

Sensorless Field-Oriented Control of Permanent Magnet Synchronous Motor (Surface and Interior) for Appliances with Angle-Tracking Phase-Locked Loop Estimator

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INTRODUCTION

Many countries pursue standards which require increasing energy efficiency in domestic appliances, such as air conditioners, refrigerators, washing machines, fans and so on. Additionally, manufacturers and consumers prefer to reduce the size of such appliances. A Permanent Magnet Synchronous Motor (PMSM) is an ideal choice for such applications due to its high efficiency, energy density and robustness.

PMSMs require sophisticated control schemes customized to suit the motor, load and the appliance system to achieve the best possible efficiency, durability and robustness.

This document discusses the control scheme and some of the load-specific algorithms for control of PMSM-driven appliances, for example, compressors, washing machines and fans.

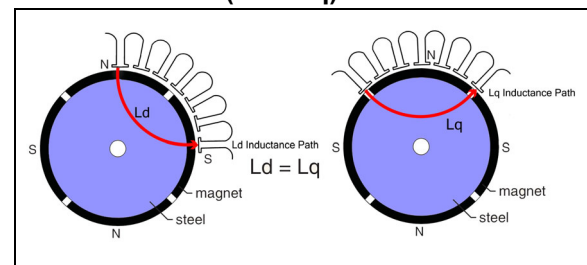
PERMANENT MAGNET SYNCHRONOUS MOTOR (PMSM)

The PMSM is made of a stationary part called the stator and a rotating part called the rotor. A stator consists of three phase windings, and when excited with a balanced three-phase voltage, it produces a rotating magnetic field. A rotor has permanent magnets, which produce their own magnetic field. The motor rotates due to torque produced when these two fields interact.

PMSMs are classified into two categories depending on the rotor construction:

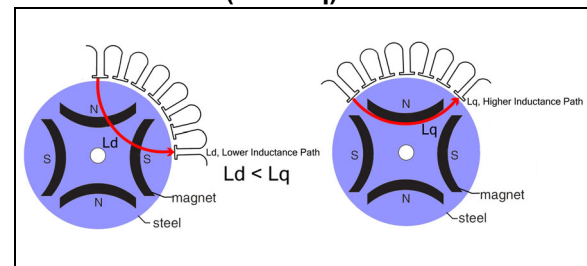
1. **Surface Mount:** The magnets are mounted on the surface of the rotor. They need special profiling to get a sinusoidal Back EMF (BEMF). This results in a symmetrical air gap reluctance for the magnetic flux path. Such a motor is called a Surface-Mounted Permanent Magnet Synchronous Motor (SPMSM).

FIGURE 1: SPMSM INDUCTANCES ($L_d = L_q$)



2. **Interior Mount:** Magnets are embedded deep inside the rotor. This results in an asymmetrical air gap reluctance for the magnetic flux path. Such a motor is called an Interior-Permanent Magnet Synchronous Motor (IPMSM).

FIGURE 2: IPMSM INDUCTANCES ($L_d < L_q$)



Practically, even the surface-mounted PMSMs have slight asymmetry in their reluctance path due to manufacturing processes and materials used. A measure of this asymmetry is called, 'saliency', which is calculated based on the inductance variation along the stator.

Saliency produces its own torque, similar to a force produced on an iron bar in a solenoid. This torque is called, 'reluctance torque', which is different and additional to the 'permanent magnetic torque' that is produced due to interaction of stator and rotor fields.

FIELD-ORIENTED CONTROL

Field-Oriented Control (FOC) is a control method in which electrical quantities of a three-phase PMSM are modeled and controlled as vectors. These vectors can be split into two orthogonal components: one along the rotor magnetic flux ('direct axis' denoted by 'd') and the other orthogonal ('quadrature axis' denoted by 'q') to it.

This gives an independent control of torque and flux, which gives the best dynamic performance possible for the motor compared to other control schemes, such as sinusoidal control or trapezoidal control.

The physical three-phase quantities of the motor are transformed into a rotating reference frame aligned with the rotor flux (field orientation). By aligning the reference frame in the direction of rotor flux, the torque and flux producing components of the currents are decoupled and can be controlled independently.

This transformation is achieved by the Clarke transformation (abc to $\alpha\beta$) and the Park transformation ($\alpha\beta$ to dq). The Park transformation transforms sinusoidal currents to DC currents. These DC currents are inputs to the Proportional Integral (PI) controllers, which control the torque and flux.

The outputs of current PI controllers are modulation indices, which are then transformed back to three-phase modulation indices, by performing the inverse Park transformation (dq to $\alpha\beta$) and inverse Clarke transformation ($\alpha\beta$ to abc).

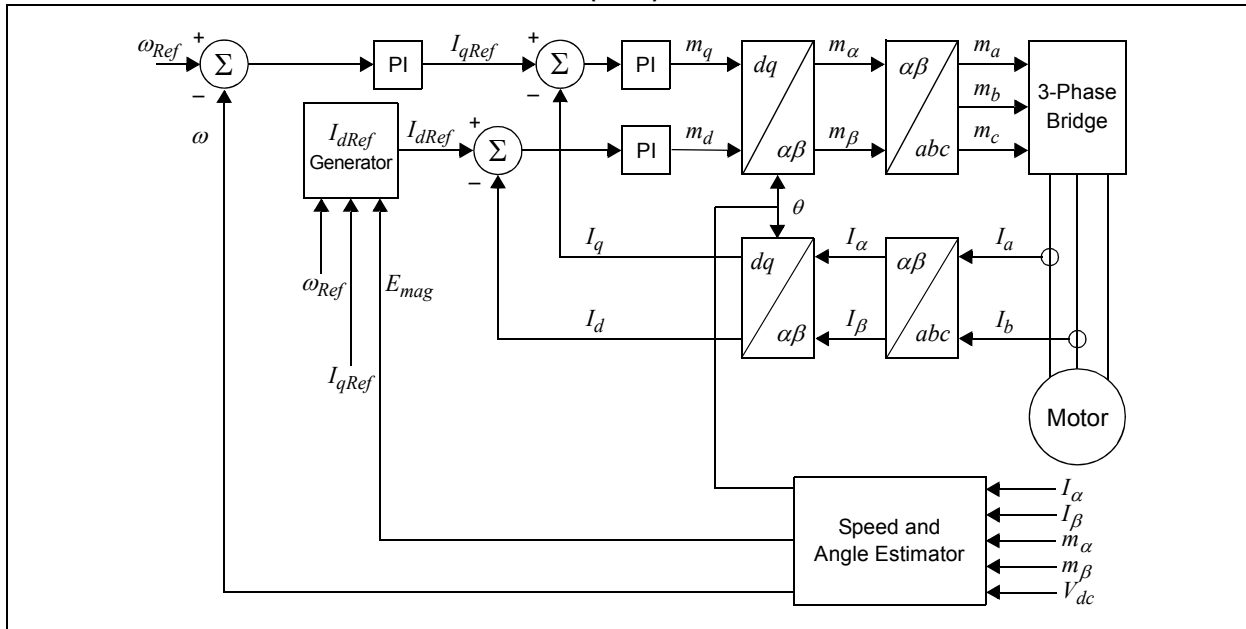
Speed control is achieved by controlling the torque produced by the motor. Since flux and torque components are decoupled, the output of the speed controller can be used as a reference for the torque producing component of the current.

In a PMSM, unlike an induction motor, the flux producing component of current can be maintained at zero as the rotor flux is produced by permanent magnets.

For additional information on FOC of PMSMs, refer to the Microchip Application notes AN1078, "Sensorless Field Oriented Control of a PMSM" and AN1292, "Sensorless Field Oriented Control (FOC) for a Permanent Magnet Synchronous Motor (PMSM) Using a PLL Estimator and Field Weakening (FW)" listed in the "References" section.

The block diagram of FOC is shown in Figure 3.

FIGURE 3: FIELD-ORIENTED CONTROL (FOC) BLOCK DIAGRAM



For orienting the reference frame in the direction of the rotor flux, the position of the rotor flux needs to be known. This can be extracted from a speed position sensor, such as an incremental encoder, Hall sensors or a resolver, or from a speed position estimator. A speed position estimator running in real time in the Digital Signal Controller (DSC) receives applied voltages and motor currents as inputs, and estimates rotor flux position and speed as outputs.

The estimator gives reliable position information only beyond certain speeds as the model is not accurate at low speeds. Hence, it is required to start the motor in open loop. The current loops can be closed to have controlled currents. In an open loop, the position of the reference frame is forcefully changed so that the motor accelerates to a speed where the estimator gives reliable information. Once the estimator gives reliable position of the rotor flux, the reference frame is slowly aligned to the rotor flux. The entire starting sequence is handled by a control state machine.

ESTIMATOR – ANGLE-TRACKING PHASE-LOCKED LOOP (AT-PLL)

The information of the rotor position is embedded in the rotor flux or BEMF. As shown in Equation 1, this can be estimated by feeding the current and voltage information to the motor model.

EQUATION 1:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{V_{dc}}{\sqrt{3}} \begin{bmatrix} m_\alpha \\ m_\beta \end{bmatrix}$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} r_s & 0 \\ 0 & r_s \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_0 - L_1 \cos(2\theta) & -L_1 \sin(2\theta) \\ -L_1 \sin(2\theta) & L_0 + L_1 \cos(2\theta) \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} + \begin{bmatrix} E_\alpha \\ E_\beta \end{bmatrix}$$

$$\therefore \begin{bmatrix} E_\alpha \\ E_\beta \end{bmatrix} = \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} - \begin{bmatrix} r_s & 0 \\ 0 & r_s \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} - \frac{d}{dt} \begin{bmatrix} L_0 - L_1 \cos(2\theta) & -L_1 \sin(2\theta) \\ -L_1 \sin(2\theta) & L_0 + L_1 \cos(2\theta) \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix}$$

Where:

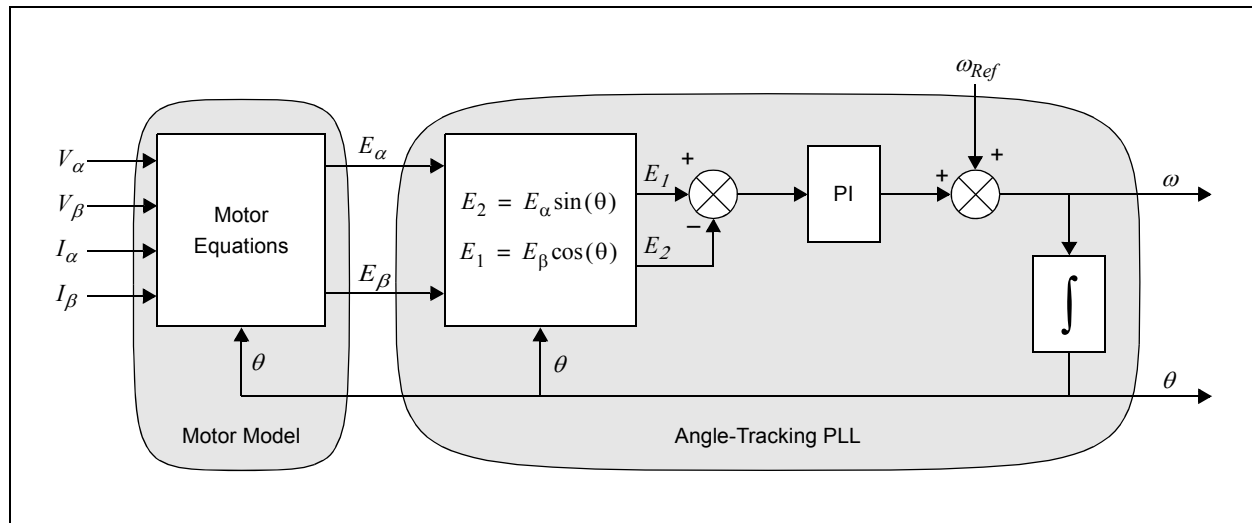
$$L_0 = \frac{L_{ds} + L_{qs}}{2} \quad \text{and} \quad L_1 = \frac{L_{ds} - L_{qs}}{2}$$

Note: $L_1 = 0$ in SPMSM.

Once the BEMF is known, the speed and position are extracted using the AT-PLL.

Figure 4 shows the block diagram implementation of the estimator (AT-PLL).

FIGURE 4: AT-PLL BLOCK DIAGRAM



D-AXIS CURRENT REFERENCE GENERATION

In FOC, the flux component of current, which is aligned to the rotor flux, is referred to as ‘D-axis’ current (I_{ds}). A positive I_{ds} strengthens the air gap flux, whereas a negative I_{ds} weakens it. Hence, by controlling I_{ds} , the air gap flux of the motor can be controlled.

The torque component of current is referred to as the ‘Q-axis’ current (I_{qs}). Controlling this component controls the speed of the motor.

Maximum Torque Per Ampere (MTPA)

Torque produced by the motor, as shown in [Equation 2](#), is a result of the interaction between the permanent magnet flux with I_{qs} (called permanent magnet torque) and I_{ds} with I_{qs} (called reluctance torque).

EQUATION 2:

$$T_e = \frac{3P}{2}(\Psi_{PM} + (L_{ds} - L_{qs})I_{ds})I_{qs}$$

By making $I_{ds} = 0$, all the current drawn by the motor can be used to produce the torque, thus ensuring that the motor operates at its optimum operating point.

For IPMSM where $L_{ds} < L_{qs}$, by making I_{ds} negative, reluctance torque can be made to aid permanent magnet torque. By appropriate referencing of I_{ds} , the total current drawn can be minimized for a given torque requirement. This algorithm ([Equation 3](#)) is called Maximum Torque Per Ampere (MTPA) and it ensures efficient operation of the IPMSM. The magnitude of I_{ds} is determined from [Equation 3](#).

EQUATION 3:

$$I_{ds} = \frac{-\Psi_{PM} + \sqrt{\Psi_{PM}^2 + (4L_1 I_{qs})^2}}{4L_1}$$

Flux Weakening

As the speed of a motor increases, the BEMF increases proportionately, leading to an increased applied voltage demand. However, when it is required to increase the speed beyond a certain point (called the nominal speed) due to limitations on the DC bus voltage (power switches, insulation and so on), no further increase in applied voltage is possible. In such scenarios, by applying a negative I_{ds} , the voltage drop across the stator inductance can be used to cancel out part of the BEMF, allowing a higher speed for a given DC bus voltage. This is called flux weakening, field weakening or extended speed operation of the motor. Here, the most optimal operating point is achieved when the applied voltage lies on the maximum voltage limit circle for that speed and load demand.

STALL DETECTION

Whenever the load on a motor increases beyond its capability, or due to improper tuning, the motor stalls. Stalls can be categorized into two kinds: Fast Stalls and Slow Stalls.

- **Fast Stalls:** Occur due to the sudden variation of the operating point in a motor, which would manifest as an overcurrent. Hence, phase current data are monitored to detect this Stall.
- **Slow Stalls:** Occur due to the slow addition of load or the improper tuning of a motor. This would manifest as a BEMF, which is much lower than the expected BEMF based on the set speed. As the BEMF information is available from the estimator, BEMF data are monitored to detect this Stall.

APPLICATION-SPECIFIC ALGORITHMS

The previous sections dealt with a generic motor application, which is the base control structure for running a PMSM. However, different applications/appliances need additional algorithms to meet their specific needs.

This section deals with algorithms implemented to fulfill these appliance-specific requirements. However, these algorithms can also be applied to address requirements of other applications. Some of the usage examples are discussed in the following sections.

Initial Position Detection (IPD)

Typically, a PMSM is started by locking to a known angle. This causes a retrograde rotation if the nearest locking position is in the opposite direction of rotation. In applications where this retrograde rotation is not allowed, IPD is used.

In the case of a salient pole motor, the inductance of the motor varies with rotor position. Hence, by applying different voltage vectors and measuring currents, relative inductances along different stator points can be estimated, and the rotor position can be obtained. Once the rotor position is obtained, the motor can be directly started from the determined position, avoiding the retrograde rotation.

Windmilling

For a typical application, when a voltage applied to a motor is removed (de-energized), the motor continues to spin due to its inertia. Additionally, for fan applications, even when the motor is de-energized, it can spin continuously due to forces of wind blowing on the fan. Under such circumstances, starting the motor does not need locking. There is a BEMF generated due to the free spinning of the motor because of the presence of permanent magnets in the rotor. This BEMF can be sensed to obtain the speed and position of the rotor. This information is then used to start the motor.

Torque Compensation

Certain loads, such as a compressor, due to their characteristics, may cause the motor to vibrate even under steady-state conditions. The frequency of these vibrations can be determined from the motor feedback. Once the frequency is known, this algorithm works to cancel out the effect of the frequency on the motor, thereby reducing the vibrations.

Soft Stop

In flux weakening, when a motor running high-inertia loads, such as a washing machine, is stopped abruptly, the energy in the mechanical system is transferred back to the electrical system. If this sudden burst of energy is not handled properly, the increased DC bus voltage might reach unsafe levels.

One way to handle the increased DC bus voltage is to reduce the motor speed in a controlled manner whenever a stop command is received. This ensures that the DC bus voltage does not reach unsafe levels. Once the speed of the motor attains a safe speed, the voltage applied to the motor can be turned off, thereby stopping the motor safely.

Usage Examples

This section deals with a few appliance-specific requirements that can be addressed with the application-specific algorithms discussed in the previous section.

FANS

The older models of fans used single-phase induction motors, where they typically continue to spin from their present speed to a set speed without any reverse rotation, even during momentary power interruptions. These legacy features are expected to be available in PMSM-driven fans.

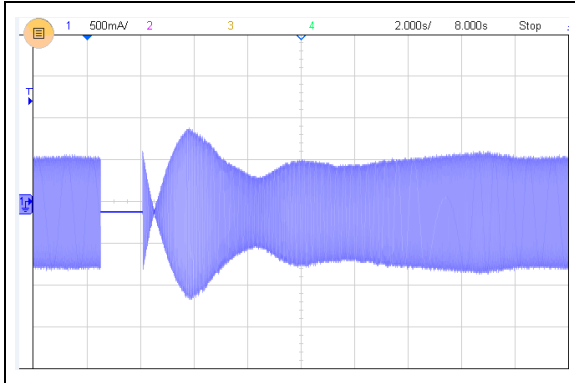
The requirements can be summarized as follows:

- Start the fan from its standstill position. There should be no noticeable backward movement of the blades.
- When a de-energized fan is running in a forward direction (due to inertia or external wind blowing), in case of a power Reset, it should be able to catch the speed on-the-fly.
- When a de-energized fan is running in a reverse direction (due to inertia or external wind blowing), it should be smoothly and safely stopped from doing so before running in the forward direction.

It can be observed that some of these requirements are aesthetic needs while running a fan, and hence, need not be the basic requirements for all fan applications. For example, a ceiling fan may have all these requirements, whereas retrograde motion may be acceptable in a kitchen-hood fan as it is concealed. It may still have a requirement to catch the speed on-the-fly in case of a power Reset. IPD (discussed in the [“Initial Position Detection \(IPD\)”](#) section) and windmilling (discussed in the [“Windmilling”](#) section) can address these sets of requirements.

Figure 5 shows the current waveform for a fan that is stopped while windmilling and then smoothly restarted in the opposite direction.

FIGURE 5: WINDMILLING: FAN MOTOR CURRENT

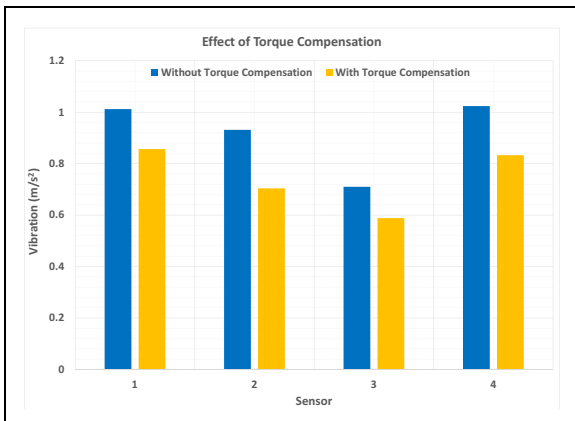


AIR CONDITIONERS AND REFRIGERATORS

Air conditioners and refrigerators have motor-driven compressors as a major component of their system, which enables heat exchange. Due to pressure variations during a compression cycle, the compressor loads the motor unevenly causing vibrations in the motor, compressor and pipes. These vibrations cause the pipes to fatigue and can lead to premature failure.

These vibrations should be minimized, especially at low motor speeds. At high speeds, the motor, compressor and pipes react less due to their typical mechanical responses. This requirement can be met by using the torque compensation algorithm discussed in the “Torque Compensation” section.

FIGURE 6: TORQUE COMPENSATION: COMPRESSOR VIBRATIONS

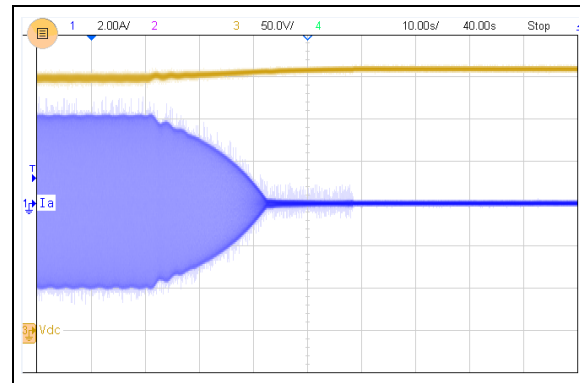


WASHING MACHINES

Washing machines are applications that have a combination of high inertia of the machine and the possibility of the motor running at a very high speed. When a washing machine is running in spin-dry mode, if a stop command is received, the application has to stop the motor safely to avoid a DC bus voltage surge. For more information, refer to the “Soft Stop” section.

Figure 7 shows the current waveform for a washing machine using a soft start algorithm to prevent a DC bus overvoltage condition.

FIGURE 7: SOFT STOP: WASHING MACHINE MOTOR CURRENT



CONCLUSION

As understood in the previous sections of this document, the algorithms and usage examples demonstrate their capabilities in achieving energy efficiency, durability and robustness of PMSM-driven appliances, such as fans, washing machines, refrigerators and air conditioners. These algorithms have been demonstrated in Microchip dsPIC[®] DSC devices and can be extended to other PMSM-based applications.

NOMENCLATURE

The following table lists the symbols and constants quoted in this document.

TABLE 1: NOMENCLATURE

r_s	Stator Resistance
L_{ds}	D-Axis Stator Inductance ($L_{ds} < L_{qs}$)
L_{qs}	Q-Axis Stator Inductance
Ψ_{PM}	Motor Back EMF (BEMF) Constant
V_α	Applied Voltage along Phase 'a'
V_β	Applied Voltage Quadrature to Phase 'a'
I_α	Stator Current along Phase 'a'
I_β	Stator Current Quadrature to Phase 'a'
E_α	BEMF along Phase 'a'
E_β	BEMF Quadrature to Phase 'a'
ω_{Ref}	Rotor Reference Speed
ω	Rotor Speed
θ	Estimated BEMF Angle
I_{dsRef}	Reference Stator Current along D-Axis
I_{qsRef}	Reference Stator Current along Q-Axis
I_{ds}	Stator Current along D-Axis
I_{qs}	Stator Current along Q-Axis
V_{dc}	Sensed DC Link Voltage

REFERENCES

- AN1078, "Sensorless Field Oriented Control of a PMSM"
- AN1292, "Sensorless Field Oriented Control (FOC) for a Permanent Magnet Synchronous Motor (PMSM) Using a PLL Estimator and Field Weakening (FW)"
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