Speed Control of Permanent Magnet Synchronous Motor Using Digital Pole Placement Controller

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***Abstract*—This paper presents a digital pole placement controller for permanent magnet synchronous motor (PMSM). The digital pole placement controller is used for speed control of this type of motors. The dynamic response of the (PMSM) with the proposed controller is studied during the starting process under the full load torque and under load disturbance. The effectiveness of the proposed digital pole placement controller is then compared with that of the conventional PI controller. The proposed controller is used in order to overcome the nonlinearity problem of PMSM and the parameter variations.**

***Index Terms*—Speed control, digital pole placement controller, permanent magnet synchronous motor.**

I. INTRODUCTION

PERMANENT magnet synchronous motors (PMSMs) fed by PWM inverters are widely used for industrial applications, especially servo drive applications, in which constant torque operation is desired. In traction and spindle drives, on the other hand, constant power operation is desired [1]. These machines have the advantages of light weight, small size, simple mechanical construction, easy maintenance, good reliability, and high efficiency. The PMSMs may be designed with surface mounted or buried magnets (also known as non-salient pole PMSMs or salient pole PMSMs, respectively) as shown in Fig. 1 [2]. It is well known that the *d*-axis and *q*-axis reactances are very important for designing control systems, in order to maximize the efficiency, power factor, etc. There are many methods to determine the *d*-axis and *q*-axis reactances of (PMSMs) [3]. For PMSMs with surface mounted magnets, the *d*-axis and *q*-axis reactances are approximately equal (the modern permanent magnets have relative permeability close to unity, therefore the effective air gap seen from the stator is nearly independent of the position). Inverter circuits make possible different control strategies (frequency variation, voltage variation, current variation), each one with specific applications. Recent developments in power electronics have brought new inverter circuits suitable for voltage, current

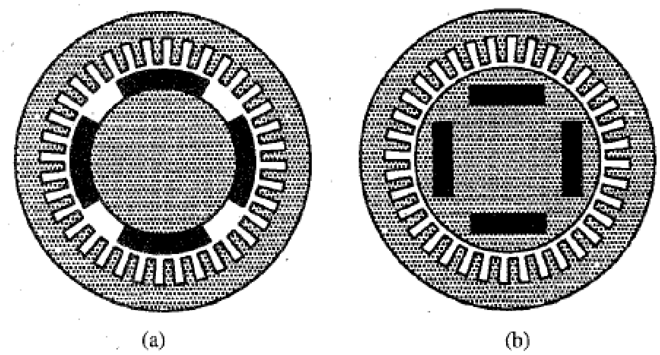

Fig. 1. Cross-sectional views of two major types of PMSM construction. (a) Surface-mounted magnets. (b) Buried (interior) magnets.

levels and switching frequencies. Permanent magnets make unnecessary rotor windings and excitation circuit. Absence of the rotor circuit improves the mechanical design [4].

There are many strategies and methods to achieve a wide range of speed control of PMSM. Essentially, the conventional proportional-integral (PI) and proportional-integral-derivative (PID) controllers have been utilized in speed control of PMSM drives due to the robustness of these controllers and they offer a wide stability margin. Moreover, the conventional fixed gain PI and PID controllers are very sensitive to parameter variations and load changes. Therefore, adaptive or self tuning PI controllers have been proposed for PMSM [5]-[8]. Also, the artificial intelligent controllers are used to solve the nonlinearity problem of the PMSM. In recent years, fuzzy logic control techniques have been applied to the control of high-performance motor drives. Unlike classical control strategies, fuzzy logic incorporates an alternative way of thinking. A fuzzy logic controller uses fuzzy logic as a design methodology, which can be applied in developing nonlinear systems for embedded control. It is considered to be low mathematical design requirements and inexpensive hardware technology. But it depends on the experience of the designer in tuning the membership functions [9]. Also, the artificial neural networks (ANNs) have used to deal with the nonlinearity of PMSM drives [10]-[12]. It can handle the characteristics of nonlinearity but it may suffer from the convergence time and the length of the training process. In [13] an adaptive neuro-fuzzy controller is used for speed control of PMSM. It has two input variables and one control output variable. Firstly the ANN architecture is described then the fuzzy logic control rules are represented and tuned. On the other hand, there are many methods based on sensorless vector and speed control of PMSM. A closed-loop state observer is

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implemented to compute the speed feedback signal [14], [15]. Also, the nonlinear H_∞ state feedback controller is designed for speed control of PMS motors. In order to obtain the approximate solution of the Hamilton-Jacobi-Isaacs inequality, Taylor Series expansion of the nonlinear terms up to desired order is obtained that result in a nonlinear H_∞ control law. So, it seems that the mathematical design of the controller is complex [16]. There is some approaches aim to design and implement auto tuning controllers which are robust against load and inertial variations [17]. Recently, direct torque control technique is applied on PMSM for controlling the speed [18]. In this study, the structure and direct torque process of the PMSM is explained and speed control system simulation is realized for low voltage high power PMSM.

In the present paper, a digital pole placement controller newly applies on permanent magnet synchronous motor for controlling its speed. This methodology solves the problem of nonlinearities and load changes of PMSM drives. The proposed controller ensures fast and accurate dynamic response with an excellent steady state performance.

II. DYNAMIC MODEL OF THE MOTOR

For analysis of control strategies, the PMSM model is used. Stator circuit electrical equations in *d-q* coordinates are [19], [20]:

$$v_d = R_s i_d + d\psi_d/dt - \omega\psi_q \tag{1}$$

$$v_q = R_s i_q + d\psi_q/dt + \omega\psi_d \tag{2}$$

Where R_s is the stator resistance, i_d is the d-axis current, Ψ_d is the total flux in the d-direction, Ψ_q is the total flux in the q-direction, and i_q is the q-axis current. Flux-linkage can also be expressed in d-q coordinates as follows:

$$\psi_d = L_d i_d + \psi_m \tag{3}$$

$$\psi_q = L_q i_q \tag{4}$$

Where L_d is the d-axis inductance, Ψ_m is the flux-linkage due to the permanent magnets, and L_q is the q-axis inductance. As d-axis is aligned with magnet's axis, there is no contribution of the magnets to q-axis magnetic flux-linkage Ψ_q. The d-q coordinate system moves jointly with rotor poles, so that the stator circuit inductance is independent of time in this system.

The mechanical equation which describes the mechanical motion of the motor can be written as follows:

$$T = Jd\omega/dt + B\omega + T_L \tag{5}$$

This equation shows that as long as there is positive difference between the motor torque T and the load torque T_L, the rotor speed will grow. Acceleration depends on the moment of inertia J and the friction coefficient B. The motor torque expression with d-q magnitudes is:

$$T = 1.5P(\psi_d i_q - \psi_q i_d) \tag{6}$$

Where p is the number of pole pairs of the rotor. Also, the motor torque can be obtained from the magnet flux-linkage and the d-q axis currents as follows:

$$T = 1.5P(\psi_m i_q - (L_q - L_d) i_d i_q) \tag{7}$$

Equation (7) shows that, if the d-axis inductance L_d is equal to the q-axis inductance L_q (PMSMs with surface mounted magnets), the motor torque depends only on the q-axis current component i_q as in the following expression:

$$T = 1.5P\psi_m i_q \tag{8}$$

III. SPEED CONTROL OF PMSM WITH THE PROPOSED CONTROLLER

The system under study is shown in Fig. 2. It consists of PMSM provided with its controlled PWM inverter. The data of the motor is given in the appendix. The drive is tested under the following condition. First the motor is started against its full load torque (3N.m) until the motor reaches the steady state speed. Then, the motor is subjected to a severe load disturbance where the shaft of the motor is broken and the load is suddenly decreased to (0N.m) after 0.04 sec.

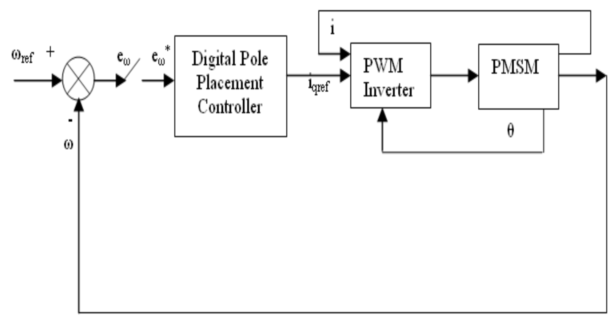

Fig. 2. Block diagram for speed control of PMSM using the digital pole placement controller.

IV. THE DIGITAL POLE PLACEMENT CONTROLLER

The Digital pole placement controller is proposed in this work for speed control and more enhancement of speed regulation. The final output of the Digital pole placement controller is used to regulate the reference q-axis current i_{qref} of the PMSM to regulate the motor shaft speed. While the input of the controller is the discrete value of the motor speed error e_ω^*, where the input sampler converts the motor speed error e_ω to its discrete value with sampling period T equals to 0.01 sec. This value of the sampling period is the most commonly used in the digital sampler.

The motor speed error (e_ω), in p.u is given by the following equation:-

$$e_\omega = \frac{(\omega_{ref} - \omega)}{\omega_{ref}} \tag{9}$$

The general form of the pulse transfer function of the digital controller, which have dominant closed loop poles that affect the behavior of the system can be written as follows [21]:

$$G_d(z) = k_d \frac{z^{-1}.\sin(yT)}{(1 - 2z^{-1}.\cos(yT) + z^{-2})} \tag{10}$$

Where k_d is the gain of the controller, and y is a constant which refers to the parameters of the controller. The discrete motor speed error e_ω^*, can be described in the z-domain by the following equation:

$$e_\omega(z) = \frac{1}{(1-z^{-1})(1-0.46z^{-1})} \quad (11)$$

The regulated signal i_{qref} can be written in the z-domain by the following equation:

$$I_{qref}(z) = e_\omega(z).G_d(z) \quad (12)$$

The dominant closed loop poles that affect the stability of the system can be written from the following equation:

$$Z_{1,2} = \cos(yT) \pm j\sin(yT) \quad (13)$$

The general form of the dominant closed loop poles in the z-domain is:

$$Z_{1,2} = \exp(-\zeta\omega_n T).[\cos(\omega_d T) \pm j\sin(\omega_d T)] \quad (14)$$

Where ζ is the damping ratio, ω_d is the damped natural frequency, rad/sec. ω_n is the undamped natural frequency, rad/sec.

By equating the real parts of (13) and (14), we get the following equation:

$$\cos(yT) = \exp(-\zeta\omega_n T).\cos(\omega_d T) \quad (15)$$

Equation (15) plays an important role in adjusting the constant y through the design process as will be shown later.

The block diagram of the Digital pole placement controller, which has a pulse transfer function $G_d(z)$ is illustrated in Fig. 3. Where,

G(k) = n*n matrix (state matrix),
H(k) = n*1 matrix (input matrix),
C(k) = 1*n matrix (output matrix),
D(k) = 1*1 (direct transmission vector),
K = state feedback gain matrix 1*n matrix,
and X(k) = state variables matrix.

The discrete time state space equations, which describe the digital pole placement controller can be written as follows [21]:

$$X(k+1) = (G-HK).X(k) + H.e_\omega^*(k) \quad (16)$$

$$I_{qref}(k) = C.X(k) \quad (17)$$

The characteristic equation of the proposed controller is given by the determinant of the matrix p, which given as follows:

$$P = [ZI - (G-HK)] \quad (18)$$

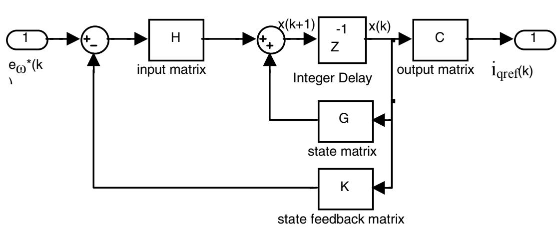

Fig. 3. The block diagram of the digital pole placement controller.

The desired closed loop poles location can be chosen according to the requirements of the motor output speed response, the stability margin and the steady state characteristics.

We use the following design procedure:

1. Derive the mathematical model of the system.
2. Choose the desired closed loop poles for pole placement.
3. Determine the state feedback gain matrix K.
4. Determine the state space model of the proposed controller.

Check the response to the given initial conditions. If the response in not acceptable, adjust the closed pole location until an acceptable response is obtained.

The objective of the digital pole placement controller is to cope with any change in the design requirements or load which needs changes in the locations of the controller poles. These poles can be placed at any desired locations by the state feedback gain matrix k. And from equations 13 and 18 the state feedback gain matrix can be designed for any desired pole locations. Therefore, the proposed controller is used to meet the design specifications and to overcome the nonlinearity problem of the motor.

The current i_{qref} is an input of the PWM inverter. The reference d-axis current i_{dref} is zero, to avoid the demagnetization effect. The d-q coordinate currents are converted into the reference three phase currents i_{abcref}. These reference currents are compared with the actual three phase stator currents for hysteresis current control loop.

V. PERFORMANCE EVALUATION

The PMSM is tested with the same load torque variations stated before in section III. The design of the digital pole placement controller is as stated in section IV. The simulation program is carried out in a numerical simulation, using one of Matlab's toolboxes, Simulink. All the system components are simulated using this program's blocks.

1. Dynamic response during Starting (Zone one)

For a good motor performance during the starting process and under load torque disturbance, the design requirements are as follow: The maximum overshooting is very small and tends to 0.1, the rise time is less than or equal to 0.01 sec, the settling time is less than or equal to 0.04 sec, the steady state value of the speed is less than or equal to 0.15. These requirements are the most commonly used in the second order systems. Therefore, according to these requirements the damping ratio ζ equals 0.6, the un-damped natural frequency ω_n is 180 rad/sec, the damped frequency ω_d is 144 rad/sed. Equation (15) is used here to determine the constant y, which yields y equals 50. Also, the steady state value of the speed $\omega(z)$ is determined from the following equation:

$$\omega_{s.s}(z) = \lim_{z\to 1}(1-z^{-1}).\omega(z) \quad (19)$$

On the other hand, (19) is used to determine the gain of the controller k_d, which will be equal to 0.04.

The state space representation of the digital pole placement controller is obtained using the direct programming method [5]. G = [0 1;-1 1.76], H = [0;1], C = [0 .02], D = [0]; K= [k_1 k_2]=[0.23 0.45].

Fig. 4, shows the dynamic response of the motor during the starting process when provided with the designed digital controller of gain k_d=0.04, and y=50 as compared with the PI controller of gains k_p = 2.6 and k_i = 1. For a fair comparison the gains of the conventional PI controller are designed according to the same design specifications and the PI controller is placed in the same position instead of the digital pole placement controller. By inspection of the dynamic response, it can be realized that the dynamic response of the PMSM when provided with the digital pole placement controller is improved compared with that obtained when the motor is provided with the PI controller. The response is fast with minimum overshoots.

On the other hand, if the motor inertia is doubled and the drive response is recorded. It can be noted from Fig. 5. that the response of the proposed digital pole placement controller follows the desired speed without any fluctuations. Therefore, it can be illustrated that the proposed controller is adaptive and robust for a wide range of speed control.

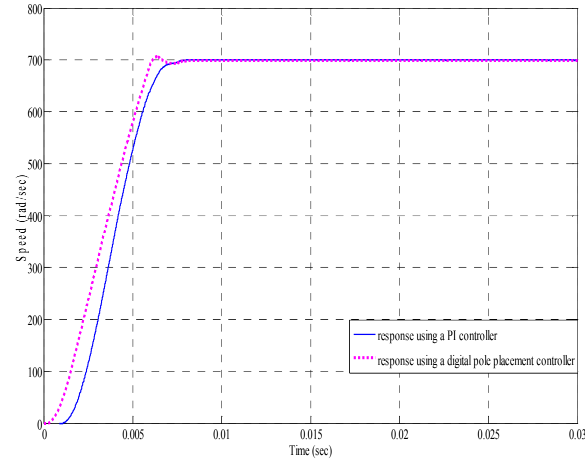

Fig. 4. The dynamic response of the motor during the starting process driven by the digital pole placement controller of gain k_d=0.04, and y=50 as compared with the PI controller of gains k_p = 2.6 and k_i = 1.

2. Dynamic response during a step down load torque Disturbance (Zone two)

For a good motor performance during this zone, the design requirements are minimum overshooting (less than or equal to 0.2), the rise time is less than or equal to 0.01 sec, the settling time is less than or equal to 0.04 sec, the steady state value is less than or equal to 0.15. Therefore, according to these requirements ζ equals 0.5, ω_n is 200 rad/sec, ω_d is 173 rad/sec, y equals 0.04, and k_d equals 0.6. G =[0 1;-1 2], H = [0;1], C = [0 0.0002], D = [0], and <u>K</u>= [0.3 0.5].

Fig. 6, shows the dynamic response of the motor during the second zone. The motor is driven by the digital pole placement controller of gain k_d=0.6, and y=0.04 as compared with the PI controller of gains k_p= 2.6 and ki =5. By inspection of the dynamic response, it can be realized that the dynamic response of the PMSM in this case, has a maximum overshoot lower than that experienced when a PI controller is used, also, it will be of better damped response after the first overshoot. Accordingly, the motor reaches its steady state speed faster. In addition, the steady state error is smaller. It also yields a much faster response that allows the motor to reach the steady state after 2ms, while in the PI technique, it reaches the steady state after 6ms. As a consequence for the minimum speed regulation

obtained when the proposed digital pole placement controller is used, a good enhancement in torque ripple is achieved, as shown in Fig. 7.

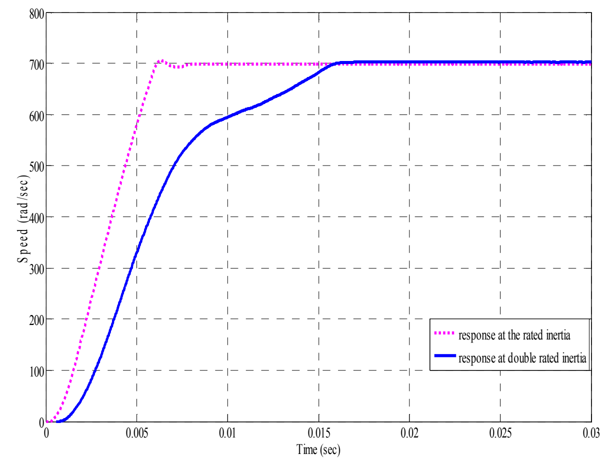

Fig. 5. Speed response of the motor using the digital pole placement controller under parameter variation (inertia).

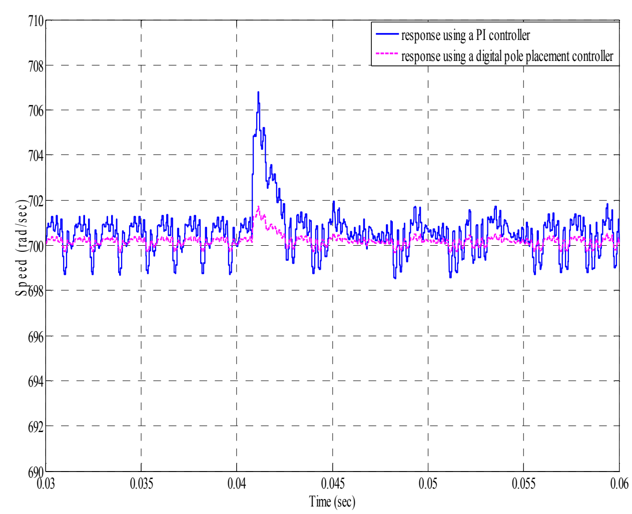

Fig. 6. The dynamic response of the motor during the second zone, driven by the digital pole placement controller of gain k_d =0.6 and y =0.04 as compared with the PI controller of gains k_p=2.6 and k_i=5.

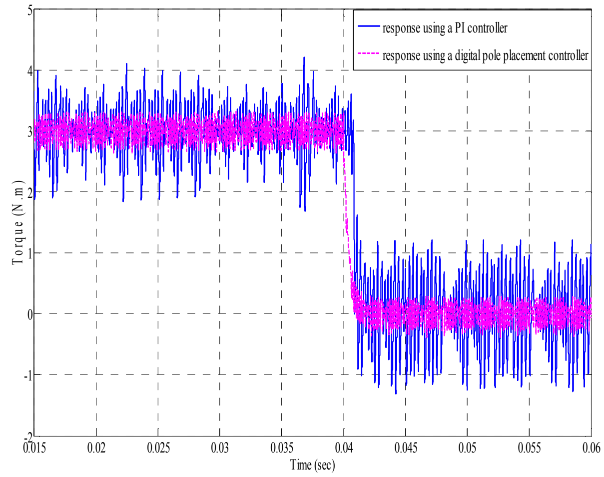

Fig. 7. The torque curve of the motor when driven by the digital pole placement as compared with that of the PI controller.

VI. Conclusion

This paper presents a digital pole placement controller, which is a newly applied to the surface-mounted permanent magnet synchronous motors for the purpose of controlling its speed. The application of the proposed controller for PMSM drives is investigated through analysis and simulation results. The dynamic response of the surface-mounted permanent magnet synchronous motor with this proposed controller is obtained and analyzed at the starting process and under load torque disturbance. By inspection of the dynamic response, it can be realized that the dynamic response of PMSM when provided with the digital pole placement controller is improved and the torque ripple is minimized in compared with that of the conventional PI controller. Therefore, the proposed controller can be used for a wide range of speed control.

VII. Appendix

The specifications of the motor under study are illustrated in table 1.

TABLE 1
MOTOR SPECIFICATIONS

Symbol	Quantity	Value
P	Rated power	1.1 KW
V	Dc voltage	220 V
n	Rated speed	3000
R_s	Stator resistance	2.875 Ω
L_d	d-axis inductance	0.0085 H
L_q	q-axis inductance	0.0085 H
Ψ_m	Magnetic flux	0.175 Wb
J	Motor inertia	0.0008 Kg.m^2
B	Friction coefficient	0 N.m.s
ps	Number of pole pairs	4

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