

7 Brushless DC Hall Effect Sensor Configuration

7.1 Brushless Motor Overview

The purpose of this chapter is to provide deterministic procedures for the user that will allow them to interface brushless motors from a variety of manufactures to PMD's products.

The brushless motors addressed in this analysis fall under the category of motors that can be commutated using Hall Effect sensors by PMD's products assuming that the correct Hall Effect sensor connection configuration is found. The important property of all motors that fall into this category is the relationship between the three motor phases and the three Hall Effect sensors. The same relationship is required when using sinusoidal commutation and Hall-based phase initialization.

There are several standards for labeling the three motor phases: A,B,C or R,S,T or U,V,W or W1, W2, W3. For the purpose of this analysis, the A, B, C labeling scheme will always be employed even though the motor under investigation may employ another labeling method.

Likewise the Hall Effect sensor connections will always be labeled Hall A, Hall B, and Hall C, even though the manufacturer may label them Hall 1, 2, 3 or Sensor 1, 2, 3.

The relationship between the motor phases and Hall Effect sensors is the property that defines the proper configuration and allows PMD products to successfully commutate the motor. The manner in which the user will go about determining this relationship will depend greatly on the information provided to them by the motor manufacturer. Industry research has determined that the content and form of the information provided by the manufacturer varies. As a result, explanations for interpreting the various information formats will be provided.

The procedure developed in this chapter assumes that the amplifier in use will do nothing more than amplify the phase signals (voltage) from the PMD controller. Some amplifiers may invert the phase signal, in which case the results of this procedure will not yield the expected rotation.

There are three independent methods for determining the Hall configuration. The selection of which method to use will depend on the information provided.

1. Hall Based Commutation Sequence Provided
2. Back EMF Diagrams
3. Trial and Error

7.2 Method #1: Hall Based Commutation Sequence Provided

This method is the most straightforward and requires the least amount of effort on the part of the user. This information is usually provided in the form of a diagram or table and may have different titles such as “Block Commutation” or “Brushless DC Motor Timing Diagram”. Some of these diagrams represent motor phase voltage during trapezoidal (six-step) commutation. Other tables may represent the state of the high-side and low-side MOSFETs of the half-bridge amplifiers for all three phases during trapezoidal commutation. Either method conveys adequate information about driving the motor phases based on Hall Effect sensor states.

The relationship between the Hall Effect sensors themselves is always consistent. In other words the Hall Effect sensor sequence seen in Figure 7.1 can be found in all motors with 120-degree Hall Effect sensors when the motor rotates. However, the direction of rotation, CW or CCW, necessary to produce this relationship can vary across different motors.

Very often the binary state of the three Hall Effect sensors will be combined to create a 3-bit binary word. The mapping between the Hall states and the three-bit word is also shown in Figure 7.1.

Below the binary word representation in Figure 7.1 is a table that represent the states of the MOSFETs of the half-bridges. Every Hall state has a unique half-bridge state defined as follows:

A+	= Phase A high side MOSFET closed
A-	= Phase A low side MOSFET closed
B+	= Phase B high side MOSFET closed
B-	= Phase B low side MOSFET closed
C+	= Phase C high side MOSFET closed
C-	= Phase C low side MOSFET closed

If the state of a MOSFET for a particular Hall state is not defined then it is assumed to be open. For example during Hall state 1-0-1, MOSFETs A-, B+, C+ and C- are all open.

Below the table of MOSFET states in Figure 7.1 is a diagram of the relative voltages through each motor phase based on the Hall states (and subsequent MOSFET states). For instance in Hall state 1-0-1, the path of the current begins at the voltage source, flows through the high side MOSFET of phase A, through motor winding A, through motor winding B, through the low side MOSFET of phase B, and finally to the ground plane.

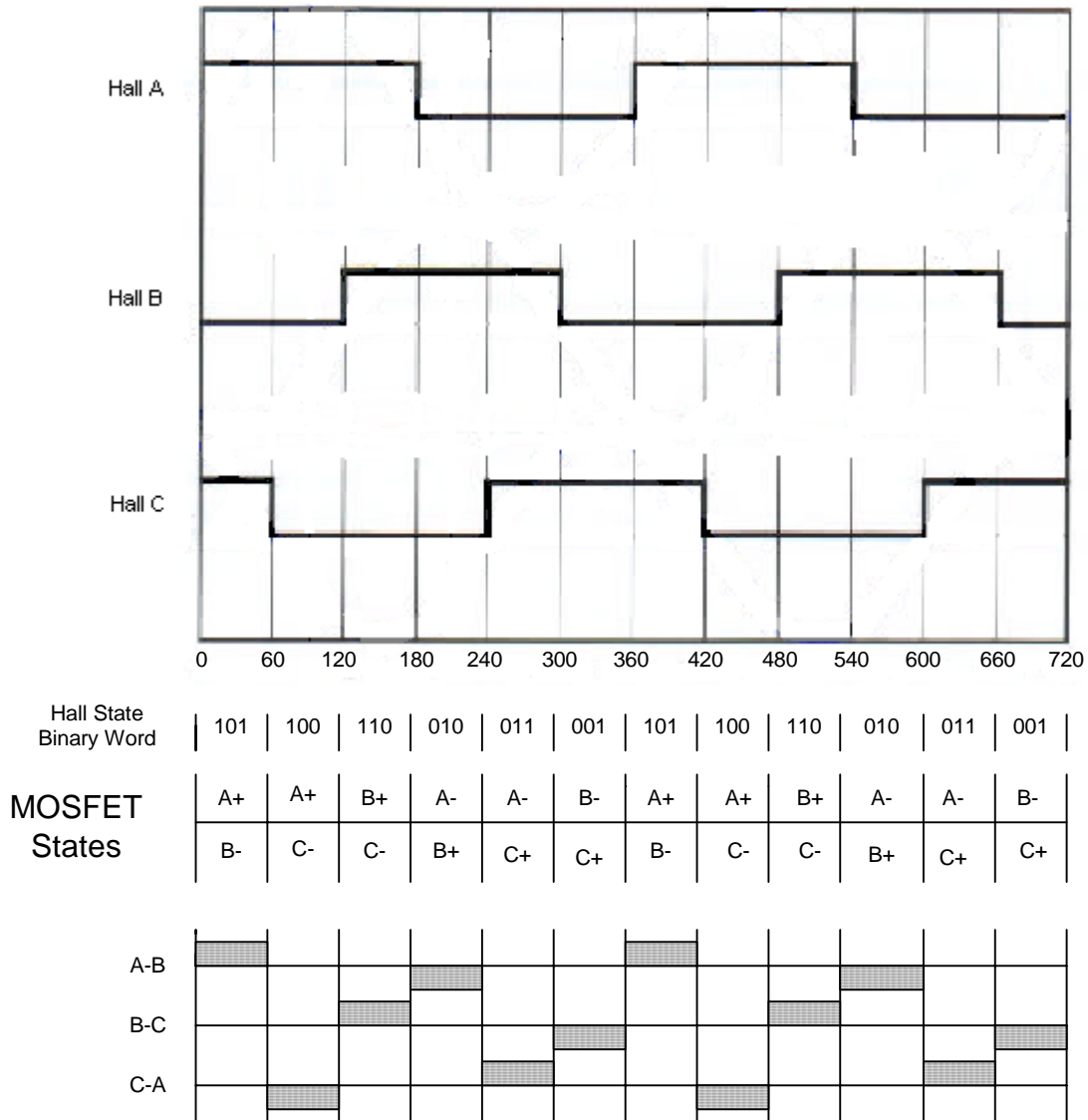


Figure 7.1 – Hall Effect Commutation Drive Voltage

If the user finds a table in the motor datasheet with the same relationship then the motor Hall Effect sensor connections between the motor and the PMD product should be A to A, B to B, and C to C. If the relationship seen in the motor datasheet is not identical then the user will need to determine which Hall Effect sensor corresponds to the given MOSFET state sequence or motor winding excitation. The tables will indicate a direction of rotation, CW or CCW. When properly configured, this will be the direction of rotation during a positive motor command.

7.3 Method #2: Back EMF Diagrams

The motor datasheet may provide a back EMF diagram instead of or in addition to a Block Commutation diagram. This diagram is created by observing the back EMF voltage produced by various motor phases while the motor is being manually driven (motor becomes a generator).

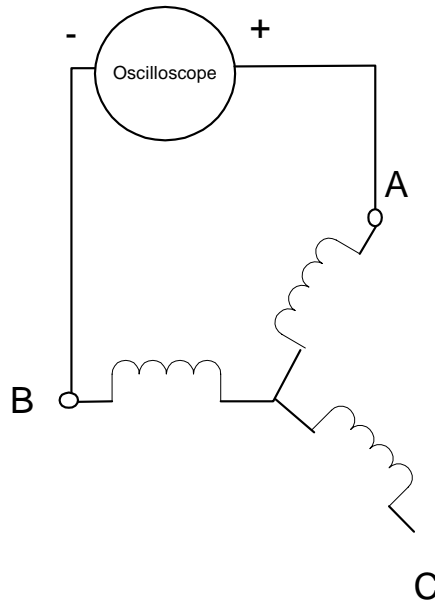


Figure 7.2 - Back EMF Measurement

Caution: Motor should be electrically “floating” when measuring back EMF. Pay attention to oscilloscope ground connections when measuring multiple phases simultaneously.

Figure 7.2 shows the three motor phases, A, B, and C. An oscilloscope is placed across phase A and B with the positive probe on phase A and the negative on phase B. When the motor is back driven, the voltage seen on the voltmeter will become an approximate sinusoid with time. If the motor RPM is high enough the top and bottom of the sinusoid may become “clipped” but the phase relationship will be maintained.

In addition to observing the back EMF of the phase, the Hall Effect sensor signal while the motor is being back driven is also observed. During rotation there is always one Hall Effect sensor signal that, when graphed along side the phase A-B back EMF values, will result in the relationship shown in Figure 7.3. Figure 7.3 refers to this Hall Effect sensor as Hall “X”. The actual label of Hall “X” depends on the specific motor being used. The important step is to determine which of the Hall Effect sensors will produce the relationship in Figure 7.3.

The details of creating such a diagram have been provided here because the user may not have possession of this information, either because the customer does not have the motor datasheet or because the motor datasheet does not provide this information.

(If the motor datasheet provides “Block Commutation” information or something similar then Method #1 should be used.)

Note that direction of rotation has not been defined in terms of Clockwise or Counter Clockwise in Figure 7.3. This is because the rotation direction that achieves this relationship is not consistent across different motors. Some motors may have to be rotated Clockwise to achieve this relationship and some may have to be rotated Counter Clockwise. The important concept is that whichever direction achieves the relationship seen in Figure 7.3 will be the direction of rotation when the PMD controller is creating a positive motor command signal. When the motor is rotated in the opposite direction the relationship between phase A-B and Hall “X” will be 180 degrees out of phase as seen in Figure 7.4. This will be the direction of rotation during a negative motor command.

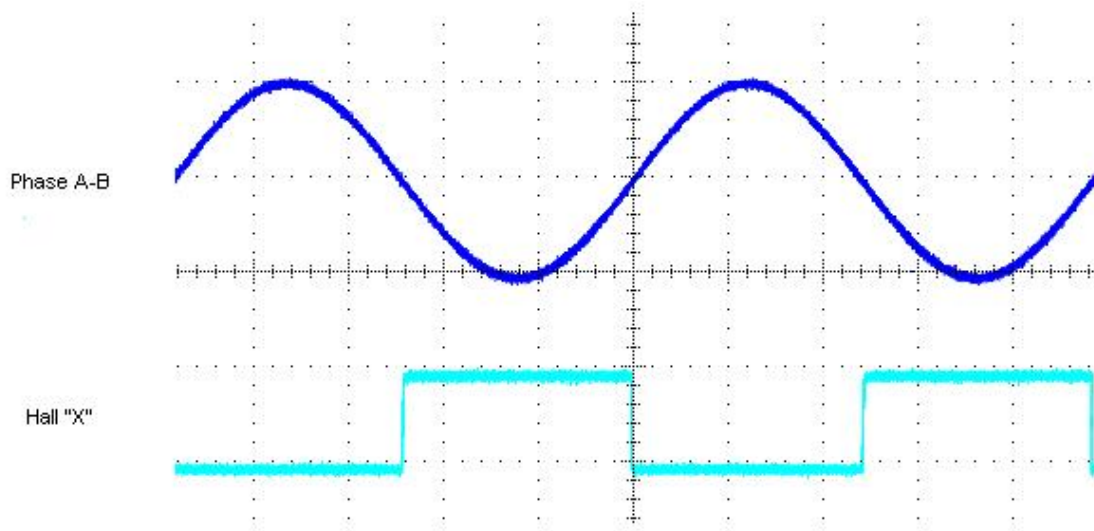


Figure 7.3 - Back EMF A-B (Positive Rotation)

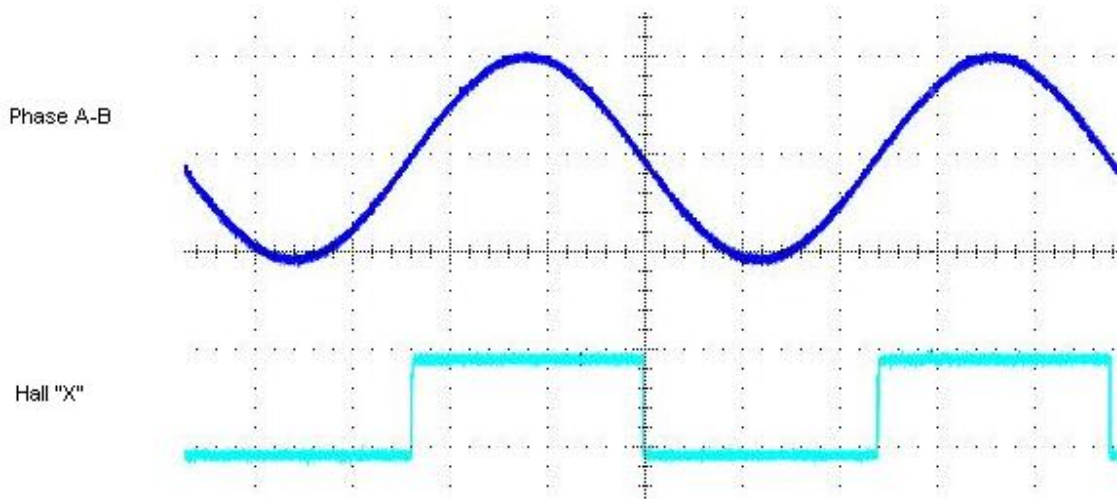


Figure 7.4 – Back EMF A-B (Negative Rotation)

The determination of Hall “X” is achieved by visual inspection of the relationship between the back EMF of a particular phase and the candidate Hall Effect sensor. For comparison sake, Figure 7.5 has been provided to demonstrate one of the possible relationships seen when one of the two **incorrect** Hall Effect sensors is being considered.

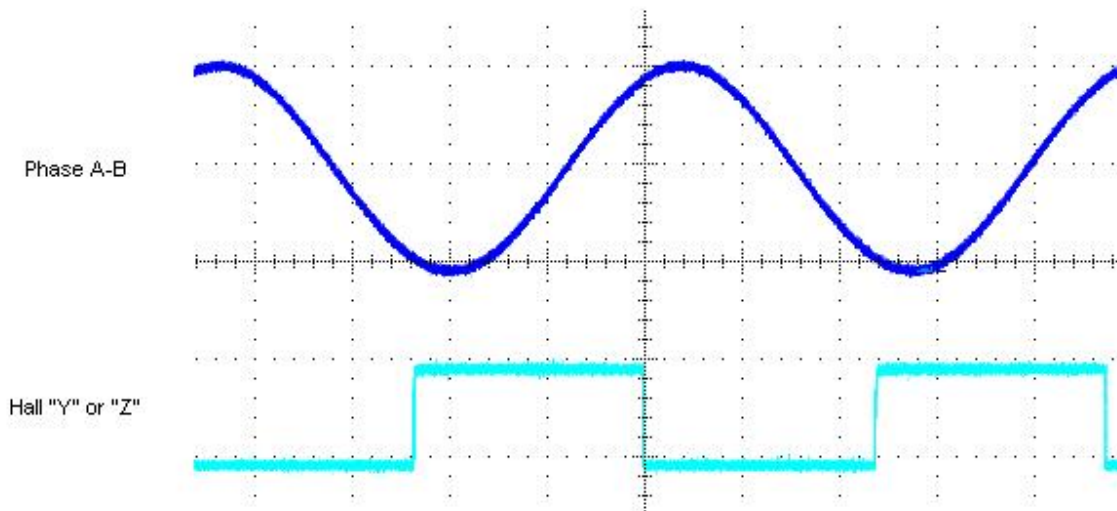


Figure 7.5 – Back EMF A-B with Incorrect Hall Effect Sensor Selection

Note the phase relationship shown in Figure 7.5 is different than the relationship seen in Figures 7.3 and 7.4. The user will know the correct Hall Effect sensor has been found when the peaks of the back EMF waveform occur exactly half between the edges of the Hall signal. The Hall signal seen in Figure 7.5 is not Hall “X” because the peaks of the back EMF waveform of phase A-B are skewed toward the Hall signal edges.

Just as the back EMF voltage of phase A-B correlates to Hall “X”, the other phases B-C and C-A will also have corresponding Hall Effect sensors (Hall “Y” and Hall “Z”) that create the exact same relationship. There is always a one-to-one relationship between corresponding motor phases and Hall Effect sensors. Furthermore there is one direction of rotation that satisfies the relationships for all phases.

7.3.1 Connecting to a PMD product

The reason such emphasis was placed on determining which motor phases correspond to which Hall Effect sensors is because that relationship will determine how the phases and sensors are connected to a PMD product. PMD products that are designed to commutate brushless motors will have Hall Effect sensor inputs labeled Hall A, Hall B, and Hall C. Once all of the motor phase versus Hall Effect sensor relationships have been determined, Hall “X” will be connected to the Hall B input, Hall “Y” will be connected to the Hall C input and Hall “Z” will be connected to the Hall A input. The same PMD products will also have motor phase outputs labeled Phase A, Phase B, and Phase C. These should be connected to the corresponding motor phases A, B, and C. (It was mentioned before that the labeling on the motor phases may actually be R,S,T or U,V,W or W1, W2, W3). Figure 7.6 demonstrates the connection configuration.

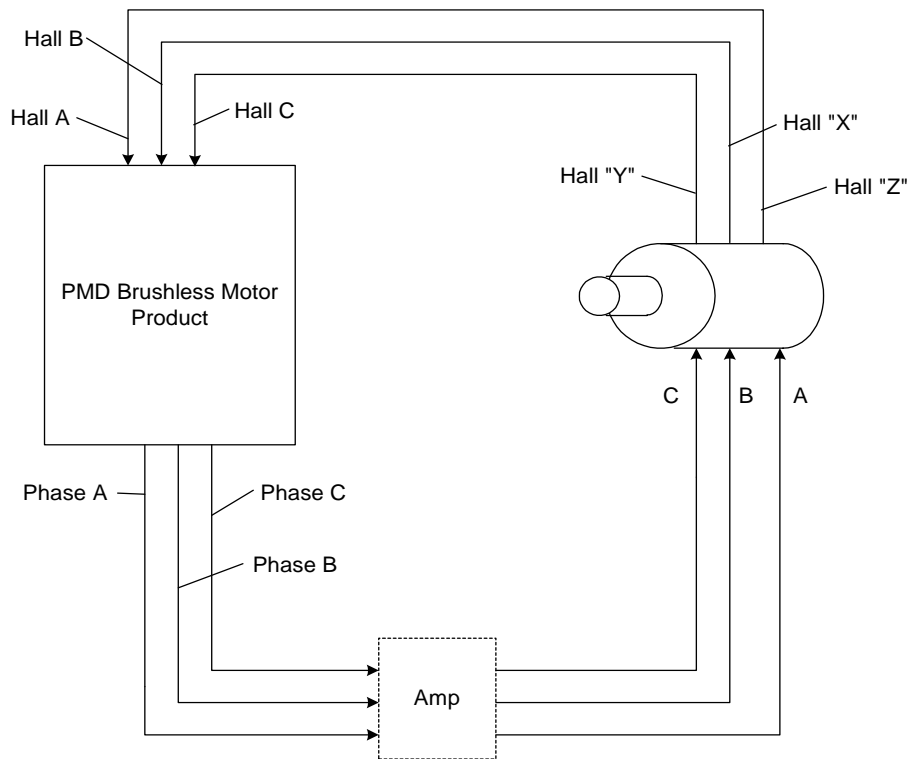


Figure 7.6 – Connections to a PMD Controller

Once the relationships have been determined and the connections established, the system is ready for Hall based commutation. With the addition of an encoder for position feedback, the system will be ready for closed loop Hall-based commutation.

PMD products allow the user to invert the interpretation of the Hall Effect sensor, meaning that the PMD product will see a Hall Effect sensor “high” state as being at a “low” state. However, it is never necessary to use the Hall Effect sensor inversion feature for the purpose of proper configuration.

It was mentioned that the rotation direction necessary for producing the relationship seen in Figure 7.2 could be Clockwise or Counter Clockwise depending on the specific motor. Motors that require a Clockwise rotation to produce this relationship will be referred to as CW motors. Likewise motors that require Counter Clockwise rotation will be referred to as CCW motors. If connections are made with regard to the defined relationship then a positive motor signal (**SetMotorCommand <positive number>**) will produce a Clockwise torque on CW motors and the same positive motor signal will produce Counter Clockwise torque on CCW motors.

It is still possible to configure a CCW motor to rotate CW with a positive motor signal and likewise it is possible to configure a CW motor to rotate CCW with a positive motor signal. This can be done without altering the connection scheme shown in Figure 7.3. One way of accomplishing this task is to use **SetSignalSense** to invert all Hall Effect sensor inputs. The other way is to use **SetSignalSense** to invert the Motor Output.

7.4 Method #3: Connection by Trial and Error

A “trial and error” method also exists for determining the relationship. The trial and error method involves permutation through all possible Hall Effect sensor configurations until the optimal configuration is found. Due to its iterative nature, this method is only advisable if the other methods cannot be followed. This may be the case if the motor manufacturer does not provide sufficient information or if the equipment necessary for back driving a motor or capturing motor signals is not available.

7.4.1 Definition of Optimal Configuration

The optimal Hall Effect sensor configuration results in the maximum motor torque for a given current supply². This means that some configurations will produce a minimal torque and other configurations will not produce any torque, but there is only one configuration that will produce a maximum torque.

Creating a setup that allows the Hall Effect sensor connections between the PMD product and a brushless motor to be easily swapped assists in proving this concept. Every permutation is tested individually by applying a positive open loop motor command to the system for a specific amount of time. The permutation that results in the maximum amount of motor displacement corresponds to the permutation that results in the maximum amount of torque for the give motor command. This permutation is the optimal configuration.

It is the linear relationship between MotorCommand and current at steady state as well as the linear relationship between motor torque and motor displacement that allows this conclusion to be drawn.

$$\text{Given: } T(i)_{OptimalConfiguration} > T(i)_{AnyOtherConfiguration} \quad (\text{eq. 7.1})$$

$$\text{Prove: } \dot{\theta}(MotorCommand)_{OptimalConguration} > \dot{\theta}(MotorCommand)_{AnyOtherConfiguration} \quad (\text{eq. 7.2})$$

at Steady State

The given equation states that the torque as a function of current of a system in the optimal configuration will be greater than the torque as a function of the same current of any system that is not in the optimal configuration.

The equation to be proved states that the velocity as a function of the MotorCommand of a system in the optimal configuration will be greater than the velocity as a function of the same MotorCommand of any system that is not in the optimal configuration at steady state. A formal proof of equation 7.2 exists in Appendix D. The validation of equation 7.2 implies that the results of the iterative procedure described above will yield the optimal Hall Effect sensor configuration.

² Parker Hannifin® -Compumotor Division, OEM770X User Guide, page 101.

7.4.2 Procedural Instructions

1. Connect PMD motor signals (PWM or DAC) to the amplifier with PMD phase A to the amplifier input labeled phase A (or equivalent). PMD phase B is connected to the input labeled phase B (or equivalent). Likewise for phase C (except when using DAC output).
2. Arbitrarily connect motor Hall wires to PMD Hall inputs.
3. Power on amplifier.
4. Initialize PMD controller for Hall-based commutation and apply an open loop motor command.
 - **SetCommutationMode** 1
 - **SetMotorMode** 0
 - **SetMotorCommand** <user_selected value>
 - **Update**
5. Send **GetActualPosition** command to PMD controller at regular intervals and note response.
6. Power off amplifier and arbitrarily select another Hall wire connection scheme and repeat steps 3 to 5.
7. Repeat step 6 until all six Hall wire connection permutations have been tried.
8. Determine which permutation produced the largest difference in the responses to the sequence of **GetActualPosition** commands in step 5.
9. Use this permutation to run the motor open loop as described in step 4 except select the negative of the value used in **SetMotorCommand**.
10. If the responses to **GetActualPosition** contain approximately the same difference as seen with the positive motor command then this permutation is the optimal configuration. If not then repeat step 9 with the permutation yielding the second largest difference from step 8.

7.4.3 Trial and Error Test Results

Based on the definition of the optimal configuration, all configuration permutations were tested and the permutation corresponding to the optimal configuration was noted. As predicted there was one optimal Hall configuration that resulted in a steady state velocity larger than the velocity produced by any other configuration. See Appendix C for the results of this test.

7.5 Conclusion

This chapter has introduced several methods the user can follow in order to determine the proper Hall configuration. The need for a procedure exists because there is no one standard relationship between Hall Effect sensor wiring and motor phases that is consistent across manufacturers. The need for different methods exist because, in addition to different Hall/motor phase relationships, the format and extent of information provided by manufactures is not consistent.

Experimental results have shown that three methods exist that will generate the exact same Hall Effect sensor wiring configuration. The details of the test motors and experimental results are summarized in Appendix C.

PMD recommends following Method #1 if possible. If the back EMF versus Hall Effect sensor relationship is provided or if the user has the ability to derive this relationship on their own, then Method #2 can be used. As a last resort the user can follow Method #3 by permutation through the six wiring configurations.

The information presented in this chapter is specific to determination of Hall Effect sensor configuration for brushless motors. Other initialization steps not covered here will be necessary if sinusoidal commutation is used. The user should also reference PMD's "Step by Step Guide to Phase Initialization" which can be found on the **PMD Application Notes Web Page**.