Reduction of Torque Ripples in PMSM Using a Proportional Resonant Controller Based Field Oriented Control

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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 application 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 performance of the PI controllers are affected by disturbances in load, variations in speed 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 implementing a proportional resonant controller by paralleling a variable frequency resonance controller with the traditional PI controller and the performance of the two controllers is compared with the help of simulation results.

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

1 Introduction

The permanent magnet synchronous motor (PMSM) drives are widely 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]. Nowadays the induction motors 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 [2]. These torque ripple induces vibrations which may destroy the whole drive system and can generate serious noise problems. The extensive application of variable speed compressors have some limitations due to the speed fluctuations at low-speed range and it causes noise at low-frequencies and serious vibration related

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problems. To compensate these periodic torque pulsations additional control effort should be used [3].

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 [4]. The proposed controller combines both of this current to reduce the speed ripples. The performance comparison between the controllers are done and evaluated through simulation results.

2 Modelling of PMSM

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:

$$V_q = R_q i_q + P\lambda_q + \omega_r \lambda_d \tag{1}$$

$$V_d = R_d i_d + P\lambda_d - \omega_r \lambda_q \tag{2}$$

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,

$$\lambda_q = L_q i_q \tag{3}$$

$$\lambda_d = L_d i_d + \lambda_f \tag{4}$$

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

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

where, P is the number of poles of the motor and k_t is the torque constant. Then the mechanical torque equation is,

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \tag{6}$$

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

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

$$\omega_e = \frac{P}{2}\omega_m \tag{8}$$

$$\frac{d\theta_m}{d_t} = \omega_m \tag{9}$$

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

3 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 [6]. 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 upset the performance of the refrigeration systems. Figure 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,

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

where,

$$\Delta T_m = T_{e^-} T_L \tag{11}$$

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 the major cause of these oscillations in speed [7]. For that, the error in torque ΔT_m must be reduced. In the case of a compressor, the load torque is position-dependent. So with the various positions of rotor, the torque differs. Also for the different rotor speeds, the torque ripple frequency varies.

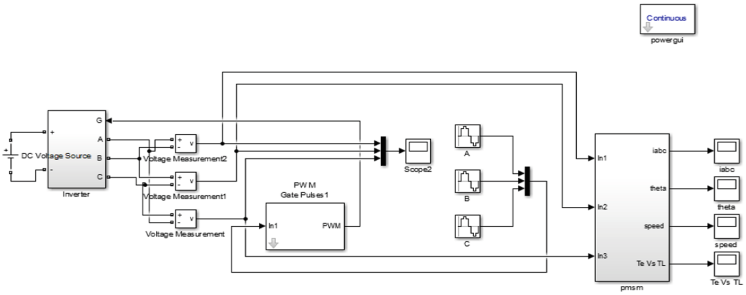

Fig. 1. MATLAB model of a PMSM with compressor load

4 Field Oriented Control

A PMSM can be operated with rapidly changing load in a broad range of speeds in adjustable speed drives applications by using Field oriented control (FOC). The torque and flux of the motor can be controlled in an efficient way using FOC. Irrespective of the machine parameters and variations in load parameters, FOC enables the motor to precisely follow the command trajectory. There are two input references or two constants for a field orientated controlled machine. First one is the component of torque aligned along the q-coordinate and the other is the component of flux aligned along the d co-ordinate [8]. This allows perfect control in both steady state and transient working operation and it is independent of the mathematical model with limited bandwidth. Torque control can be obtained by adjusting the orientation of the stator current vector with respect to the rotor field. When the angle between rotor flux and stator current is 90 degree, torque production will be maximum [9]. Also FOC can maintain a constant reference which enables the application of direct torque control, since in the (d, q) reference frame the equation for the torque is:

$$T \propto \varphi_R i_q \tag{12}$$

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.

5 FOC of PMSM with PI Controller

Vector controlled PMSM drives offers better dynamic response and slighter torque pulsations, and needs only a constant switching frequency. The performance of the system is greatly affected by the outer loop in vector control. PI controllers are usually chosen for control applications. When PI controllers are used, systems with open loop transfer functions of type 1 or more have zero error at steady state for a step input [10]. A PI controller can be represented in the s-domain as,

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

where, K_P is the Proportional Gain term and K_I is the integral coefficient of speed loop. The MATLAB model of field oriented control in PMSM drive using PI controller is shown in the Fig. 2

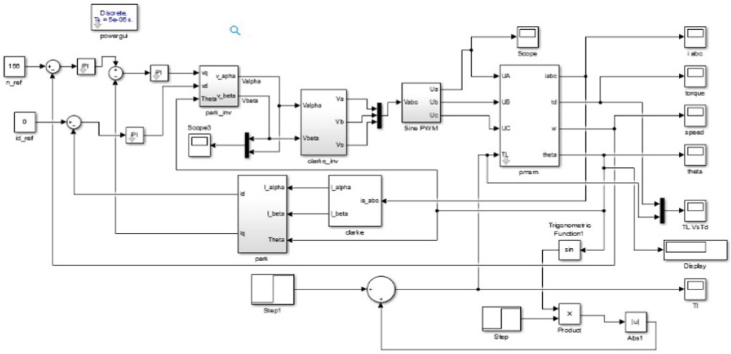

Fig. 2. MATLAB model of FOC in PMSM using PI controller

6 Proposed Scheme

6.1 Resonant Controller

The gain of a proportional resonant current controller $G_{PR(s)}$ is represented by [9]:

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

where, K_P is the Proportional Gain and K_I is the Integral gain. 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 ω_0. Now the PR controller have finite gain at the ac frequency $\omega_{0.}$ So that the controller can provide a very lesser steady state error [11]. The PR controller can be easily realizable in digital system using the above equation 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 [12]. In $G_{PI-RES(s)}$, K_{ri} represents the resonance coefficient, and ω_C denotes the damping coefficient.

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

6.2 FOC of PMSM with PI-RES Controller

Due to the dynamics of the integral component, PI controllers cannot provide a sinusoidal reference without steady state error. A proportional resonant (PR) controller is more suitable to operate with sinusoidal references [13]. Also, it is free from the above mentioned demerits. The conventional outer speed control loop with a PI controller can be shown as in Fig. 3. T_{di} is the inner control loop delay. ω_{ref} is the reference speed, it is usually constant. Here the speed loop with PI controller have only limited bandwidth, and the integrators can achieve better error free control only at zero frequency and it is difficult at other frequencies. So it is difficult to achieve $\Delta T_m \simeq 0$. PI controllers are tuned in such a way as to have high Integral gain [14]. Then the proportional constant is increased to get adequate response.

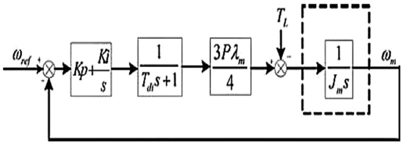

Fig. 3. Block diagram of the outer speed loop with a PI controller

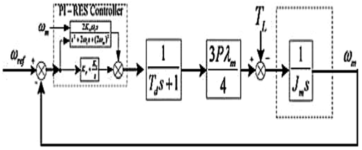

Fig. 4. Block diagram for outer control loop with a PI-RES controller

The block diagram for the outer speed loop by using a proportional resonant controller is shown in Fig. 4. The Proportional resonant controller can provide gain for a specific resonant frequency. At other frequencies also, it cannot provide gain [15]. Since the speed ripples with twice the rotor frequency, a resonant controller resonating at twice the rotor frequency along with the conventional PI controller forms a proportional resonant controller, which can give better results. It can control the harmonics better than that of traditional PI controller [16]. The resonating term is tuned nearer to twice the frequency of the rotor to mitigate the speed ripples. This controller produces a rippled torque current reference which counteracts the torque ripple from the compressor load. Figure 5 shows the MATLAB model of the FOC in permanent magnet-synchronous motor drive using PI-RES controller. The torque current reference is taken from the output of the speed controllers.

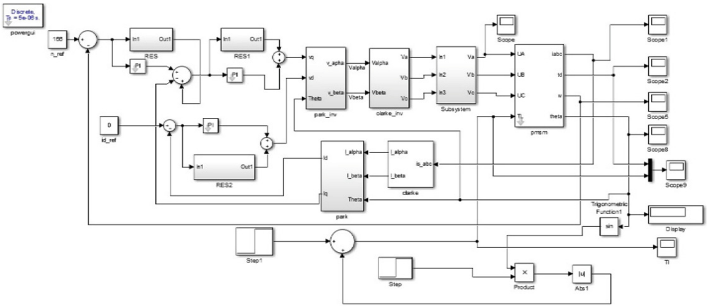

Fig. 5. MATLAB model of FOC in PMSM using PI-RES controller

7 Simulation Results

The proposed method was simulated in MATLAB 2010. A position dependent load torque is applied for representing the compressor. There present lots of ripples in the system without any controller. Figure 6 shows the torque and speed ripples obtained from PMSM without using any controller.

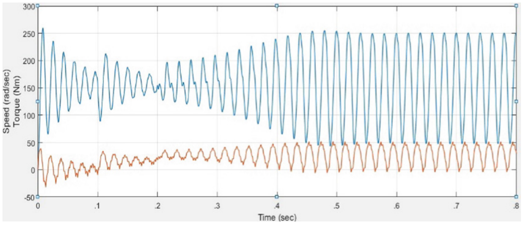

Fig. 6. Output torque and speed response of PMSM

To reduce these torque pulsations, a PI controller based field oriented control is used and the result is as shown in Fig. 7.

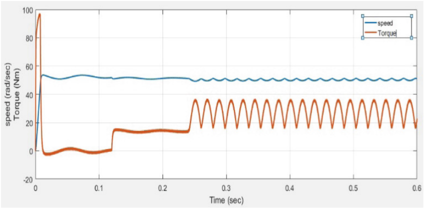

Fig. 7. Output torque and speed ripples in FOC of PMSM using PI controller at 52.36 rad/sec

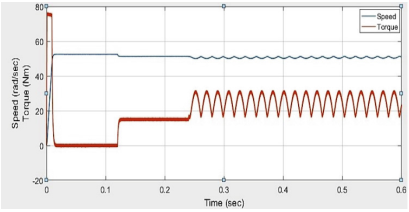

Fig. 8. Output torque and speed response of FOC of PMSM using PI-RES controller at 52.36 rad/sec

From the results it is clear that the system with PI controller contain 57.89% torque ripples. To reduce this pulsations, a PI-RES controller is implemented and the ripple content is shown as in Fig. 8. It reduce the ripples to 50%. Thus the ripples are reduced by using the new controller. The performance of the system with both PI and PI-RES controllers are analysed at 52.36 rad/sec.

8 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 combined along with the proportional integral controller as a new PI-RES controller. It enables to reduce the ripples in speed when position dependent load is applied. So that it provides longer lifetime for the system and saves energy to an extent. It is clear from the results that the new technique was more better than the conventional methods using PI controller.

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