Application Note

AC Permanent Magnet Motor Control

Applicable Product: V1000

INTRODUCTION

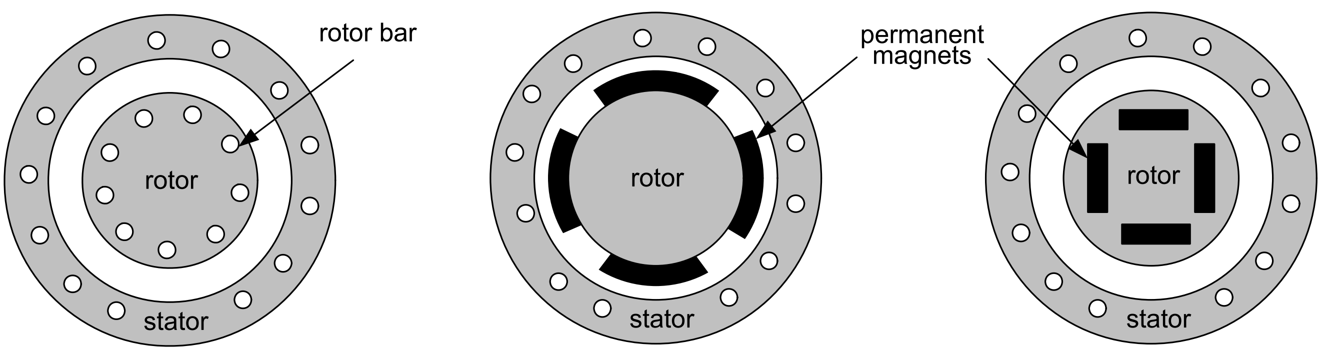
The V1000 has a permanent magnet (PM) motor drive capability but all the motor parameters should be manually set because the Auto Tuning function does not support PM motors. This document explains V1000 parameter settings for the PM motor drive. It also describes the PM motor parameter measurement procedures when the motor data are not available.

PM MOTOR BASICS

SPM and IPM motors

Fig. 1 shows the structures of an induction motor and two widely-used PM motors. The magnets of the surface-mounted PM (SPM) motor in Fig.1(b) are attached on the surface of the rotor, whereas those of the interior-buried PM (IPM) motor are buried inside as shown in Fig.1(c). Table 1 compares the general features of Induction motors, SPM and IPM motors. The magnets of SPM motors need to be fixed on the rotor surface using adhesive, thus mechanical strength is weaker than IPM motors especially in the high speed region. The rotor magnetic flux of the induction motor is induced by the rotation of the stator magnetic field. The IPM motor has high efficiency and high torque because it utilizes both magnet and reluctance torques caused by the magnetic saliency.

Figure 1. The motor structures of the IM, SPM and IPM motors



(a) squirrel cage induction motor (IM)

(b) surface mounted permanent magnet motor (SPM)

(c) interior permanent magnet motor (IPM)

Table1. Comparison table of IM, SPM and IPM motors

Items	Induction motor	SPM motor	IPM motor
Size	×	○	○
Efficiency	Δ	○	○
Motor cost	○	×	×
Mechanical robustness	○	×	Δ
Field weakening	○	×	Δ
Inductance saliency (reluctance torque)	No	No	Yes
Torque generation	rotor flux induced by stator flux	magnet torque	magnet and reluctance torque

Good : ○ medium : Δ Bad : ×

PM Motor Equivalent Circuit

Fig. 2 shows the definition of the motor dq-axes. The north pole of the rotor is defined as d-axis. The PM motor electrical circuit equations are given by (1)-(7) where all the AC quantities are transformed into DC quantities for the convenience of analysis, i.e. the synchronous reference frame is used. Fig. 3 shows PM motor back-emf voltage waveform. The equivalent circuits in Fig. 4 are useful to analyze the motor voltage and power factor according to the motor current and speed.

$$V_{de} \text{ (d-axis stator voltage) } = R_s I_{de} + pL_d I_{de} - \omega L_q I_{qe} \quad (1)$$

$$V_{qe} \text{ (q-axis stator voltage) } = R_s I_{qe} + pL_q I_{qe} + \omega L_d I_{de} + \omega \Phi_{mag} \quad (2)$$

$$V_{LL} \text{ (line-line rms voltage)} = \sqrt{3} / \sqrt{2} \cdot \sqrt{V_{de}^2 + V_{qe}^2} \quad (3)$$

$$I_{sp} \text{ (phase current, peak) } = \sqrt{I_{de}^2 + I_{qe}^2} \quad (4)$$

$$P_{out} \text{ (motor power) } = \frac{3}{2}\omega \left\{ \left(L_d - L_q\right) I_{de} I_{qe} + \Phi_{mag} I_{qe} \right\} \quad (5)$$

$$T_e \text{ (motor torque) } = \frac{n_{pole}}{2\omega} P_{out}$$

(6)

$$E_s \text{ (motor back-emf, phase voltage peak) } = \omega \Phi_{mag} \quad (7)$$

where

I_{de} : d-axis stator current I_{qe} : q-axis stator current I_{sp} : phase current (peak)

R_s : stator resistance L_d : d-axis inductance L_q : q-axis inductance

Φ_{mag} : magnet flux (phase, peak) ω : rotor electrical angular speed ($\omega = 2\pi f$)

n_{pole} : number of poles p : derivative operator

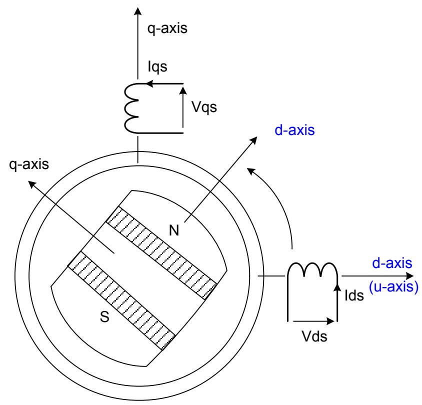


Figure 2. dq-axes model of a PM motor.

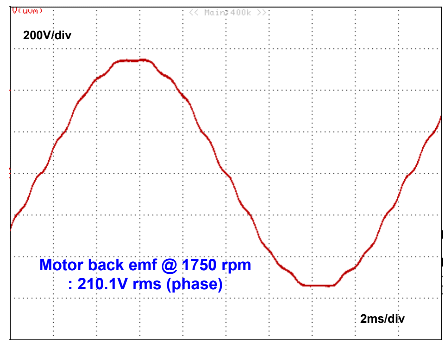


Figure 3. PM motor back-emf at 1750 rpm

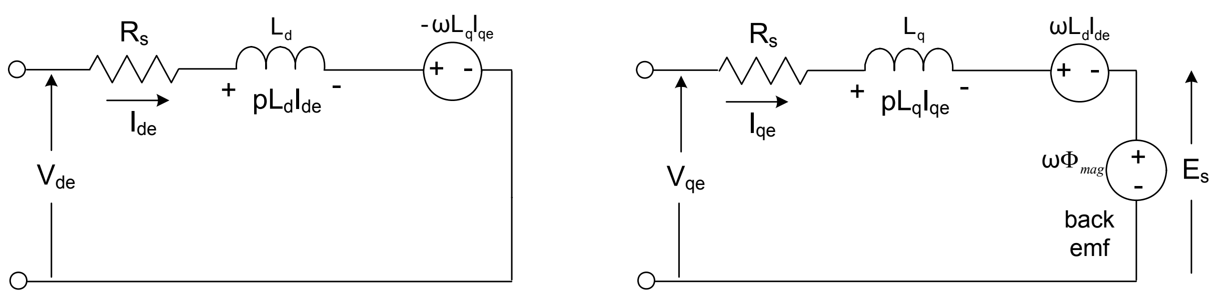


Figure 4. Equivalent circuits of the PM motor in the synchronous dq-axes frame.

Example.

Let's calculate the PM motor voltage rating using equations (1)-(7) at the rated current and rated speed conditions.

- Given parameters

- SPM motor specification : 5HP, 7.1 Arms, 1750 rpm (58.33Hz), 4 poles
- Rs= 1.492 Ohm, Ld=Lq=23.3mH, back-emf (phase) = 210.1Vrms@ 1750 rpm (58.3Hz)

i) At the full load and rated speed condition of 7.1 A and 1750rpm (58.3Hz),

$I_{de} = 0$ (no flux control) and $I_{qe} = \sqrt{2} \cdot 7.1 = 10.04$ (A).

From (1), $V_{de} = -2\pi \cdot 58.3(\text{Hz}) \cdot 23.3 \cdot 10^{-3}\,(\text{H}) \cdot 10.04\,(\text{A}) = -85.7$ (Vpeak)

From (2), $V_{qe} = 1.492 \cdot 10.04\,(\text{A}) + \sqrt{2} \cdot 210.1\,(\text{V}) = 312.1$ (Vpeak)

From (3), $V_{LL} = \dfrac{\sqrt{3}}{\sqrt{2}} \sqrt{(V_{de}^2 + V_{qe}^2)} = 396.3$ (Vrms)

ii) At the 150% load, $I_{qe} = 1.5 \cdot \sqrt{2} \cdot 7.1 = 15.06$ (A)

From (1)-(3), $V_{LL} = 422$ (Vrms)

PM Motor Parameter Measurement

NOTE: Please do not connect the tested PM motor to the V1000 drive.

1) E5-02 : Rated motor power (kW), E5-03 : RMS motor current (A)

Refer to the motor name plate data.

2) E5-04 : Motor pole number (poles)

If the motor rated input frequency and the rated speed are specified, E5-04 can be obtained from following equation.

$$\text{E5-04} = \text{poles} = \frac{120 * \text{rated frequency (Hz)}}{\text{rated speed (r/min)}} \qquad (8)$$

- Experimentally E5-04 can be calculated as follows.
  1. Rotate the tested PM motor using another motor.
  2. Measure the frequency of the motor back emf voltage at the rated speed.
  3. Use equation (8) to get E5-04.

3) E5-05 : Motor stator resistance per phase (ohm)

1. Measure motor terminal resistances R(u-v), R(v-w), and R(w-u) respectively using an ohm meter that has 10^{-3} ohm range resolution or better.
2. Take an average of the terminal resistances.
3. The half of the average terminal resistance corresponds to E5-05.

4) E5-06 and E5-07 : PM motor d- and q-axis inductances (mH)

In case of SPM motors, terminal inductance doe not changes according to the rotor position (i.e. $L_d = L_q$) if the saturation effect by the magnets is neglected. But the rotor of the IPM motors have magnetic saliency, and the inductance measurement results will change according to the rotor position (i.e. $L_d \neq L_q$). Appendix 1 provides further information.

5) E5-09 and E5-24 : PM motor back-emf voltage

- Experimentally the motor back-emf voltage can be measured as follows.
  1. Rotate the tested PM motor using another motor.
  2. Measure the motor back-emf voltage at the rated speed.
  3. Use equation (9) and (10) to get E5-09 and E5-24.

$$\text{E5-09} = \frac{V_{motor}\text{(phase, peak)}}{2\pi f_{rate}\text{(Hz)}} * 10^3 \qquad (9)$$

$$\text{E5-24} = \frac{V_{motor}\text{(line-line, rms)}}{\text{speed (r/min)}} * 10^3 \qquad (10)$$

It should be noted that a sinusoidal back-emf waveform is preferred to the trapezoidal shape for the better control performance. Motors with the trapezoidal back-emf may cause torque ripples or hunting in the steady state condition.

PM Motor Parameters

First, set A1-02 to 5 (PM open loop vector).

1) E1-xx Parameters (200V class)

Parameter	Description	Unit	Range	Default	Remarks
E1-01	Input voltage setting	V	155 - 255	230	Drive input voltage
E1-04	Max output frequency	Hz	40.0-400.0	60	Maximum output frequency
E1-05	Max output voltage	V	0.0 to 255.0	230	Output voltage at E1-04 frequency
E1-06	Base Frequency	Hz	0.0 - E1-04	60	Motor rated frequency
E1-09	Minimum output frequency	Hz	0.0 - E1-04	1.5	Motor stops below this frequency

2) E5-xx Parameters

Table 2. E5-xx Parameters for V1000 PM Motor Drives.

Parameter	Description	Unit	Range	Symbol	Remarks
E5-01	Motor code		0000 - FFFF		FFFF for non-Yaskawa motors
E5-02	Motor rated power	kW	0.4-18.50	P_{out}	Refer to motor name plate
E5-03	Motor rated current	A	10% to 200% of the drive rated current	$I_p / \sqrt{2}$	Rms current Refer to motor name plate
E5-04	Motor pole number	pole	2 – 48	N_{pole}	Poles = $\frac{120 * \text{rated frequency}}{\text{rated speed (r/min)}}$
E5-05	Motor winding resistance	ohm	0.000 – 65.000	R_s	Per phase stator resistance
E5-06	Motor d-axis inductance	mH	0.00 -300.00	L_d	D-axis synchronous inductance
E5-07	Motor q-axis inductance	mH	0.00 -600.00	L_q	Q-axis synchronous inductance
E5-09 *	Motor back-emf voltage	$\frac{\text{mV}}{\text{(rad/s)}}$	0. 0 -2000.0	E_s	Phase peak voltage (mV) per electrical angular speed (rad/s)
E5-24 *	Motor back-emf voltage	$\frac{\text{mV}}{\text{(r/min)}}$	0. 0 -2000.0	E_s	Line-to-line rms voltage (mV) per mechanical motor speed (r/min)

* Note: An alarm will be triggered if both E5-09 and E5-24 are set to 0, or if neither parameter is set to 0.

2) PM Motor Control Parameters (listed in the V1000 Technical Manual)

No.	Name	Description	Range	Default when A1-02=5	Control Mode		
					V/f	OLV	PM
A1-02	Control Mode Selection	Sets the control method of the drive 5 : PM open loop vector	0, 2, 5	0	S	S	S
C4-01	Torque Compensation Gain	Sets the torque compensation function gain. Normally no change is required	0.00 to 2.50	0	A	A	A
C4-02	Torque Compensation Primary Delay Time	Sets the torque compensation filter time. Increase this setting when motor oscillation occurs. Reduce the setting if there is not enough response from the motor.	0 to 60000	100 ms	A	A	A
n8-45	Speed Feedback Detection Control Gain	Sets the gain for internal speed feedback detection control. Typically adjustment is not required. Increase this setting if hunting occurs. Decrease to lower the response.	0.00 to 10.0	0.8	-	-	A
n8-47	Pull-In Current Compensation Time Constant	Sets the time constant to make the pull-in current and actual current value agree. Decrease the value if the motor begins to oscillate. Increase the value if it takes too long for the current reference to equal the output current.	0.00 to 100.0 s	5.0 s	-	-	A
n8-48	Pull-In Current *	Defines the amount of current provided to the motor during no-load operation at a constant speed. Set as a percentage of the motor rated current. Increase this setting when hunting occurs while running at a constant speed.	20 to 200%	30%	-	-	A
n8-49	Load Current	Sets the amount of d-axis current when using Energy Saving control.	-200.0 to 0.0%	0%	-	-	A
n8-51	Acceleration Pull-In Current	Sets the pull-in current during acceleration as a percentage of the motor rated current (E5-03). Set to a high value when more starting torque is needed.	0 to 200%	50%	-	-	A
n8-54	Voltage Error Compensation Time Constant	Sets the time constant for voltage error compensation. Adjust the value when hunting occurs at low speed. Hunting occurs with sudden load changes. Increase in steps of 0.1 or disable the compensation by setting n8-45 to 0. Oscillations occur at start. Increase the value in steps of 0.1.	0.00 to 10.00 s	1.00 s	-	-	A
n8-55	Load Inertia	Sets the ratio between motor and machine inertia. 0: less than 1:10. 1: between 1:10 to 1:30. 2: between 1:30 to 1:50. 3: higher than 1:50.	0 to 3	0	-	-	A
n8-62 <24>	Output Voltage Limit	Sets the limit for the output voltage. Adjustment is normally needed only if the input voltage is below the n8-62 set value. In this case set n8-62 to the input voltage.	0.0 to 230.0	200 Vac	-	-	A
n8-65 <59>	Speed Feedback Detection Control Gain during ov Suppression	Sets the gain used for internal speed feedback detection during ov Suppression	0.00 to 10.00	1.50	-	-	A

<24> Values shown here are for 200 V class drives. Double the value when using a 400 V class drive.
<59> Available in drive software 1011 and later.
* Definition of the pull-in and pull-out torques are described in section 6.

5. Precautions on PM Motor Application

Carry out a test run according to "Subchart A3: Operation with Permanent Magnet Motors" of "4.4 Start-up Flowcharts" in the Startup & Installation Instruction.

5.1 Selection

- Select the motor rated current in the range between 50% and 100% of the Inverter rated current.

5.2 Initial Setting

- Set parameter A1-02 (Control Method Selection) to 5 (PM Open Loop Vector).
- Set parameter E5-01 (Motor Code Selection (for PM motor)) according to the motor type.

5.3. Adjustment Procedure

1) Perform no-load operation to confirm that there is no vibration, overrun, a failure to start or overcurrent.
2) Set n8-55 (Load Inertia) for PM motor according to the machine inertia (motor shaft conversion) to be applied.
3) In the same way, set C2-01 (S-Curve Characteristic at Accel Start) and n8-51 (Acceleration Time Pull-In Current) in advance according to the load inertia and load torque.
4) Perform actual-load operation. If vibration, overrun or a failure to start occurs, try to adjust the following parameters.

(Overrun at startup, a failure to start at heavy load and high inertia)

- Increase the set value of n8-55 (Load Inertia) to be suitable for the load if it is lower than the actual value.
- Increase n8-51 (Acceleration Time Pull-In Current) by 10%. (Default: 50%, recommended value: 50 to 150%)
- Increase C4-01 (Torque Compensation Gain) by 0.10. (Default: 0.00, recommended value: 0.00 to 1.00)
- Increase C2-01 (S-Curve Characteristic at Accel Start) and C1-01 (Acceleration Time) according to the load.
- Decrease C6-02 (Carrier Frequency Selection). (Default: Depends on ND/HD and capacity.
- Recommended value: 2 kHz to default)
- Accelerate the motor after pulling in the motor once at a low speed by using b6-01 (Dwell Reference at Start) and 02 (Dwell Time at Start). (Recommended value: b6-01 = 3.0 to 6.0 Hz, b6-02 = 0.3 to 1.0 second)

(Hunting or pull-out with impact loads and heavy loads at constant speed)

- Increase the load inertia setting (n8-55) to match the actual load if set too low.
- Slowly increase the torque compensation gain set to C4-01 in intervals of 0.10 (Default: 0.00, recommended value: 0.00 to 1.00)

(Overrun at a light load or by oscillation of control and machine systems)

- Increase or decrease n8-45 (Speed Feedback Detection Control Gain) by 0.10 according to the situation.

(Default: 0.80, recommended value: 0.20 to 2.00)

- Decrease the set value of n8-55 (Load Inertia) to be suitable for the load if it is higher than the actual value.
- Increase or decrease C4-02 (Torque Compensation Primary Delay Time) by 20 msec according to the situation. (Default: 100 msec, recommended value: 20 to 200 msec)
- Decrease C6-02 (Carrier Frequency Selection). (Default: Depends on ND/HD and capacity.
- Recommended value: 2 kHz to default)
- In case of oscillation only in the specific operation frequency band, use d3-01 to 04 (Jump Frequencies) to avoid the frequency band where oscillation is apt to occur.
- Increase H3-13 (Analog Input Filter Time Constant) if oscillation occurs because of a ripple in analog frequency reference. (Recommended value: 0.03 to 1.00 second)

(Excessive current although there is no problem in startup or operation)

- Decrease the set value of n8-55 (Load Inertia) to be suitable for the load if it is higher than the actual value.
- Decrease n8-51 (Acceleration Time Pull-In Current) by 10%. (Default: 50%, recommended value: 50 to 150%)
- Decrease n8-48 (Pull-In Current) by 10% if it is too large. (Default: 30%, recommended value: 20 to 40%)
- Decrease C4-01 (Torque Compensation Gain) by 0.10. (Default: 0.00, recommended value: 0.00 to 1.00)
- When current fluctuates periodically, refer to the previous item (Overrun at a light load or by oscillation of control and machine systems) to adjust it.

NOTE: If the above adjustment does not work, confirm again that the value of E5-01 is suitable for the motor.

NOTE: If a failure to start or step-out or overrun during running should occur because the load torque or load inertia has been increased or decreased, decrease L3-02 (Stall Prevention Level during Acceleration) or L3-06 (Stall Prevention Level during Run) to prevent these failures. Or use L6-01 to 11 (Overtorque Detection) to detect these failures in advance and stop operation.

5) According to the operational conditions, change the load status and perform test run again to confirm that there is no vibration, overrun or a failure to start.

   NOTE: With PM motor control, b3-24 (Speed Search Method Selection) is set to 1 (Speed Estimation Type) internally and parameter is not displayed.

   NOTE: When operation must be continued after a momentary power loss with operational frequency exceeding 120 Hz, use the KEB function to continue operation. When a motor that is coasting with operational frequency exceeding 120 Hz must be restarted after stopping the motor once using the short circuit brake function. However, in this case, a mechanical shock may occur during short circuit braking or excessive current of 150 to 200% may flow.

6) Check the parameters using the Verify Function, and store them in the Inverter as the final set values.
7) Carry out heat run test to confirm that there is no motor overheat, torque reduction, excessive current if necessary.

6. Trouble Shooting for PM motor drive

Unstable Motor Speed (listed in the V1000 Technical Manual)

Cause	Possible Solutions
The motor code for PM (E5-01) is set incorrectly. (Yaskawa motors only)	Set parameter E5-01 in accordance with the motor being used.
The drive is operating at less than 10% of the speed reference.	Consult with Yaskawa about using a different type of motor when attempting to operate at 10% of the speed reference.
Motor hunting occurs.	Set and carefully adjust the following parameters in the order listed: • n8-45 (Speed Feedback Detection Suppression Gain) • n8-55 (Load Inertia for PM Motors) • C4-02 (Torque Compensation Primary Delay Time)
Hunting occurs at start.	Increase the S-curve time at the start of acceleration (C2-01).
Too much current is flowing through the drive.	• If using a PM motor, set the correct motor code to E5-01. • If using a specialized motor, set parameter E5-xx to the correct value according to the Motor Test Report.

Pull-out fault (listed in the V1000 Technical Manual)

LED Operator Display Fault Name		LED Operator Display Fault Name
StO	STO	Pull-Out Detection Motor pull-out has occurred.
Cause		Possible Solutions
The motor code for PM (E5-01) is set incorrectly. (Yaskawa motors only)		• Enter the correct motor code for the PM being used into E5-01. • For special-purpose motors, enter the correct data to all E5 parameters according to the Test Report provided for the motor.
Load is too heavy.		• Increase n8-55 (Load Inertia for PM). • Increase n8-51 (Pull-In Current during Accel/Decel for PM). • Reduce the load. • Increase the motor or drive capacity.
Load inertia is too heavy.		Increase n8-55 (Load Inertia for PM).
Acceleration and deceleration times are too short.		• Increase the acceleration and deceleration times (C1-01 through C1-08). • Increase the S-curve acceleration and deceleration times (C2-01).

Pull-in Torque – The maximum torque developed by a PM motor when the motor pulls its connected load inertia into synchronism. It is usually the most critical at starting. The motor will not be able to start under the load torque beyond this value.

Pull-Out Torque– Pull-out torque is the maximum torque at given speeds that the motor can generate while running in synchronism. If the motor runs under the load torque beyond this value, it will stall.

Appendix 1

- **PM motor parameter test using a LCR meter**

1. Connect a LCR meter to the tested PM motor as shown in Fig. A1. Set the test signal frequency of the LCR
meter close to the rated frequency of the motor.

2. Measure the motor inductances L_{motor} at various rotor positions.

   L_{motor} and the rotor position θ has relationship of equation (a1).

$$L_{motor} = \frac{3}{2}\left[\frac{(L_d + L_q)}{2} - \frac{(L_d - L_q)}{2}\cos 2\theta\right] \qquad \text{(a1)}$$

   where L_d and L_q are motor d and q inductances respectively.

3. E5-06 and E5-06 can be obtained using measured inductance data. Among the measured data, minmum and maximum values have the relationship of equation (a2).

$$E5-06 = L_d = \min\left[\frac{2}{3}L_{motor}\right] \qquad \text{(a2)}$$

$$E5-07 = L_q = \max\left[\frac{2}{3}L_{motor}\right]$$

4. If L_d and L_q data under motor current loaded condition are available, use them instead of LCR meter results.

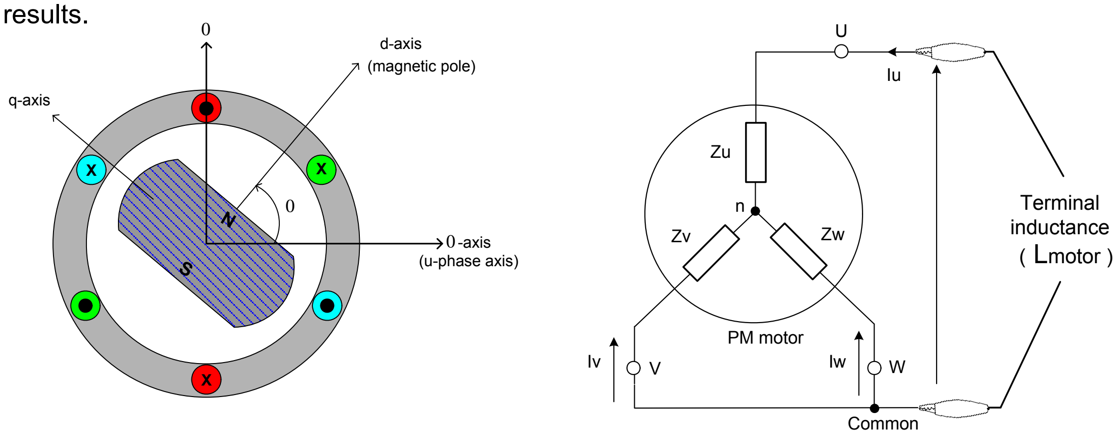
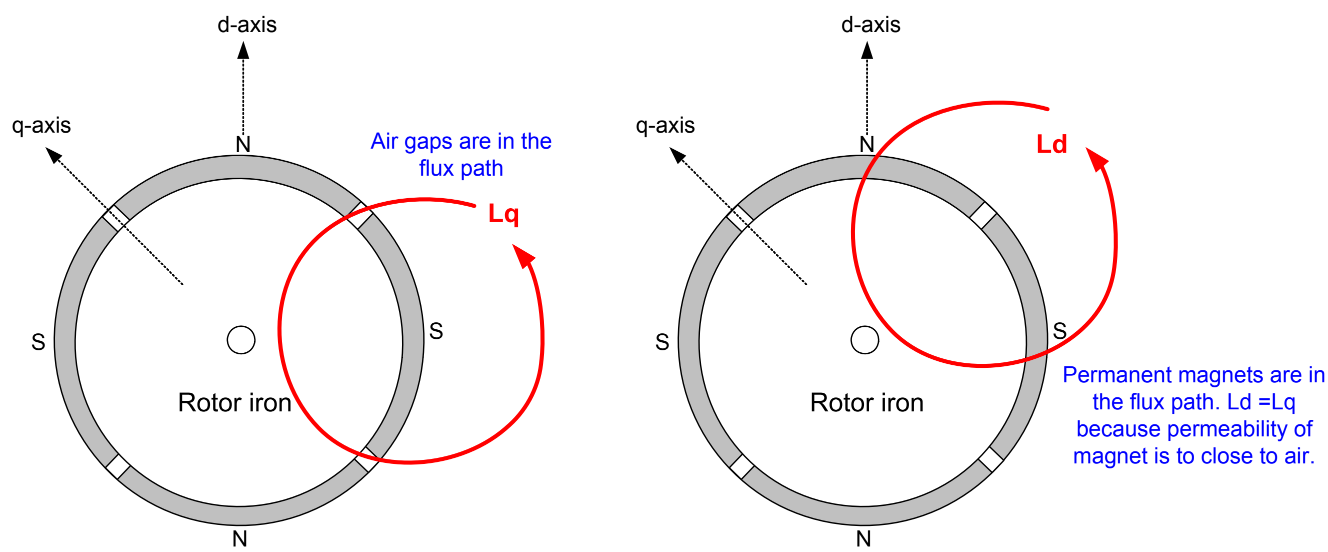


Figure A1. LCR meter connection for the PM motor inductance measurement.

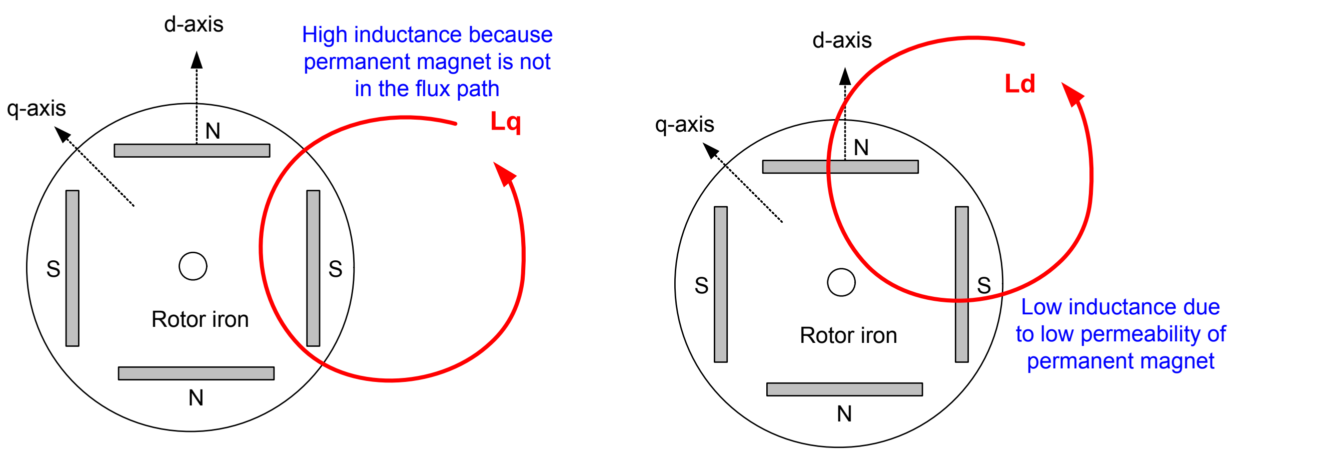
Appendix 2

- **Magnetic Saliency in Interior Permanent Magnet (IPM) motors**



Ld and Lq inductances are same in SPM motor.

Figure A3. Rotor flux path for four-pole SPM motor. A north-pole of permanent magnet is defined as d-axis.



Lq inductance is bigger than Ld in IPM motor.

Figure A3. Rotor flux path for four-pole IPM motor. A north-pole of permanent magnet is defined as d-axis.