Sensorless Vector Control of PMSM Drive Using Fuzzy Logic, for EV/HEV Applications

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ABSTRACT

A fuzzy logic technique is presented in this paper for sensorless speed and position identification of vector-controlled PWM inverter-fed PMSM drives used in EV/HEV propulsion systems. Fuzzy logic is used to estimate the rotor speed and position. Operation of the drive is studied by numerical simulation. The performance for different drive conditions is also analyzed and the results are shown in the paper. Simulation results show that the proposed control method can be effectively used in controlling the PMSM drives with high performance for EV/HEV applications. It is found that the fuzzy logic system is reliable without using any speed or position sensor.

1. INTRODUCTION

With increasing environmental concerns and the future shortage of gasoline supplies, optimum usage of energy and decreasing the pollution of vehicles is inevitable. The ICE automobile at present is a major source of urban pollution. Electric and hybrid electric vehicles (EV/HEV) produce much less poisonous gases than ICE vehicles and save more energy. This is why there has been a renewed interest in electric and hybrid electric vehicles in recent years which seems to be more serious and more fruitful than ever before. Advances in power electronics and digital signal processors (DSP) also help to make EV/HEV popular [1]. Since electric and hybrid electric vehicles have to compete with existing IC engine vehicles, higher efficiency and power density as well as lower cost and reliability are key elements for electric and hybrid electric propulsion systems [2].

In a vehicle, the driver gives his command by stepping on the pedals. Then the control system receives the input signal gathered from the pedal and changes it to the PWM signals. Thus it is important to have flexible torque control and an appropriate motor with its controller system for electric and hybrid propulsion systems.

There are primarily four types of electric motors: the DC motor, the induction motor, the switched reluctance motor and the permanent magnet synchronous motor, which are commonly used for EV/HEV applications [3]. PMSM drives are receiving increased attention for these applications because of advantages such as high efficiency, robustness, superior power density, reliability, high torque to inertia ratio, low weight, small size and simple arrangement on the vehicle [4].

PMSM drives require absolute rotor position and speed signals for high performance control applications. These signals can be obtained from electromechanical sensors such as resolvers or absolute encoders coupled to the shaft of the motor. The presence of the shaft sensor not only increases the cost, complexity and maintenance but also impairs the robustness and reliability of the system [5]. Therefore, there has been a large amount of research effort spent in order to develop a reliable control strategy without any rotational transducer.

For the last decade a number of techniques have been suggested for rotor position and speed estimation, most of which are based on the motor equations. One method is based on rotor flux position estimation using back EMF [6-10]. Since in PMSM drives the magnitude of back EMF is position-dependent, if this can be accurately monitored, the rotor position can be accurately determined in real time. Such an approach is very simple and effective, but fails at low and zero speed. Low-speed operation is quite critical, since the motor back EMF is too low and estimation results are very sensitive to stator resistance variations or simply measurement noises.

The rotor position can also be estimated by using inductance variations due to saturation and geometrical effects. In this case, the calculated inductance is used to estimate the position of the rotor using a set of stored data relating the phase inductance and the rotor position. The other technique is the so-called observer-based method, in which the position/speed information can be derived by measuring phase voltages and currents and by manipulating the mathematical model of the machine. The observers are heavily dependent on the machine parameters. Therefore, the ability to estimate the rotor position will deteriorate as the parameters of the machine vary with thermal and operational conditions. In another method, terminal voltages and stator currents are sensed and processed to produce the stator flux linkage space vector. The angle of this vector is used to produce the command signals. A speed signal is also derived from the rate of change of the angle of the flux linkage.

In recent years, artificial intelligence (neural network, fuzzy logic, fuzzy-neural network) has been used in a wide variety of applications. Among them fuzzy logic is finding more and more applications that include management, economics, medicine and recently in closed loop operation of variable speed drives.

In this paper fuzzy logic has been used to estimate the rotor speed and position. Operation of the drive is studied by numerical simulation, and the performance for different conditions is analyzed and the results are presented. By using fuzzy logic it is possible to save a lot of development and implementation time.

2. MODEL OF PMSM DRIVES

The dynamic behavior of the PMSM drive, in the d-q coordinates which rotate synchronously with an electrical angular velocity ω, can be described by the following set of equations[13]. The flux linkage equations of a PMSM drive are given as:

$$\psi_q = \omega_b \int \left\{ v_q - \frac{\omega_r}{\omega_b}\psi_d + \frac{r_s}{x_{ls}}\left(\psi_{mq} - \psi_q\right) \right\} dt \qquad (1)$$

$$\psi_d = \omega_b \int \left\{ v_d + \frac{\omega_r}{\omega_b}\psi_q + \frac{r_s}{x_{ls}}\left(\psi_{md} - \psi_d\right) \right\} dt \qquad (2)$$

$$\psi'_{kq} = \frac{\omega_b r'_{kq}}{x'_{lkq}} \int \left(\psi_{mq} - \psi'_{kq}\right) dt \qquad (3)$$

$$\psi'_{kd} = \frac{\omega_b r'_{kd}}{x'_{lkd}} \int \left(\psi_{md} - \psi'_{kd}\right) dt \qquad (4)$$

$$\psi_{mq} = x_{MQ}\left(\frac{\psi_q}{x_{ls}} + \frac{\psi'_{kq}}{x'_{lkq}}\right) \qquad (5)$$

$$\psi_{md} = x_{MD}\left(\frac{\psi_d}{x_{ls}} + \frac{\psi'_{kd}}{x'_{lkd}} + i'_m\right) \qquad (6)$$

$$\frac{1}{x_{MQ}} = \frac{1}{x_{mq}} + \frac{1}{x'_{lkq}} + \frac{1}{x_{ls}} \qquad (7)$$

$$\frac{1}{x_{MD}} = \frac{1}{x_{md}} + \frac{1}{x'_{lkd}} + \frac{1}{x_{ls}} \qquad (8)$$

The equations describing currents are:

$$i_q = \frac{\psi_q - \psi_{mq}}{x_{ls}} \qquad (9)$$

$$i_d = \frac{\psi_d - \psi_{md}}{x_{ls}} \qquad (10)$$

Also, the torque equations are:

$$T_{em} = \frac{3n_p}{2\omega_b}\left(\psi_d i_q - \psi_q i_d\right)$$

$$= \frac{3n_p}{2}\left(\psi_f i_q + \left(x_d - x_q\right) i_d i_q\right) \qquad (11)$$

$$T_{em} + T_{mech} - T_D = \frac{J}{n_p}\frac{d\omega_r}{dt} \qquad (12)$$

From eq.(11) it can be seen that for an SPMSM drive, the correspondence between torque and i_q is direct, while for an IPMSM drive, this correspondence involves both i_d and i_q and is more complex. For both motors it is advantageous to control both currents separately in a closed loop.

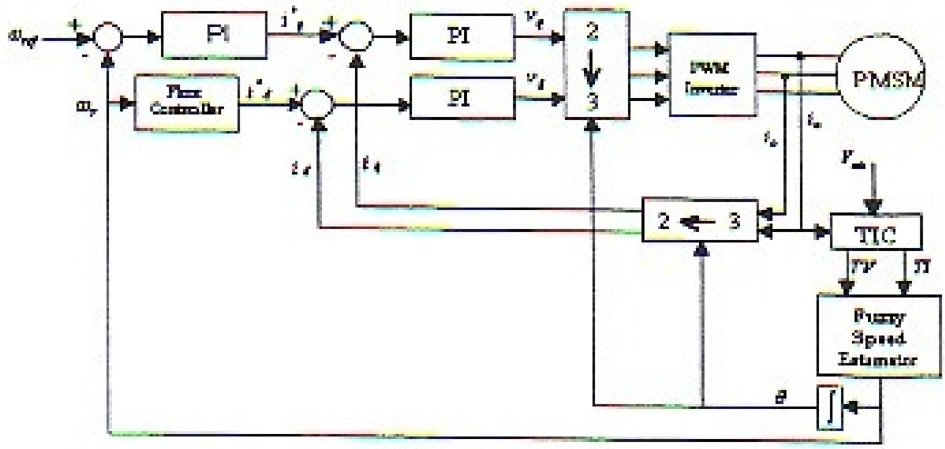


Figure (1): Block Diagram Of a Vector-Controlled PMSM Drive

3. CONTROL OF PMSM DRIVES

In general, a driving system for EV/HEV includes a battery pack as the electric power source, an AC traction motor, a DC/AC inverter and a microprocessor control unit. In such a system the battery pack defines a DC power bus which is connected to the inverter, and the inverter in turn is connected to the AC motor. The inverter converts the DC power from the battery pack into the sinusoidal current signals which are transmitted to the stator of the motor to operate the motor and control the torque. The inverter receives electrical switching/control signals from the microprocessor unit based on a control algorithm. There are many control algorithms, for example, open-loop volt per hertz control, vector control, sensorless vector control and direct torque control.

In a vector control technique, electrical signals representing the phase currents and the position/speed of the motor are communicated to the microprocessor unit, and it maps these data onto a d-q coordinate system to achieve feedback control. The d-axis current component (i_d) is used to control the flux, and the q-axis current component (i_q) is used to control the torque of the motor. The d-q coordinate system rotates synchronously with the rotor flux of the motor and both i_d and i_q can then be treated and controlled as DC values. In this way, independent and decoupled control of both flux and torque of the motor is achieved, and the AC motor can be controlled as a DC motor.

To obtain maximum torque-to-current ratio, below the base speed, the direct current reference i_d^* is set equal to zero and then the torque is directly proportional to i_q. Because the available voltage is limited by the maximum output of the inverter above the base speed, air-gap flux must be weakened by demagnetizing current in the direct axis, which is called flux weakening control. Vector control is achieved in the flux weakening region by controlling i_d to a negative value and i_q to produce the required torque. The overall block diagram of the proposed vector controlled drive is shown in Figure 1.

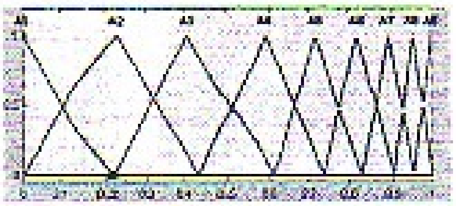
4. SPEED ESTIMATION USING FUZZY LOGIC

The objective of fuzzy control is to design a system with acceptable performance characteristics over a wide range of uncertainty[11]. Fuzzy control is basically nonlinear and adaptive in nature, giving robust performance in the face of parameter variation and load disturbance effects. Many researchers have reported that fuzzy logic control yields results which are superior to those obtained using conventional control algorithms [11-13].

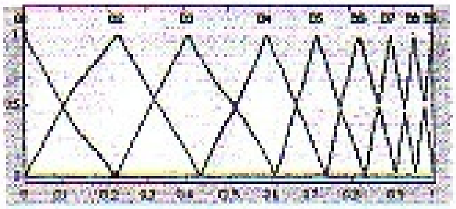
As shown in Figure1, the TIC block receives the line-to-line voltage (V_{ab}) and the line current (I_a) and calculates the time interval between two successive zero-crossing points of V_{ab} (TV) and does the same for I_a (TI). Thus the fuzzy system inputs are TV and TI , which are applied to a set of estimation rules to calculate the state of the output variable, which is the rotor speed. In fact, for every given input condition defined by $TV(k)$ and $TI(k)$, the fuzzy estimator will compute the output variable representing the rotor speed (ω_r).

In order to obtain the best estimation accuracy, the number of membership functions and their shapes are iterated and rule bases are evaluated based on simulation results. The input and output variables of the fuzzy system are expressed on several linguistic levels, such as "very small", "small", "medium", "very very big", etc. Each level is described by a fuzzy set.

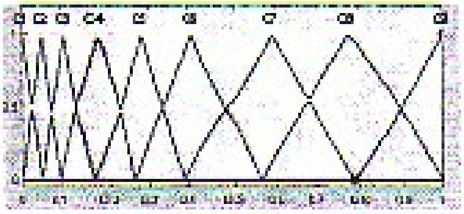
In this paper, the inputs and output of the fuzzy system are each defined by 9 triangular membership functions, shown in Figure 2.



a) Time Interval between two successive zero-crossing point of V_{ab}



b) Time interval between two successive zero-crossing point of I_a



c)Rotor speed

Figure (2): Fuzzy sets of the Input and output variables of the fuzzy system

Also, we used a mamdani type fuzzy logic inference system that contains four main parts: fuzzifier, knowledge base, inference engine and defuzzifier. In the fuzzification stage, Input signals TV and TI are scaled and transformed into fuzzy quantities (linguistic variables) based on membership functions. The data base and the rule base form the knowledge base. The data base contains a description of input and output variables using fuzzy sets, and the rule base contains a collection of fuzzy conditional statements called if-then rules. The inference engine evaluates the set of if-then rules and determines the appropriate output signal, which is a linguistic value. Then this output is converted to a non-fuzzy value by the defuzzifier based on the consequent membership functions of the rules.

5. SIMULATION RESULTS

The proposed control system of a PMSM drive for EV/HEV applications has been simulated. The simulation investigation has been performed on a surface-mounted PMSM with the parameters shown in Table 1.The motor is accelerated from standstill to rated speed without load, and then in steady state a load torque is applied. Figure 3 shows the speed response of the motor during acceleration and steady state. It can be seen that the sensorless drive using the fuzzy logic speed estimator performs well. Figure 4 show the q-axis current (i_q), electromagnetic torque (T_{em}) and d-axis current (i_d) responses respectively. As shown in this illustration, i_d is almost zero and the torque is proportional to i_q.

Table 1: Motor Parameters

P 3kW	x_{ls} 1.15Ω
n 3600 rpm	r'_{kd} 1.5Ω
r_s .3Ω	r'_{kq} 1.5Ω
x_d 9.625Ω	x'_{kd} 2.34Ω
x_d 9.625Ω	x'_{kq} 2.34Ω

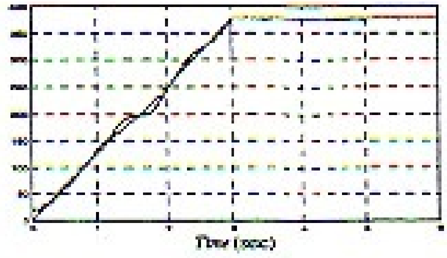
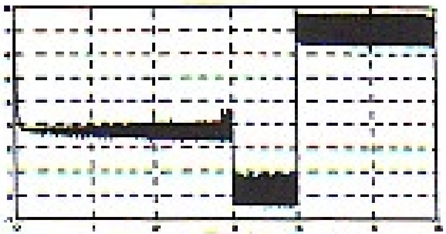
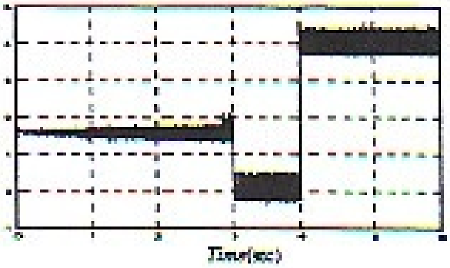


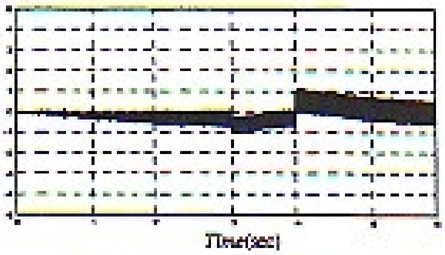
Figure (3): Estimated And Actual Rotor Speed



a) q-axis current component (i_q)



b) Electromagnetic torque (T_{em})



c) d-axis current component (i_d)

Figure (4): q-axis current, d-axis current and torque responses

6. CONCLUSION

An estimation method based on fuzzy logic for sensorless vector controlled PMSM drives for EV/HEV applications has been proposed in this paper. A mamdani type fuzzy controller is used to estimate the rotor speed. The fuzzy system inputs are the time interval between two successive zero-crossing points of the line-to-line voltage and the time interval between two zero-crossing points of the line current. The effectiveness of this method is verified by simulation. Using the proposed method reduces the necessary memory space and processing time.

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