Application Paper **AP040220EN** Effective May 2021

Permanent magnet synchronous motor control (PMSM) using PowerXL DM1 variable frequency drives

Contents

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Overview

A PM motor is an AC motor that uses magnets imbedded into the rotor (IPM) or attached to the surface of the motor's rotor (SPM). There are four key, three-phase AC motors. **Figure 1** and **Table 1** shows the comparison between different three-phase AC motors.

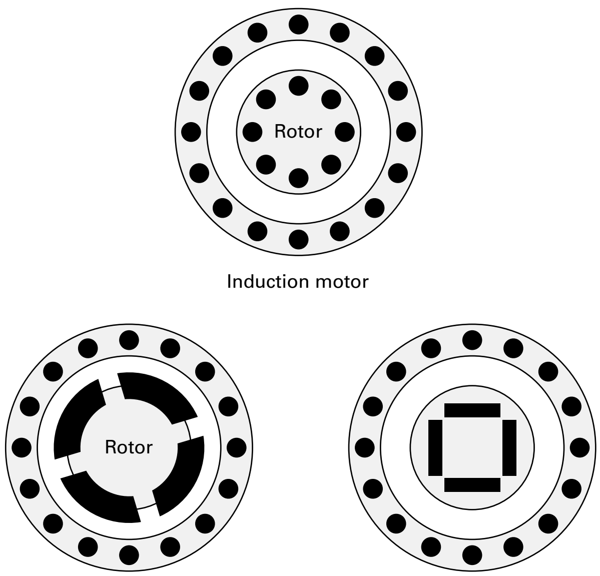

Figure 1. Motor comparison

Table 1. Comparing IM, SPM, IPM and LSPM

Characteristics	Induction motor	SPM motor	IPM motor	Line start PM motor
Permanent magnet (PM)	No PM	Surface mounted PM	Imbedded PM	Has PM and rotor with rotor bars
Efficiency	Low to medium	High	High	High
Size	Large	Small	Small	Small
Torque generation	Reluctance torque	Magnetic torque	Magnetic and reluctance torque	Magnetic and reluctance torque
Mechanical strength	High	Weaker than IPM	High	High
Applications	Good for many applications	Not good for high-speed applications	Good for high-speed applications	Good for high-starting torque
Magnetic saliency	Low	Low ($L_d \sim L_q$)	High ($L_q > L_d$)	Low to medium

Required PM motor details

Once the user has selected/ordered the PM motor for the application, the following motor details from the motor data sheet or the motor nameplate are required for successful commissioning of the drive.

- Motor Rated Voltage = XXX Volts
- Motor Rated Current = XXX Amps
- Motor Rated Speed = XXXX RPM
- Maximum Speed Rating = XXXX RPM
- Motor Rated Frequency = XXX Hz
- Maximum operating Frequency = XXX Hz
- Power Factor (PF) = 0.XX
- Motor Poles = X
- Stator Resistor = 0.XXX Ohms,
- d-axis Inductance (L_d) = X.X mH
- q-axis Inductance (L_q) = X.X mH
- PM (Motor Back EMF) BEMF = XXX.X Volts
- Inertia = 0.XXX
- Motor Type = IPM or SPM

Example of typical IPM motor details:

- Motor Rated Voltage = 230 Volts
- Motor Rated Current = 11.6 Amps
- Motor Rated Speed = 1800 RPM
- Motor Rated Frequency = 90 Hz
- Power Factor (PF) = 0.857
- Motor Poles = 6
- Stator Resistor = 0.2 Ohms,
- d-axis Inductance (L_d) = 4.3 mH
- q-axis Inductance (L_q) = 8.7 mH
- PM (Motor Back EMF) BEMF = 113.1 Volts
- Inertia = 0.017
- Motor Type = IPM

Example of typical SPM motor details:

- Motor Rated Voltage = 230 Volts
- Motor Rated Current = 11 Amps
- Motor Rated Speed = 3000 RPM
- Maximum Speed Rating = 6000 RPM
- Motor Rated Frequency = 150 Hz
- Maximum operating Frequency = 300 Hz
- Power Factor (PF) = 0.98
- Motor Poles = 6
- Stator resistor = 1.492 Ohms
- d-axis Inductance (L_d) = 23.3 mH
- q-axis Inductance (L_q) = 23.3 mH
- PM (Motor Back EMF) BEMF = 110.1 Volts
- Inertia= 0.018
- Motor Type = SPM

As indicated in **Table 1**, the PM motor type can be classified as IPM or SPM from the manufacturer's datasheet or by reviewing the L_d and L_q values given on the motor nameplate or by taking physical measurements on the PM motor.

PM motor control parameters

Table 2. Parameter configuration for a PM motor

Parameter group	Item	Description	Parameter number	Notes/explanation	Sample parameter setting
P1. Basic Motor Nominal Setting	1	Min Frequency (Hz)	P1.1	Should be user defined based on the motor nameplate and process requirement	0
	2	Max Frequency (Hz)	P1.2	Should be user defined based on the motor nameplate and process requirement	90
	3	Accel Time 1 (Sec)	P1.3	Should be user defined based on the motor nameplate and process requirement	20
	4	Dccel Time 1 (Sec)	P1.4	Should be user defined based on the motor nameplate and process requirement	20
	5	Motor Type Selection	P1.5	User should select the type of PM motor under test (IPM, SPM)	IPM
	6	Motor Nom Current (Amp)	P1.6	Based on the motor nameplate	11.6
	7	Motor Nom Speed (RPM)	P1.7	Based on the motor nameplate	1800
	8	Motor PF	P1.8	Based on the motor nameplate	0.857
	9	Motor Nom Volt (Volts)	P1.9	Based on the motor nameplate	230
	10	Motor Nom Frequency (Hz)	P1.10	Based on the motor nameplate	90
	11	Local Control Place	P1.11		Keypad
	12	Local Reference Place	P1.12		Keypad
	13	Remote 1 Control Place	P1.13	Defines the digital inputs for the remote commands	I/O Terminal Start 1
	14	Remote 1 Reference	P1.14	Defines the signal location for the speed reference in remote mode	Drive Ref Pot
P2. Digital Inputs	15	DI1 Function	P2.2.1		IO Terminal Start Signal 1
	16	DI2 Function	P2.2.3		Run Enable
P5. Motor Control	17	Motor Control Mode	P5.1.1	PM control1 for SPM, PM control2 for IPM	PM Control2
	18	Current Limit (Amps)	P5.1.2	This is the maximum current allowed by the drive (130% of the rated current)	15.1
	19	Switching Frequency	P5.1.10		4 kHz
	20	OverVoltage Controller	P5.1.12		Max Freq + 8 Hz
	21	Stator Resistance (Ohms)	P5.1.17	User should ID Run on the drive to fill these parameter values. Please see the procedure below to initiate the ID Run.	0.304
	26	Motor Inertia (kgm2)	P5.1.22		0.016
	27	PM BEMF Voltage (V)	P5.1.23		200.4
	28	PM d-axis Stator Inductance (mH)	P5.1.24		6.34
	29	PM q-axis Stator inductance (mH)	P5.1.25		11.32
P5. Motor Control	30	PM Initial Selection	P5.2.15	User can select Six Pulse or HFI if the application does not want the motor to move before the drive starts controlling the motor. Selecting Align will set the drive for aligning the motor with U-phase axis	Align
	31	PM Initial Time (Sec)	P5.2.16	This is the time the drive will try to align the rotor with U-phase. In other words, drive will inject DC current for this time to align the rotor	0.7
	32	PM Excited Current (%)	P5.2.17	This is the % of rated AC current the drive will inject in order to align the rotor	50
	33	PM Excited Current Off Frequency (10%)	P5.2.18	PM excited current cut off frequency	10
	34	Observer (Kp) (%)	P5.2.19	Linear gain of the PM/IM observer	100

As the PM motor control uses the sensorless vector control (SVC) concept, the drive might need tweaking of the regulator parameters to attain additional stability.

A PI regulator is used in the speed control loop to eliminate the speed error by producing appropriate torque current reference. To obtain a desired dynamic performance and steady-state accuracy, it is important to design and tune the PI regulator parameters, including proportional gain and integral gain. In the PowerXL™ DM1 series, two sets of PI regulator parameters are available from the parameter list. Depending on the motor output frequency range, the different proportional gain and integral gain can be chosen for the desired speed control results. **Figure 2** shows how the p-gain and i-gain are determined by two sets of parameters corresponding to the frequency range.

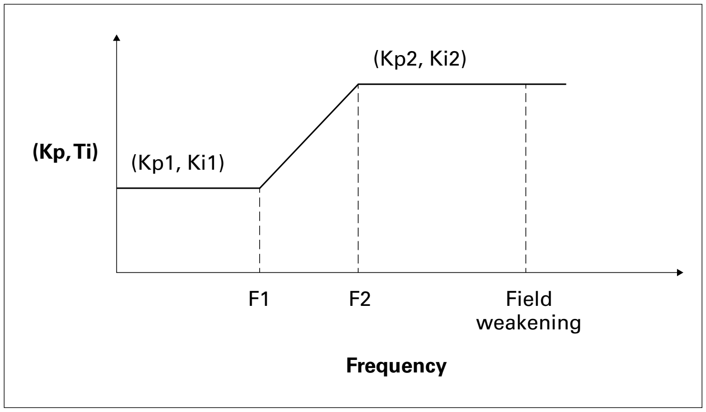

Figure 2. Output frequency

If output frequency is less than or equal to frequency F1, then Kp1 and Ti1 will be used for PI regulator proportional gain and integral gain.

If output frequency is greater than or equal to frequency F2, Kp2 and Ti2 will be used for PI regulator proportional gain and integral gain.

If output frequency is between frequency F1 and F2, the proportional gain and integral gain are calculated linearly by two points (Kp1, Kp2) and (F1, F2), or (Ti1, TI2) and (F1, F2), respectively.

Table 3. Speed PI regulator parameters

Parameter	Name	Range	Default
P5.2.2	Speed Control Kp1 (%)	0 … 6000	100
P5.2.3	Speed Control Ti1 (%)	0 … 30000	100
P5.2.4	Speed Control FS1 (Hz)	0 Hz … 10 Hz	5
P5.2.5	Speed Control FS2 (Hz)	5 Hz … 90 Hz	10
P5.2.6	Speed Control Kp2 (%)	0 … 6000	50
P5.2.7	Speed Control Ti2 (%)	0 … 30000	200

Motor identification

The motor identification MUST be performed for the PM motor control (P1.5 = IPM or SPM) to gain the required parameter values for the motor to have optimal performance.

ATTENTION

THE MOTOR DATA (E.G., THE RESISTANCE) CHANGE WITH THE TEMPERATURE. THEREFORE, THE MOTOR IDENTIFICATION RUN SHALL BE PERFORMED WITH A WARM MOTOR.

The kind of motor identification run is determined by the setting of P5.1.16 "Identification."

The following motor data are identified:

- Motor Stator Resistance R1 (P5.1.17) (for both IM and PM)
- Motor Inertia (P5.1.22) for both IM and PM
- PM BEMF Voltage (P5.1.23) for PM only
- PM d-axis stator inductance (P5.1.24) for PM only
- PM q-axis stator inductance (P5.1.25) for PM only

P5.1.16 = 0: No Action
No identification of the motor data will be performed. This is the setting during normal operation of the drive.

P5.1.16 = 1: Identification Only Stator Resistor
During the identification run, only the stator resistance is identified. The other values remain unchanged.

P5.1.16 = 2: Identification with Run
The values for the parameters P5.1.17 to P5.1.25 are identified. The measurement is done with a running motor that must be unloaded (load decoupled, no gearbox …).

P5.1.16 = 3: Identification No Run
The values for the parameters P5.1.17 to P5.1.25 are identified. During the measurement, the motor is standing still.

How to perform a motor identification run

1. Before starting a motor identification run, the motor data (parameters P1.1 to P1.10) must be set.
2. Select the motor control mode P5.1.1 = "SPM or IPM."
3. Select in P5.1.16 "Identification" which kind of identification shall be performed (P5.1.16 = 1…3).
4. Remove any connection between the drive and a PC during identification run.
5. Apply START command.

   The identification of the motor data takes place automatically and is active for about 30 s respectively until the START signal will be removed.

   On the keypad, "Motor Identification" is shown.

   The motor data are identified and assigned to the respective parameters.

   In case an identification is not possible, the fault message "Motor ID Fault" (#57) is displayed. One reason could be that the rated power of the connected motor deviates too much from one of the variable frequency drives. Alternatively, the motor data can be set manually on the basis of technical information supplied by the motor manufacturer.
6. After a motor identification run, the START signal must be reapplied to start the motor. The motor doesn't start automatically, even when the START signal is still applied to the respective terminal.

   Parameter P5.1.16 "Identification" is reset to "0: No action" automatically as soon as the identification run is finished.

Motor parameter measurement

In case the motor ID run fails, the user can take the following measurements to set the PM motor values manually. The user can also get the motor parameter from the motor datasheet.

Number of motor poles

Motor nameplate data:

- Motor Nominal Frequency (Hz)
- Motor Nominal Speed (RPM)

Equation A: Motor poles = (120 * Nominal Frequency [Hz]) / Nominal Speed (RPM)

The number of poles can also be calculated using the following procedure:

1. Spin the PM motor under test using another prime mover.
2. Measure the frequency of the motor back EMF voltage at the nominal speed.
3. Using Equation A above, calculate the number of motor poles.

Motor stator resistance per phase

Using an ohm meter or an LCR meter with milli-ohm resolution, measure the motor terminal resistance and take measurements shown in **Table 4** to calculate the values.

Table 4. Stator resistor measurements

Description	Ohms
R_{U-V}	
R_{V-W}	
R_{W-U}	
Average ($[R_{U-V} + R_{V-W} + R_{W-U}]/3$)	
Half the average for per phase ($([R_{U-V} + R_{V-W} + R_{W-U}]/3)/2$)	

PM motor d- and q-axis inductances

1. Use the LCR meter for measuring the inductance of the PM motor.
2. Set the measurement frequency on the LCR meter to rated frequency of the motor.
3. Connect the phase V and U of the motor, making a common point.
4. Connect the LCR meter between the phase W terminal of the motor and the common point created in step 3.
5. Measure the motor inductances L_m at various rotor positions, as the inductance changes according to the rotor position depending on the magnetic saliency.
   a. Neglecting the magnetic saturation, the SPM motor's terminal inductance remains approximately equal for different positions. That is $L_d \sim L_q$.
   b. For IPM motors, the magnetic saliency causes the inductance to change depending upon the rotor position.

Table 5. PM motor L_d and L_q measurement

	Rotor position	L_m (mH)
SL. No.	Degrees (°) from a ref. point	Measured between T_w and $T_{com(vu)}$
1	0	
2	30	
3	60	
4	90	
5	120	
6	180	
7	210	
8	240	
9	270	
10	300	
11	330	
12	360	
L_d = [2/3* L_m **Minimum** of 1 to 12]		
L_q = [2/3* L_m **Maximum** of 1 to 12]		

PM motor back electromotive force (back EMF) measurement

1. Using the suitable instrumentation for the required motor rating, measure the motor back EMF voltage on the PM motor under test.
2. The back EMF should be measured at the motor terminal by rotating the PM motor at the rated speed.
3. Calculate the back EMF using the equations in **Table 6**.

Table 6. PM motor back EMF line-to-line (L-L) voltage measurement

SL. No.	Description	L-L voltage (V)
1	V_{UV}	
2	V_{VW}	
3	V_{WU}	
Total: V_{BEMF} ($[V_{UV} + V_{VW} + V_{WU}]/3$)		

Field-/flux-weakening control (FWC)

The operation beyond the motor nominal speed requires the drive to provide output voltage higher than its DC link voltage. Raising output voltage above DC link voltage is not possible as it would be against physics; instead, the drive uses the field-weakening algorithm.

The field-weakening algorithm uses the concept of reducing the Isd component of the stator current, as the I_{sd} is the flux-producing component of the current. The magnetizing current is kept at zero until the strength of the permanent magnet field is reduced.

A negative I_{sd} current reduces the flux and, in turn, reduces the back EMF, helping to achieve the higher speed without having to increase the output voltage. The back EMF is reduced because I_{sd} is working to reduce the flux from the permanent magnets. The nominal DC bus voltage now has reserve for the motor to run beyond the nominal speed. Once the motor is running in field-weakening (FW) zone, the motor runs in constant power zone as the FW algorithm is trying to maintain nominal voltage while the load current remains constant.

If the motor is designed for field weakening, the field-weakening point (FWP) and the maximum frequency must be defined in the drive parameter list. Therefore, in addition to the parameter setting listed in PM Motor Control Parameter section of this document, the parameters listed below should also be set by the user.

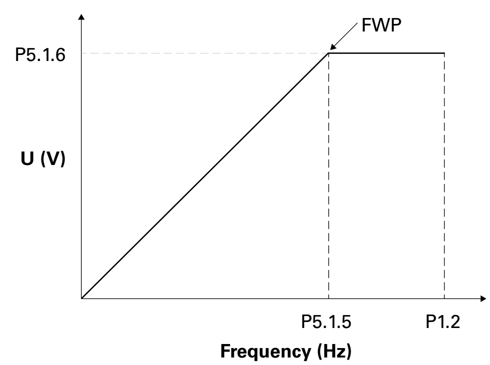

Figure 3. Output frequency

P1.2 "Max Frequency"
This is the maximum frequency for the application. This frequency may be above the "Motor Nom Frequency" (P1.10).

P5.1.5 "Field Weakening Point"
This parameter defines the frequency at which the maximum output voltage, defined with P5.1.6, is reached.

P5.1.6 "Voltage at FWP"
This is the maximum voltage of the variable frequency drive in percent of the Motor Nom Voltage (P1.9). This voltage is reached at the field-weakening point (FWP) defined with P5.1.5.

Note: At a change of parameter P1.10 "Motor Nom Frequency," P5.1.5 is automatically set to the same frequency value. In applications where the frequency at FWP is different from the Motor Nom Frequency, P1.10 must be set before setting P5.1.5. The same is true for the voltage. Here, P1.9 "Motor Nom Voltage" must be set before setting P5.1.6 "Voltage at FWP."

Table 7. Parameters for the field-weakening control

Parameter	Name	Range	Default
P1.2	Max Frequency	P1.1 … 400 Hz	100 Hz
P5.1.5	Field Weakening Point	8.0 Hz … P1.2	P1.10
P5.1.6	Voltage at FWP	10 … 200 % • P1.9	P1.9

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