Modeling of Flatness-Based Control with Disturbance Observer-Based Parameter Estimation for PMSM Drive

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Abstract: - This paper presents a modeling of nonlinear control with parameters identification for the permanent magnet synchronous motor (PMSM) drive. A resistance in series with an inductance and the conduction losses in semiconductor switching devices of inverters represented by $v_{dq} = R_*i_q$ as well as the torque load $T_L$ are going to be estimated by observer method based on extended Luenberger observer (LOB). The simulation and experimental results show the proposed control provides the rapid response and flat of the current control loop for the PMSM drive system. Moreover, the observer approach precisely estimates both $v_{dq}$ and $T_L$, and the converging time is less than 0.1 sec. The test bench was implemented by small-scale PMSM 1 kW, 3,500 rpm, 6 ampere rated to validate the proposed control approach.

Key-Words: - Disturbance observer (DOB), SPMSM, Flatness-based control modeling, Extended Luenberger Observer

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1 Introduction

Currently, Permanent-Magnet Synchronous Machines (PMSMs) have been widely used in many applications such as robotics, numerical controls, and electric vehicles, etc., since they have the significant advantages like high power ratio, small volume, and simple structure. Moreover, with the development of a full electric aircraft, PMSMs are the appropriate player for the electrical propulsion system in aviation. Although there are many advantages of PMSMs, it is still challenging to control them getting high performance for all operating conditions. It is due to a nonlinear multivariable system and subjected to unknown parameters uncertainty of them that nonlinear control approaches are more reasonable than linear control. To get around this problem, many researchers have proposed diverse control design methods, e.g., adaptive control [1], neural network control [2], nonlinear feedback linearization control [3], disturbance-observer-based control [4], model predictive control [5], fuzzy-logic-based controller [6], robust control [7] and the combination of these concepts [8]. One of the nonlinear control systems adapted to control PMSM is the flatness-based control system [9]-[10]. As the flatness-based control is a model-based control, the performance of the controller relies on the accuracy of the machine parameters such as the stator resistance $R_s$, load torque disturbance $T_L$, etc. However, these are difficult to measure directly, so state observer method is often utilized to estimate these parameters. Many parameter estimation methods have been investigated in the literature review, and one of the observer methods is Extended Luenberger Observer (ELO) that has advantages over conventional observers such as independence from mathematical model accuracy, robustness, and good dynamic performance [11]. Also, only observer gains need to be tuned, and the tuning process is not complicated because the gains are determined by the desired observer. In this paper, flatness-based control is going to utilize to control PMSM, and also an observer approach is introduced to improve the performance of the proposed control. In the following sections, a detailed theoretical analysis of the proposed method is presented. Finally, practical implementation results based on the dSPACE 1104 DSP system are shown to confirm its correctness.
2 Proposed Control Design

2.1 Modeling of the PMSM/inverter

\[ \frac{di_d}{dt} = \frac{1}{L_d} (v_d - R_s i_d + \omega_c \cdot L_q i_q) \]  
\[ \frac{di_q}{dt} = \frac{1}{L_q} (v_q - R_s i_q - \omega_c \cdot L_d i_d - \omega_c \cdot \Psi_m) \]  
\[ \frac{d\omega_m}{dt} = \frac{1}{J} (T_e - B \cdot \omega_m - T_L) \]

Where \( v_d \) and \( v_q \) are the d, q axis voltages, \( i_d \) and \( i_q \) are the d, q axis stator currents, \( L_d \) and \( L_q \) are the d, q axis inductances, \( R_s \) and \( \Psi_m \) are the resistance (or system losses) and the magnet’s flux linkage, respectively; and \( \omega_c, \omega_m, p, T_e, T_L, B, J \) are electrical angular frequency, mechanical angular frequency, number of pole pairs, electromagnetic torque, load torque, viscosity, and inertia, respectively.

2.2 Flatness-based Control design

For the first is to analyze the flatness-based control that is mentioned by [9], to utilize for PMSM control. As \( L_s = L_a = L_d \) is defined for non-salient machine. Flat outputs \( y = [i_d \ i_q \ \omega_m]^T \), control variable \( u = [v_d \ v_q \ i_d]^T \), and state variable \( x = [i_d \ i_q \ \omega_m]^T \) are assigned respectively. Then, the state variables \( x \) can be written as \( x = [\varphi_1(y_1) \ \varphi_2(y_2) \ \varphi_3(y_3)]^T \). From (1), (2), and (3), the control variable \( u \) can be calculated from the flatness output \( y \) and its time derivatives (called inverse dynamics):

\[ u_1 = L_s \cdot i_d + R_s \cdot i_d - \omega_c \cdot L_s \cdot i_q = \varphi'_1(y_1, \dot{y}_1, \ddot{y}_2) = v_d \]  
\[ u_2 = L_s \cdot i_q + R_s \cdot i_q + \omega_c \cdot L_d \cdot i_d + \omega_c \cdot \Psi_m = \varphi'_2(y_1, \dot{y}_2, \ddot{y}_3) = v_q \]  
\[ u_3 = (J \cdot \dot{\omega_m} + T_L + B \cdot \omega_m) / p \cdot \Psi_m = \varphi'_3(y_3, \dot{y}_3) = i_{COM} \]

Fig. 1 A three-phase inverter is driving the PMSM where \( V_{BUS}, i_{BUS}, i_a, \) and \( i_c \) are DC bus voltage, the input inverter current, the motor phase current, respectively.

Fig. 1 shows a system configuration of a three-phase inverter connected to the PMSM. The sinusoidal pulse-width modulation technique (SPWM) is applied to inverter to achieve a sinusoidal output voltage with minimal undesired harmonics. The classic rotor reference frame of the PMSM is [9]-[12]:

The control law of the current and speed control loop detailed depics in Fig. 2. The input reference of each module of the current control is \( y_{REF} \), where \( i = 1, 2 \) (\( y_{REF}^i = i_a = 0 \)), and \( y_{REF}^{COM} = i_{COM} \), and the input reference of the speed control is \( y_{REF}^s = \omega_m \). The control law based on the second-order control law is used by (9) for current loop and (10) for the speed loop, to guarantee that the control of the flatness output variable converges to their reference trajectory.

\[ \dot{y}_i = \dot{y}_{REF} + K_i (y_{REF} - y_i) + K_{i1} \int_0^t (y_{REF} - y_i) dt \]  
\[ \dot{y}_3 = \dot{y}_{REF} + K_{i3} (y_{REF} - y_3) + K_{i2} \int_0^t (y_{REF} - y_3) dt \]

where \( K_{i1}, K_{i2}, K_{i0}, \) and \( K_{20} \) are the controller parameters defining as follows:

\( K_{i1} = 2\zeta_1 \omega_1, K_{i2} = \omega_1^2, K_{i0} = 2\zeta_2 \omega_3, K_{20} = \omega_3^2 \)

Fig. 3 shows the whole control system of the PMSM control using the flatness-based control system proposed in this research. Error tracking (\( e_1 = y_{REF} - y_1 \) and \( e_2 = y_{REF} - y_2 \)) are defined as follows

\[ q_i(s) = e_1^2 + 2\zeta_1 \omega_1 e_1 + \omega_1^2 \]  
\[ q_{i3}(s) = e_3^2 + 2\zeta_3 \omega_3 e_3 + \omega_3^2 \]

\( \zeta_1 \) and \( \zeta_3 \), are the desired dominant damping ratio, and \( \omega_1 \) and \( \omega_3 \) are natural frequency respectively.
It is evident that the control system is stable for the positive value of $K_{1s}$, $K_{2s}$, $K_{1vo}$, and $K_{2vo}$. However, “based on a cascade control structure and constant switching frequency in power electronic inverters, the frequencies of the system must meet the following rule: $\omega_3 < \omega_2 < \omega_6$, where $\omega_3$ is the cut off frequency of the speed control loop, $\omega_2$ is the cut off frequency of the current control loop and $\omega_6$ is the switching frequency” [24]. Finally, a second-order is used by (13) to limit the transient current and speed command, so that they are going to keep smooth transition during the instantaneous variation that is:

$$\frac{\omega_{REF}(s)}{\omega_{COM}(s)} - \frac{l_{REF}(s)}{l_{COM}(s)} = \frac{1}{(s + 2\zeta \omega_i) + \frac{2\zeta \omega_i}{\omega_m} s + 1}$$

where $\zeta$ and $\omega_m$ where $i = 2, 4$ are the desired dominant damping ratio and natural frequency respectively.

### 3 Extended Luenberger Observer

In this section, the estimation of unknown parameters and state variables are explained by using an observer concept. At the beginning of using this methodology came from studying about “the disturbance observer” that had many pieces of research proposed in the past, such as [13]-[23]. The study found that the disturbance observer has several methodologies, but the distinctive methodology is Extended State Observer (ESO). Due to the robustness against parameter mismatch and signal noise. Also, only observer gains need to be tuned, and the tuning process is not complicated because the gains are determined by the desired observer bandwidth. Refer to the inverse dynamic Equation (6), (7) and (8), the resistance $R_i$ represented by $v_{oi}(=R_on_i)$ and load torque $T_i$ are estimated by observer method. In order to apply the methodology, all the system equations are expressed by the state space equation shown as follows.

$$\dot{x}(t) = f(x(t), u(t), t)$$

$$y(t) = g(x(t), u(t), t)$$

It is assumed that the time constant of the load torque, and state variable is much larger than of a controller. Thus the derivative of the load torque $dtLc/dt$ and state variable $dv_{oi}/dt$ can be considered as zero. As it a state observer dedicated to the linear system, it was necessary to linearize the considered system around one operating point. The linearization model of PMSM can be written as

$$\dot{x}(t) = Ax(t) + Bu(t)$$

$$y(t) = Cx(t)$$

where $x(t) = [i_q \omega_m v_{iq} T_i]^T$, output variables are $y = [i_q \omega_m]$ and input variables are $u = [v_{iq} v_{ic}]^T$.

$$A = \begin{bmatrix} 0 & -\psi_m & -1 & 0 \\ \frac{L_q}{L_q} & -\frac{1}{L_q} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The state observer equation by using the luenberger observer is defined as follows.

$$\dot{x}(t) = Ax(t) + Bu(t) + LC(y(t) - \hat{y}(t))$$

$$\dot{\hat{y}}(t) = C\hat{x}(t)$$

$$\dot{\hat{x}}(t) = (A - LC)x(t) + Bu(t) + LC(x(t) - \hat{x}(t))$$

The estimated error $e(t) = x(t) - \hat{x}(t)$ is defined:

$$x(t) - \hat{x}(t) = A(x(t) - \hat{x}(t)) + Bu(t) + LC(x(t) - \hat{x}(t))$$

If the matrix gain $L$ is appropriately designed, the estimated error $e(t) = \hat{x}(t) - x(t)$ will tend to zero. It means
that the estimated states $\hat{x}(t)$ approach the actual states $x(t)$.

Block diagram for Luenberger observer is shown in Fig. 3. The observability matrix $(Q_b)$ (18), (19) has rank 4. It is full rank, and the system is completely observable. It is realized by choosing the value of the gain matrix $L$ so that $(A - LC)$ eigenvalues approach $(-200 - 200 - 33 - 60)^T$. Those values have been tuned experimentally to obtain better performances as possible. For the operating point, at speed $(n) = 1500$ rpm, $\omega_{e0} = 157.0796$ rad/sec, and $i_{d0} = 0$, the matrix $L$ is obtained by (26). For this estimation, even if the system has been linearized around one operating point, it has been experimentally verified that the estimation was converging in the speed range 0-1500 rpm with no change of the value of the matrix $L$. The closed-loop system pole locations can be arbitrarily placed if and only if the system is controllable.

$$L = \begin{bmatrix} 260 & -18.811 \\ 395.357 & 230.9174 \\ -423.720 & 0 \\ 0 & -11.088 \end{bmatrix}$$ (26)

### 4 Stability and Control Conclusion

In this section, the stability of the flatness-based control including the extended Luenberger observer is going to be explained. The control conclusion and stability of the flatness-based control was mentioned by [24] that the stability of the control systems was guaranteed. For the stability of the ELO is explained by the design controllers and observers using state-space (or time-domain) methods. For the LTI (Linear Time-Invariant) systems are written as follows.

$$\dot{x}(t) = Ax(t) + Bu(t)$$ (27)

$$y(t) = Cx(t) + Du(t)$$ (28)

The first step is to analyze whether the open-loop system (without any control) is stable. The eigenvalues of the system matrix, $A$, (equivalent to the poles of the transfer function) determine the stability. The eigenvalues of the $A$ matrix are the values of $s$ where $\det(sI - A) = 0$. It is important to note that a system must be completely controllable and observable to allow the flexibility to place all the closed-loop system poles arbitrarily. A system is controllable if there exists a control input, $u(t)$, that transfers any state of the system to zero in finite time. It is able be shown that the LTI system (27) is controllable if and only if its controllability matrix, $Q_c$, has full rank or $\det(Q_c) \neq 0$ (i.e. if rank($Q_c$) = $n$ where $n$ is the number of states).

$$Q_c = [B|AB|A^2B|...|A^{n-1}B]$$ (29)

Meanwhile, the system is observable if and only if the observability matrix, $Q_o$, has full rank or $\det(Q_o) \neq 0$ (i.e. if rank($Q_o$) = $n$ where $n$ is the number of states).

$$Q_o = \begin{bmatrix} C \\ CA \\ CA^2 \\ ... \\ CA^{n-1} \end{bmatrix}$$ (30)

Controllability and observability are dual concepts. A system $(A,B)$ is controllable if and only if a system $(A',C,B',D)$ is observable. This fact will be useful when designing an observer. Ackermann's formula can also be employed to place the roots of the observer characteristic equation at the desired locations [25]. Consider the observer gain matrix.

$$L = [L_1, L_2, ..., L_n]^T$$ (31)

and the desired observer characteristic equation

$$q(\lambda) = \lambda^n + \beta_{n-1}\lambda^{n-1} + ... + \beta_1 \lambda + \beta_0$$ (32)

The $\beta$'s are selected to meet given performance specifications for the observer. The observer gain matrix is then computed via

$$L = q(A)Q_b^{-1}[0 \ 0 \ 0 \ 1]^T$$ (33)

where $Q_b$ is the observability matrix and

$$q(A) = A^n + \beta_{n-1}A^{n-1} + ... + \beta_1 A + \beta_0 I$$ (34)

### 4 Simulation and Experimental Result

#### 4.1 Laboratory Setup

The main PMSM parameters are presented in Table 1, and the flatness-based controller parameters are defined in Table 2. The laboratory setup showing in Fig. 4 composed of a 6-pole, 1-kW PMSM coupled with a 0.25-kW Separate Excited DC motor that was served as a power supply for a purely resistive load. The stator windings of the PMSM were fed by a 3-kW, 3Φ DC–AC voltage-source inverter (VSI) that was operated at a switching frequency of 10 kHz.
The input voltage is obtained through diode rectifier as shown in Fig. 1. The drive system is also equipped with an incremental encoder mounted on the rotor shaft and has a resolution of 4096 lines/revolution.

4.2 Performance of Speed acceleration
Fig. 5 shows the experimental results of speed acceleration response at light load condition (friction losses), \( n_{COM} = 0 - 1500 \) rpm and \( i_{dCOM} = 0 \) A. It is important to mention that the motor speed is able to track accurately the command.

During the acceleration period, the \( q \)-axis \( i_q \) equals the motor maximum capability \( i_{q\text{max}} = +6 \) A. This ensures that the PMSM runs up in the shortest time possible, and subsequently the current \( i_q \) decreases in order to satisfy the small friction torque.

4.3 Performance of state variables estimation
Fig. 6(a) and 6(b) show the simulation and experimental results respectively of the state variable, \( T_I \) estimation. The experimental result is quite corresponding to the simulation results. The results reflect that when the load torque is suddenly applied to PMSM from 0 Nm to 2 Nm, it can be correctly estimated by ELO, and the converging time is less than 0.1 s.

Next, Fig. 7(a) and 7(b) show the simulation and experimental results respectively of state variable, \( v_{iq} = (R_s i_q) \) estimation. The experimental result is coincident to the simulation result. In the figure illustrates that \( v_{iq} \) can be precisely estimated by the proposed observer.
Fig. 6 Simulation and experimental results of TL estimation: (a) Simulation and (b) Experimental.

4.4 Speed Reversal of flatness-based controller
The experimental results of speed reversal responses of the system demonstrate in Fig. 8, where the motor is forced to reverse its direction. The system operates in a regenerative mode until the speed of the rotor will become positive; and thereafter, the system changes to motoring mode until the rotor speed reaches reference value. The experimental results reflect that the speed of PMSM can efficiently be controlled by flatness-based control. During steady-state region, the speed measurement is able to almost 100% track the speed reference and the speed command, and $q$-axis current is restrained without exceeding the current limitation (+6 Ampere).

4.3 Performance of disturbance rejection
To guarantee the stability of the control system, in this section is going to illustrate the response of the whole systems shown in Fig. 9 that including Ch1: speed measurement $n$, Ch2: $q$-axis current $i_q$, Ch3: $d$-axis current $i_d$, Ch4: $T_{Lst}$, Ch5: $v_{TQ}$, Ch6: phase current $i_a$, Ch7: phase current $i_c$, and the trajectories of the transient stator current vector. The results reflect that the stability of flatness-based control and ELO is appropriately designed. These results show that the ELO has better disturbance rejection ability. Moreover, the performance of the proposed control is improved because the performance of the control system depends on these parameters of the machine.

4.5 Comparison between Flatness-based and PI Controller
PI controller for the PMSM drive is going to describe briefly in this section because it has mentioned in the introduction section. Fig. 10 shows the block diagram of the closed-loop transfer function of the current control. $K_p$ and $K_i$ parameters are determined according to (35), (36). This approach explained by [26].
Fig. 8 Experimental results of speed reversal.

τs was obtained by checking the step response and pick the time when step response reaches 63.2 % of the steady-state value.

\[
K_{pi} = 2\zeta R_s \tau_s \omega_m - R_s \tag{35}
\]

\[
K_{pi} = R_s \tau_s \omega_m^2 \tag{36}
\]

where \(\zeta = 1\) and \(\omega_m = 286.0379\) rad/sec.

Next, the closed-loop transfer function between \(\omega_{\text{REF}}\) and \(\omega_m\) is represented by a block diagram, as shown in Fig 11. The lag compensator (or PI controller) expressed by (37) is achieved by sisotool (plant)

\[
G_c = \frac{0.12(s + 70)}{s} \tag{37}
\]

Fig. 9 Experimental results of disturbance rejection.

Fig. 10 Closed-loop current control transfer function.
that with the PI control is 0.015 sec. This demonstrates that the flatness-based control has better dynamic performance than a PI control.

4 Conclusion

This paper has presented the state variables estimation using the extended Luenberger observer to improve the performance of flatness-based control for PMSM Drive. It turns out that the extended Luenberger observer has better disturbance rejection ability. Additionally, the performance of the proposed control is improved because the performance of the controller depends on these parameters of the machine. A test bench has been developed using a PMSM drives to practically illustrate the benefits of the proposed controller. The experimental results have shown the ability of the proposed approach to reject the effect of the uncertainty disturbance torque and a resistance in series with an inductance and the switching as well as conduction losses in semiconductor switching devices of inverters. Thereby, the proposed control design provides practitioners with an alternative and effective method to build a robust nonlinear controller.

References:


