications of this motor have some limitations. Vector controlled PMSM drives can be used to supply lesser torque ripples and better dynamic response. Conventionally Proportional integral (PI) controllers are used for this. But the performances of the PI controllers are affected by load disturbances, speed variations and parameter variations due to its constant proportional gain and integral time constant. The novelty of this work is implementing a new control technique by using a PI-resonant (PI-RES) controller by paralleling a variable frequency resonance controller with the conventional PI controller.

Keywords: Permanent magnet synchronous motors, Proportional integral (PI) controllers, PI-resonance (PI-RES) controllers, Torque ripples, Field oriented control

I. INTRODUCTION

The permanent magnet synchronous motor (PMSM) drives are extensively used for many industrial applications such as industrial servo applications, robotics etc. They have high efficiency, smaller parts, less weight, high torque density and small size [1]. The back EMF of the motor is sinusoidal and its field excitation is provided by permanent magnets. PMSM is considered as a combination of both BLDC motors and Induction motors, since the stator construction of both are similar. Nowadays the traditional induction motor used in compressors are gradually being replaced by PMSM due to the increasing demand for energy efficiency and variable-speed systems performance. The major drawback with this motor for some applications is the presence of torque ripples, which significantly depends on the machine saliencies, anisotropies and rotor magnet field distributions. The machine should be free of torque ripples for applications like conveyor belt control which requires precise tracking. Cogging torque, mutual torque, current measurements errors, flux harmonics and unbalanced phases are the various sources of torque pulsations in a PMSM. This torque ripple induces vibrations which may destroy the whole drive system and can generate serious noise problems. The torque ripple can be reduced during the manufacturing process itself, by selecting a geometry that reduces the torque harmonics at the machine design stage by reducing the anisotropies. It can be minimized at the control stage or by reducing the construction error tolerance. But it is not possible to totally eliminate the torque ripple by design and construction. The extensive applications of variable speed compressors have some limitations due to the speed fluctuations at low-speed range and it results in low-frequency noise and serious vibration problems. To overcome this, the compressor can be operated at high speed. But it decreases the overall system efficiency. Otherwise, to compensate these periodic torque pulsations additional controls effort should be used. In this work, the conventional PI speed controller and a variable frequency resonant controller are applied in parallel to form a proportional resonant speed controller. It eliminates the ripples by providing a reference torque current. The resonance controller generates a compensation torque current and the PI controller produces a main reference current. The proposed controller combines both of this current to minimise the speed ripples. The proportional resonant controller is also used in the inner control loops to give the control voltages for pulse width modulation. The performance the new control method is evaluated through simulation results.

II. PMSM MODELLING

The d-q model of PMSM on rotor reference frame without having damper winding has been developed. The stator and rotor mmf rotates at the same speed. The modelling follows these assumptions:

1. Rotor flux is concentrated along d axis.
2. The induced EMF is sinusoidal.
3. Hysteresis losses and eddy currents are negligible.
4. There are no field current dynamics.
5. The stator windings are balanced with sinusoidal distributed magneto-motive force (mmf).
6. The saturation and parameter changes are neglected.
7. Variations in rotor temperature with time is neglected.

The stator voltages in d-and q-axes are obtained as the sum of the resistive voltage drops and the derivative of the flux linkages in the corresponding windings [5].

The flux-linkage equation for stator are given by:

$$V_q = R_q i_q + P\lambda_q + \omega_r \lambda_d \quad (1)$$

$$V_d = R_d i_d + P\lambda_d - \omega_r \lambda_q \quad (2)$$

where, V_d and V_q are the voltages in the d-axis and q-axis windings, i_d and i_q are the stator currents in d-axis and q-axis, R_d and R_q are the stator resistance in d-axis and q-axis, λ_d and λ_q are the stator flux linkage in d-axis and q-axis, ω_r is the rotor speed of the machine.

Flux Linkages in d and q axis is given by,

$$\lambda_q = L_q i_q \quad (3)$$

$$\lambda_d = L_d i_d + \lambda_f \quad (4)$$

Using the method of field-oriented control of the PMSM, the d-axis current is usually controlled to be zero. The developed motor torque is given by,

$$T_e = \frac{3P}{4}(\lambda_m i_q) = k_t i_q \quad (5)$$

where, P is the number of poles of the motor and kt is the torque constant. The mechanical Torque equation is,

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \quad (6)$$

The mechanical speed and position of the motor are expressed as,

$$\omega_m = \int \frac{1}{J}(T_e - T_L - B\omega_m)dt \quad (7)$$

$$\omega_e = \frac{P}{2}\omega_m \quad (8)$$

$$\frac{d\theta_m}{d_t} = \omega_m \quad (9)$$

where, ω_m is the mechanical speed, θ_m is the mechanical position, J is the inertia, T_L is the external load and B is the viscous coefficient.

III.PMSM WITH COMPRESSOR LOAD

PMSM motors are widely used to improve the efficiency of compressors used for air conditioning purpose. Compressors in refrigeration application also require better efficiency and torque performance at low speeds. These requirements are achieved by PMSM motors due to their increased life time compared to DC motors, and high torque at low speeds. But PMSM motors produce speed ripples at low speeds. It may affect the performance of the refrigeration system. Fig.1 shows the MATLAB model of PMSM with a compressor load. Since viscosity coefficient Bm is very small, it can be neglected. Differentiator s can be used instead of (d/dt), from (3), the plant transfer function between the motor speed and the torque is,

$$\omega_m(s) = \frac{\Delta T_m}{J_m s} \quad (10)$$

where,

$$\Delta T_m = T_e - T_L \quad (11)$$

At low operating speeds, the speed will oscillate at the same harmonic frequencies as those of the torque ripple, ΔT_m. It is essential to reduce the speed ripples, which are major cause of these speed oscillations. For that, the error torque pulsation ΔT_m should be reduced. In the case of a compressor, it have position-dependent load torque. So the torque varies for different position of rotor. Also for different rotor speeds the torque ripple frequency varies. In tradition case, the load torque usually is constant in steady-state condition. The outer speed loop can achieve good performance either in steady-state or dynamic-state by using PI controller.

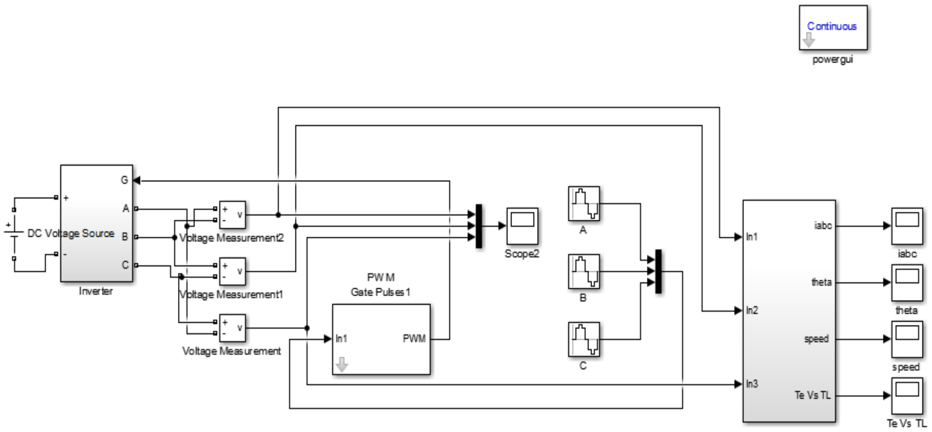

Fig.1 MATLAB model of a PMSM with compressor load

IV. FIELD ORIENTED CONTROL

A PMSM can be operated with rapidly changing load in a wide range of speeds in adjustable speed drive applications by using Field oriented control (FOC). It can be used for high speed applications where field weakening is required. The motor torque and flux can be controlled in an efficient way using FOC. It is also known as vector control or decoupling control. Irrespective of the machine parameters and load parameter variations, FOC enables the motor to accurately track the command trajectory. There are two input references or two constants for a field orientated controlled machine. First one is the torque component aligned along the q coordinate and the other is the flux component aligned along the d co-ordinate. The control structure of FOC handles instantaneous electrical quantities and are based on projections [6]. This makes the control accurate in steady state and transient working operation and independent of the limited bandwidth mathematical model. Using FOC, a synchronous motor can be controlled like a separately excited dc motor. It can be obtained by adjusting the stator mmf orientation or the current vector with respect to the rotor flux. When the angle between rotor magnetic field and stator field is 90 degree, torque production will be maximum.

FOC consists of vectors to control the orientation of stator currents. A three phase time and speed dependent system can be transformed into a two co-ordinate (d and q co-ordinates) time invariant system using field oriented control. Also FOC can maintain a constant reference which enables the application of direct torque control, because in the (d,q) reference frame the expression of the torque is:

$$T \propto \varphi_R i_q \qquad (12)$$

where φ_R is the amplitude of rotor flux and i_q is the q-axis stator current. A linear relationship between torque and current (i_q) is obtained by maintaining the amplitude of the rotor flux (φ_R) at a fixed value. We can then control the torque by controlling the torque component of stator current vector. Thus by using FOC, torque and flux can be independently controlled.

V. PROPOSED SCHEME

A. PI controller

PI controllers have the property that systems with open loop transfer functions of type 1 or above have zero steady state error with respect to a step input. PI controllers are usually chosen for control applications. A PI controller can be expressed in the s-domain as,

$$G_{PI}(s) = K_P + \frac{K_I}{s} \qquad (13)$$

where, K_P is the Proportional Gain term and K_I is the integral coefficient of speed loop. The conventional outer speed control loop with a PI controller can be shown as in Fig.2. T_{di} is the delay in the inner control loop. ω_{ref} is the constant reference speed, it is usually constant. Here the speed loop with PI controller have only limited bandwidth, and these standard integrators that can achieve better error free control only at zero frequency but not at other frequencies. So it is difficult to achieve $\Delta T_m \simeq 0$.

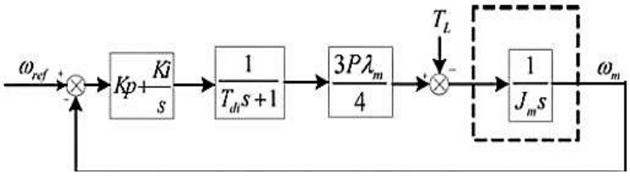

Fig. 2 Control block diagram of the outer speed loop with a PI controller

B. Resonant controller

The gain of a proportional resonant current controller $G_{PR(s)}$ is represented by [7]:

$$G_{PR}(s) = K_P + K_I \frac{2\omega_C s}{s^2+2\omega_c s+\omega_0{}^2} \quad (14)$$

where, K_P is the Proportional Gain term, K_I is the Integral gain term. The dynamics of the system; bandwidth, phase and gain margins are determined by the K_P term and ω_0 is the resonant frequency, ω_C is the bandwidth around the ac frequency of ω_0. The gain of the PR controller at the ac frequency ω_0 is now finite but it is still large enough to provide only a very lesser steady state error. This equation also makes the controller more easily realizable in digital systems due to their finite precision. At the resonant frequency ω, $G_{PR(s)}$ delivers infinite gain in open loop. When implemented in closed loop, it enables perfect tracking of components oscillating at ω. When $G_{PR(s)}$ controllers and $G_{PI(s)}$ are engaged in parallel for $G_{PI-RES(s)}$, only a single gain K_P should be tuned [9]. In $G_{PI-RES(s)}$, K_{ri} is the resonance coefficient, and ω_C is the damping coefficient.

$$G_{PI-RES}(s) = K_P + \frac{K_I}{s} + \frac{2K_{ri}\,\omega_C s}{s^2+2\omega_c s+\omega_0{}^2} \quad (15)$$

C. FOC of PMSM with PI-RES controller

Normally PI controllers cannot provide a sinusoidal reference without steady state error, due to the dynamics of the integral component. A proportional resonant (PR) controller is more suitable to operate with sinusoidal references. Also, it is free from the above mentioned demerits. The control block diagram for the outer speed loop by using a PI-RES controller is shown in Fig.3.

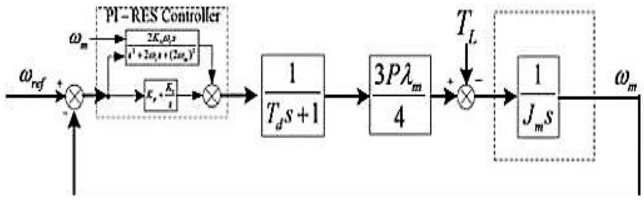

Fig.3 Block diagram for outer speed control loop by using a PI-RES controller

The PR controller can provide gain at a resonant frequency and almost no gain exists at the other frequency [8]. Since the speed ripples with twice the rotor frequency, a twice rotor frequency resonant controllers combined with the traditional PI controller to form a new PI-RES controller can give better response. It can control the harmonics better than that of traditional PI controller [9]. The resonance term is tuned about the second harmonic frequency of the rotor to mitigate the speed ripples. This controller produces a rippled torque current reference which counteracts the rippled term of load torque of compressor. Another resonant controller is added in the inner current loop, to obtain the error free control of ac term of torque current generated by the resonance compensator. Fig.4 shows the MATLAB model of FOC in PMSM drive using PI-RES controller. In this a PI-RES controller is used in the outer speed control loop to adjust the speed. The PI term in this is used to provide good dynamic performance for a speed step, and the speed ripple with the frequency of twice ω_m is eliminated using the resonant term. A PI-RES controller is also employed in the inner current control loop to regulate both dc and ac current in the rotating frame with the frequency of ω_e. The torque current reference is obtained from the output of the speed controller.

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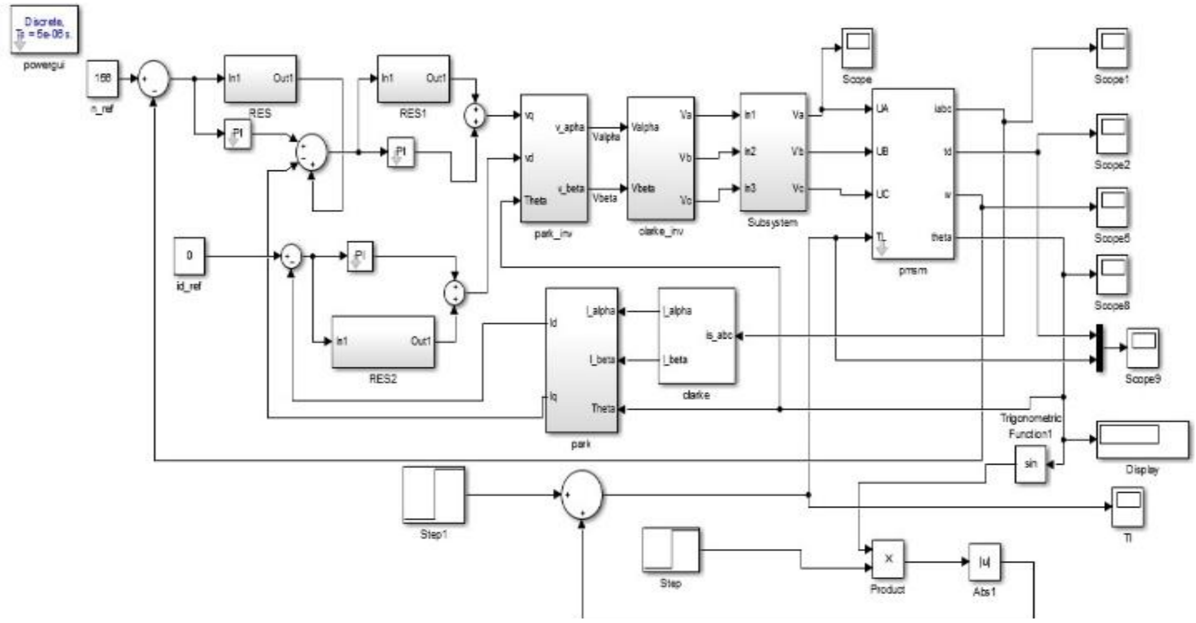

Fig.4 MATLAB model of FOC in PMSM using PI-RES controller

VI. SIMULATION RESULTS

The proposed method was simulated in MATLAB 2010. Fig.5 shows the torque and speed ripples obtained from PMSM without using any controller. It shows that the speed and torque severely ripples. Fig.6 shows the torque and speed ripples in the system by when PI-RES controller is implemented at 52.36 rad/sec.

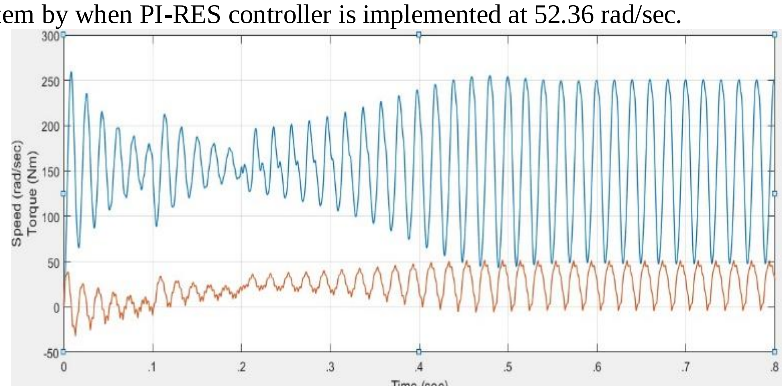

Fig.5 Output torque and speed response of PMSM

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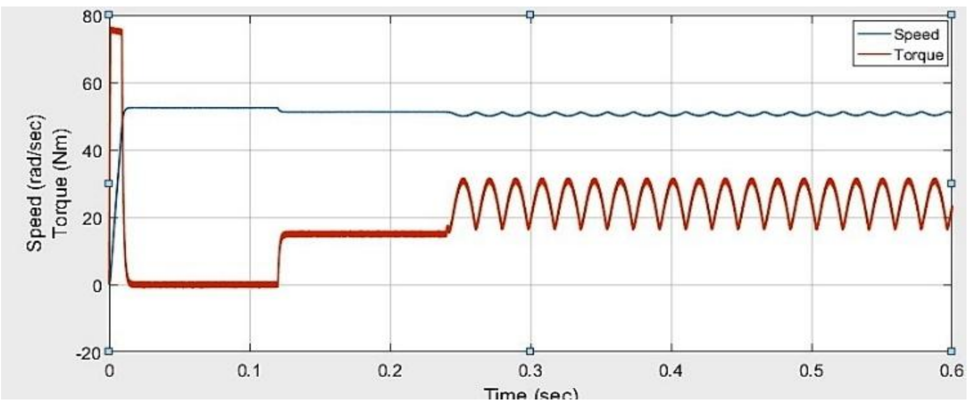

Fig.6 Output torque and speed response of FOC of PMSM using PI-RES controller at 52.36 rad/sec

When the motor is operated at 156 rad/sec using PI-RES controller, the torque and speed ripples are obtained as below.

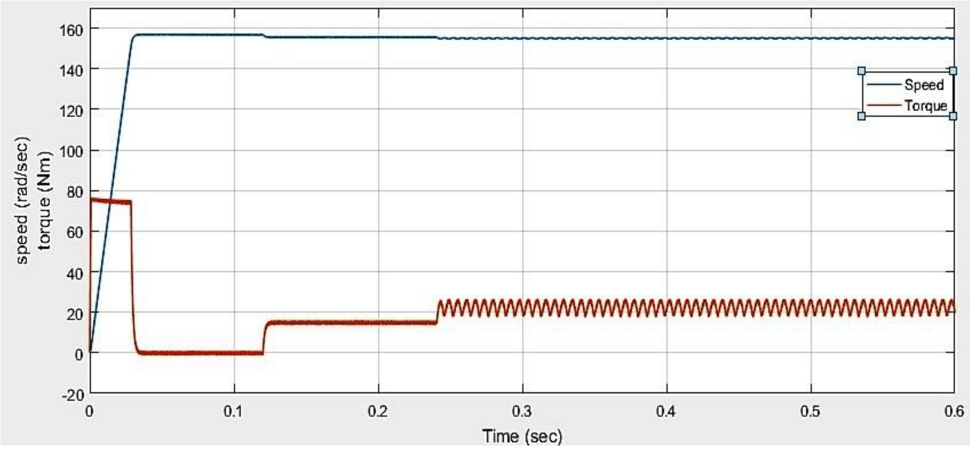

Fig.7 Output torque and speed response of FOC of PMSM using PI-RES controller at 156 rad/sec

The variation in torque by using the new conroller at different speed shows that by using the PI-RES controller, the ripple can be reduced to an extent. The torque ripple obtained from the PI-RES controller at 52.36rad/sec and 156 rad/sec has an identifiable change and it decreases as the speed increases as shown in Table.1

Table.1 Comparison of torque ripple output

CONTROL TECHNIQUE	TORQUE RIPPLE (%)
FOC of PMSM with PI-RES controller at 52.36 rad/sec	44.73
FOC of PMSM with PI-RES controller at 156 rad/sec	34.21

VII. CONCLUSION

A proportional resonant controller based Field oriented control method for mitigating the torque ripple in PMSM drive with a compressor load is simulated in MATLAB and the results are plotted. Torque ripples at low speed is the main disadvantage associated with PMSM which leads to problems such as mechanical vibration, fluctuations in speed and noise. So a parallel combination of a variable frequency resonant controller is applied along with the conventional PI controller as a PI-RES controller. It enables to reduce the speed ripples when the load rippled periodically with the speed. So that it provides longer lifetime for the system and saves energy to an extent. It is clear from the resullts that the method was more effective in minimising the ripples at low speeds.

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