Description

This document describes 120° square-wave commutation for brushless DC motors, focusing on commutation waveforms, rotor position detection using Hall sensors, and sensorless rotor position detection based on back-EMF zero-crossing points.
Table of Contents

Description.............................................................................................................................................1
Table of Contents ...................................................................................................................................2
1. 120° square-wave commutation..................................................................................................5
   1.1. Overview of 120° square-wave commutation........................................................................6
   1.2. Output voltage and current waveform model for 120° square-wave commutation ...........9
   1.3. Back-EMF ....................................................................................................................................10
   1.4. Neutral-point voltage during 120° commutation....................................................................11
2. Considering actual voltage waveforms during 120° square-wave commutation..............13
   2.1. Commutation periods (diode freewheeling periods)..............................................................14
   2.2. Considering the t1, t2, t3, t4, t5, and t6 periods in the voltage waveform of Figure 2.2....15
3. 120° square-wave commutation drive scheme.............................................................19
   3.1. 120° square-wave commutation control using Hall sensors ............................................19
   3.2. Sensorless 120° square-wave commutation control.............................................................22
      3.2.1. Sensorless rotor position detection.............................................................................23
RESTRICTIONS ON PRODUCT USE..............................................................................................24
List of Figures

Figure 1.1 120° commutation using an inverter ................................................................. 6
Figure 1.2 Switching of six devices for 120° square-wave commutation .................. 6
Figure 1.3 Theoretical voltage waveforms during the 120° commutation sequence .......... 7
Figure 1.4 PWM signal ............................................................................................................. 8
Figure 1.5 Voltage and current waveforms during 120° square-wave commutation .... 9
Figure 1.6 Back-EMF induced during 120° square-wave commutation .................. 9
Figure 1.7 Voltage and current during 120° square-wave commutation .................. 10
Figure 1.8 Inverter circuit ....................................................................................................... 11
Figure 1.9 Neutral-point voltage and voltages of each phase ........................................ 12
Figure 1.10 Neutral-point voltage ......................................................................................... 12
Figure 2.1 Upper-arm chopper signals for 120° square-wave commutation .................. 13
Figure 2.2 Inverter phase terminal voltage (upper-arm chopping) ............................. 13
Figure 2.3 Phase terminal voltage waveforms (upper-arm chopping) ....................... 14
Figure 2.4 Commutation period A ...................................................................................... 14
Figure 2.5 Commutation period B ...................................................................................... 15
Figure 2.6 Commutation timing of the devices in the inverter ........................................ 15
Figure 2.7 Current path when Q_{W-H} is in PWM mode and Q_{V-L} is on ................... 16
Figure 2.8 Current path immediately after Q_{W-H} switches off ................................ 16
Figure 2.9 Current path when Q_{U-H} is on ......................................................................... 17
Figure 2.10 Current path immediately after Q_{U-H} switches off ................................ 17
Figure 2.11 Current path immediately after Q_{U-H} switches off ................................ 18
Figure 3.1 Hall sensor positions ......................................................................................... 19
Figure 3.2 Hall sensor waveforms ...................................................................................... 19
Figure 3.3 Phase terminal voltage, back-EMF voltage, and Hall sensor voltage of each phase 20
Figure 3.4 Hall sensor signals vs. inverter switching timing ........................................... 20
Figure 3.5 Logic circuit that provides the switching signals ........................................ 21
Figure 3.6 Zero-crossing points for rotor position detection ........................................ 22
Figure 3.7 Example of sensorless rotor position detection (analog method) ............. 23
List of Tables

Table 1.1 120° square-wave commutation techniques................................................................. 7
Table 3.1 Truth table................................................................................................................ 21
1. 120° square-wave commutation

In recent years, brushed DC motors have been replaced by brushless DC (BLDC) motors. A control circuit called an inverter is used to drive a BLDC motor. There are two major commutation techniques: 120° square-wave commutation and 180° sinusoidal (sine-wave) commutation. Sine-wave commutation is superior to square-wave commutation in terms of control precision, efficiency, and acoustic noise. However, sine-wave commutation increases system complexity and therefore incurs extra costs. In contrast, a motor system driven using square-wave commutation is less complicated and costly if lower control precision, reduced efficiency, and higher acoustic noise are permitted.

*1 Brushless DC (BLDC) motor

A BLDC motor uses a permanent magnet as a rotor (i.e., a rotating assembly) and coil windings as a stator (i.e., a stationary part). A brushless motor is controlled by an external inverter that applies the current to the coil windings for each phase based upon the rotating speed (rotor position) detected.

In the case of a brushed DC motor, the positional relationship between the rotor and the stator is mechanically detected, and the electric currents in the stator windings are switched using brushes and commutators. As opposed to a brushed DC motor, a BLDC motor uses a permanent magnet as a rotor and a set of electromagnets as a stator. Since the BLDC motor has no mechanical part for switching electric currents in the stator windings, it is necessary to sense the positional relationship between the rotor and the stator in order to control electric currents applied to the stator windings. Therefore, the BLDC motor requires a semiconductor inverter circuit that generates AC currents for the commutation of the stator windings. BLDC motors are divided into two categories, depending on the position of the rotor’s permanent magnet: interior permanent magnet (IPM) motors and surface permanent magnet (SPM) motors.

Commutation techniques are classified into two major types: square-wave commutation and sine-wave (180-degree) commutation. Furthermore, depending on the method of rotor position detection, there are two types: detection using sensors (Hall sensors or Hall ICs) and sensorless detection.

*2 Inverter

An inverter is a semiconductor-based power converter. An inverter that converts a direct current into an alternating current is called a DC-AC inverter. However, the term “inverter” generally refers to a circuit that combines an AC-DC converter (that changes an alternating current into a direct current) and a DC-AC converter so as to be able to generate arbitrary frequencies and voltages. The greatest advantage of using an inverter to drive a motor is that it can change the phase and frequency of motor drive currents according to the rotor position and therefore provides high drive efficiency and smooth motor rotation with little vibration at low to high RPM. Due to its ability to arbitrarily control the output voltage and frequency, an inverter is widely used for AC and BLDC motor applications. Inverter control also helps reduce power consumption and improve efficiency.
1.1. Overview of 120° square-wave commutation

For 120° commutation of a BLDC motor, the commutation pattern is controlled using a three-phase bridge inverter composed of six switching devices. In one phase, the high-side device is turned on; in another phase, the low-side device is turned on; and in the remaining phase, both the high- and low-side devices are turned off. Figure 1.1 shows an example of an inverter circuit and its current path.

Figure 1.1 120° commutation using an inverter

Figure 1.2 models the switching patterns for the six devices of the inverter for 120° square-wave commutation. In this switching scheme, each phase is connected to the power source for 120 electrical degrees, off for 60 electrical degrees, connected to GND for 120 electrical degrees and again off for 60 electrical degrees.

Figure 1.3 shows the Phase-U voltage relative to the theoretical neutral point of a motor and the U-V phase-to-phase voltage for 120° square-wave commutation. This commutation technique always conducts electric currents through two resistive components (i.e., windings) at any one time. Therefore, the phase voltage relative to a motor’s neutral point always becomes $V_{DD}/2$. In reality, however, back-EMF induced in the motor windings must be considered (see Section 1.3, “Back-EMF”). This is discussed in greater detail in Section 1.2, “Output voltage and current model of 120° square-wave commutation.”

Figure 1.2 Switching of six devices for 120° square-wave commutation
The foregoing is a general summary of 120° commutation. In practice, there are several control techniques for 120° commutation, some of which use PWM control. Table 1.1 shows several commutation control techniques. It conceptually illustrates the drive signals for the high-side and low-side devices of an inverter for one electrical cycle. \( Q_H \) is the high-side device, and \( Q_L \) is the low-side device.

**Table 1.1 120° square-wave commutation techniques**

<table>
<thead>
<tr>
<th>One side PWM</th>
<th>Non-complementary switching</th>
<th>Complementary switching</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_L ): High side ( Q_H ): Low side</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60° PWM</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 1.3 Theoretical voltage waveforms during the 120° commutation sequence**

![Diagram showing theoretical voltage waveforms during 120° commutation sequence]
*3 PWM control

Pulse-width modulation (PWM) is a technique using semiconductor switching devices for controlling the power supplied to an electrical load. The output power fed to the load is controlled by turning switching devices on and off repeatedly. PWM modulates a constant voltage as a series of pulses with a constant cycle while changing the period during which the pulse is on. A desired output voltage which is adjusted with width of the “on” pulse is provided by turning on and off switching devices at fast rate. Due to its excellent controllability and efficiency, PWM is commonly used by inverter circuits. An inverter circuit provides an optimal voltage for motor drive by changing the “on” duty cycle of a PWM signal.

**PWM signal generation**

There are several ways to generate a PWM signal. The following shows a typical method based on a triangle waveform that is commonly used for 120° commutation. In Figure 1.4, the dashed line indicates a reference voltage. The triangular signal is compared with the reference voltage using a comparator. When the triangular signal is higher than the reference voltage, the PWM signal is in the Low state; otherwise, it is in the High state. The pulse width and the duty cycle of the PWM signal can be changed by adjusting the reference voltage.

![Signal compared with the reference signal](image)

*Figure 1.4 PWM signal*
1.2. Output voltage and current waveform model for 120° square-wave commutation

Figure 1.5 shows the output voltage and current waveforms from Phase U of the inverter circuit of Figure 1.1. (The other two phases have identical waveforms.) With 120° commutation, there are periods in each electrical cycle during which each phase does not conduct current. During these periods, voltage also appears at the phase terminals. Taking Phase U, for example, Phase V and Phase W conduct current during a period in which Phase U is not conducting. While Phase U is not conducting current, the Phase-U terminal voltage seems to be equal to $V_{DD}/2$, i.e., the voltage at the neutral point of the Phase-V and Phase-W windings. In reality, however, the back-EMF induced in each phase by the rotation of a motor (see Section 1.3) is added to the Phase-U terminal voltage. Figure 1.6 shows an enlarged view of a period during which back-EMF occurs. Phase U conducts current only while it is energized.

![Diagram of 120° Square-Wave Commutation](image)

Figure 1.5 Voltage and current waveforms during 120° square-wave commutation

![Diagram of Back-EMF](image)

Figure 1.6 Back-EMF induced during 120° square-wave commutation
1.3. Back-EMF

Back-EMF (also known as back electromotive force) is the electromotive force or voltage produced by electromagnetic induction when a magnetic field from a magnet passes (rotates) through a coil that is conducting current. The faster a magnet rotates, the larger the back-EMF is induced in the coil generates because a greater amount of magnetic flux from the magnet passes through the coil’s magnetic flux per unit period of time. A motor (rotor) acts as a generator when it is turned by an external force to produce back-EMF. A motor also rotates when voltage is externally applied. Back-EMF is induced in the motor while it is rotating. The following equation represents the relationship between the externally applied voltage and the back-EMF voltage.

$$e_a = K_e N$$

where $e_a$ is the back-EMF voltage, $K_e$ is the back-EMF constant in $V/(r/min)$, and $N$ is a motor’s rotation speed in $r/min$.

Figure 1.7 shows this relationship. The sum of the voltage drop ($R_a i_a$) across the winding resistance ($R_a$) and the internal back-EMF induced by a rotating motor ($e_a$) equals the externally applied voltage ($V$). (Here, other voltage drops are ignored.)

**Supplemental information:** Relationships among back-EMF, motor supply voltage, and motor rotation speed

1. **The larger the supply voltage** ($V$) **to a BLDC motor, the faster the motor rotates.**
   1. In Figure 1.7, the voltage across the winding resistance ($R_a$) increases, causing the rotation current ($i_a$) to increase.
   2. An increase in $i_a$, in turn, causes a motor’s rotation torque to increase.
   3. An increase in torque increases the rotational speed of the motor.
   4. The faster the motor rotates, the larger the back-EMF.

As the supply voltage to a motor is increased, its rotational speed increases until an increase in back-EMF caused by the increase in rotational speed and the current flowing in the motor settle into a new stable state.

1. **When the supply voltage to a BLDC motor is constant, an increase in the motor load causes its rotation to slow down.**
   1. A motor slows down as its load increases.
   2. As a result, the back-EMF induced by the rotation of the motor decreases. Since the motor supply voltage is constant, this causes the voltage across the winding resistance to increase. This, in turn, causes the current flowing in the motor to increase.
   3. The increase in motor current causes the motor’s torque to increase.

As the load on a motor increases, its rotational speed decreases, causing the torque to increase until the load and the torque settle into a new stable state.
1.4. Neutral-point voltage during 120° commutation

As shown in Figure 1.8, one of the high-side devices and one of the low-side devices are on at any one time during the 120° commutation sequence. (The high-side and low-side devices of the same phase never turn on simultaneously.) While the high-side \( Q_{V-H} \) and the low-side \( Q_{W-L} \) are on, Phase-U winding is de-energized.

![Figure 1.8 Inverter circuit](image)

The Phase-U voltage in this state can be explained using Figure 1.9. As the motor is rotating, back-EMF voltages \( (e_u, e_v, \text{ and } e_w) \) are induced in the winding of each phase. Let the voltage at the neutral point of the three-phase coil be \( v_n \) and the voltages at the phase terminals relative to the neutral point be \( v_U, v_V, \text{ and } v_W \). In Figure 1.8, the Phase-V and Phase-W windings are short-circuited to \( V_{DD} \) and GND respectively. Hence, \( v_V=V_{DD} \) and \( v_W=0 \). Let the current that flows from \( V_{DD} \) to GND via the Phase-V and Phase-W windings be \( i \). At this time, the neutral-point voltage is at the midpoint of \((V_{DD}-e_V)\) and \((0-e_W)\) because the voltage drops across Phase V and Phase W are equal:

\[
V_N = \frac{(V_{DD}-e_V-e_W)}{2} \quad \text{(Equation 1)}
\]

Equation 1 can also be derived from the fact that the neutral-point voltage is lower than the neutral-point reference voltage \( (V_{DD}/2) \) by \( (e_V+e_W)/2 \) as shown in Figure 1.10.

The back-EMF voltages, \( e_u, e_v, \text{ and } e_w \), are sine waves that are 120° out of phase from each other. Therefore, letting the constant proportional to a motor’s rotational speed be \( k \) \((\geq 0)\) and the electrical angle be \( \theta \) \((0 \leq \theta \leq 360°)\), the back-EMF voltages in each phase are:

\[
e_u = k \cdot \sin\theta
\]
\[
e_v = k \cdot \sin(\theta-120°)
\]
\[
e_w = k \cdot \sin(\theta+120°) \quad \text{(Equation 2)}
\]

From Equation 2, a trigonometric calculation provides:

\[
e_v + e_w = -e_u \quad \text{(Equation 3)}
\]

The following is obtained by substituting Equation 3 into Equation 1:

\[
V_N = \frac{(V_{DD}+e_U)}{2} \quad \text{... Neutral-point voltage} \quad \text{(Equation 4)}
\]

Equation 1 and Equation 2 consider the neutral-point voltage when Phase U is in the de-energized state. The same principle also applies to Phase V and Phase W.
At this time, since current does not flow in the Phase-U coil, no voltage drop occurs across it. Therefore, the Phase-U terminal voltage is:

\[ v_U = v_N + e_U \]  
(Equation 5)

Substituting \( v_N \) of Equation 4 into Equation 5:

\[ v_U = \left( \frac{V_{DD}}{2} \right) + \frac{3}{2} e_U \]

\[ = \left( \frac{v_V + v_W}{2} \right) + \frac{3}{2} e_U \]  
(Equation 6)

Although the foregoing describes the Phase-U terminal voltage in the de-energized state, the same principle also applies to the Phase-V and Phase-W terminals in the de-energized state.

Figure 1.9 Neutral-point voltage and voltages of each phase

Figure 1.10 Neutral-point voltage
2. Considering actual voltage waveforms during 120° square-wave commutation

As described above, there are various 120° commutation techniques. The phase terminal voltage waveforms differ, depending on the technique used. This section shows an example that drive signals shown in Figure 2.1 are applied to each switching device of the inverter shown in Figure 1.1.

![Figure 2.1 Upper-arm chopper signals for 120° square-wave commutation](image)

Figure 2.2 shows the voltage that appears at the Phase-U terminal when the signals shown in Figure 2.1 are applied to the switching devices of the inverter. As shown in Figure 2.2, voltage appears at the Phase-U terminal even while both the high-side and low-side switching devices for Phase U are off (i.e., while Phase U is de-energized). This is due to back-EMF induced by the rotation of a motor. Figure 2.2 illustrates only the concept without taking changes in the neutral-point voltage into consideration. For reference, Figure 2.3 shows an example of phase terminal voltage waveforms obtained from an actual circuit.

![Figure 2.2 Inverter phase terminal voltage (upper-arm chopping)](image)
2.1. Commutation periods (diode freewheeling periods)

a) Commutation period A (diode freewheeling period) in the phase voltage waveform of Figure 2.2

During commutation period A, the low-side QU-L device remains off after being on for 120 electrical degrees. As shown in Figure 2.4, after QU-L turns off, a current flows back through the body diode in QU-H until the energy stored in the Phase-U winding \( \frac{1}{2} \times LI^2 \), where \( L \) is the inductance of the Phase-U winding) disappears. Since the cathode of the body diode in QU-H is connected to VDD, its anode voltage (i.e., the voltage at the Phase-U terminal) increases to the VDD voltage while the freewheel current continues flowing. After that, the voltage at the Phase-U terminal becomes equal to the back-EMF voltage.

![Figure 2.3 Phase terminal voltage waveforms (upper-arm chopping)](image)

![Figure 2.4 Commutation period A](image)
b) Commutation period B (diode freewheeling period) in the phase voltage waveform of Figure 2.2

During commutation period B, the low-side $Q_{U-H}$ device remains off after being on for 120 electrical degrees. As shown in Figure 2.5, after $Q_{U-H}$ turns off, a current flows back through the body diode in $Q_{U-L}$ until the energy stored in the Phase-U winding ($\frac{1}{2} \times LI^2$, where $L$ is the inductance of the Phase-U winding) disappears. Since the cathode of the body diode in $Q_{U-L}$ is connected to GND, its anode voltage (i.e., the voltage at the Phase-U terminal) decreases to the GND voltage while the freewheel current continues flowing. After that, the voltage at the Phase-U terminal becomes equal to the back-EMF voltage.

![Figure 2.5 Commutation period B](image)

2.2. Considering the t1, t2, t3, t4, t5, and t6 periods in the voltage waveform of Figure 2.2

This section describes each of the periods shown in Figure 2.2. Figure 2.6 shows the commutation timing of each device in the inverter.

![Figure 2.6 Commutation timing of the devices in the inverter](image)
1) Voltage during t1

Figure 2.6 indicates that $Q_{W-H}$ is in PWM mode and that $Q_{V-L}$ is continuously on.

- **When $Q_{W-H}$ is on in PWM mode (Figure 2.7)**
  
  The Phase-U terminal voltage is as follows (see Equation 5):
  \[ v_U = v_N + e_U \]
  
  where $v_N$ is the neutral-point voltage, and $e_U$ is the Phase-U back-EMF voltage.

  The neutral-point voltage, $v_N$, is $v_N = (V_{DD} + e_U) / 2$ (see Equation 4).

  The Phase-U terminal voltage is also represented by the following equation (see Equation 6):
  \[ v_U = (V_{DD}/2) + (3/2)e_U \]

  Therefore, the sum of the Phase-U back-EMF voltage and the neutral point voltage appears at the Phase-U terminal. (At this time, $e_U$ is negative relative to the neutral-point voltage.)

- **While $Q_{W-H}$ is off (Figure 2.8)**

  The freewheel current flows through the body diode in $Q_{W-L}$, causing both $v_W$ and $v_V$ to be equal to GND.

  Therefore, the Phase-U terminal voltage, $v_U$, becomes $0 + (3/2)e_U$. Because the Phase-U back-EMF voltage is negative, the result of this equation is equal to or less than 0. This means $v_U$ remains at 0 V.

  (At this time, the neutral-point voltage is $e_U/2$. The effect of back-EMF caused by switching is not taken into account in the above description.)
2) Voltage during $t_2$

Period $t_2$ can be considered in the same manner as for $t_1$.

- **While $Q_{W-H}$ is on**
  The voltage at the Phase-U terminal, $v_U$, becomes $(V_{DD}/2) + (3/2)e_U$.
  (At this time, $e_U$ is positive.)

- **While $Q_{W-H}$ is off**
  The freewheel current flows through the body diode in $Q_{W-L}$, causing both $v_W$ and $v_V$ to be equal to GND as shown in Figure 2.8.
  Therefore, the Phase-U terminal voltage, $v_U$, becomes $0 + (3/2)e_U$. Since the Phase-U back-EMF voltage is positive, $v_U$ equals $(3/2)e_U$.
  (At this time, the neutral-point voltage is $e_U/2$. The effect of back-EMF caused by switching is not taken into account in the above description.)

3) Voltage during $t_3$

While $Q_{U-H}$ is on, the Phase-U terminal voltage equals $V_{DD}$ as shown in Figure 2.9. While $Q_{U-H}$ is off, a freewheel current flows through the body diode in $Q_{U-L}$, causing the Phase-U terminal voltage to be equal to GND.
4) Voltage during t4
The operation during t4 can be considered in the same manner as for t2. The only difference is that the high-side device of Phase W and the low-side device of Phase V switch on and off during t2, whereas the low-side device of Phase W and the high-side device of Phase V switch on and off during t4.

5) Voltage during t5
The operation during t5 can be considered in the same manner as for t1. The only difference is that the high-side device of Phase W and the low-side device of Phase V switch on and off during t1, whereas the low-side device of Phase W and the high-side device of Phase V switch on and off during t5.

6) Voltage during t6
During t6, the low-side device of Phase U, QU-L, remains on (without PWM), causing the Phase-U terminal voltage to become equal to GND.

Figure 2.11 Current path immediately after QU-H switches off
3. 120° square-wave commutation drive scheme

To drive a BLDC motor (that uses a permanent magnet as a rotor and coil windings as a stator), it is necessary to detect the rotor position and accordingly control electric currents applied to the coil windings. During 120° commutation, the rotor position can be detected in one of the two ways: detection using Hall sensors and sensorless detection (i.e., detection of the rotor position through the sensing of the back-EMF voltage induced by the rotation of a motor).

3.1. 120° square-wave commutation control using Hall sensors

A motor can be rotated by changing the directions of currents applied to the motor coil windings according to the rotor position. Hall sensors are commonly used for rotor position detection. Hall sensors are placed 120 electrical degrees apart as shown in Figure 3.1. Their output signals change with the changes in magnetic fields from the permanent magnet (Figure 3.2). Commutation patterns for each phase of the inverter circuit are created every 60 electrical degrees by combining the signals from three Hall sensors. (This means the commutation sequence consists of six steps).
Figure 3.3 shows the terminal voltage, back-EMF voltage, and Hall sensor voltage of each phase. The rotor position is sensed from the voltages of Hall sensors, and the drive signals for each phase are generated according to the rotor position. Figure 3.4 shows the relationship between the voltages of Hall sensors and the drive signals. Table 3.1 is a truth table representation of this relationship.
The Boolean logic for QU-H to QW-L in the above truth table can be represented using a disjunctive normal form. Using this Boolean expression, the Hall sensor signals can be converted to the drive signals for each device of the inverter. Figure 3.5 shows an example of a logic circuit represented by the Boolean expression.

\[
\begin{align*}
Q_{U-H} &= H_U R_V H_W + H_U R_V H_W = H_U R_V (H_W + R_W) = H_U R_V \\
Q_{V-H} &= H_V R_W, Q_{W-H} &= H_W R_U \\
Q_{U-L} &= H_U R_V H_W + H_U H_V H_W = H_U H_V (H_w + R_W) = H_U H_V \\
Q_{V-L} &= H_V H_W, Q_{W-L} &= H_W H_U
\end{align*}
\]

Table 3.1 Truth table

<table>
<thead>
<tr>
<th>Pattern</th>
<th>QU-H</th>
<th>QV-H</th>
<th>QW-H</th>
<th>QU-L</th>
<th>QV-L</th>
<th>QW-L</th>
</tr>
</thead>
<tbody>
<tr>
<td>t1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>t2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>t3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>t4</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>t5</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>t6</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hall sensor output</th>
<th>H_U</th>
<th>H_V</th>
<th>H_W</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
3.2. Sensorless 120° square-wave commutation control

Sensorless motor control does not use any sensors to detect the rotor position. Instead, the back-EMF voltages from the motor windings can be used for rotor position detection. Back-EMF is the voltage induced in a coil that opposes the change in its magnetic flux that induced it. However, the back-EMF induced in the motor winding of each phase cannot always be detected while a motor is rotating.

Motor terminals cannot be used to measure back-EMF while drive voltages are being applied to them. With 120° commutation, two of the three phases are conducting current at any one time while the other one is not. Back-EMF appears at the terminal of the non-conducting phase*4, which is measured for rotor position detection. More specifically, the zero-crossing points of back-EMF that appears at each phase terminal are detected.

As shown in Figure 3.6, a three-phase motor has two zero-crossing points for each phase (six points for three phases) per revolution of a motor (i.e., 360 electrical degrees). This means the rotor position can be detected every 60 electrical degrees. The 120° commutation signals necessary to switch on and off the devices of an inverter are generated based on the zero-cross signals. For example, the interval between two zero-crossing points (60 electrical degrees) is measured to generate a period of time for the next 30 electrical degrees.

*4 In Figure 3.6, the back-EMF and neutral-point voltages are ignored.

![Figure 3.6 Zero-crossing points for rotor position detection](image)

Figure 3.6 Zero-crossing points for rotor position detection
3.2.1. Sensorless rotor position detection

For sensorless rotor position detection, the zero-crossing points of back-EMF that appears at each phase terminal are detected. There are analog and digital methods for zero-cross detection.

The analog sensorless method feeds each phase voltage to an RC filter in order to extract back-EMF. The zero-crossing points of back-EMF are then detected to generate a drive signal for a motor winding. Figure 3.7 shows a simplified diagram of this circuit.

![Motor terminal voltage diagram](image)

**Figure 3.7 Example of sensorless rotor position detection (analog method)**

The digital sensorless method compares each phase voltage with a reference voltage. The comparator detects a zero-crossing point of back-EMF when the magnitude relationship of the phase and reference voltages changes. The digital sensorless method uses a digital circuit to generate drive signals for the motor windings.

In actual applications, the withstand voltage of a comparator imposes a restriction on the maximum motor voltage. Therefore, a voltage translation of the comparator input is necessary for high-voltage motor applications.
RESTRICIONS ON PRODUCT USE

Toshiba Corporation and its subsidiaries and affiliates are collectively referred to as "TOSHIBA". Hardware, software and systems described in this document are collectively referred to as "Product".

- TOSHIBA reserves the right to make changes to the information in this document and related Product without notice.
- This document and any information herein may not be reproduced without prior written permission from TOSHIBA. Even with TOSHIBA's written permission, reproduction is permissible only if reproduction is without alteration/omission.
- Though TOSHIBA works continually to improve Product’s quality and reliability, Product can malfunction or fail. Customers are responsible for complying with safety standards and for providing adequate designs and safeguards for their hardware, software and systems which minimize risk and avoid situations in which a malfunction or failure of Product could cause loss of human life, bodily injury or damage to property, including data loss or corruption. Before customers use the Product, create designs including the Product, or incorporate the Product into their own applications, customers must also refer to and comply with (a) the latest versions of all relevant TOSHIBA information, including without limitation, this document, the specifications, the data sheets and application notes for Product and the precautions and conditions set forth in the "TOSHIBA Semiconductor Reliability Handbook" and (b) the instructions for the application with which the Product will be used with or for. Customers are solely responsible for all aspects of their own product design or applications, including but not limited to (a) determining the appropriateness of the use of this Product in such design or applications; (b) evaluating and determining the applicability of any information contained in this document, or in charts, diagrams, programs, algorithms, sample application circuits, or any other referenced documents; and (c) validating all operating parameters for such designs and applications. TOSHIBA ASSUMES NO LIABILITY FOR CUSTOMERS’ PRODUCT DESIGN OR APPLICATIONS.

- PRODUCT IS NOT INTENDED NOR WARRANTED FOR USE IN EQUIPMENTS OR SYSTEMS THAT REQUIRE EXTRAORDINARILY HIGH LEVELS OF QUALITY AND/OR RELIABILITY, AND/OR A MALFUNCTION OR FAILURE OF WHICH MAY CAUSE LOSS OF HUMAN LIFE, BODILY INJURY, SERIOUS PROPERTY DAMAGE AND/OR SERIOUS PUBLIC IMPACT ("UNINTENDED USE"). Except for specific applications as expressly stated in this document, Unintended Use includes, without limitation, equipment used in nuclear facilities, equipment used in the aerospace industry, lifesaving and/or life supporting medical equipment, equipment used for automobiles, trains, ships and other transportation, traffic signaling equipment, equipment used to control combustions or explosions, safety devices, elevators and escalators, and devices related to power plant. IF YOU USE PRODUCT FOR UNINTENDED USE, TOSHIBA ASSUMES NO LIABILITY FOR PRODUCT. For details, please contact your TOSHIBA sales representative or contact us via our website.

- Do not disassemble, analyze, reverse-engineer, alter, modify, translate or copy Product, whether in whole or in part.
- Product shall not be used for or incorporated into any products or systems whose manufacture, use, or sale is prohibited under any applicable laws or regulations.
- The information contained herein is presented only as guidance for Product use. No responsibility is assumed by TOSHIBA for any infringement of patents or any other intellectual property rights of third parties that may result from the use of Product. No license to any intellectual property right is granted by this document, whether express or implied, by estoppel or otherwise.

ABSSENT A WRITTEN SIGNED AGREEMENT, EXCEPT AS PROVIDED IN THE RELEVANT TERMS AND CONDITIONS OF SALE FOR PRODUCT, AND TO THE MAXIMUM EXTENT ALLOWABLE BY LAW, TOSHIBA (1) ASSUMES NO LIABILITY WHATSOEVER, INCLUDING WITHOUT LIMITATION, INDIRECT, CONSEQUENTIAL, SPECIAL, OR INCIDENTAL DAMAGES OR LOSS, INCLUDING WITHOUT LIMITATION, LOSS OF PROFITS, LOSS OF OPPORTUNITIES, BUSINESS INTERRUPTION AND LOSS OF DATA, AND (2) DISCLAIMS ANY AND ALL EXPRESS OR IMPLIED WARRANTIES AND CONDITIONS RELATED TO SALE, USE OF PRODUCT, OR INFORMATION, INCLUDING WARRANTIES OR CONDITIONS OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, ACCURACY OF INFORMATION, OR NONINFRINGEMENT.

Do not use or otherwise make available Product or related software or technology for any military purposes, including without limitation, for the design, development, use, stockpiling or manufacturing of nuclear, chemical, or biological weapons or missile technology products (mass destruction weapons). Product and related software and technology may be controlled under the applicable export laws and regulations including, without limitation, the Japanese Foreign Exchange and Foreign Trade Law and the U.S. Export Administration Regulations. Export and re-export of Product or related software or technology are strictly prohibited except in compliance with all applicable export laws and regulations.

Please contact your TOSHIBA sales representative for details as to environmental matters such as the RoHS compatibility of Product. Please use Product in compliance with all applicable laws and regulations that regulate the inclusion or use of controlled substances, including without limitation, the EU RoHS Directive. TOSHIBA ASSUMES NO LIABILITY FOR DAMAGES OR LOSSES OCCURRING AS A RESULT OF NONCOMPLIANCE WITH APPLICABLE LAWS AND REGULATIONS.