120° Square-Wave Commutation for Brushless DC Motors

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.

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1. 120° square-wave commutation

In recent years, brushed DC motors have been replaced by brushless DC (BLDC) motors*1. A control circuit called an inverter*2 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.

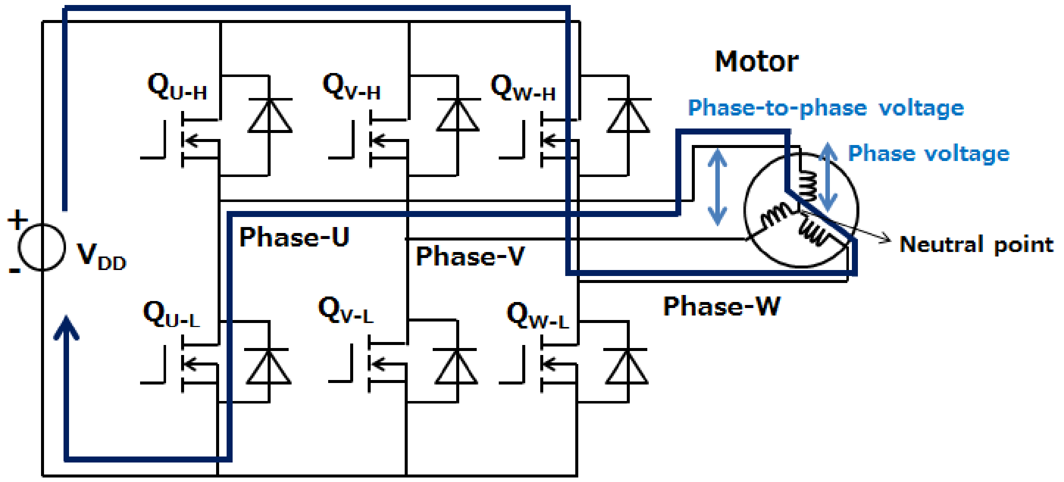


Figure 1.1 120° commutation using an inverter

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."

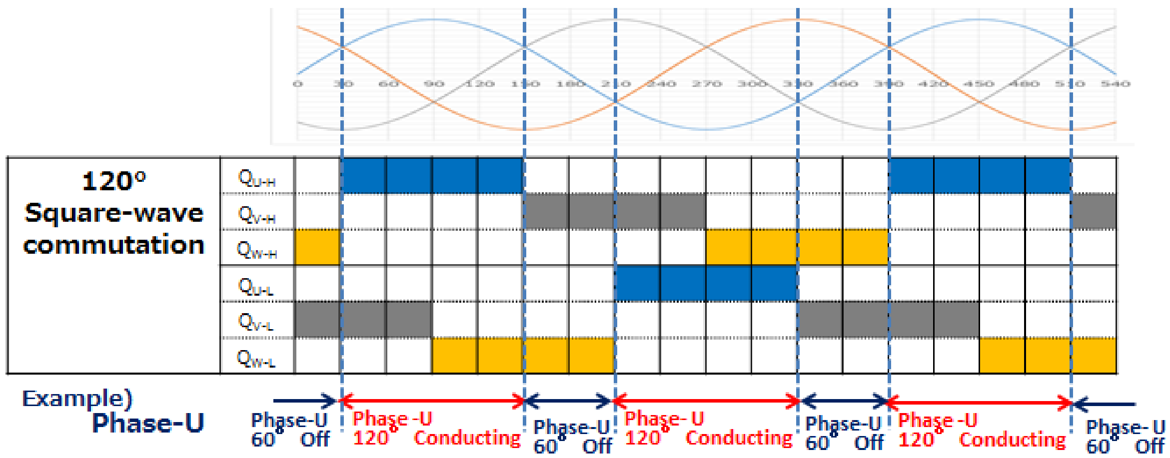
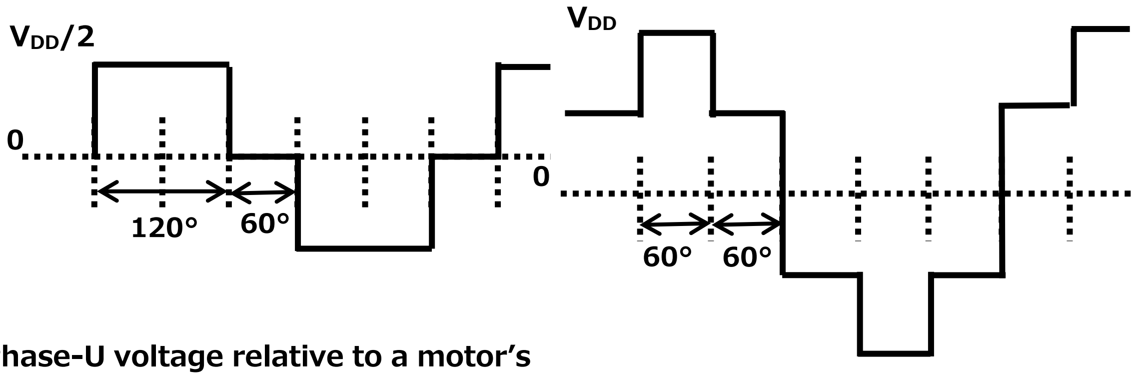


Figure 1.2 Switching of six devices for 120° square-wave commutation



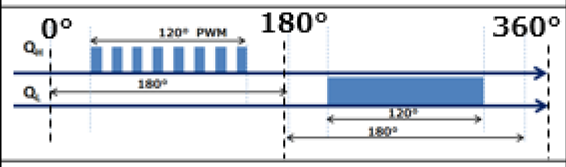
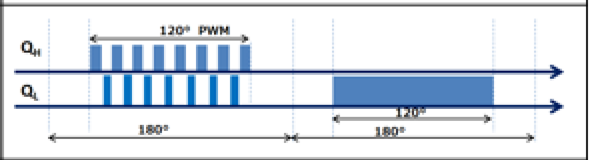
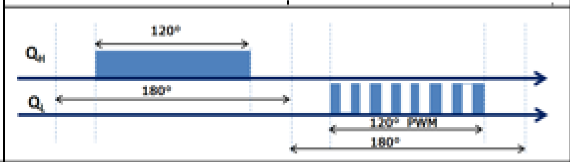
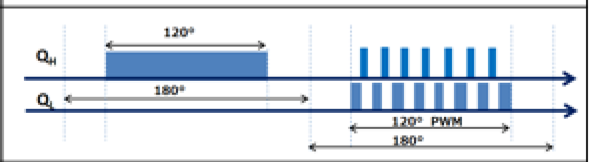
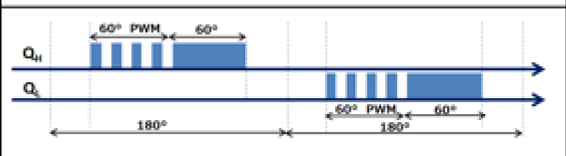
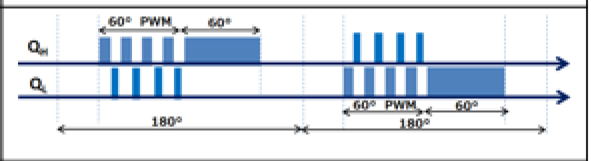
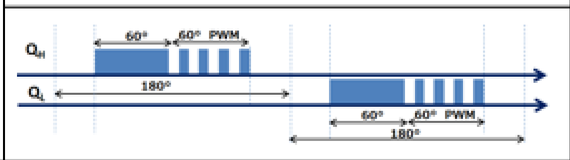
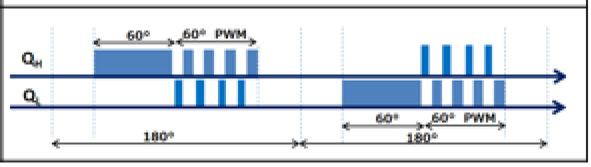
Phase-U voltage relative to a motor's neutral point

Phase-to-phase voltage (U-V)

Figure 1.3 Theoretical voltage waveforms during the 120° commutation sequence

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[*3]. 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

	Non-complementary switching	Complementary switching
One side PWM		
Q_H : High side Q_L : Low side		
60° PWM		
Q_H : High side Q_L : Low side		

***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.

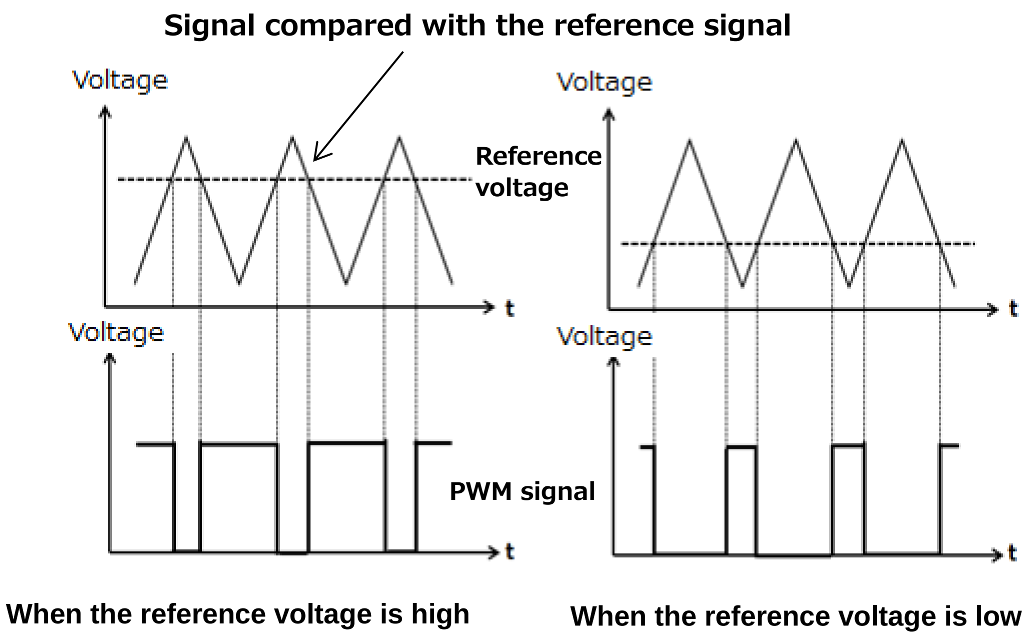


Figure 1.4 PWM signal

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.

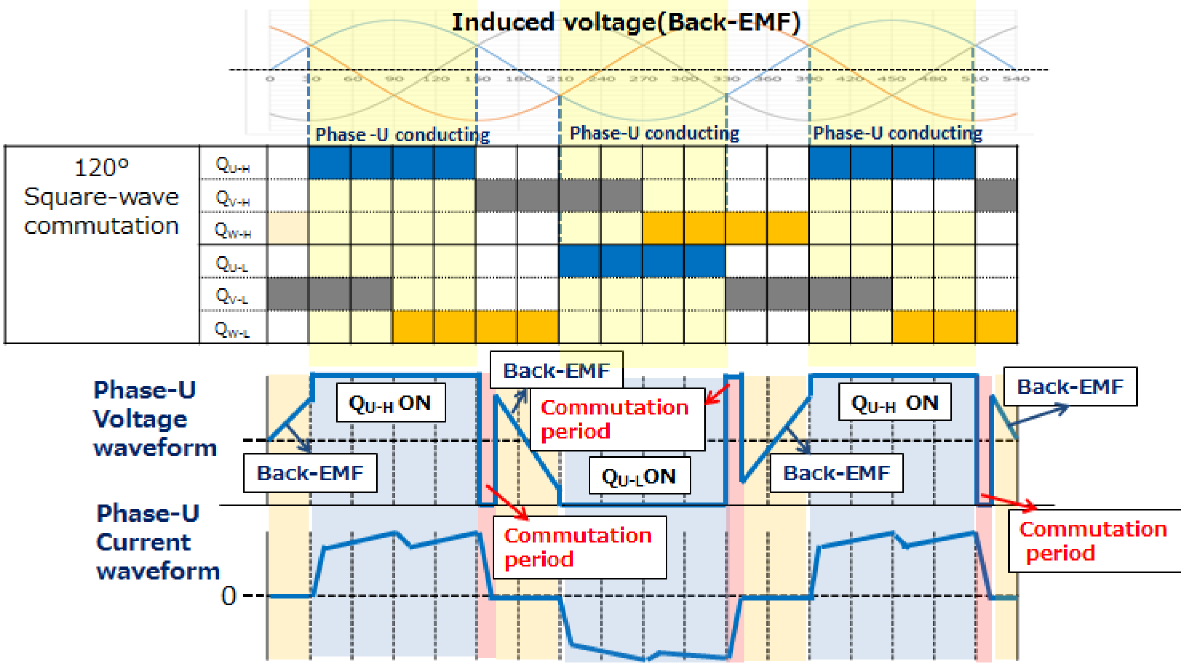


Figure 1.5 Voltage and current waveforms during 120° square-wave commutation

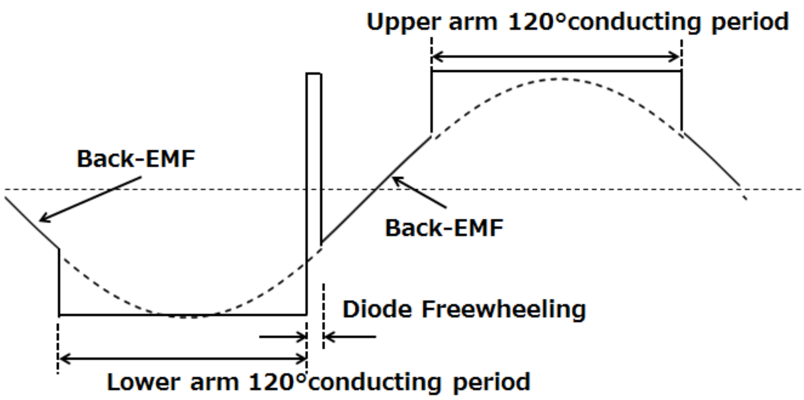


Figure 1.6 Back-EMF induced during 120° square-wave commutation

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.
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.)

$$e_a = K_e N$$

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.

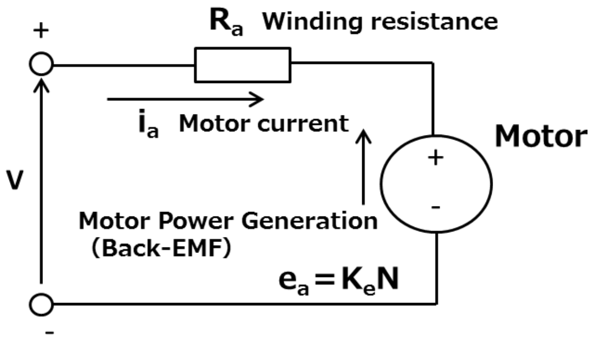


Figure 1.7 Voltage and current during 120° square-wave commutation

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

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.

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 $Q_{V\text{-}H}$ and the low-side $Q_{W\text{-}L}$ are on, Phase-U winding is de-energized.

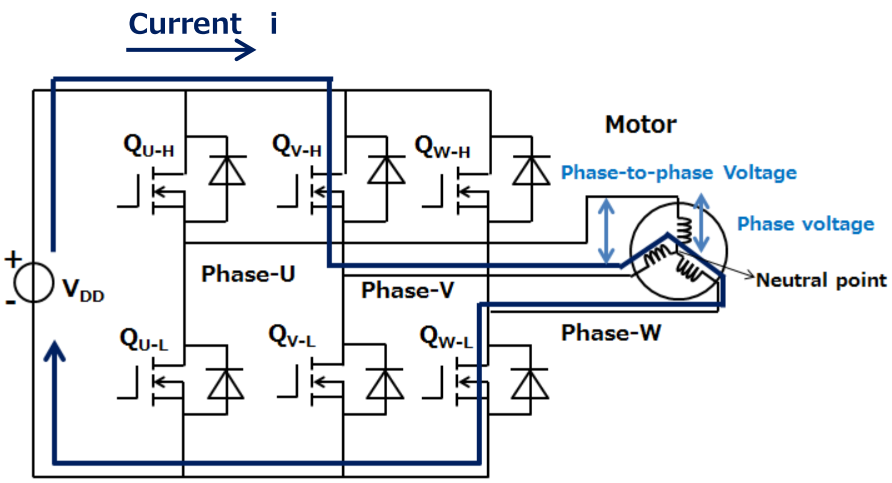


Figure 1.8 Inverter circuit

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, 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, 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:

$V_N=(V_{DD}-e_V-e_W)/2$ (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, 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 (≥0) and the electrical angle be θ (0≤θ≤360°), the back-EMF voltages in each phase are:

$e_U=k\cdot\sin\theta$
$e_V=k\cdot\sin(\theta-120°)$
$e_W=k\cdot\sin(\theta+120°)$ (Equation 2)

From Equation 2, a trigonometric calculation provides:

$e_V+e_W=-e_U$ (Equation 3)

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

$v_N=(V_{DD}+e_U)/2$ ... Neutral-point voltage (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:

$v_U = (V_{DD}/2) + (3/2)e_U$

$= ((v_V + v_W)/2) + (3/2)e_U$ (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.

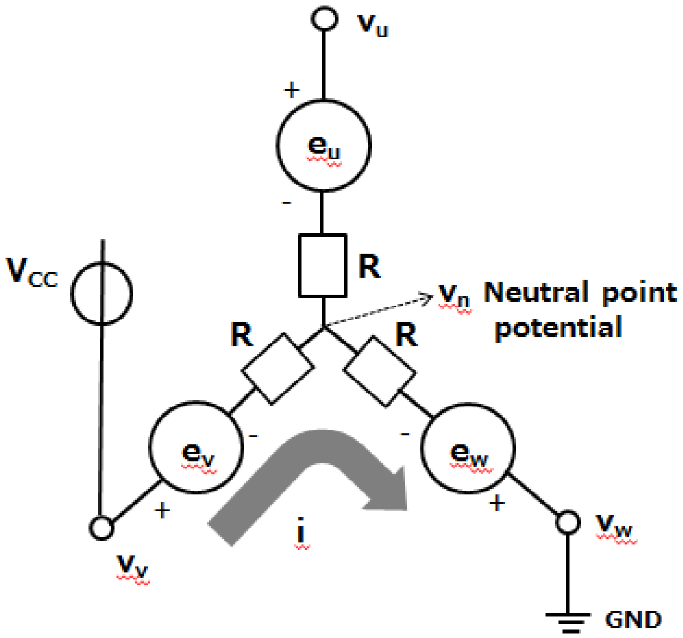


Figure 1.9 Neutral-point voltage and voltages of each phase

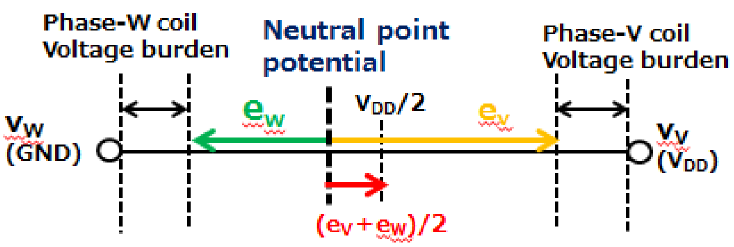


Figure 1.10 Neutral-point voltage

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.

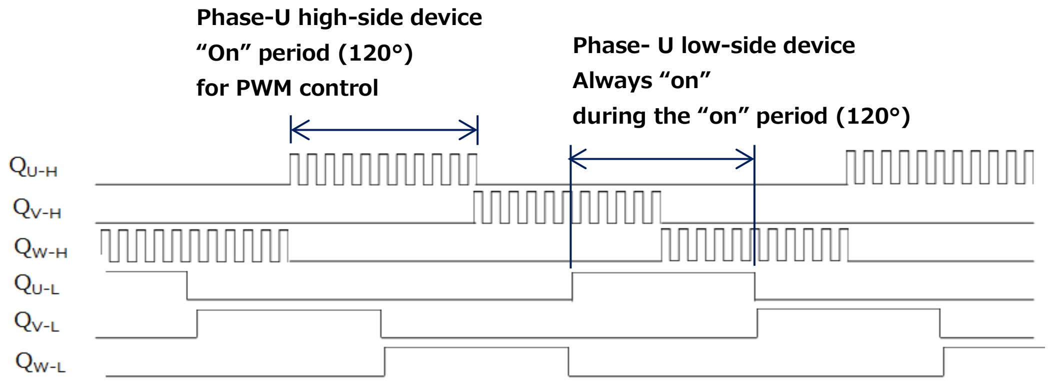


Figure 2.1 Upper-arm chopper signals for 120° square-wave commutation

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.

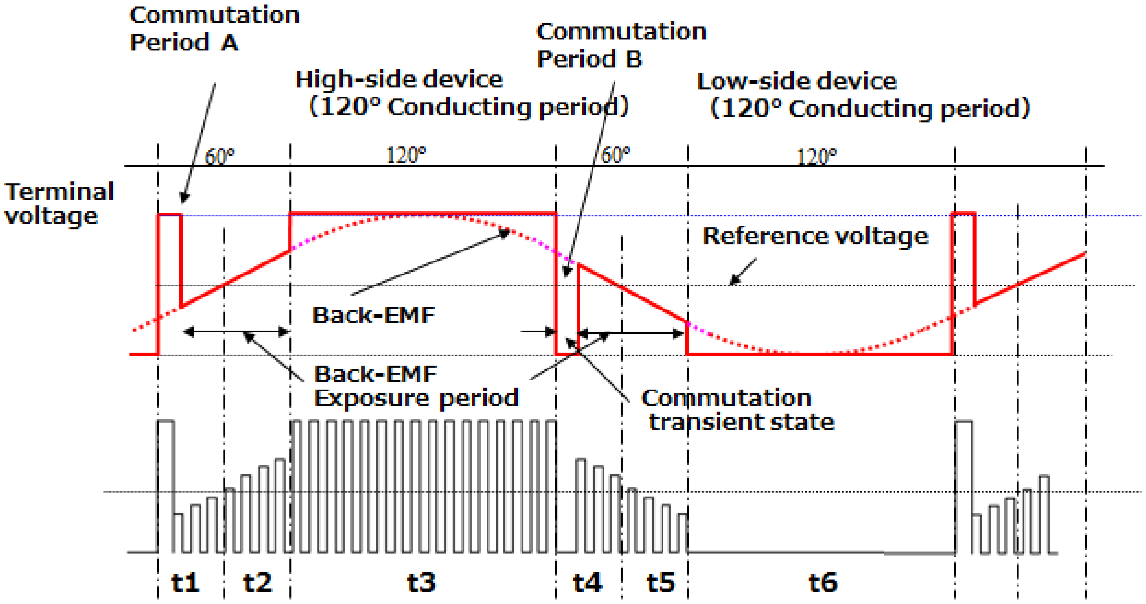


Figure 2.2 Inverter phase terminal voltage (upper-arm chopping)

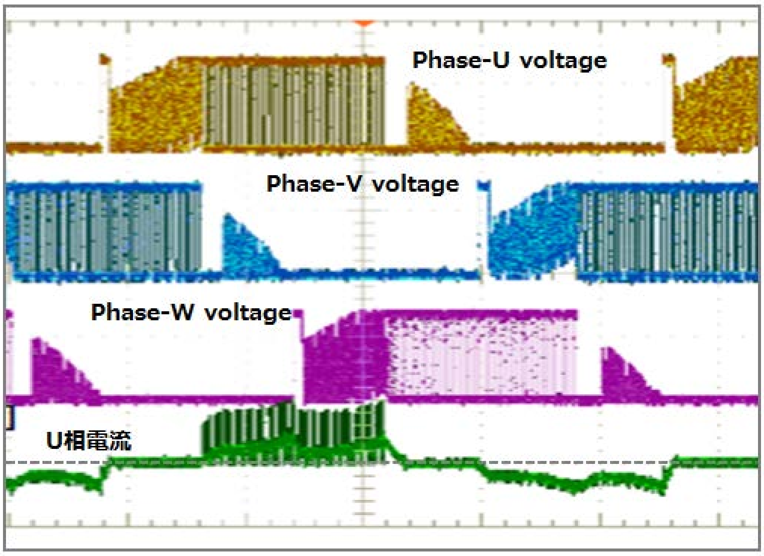


Figure 2.3 Phase terminal voltage waveforms (upper-arm chopping)

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 Q_{U-L} device remains off after being on for 120 electrical degrees. As shown in Figure 2.4, after Q_{U-L} turns off, a current flows back through the body diode in Q_{U-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 Q_{U-H} is connected to V_{DD}, its anode voltage (i.e., the voltage at the Phase-U terminal) increases to the V_{DD} voltage while the freewheel current continues flowing. After that, the voltage at the Phase-U terminal becomes equal to the back-EMF voltage.

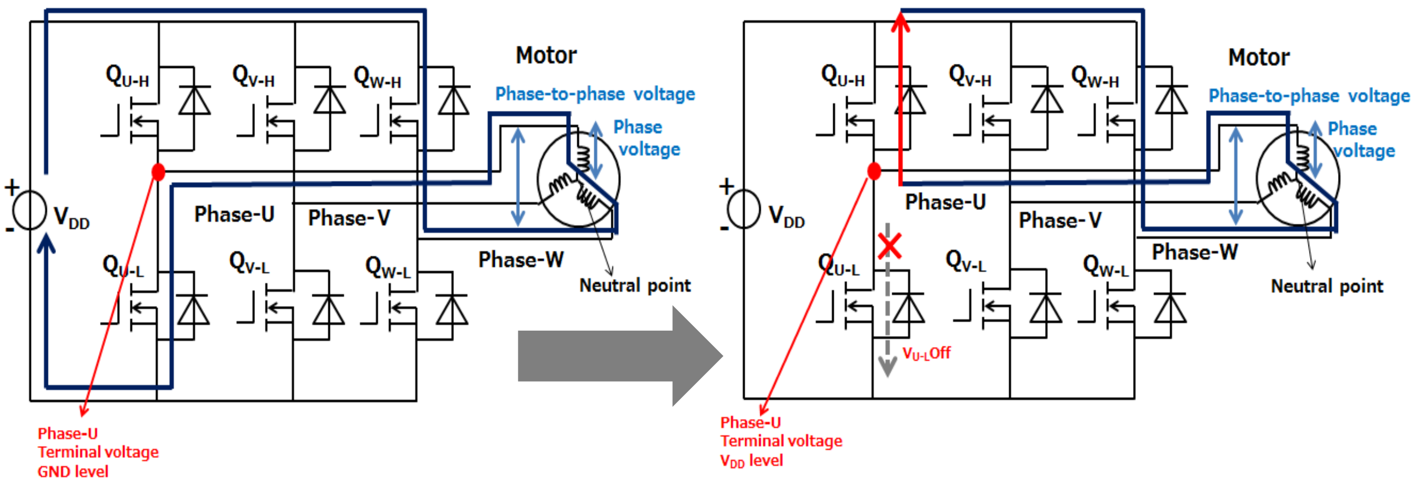


Figure 2.4 Commutation period A

b) Commutation period B (diode freewheeling period) in the phase voltage waveform of Figure 2.2

During commutation period B, the low-side $Q_{U\text{-}H}$ device remains off after being on for 120 electrical degrees. As shown in Figure 2.5, after $Q_{U\text{-}H}$ turns off, a current flows back through the body diode in $Q_{U\text{-}L}$ 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 $Q_{U\text{-}L}$ 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.

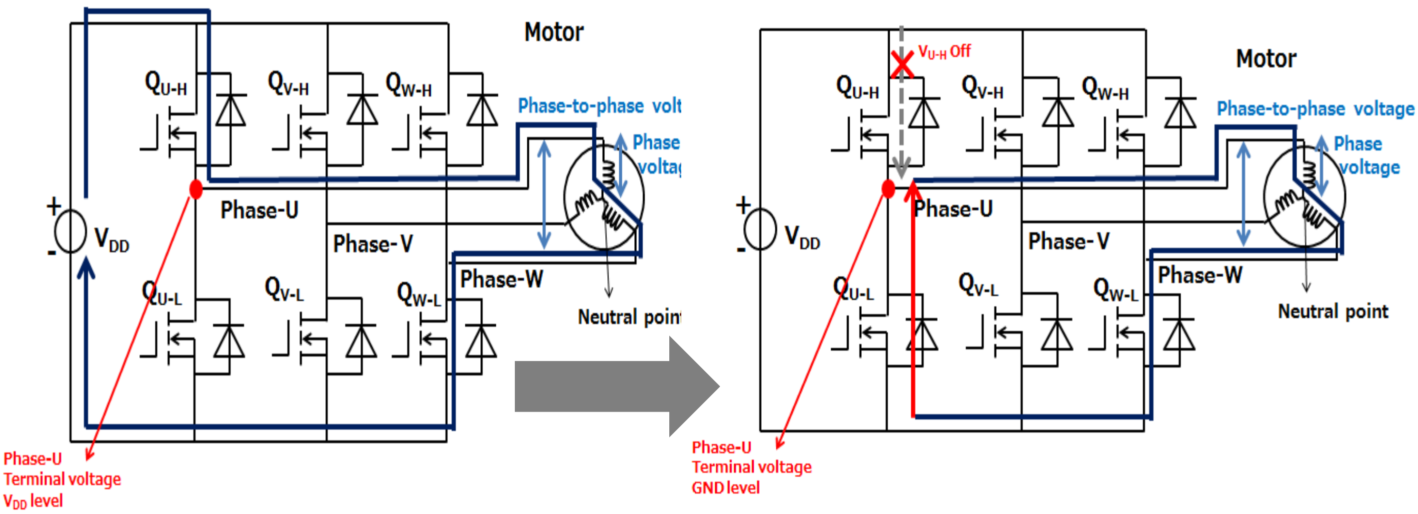


Figure 2.5 Commutation period B

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.

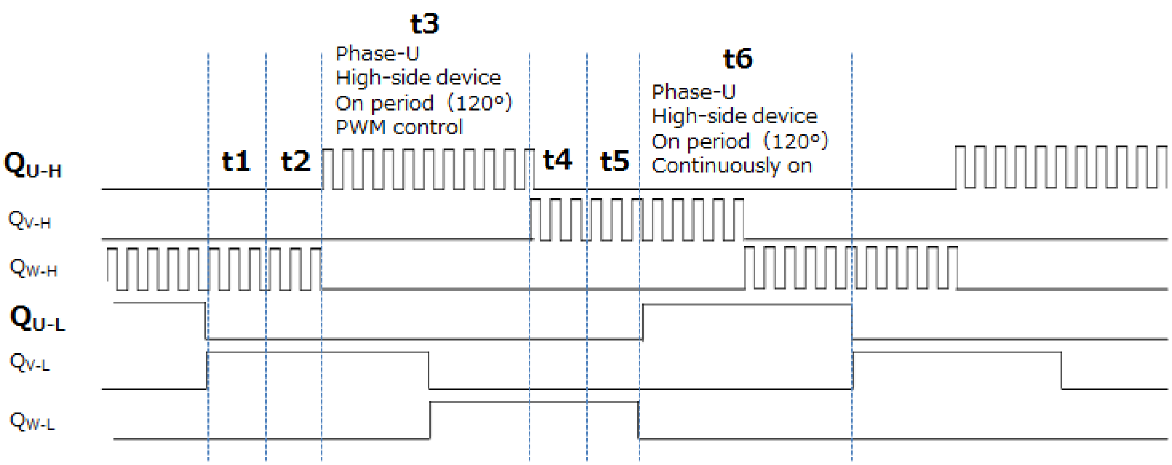


Figure 2.6 Commutation timing of the devices in the inverter

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.)

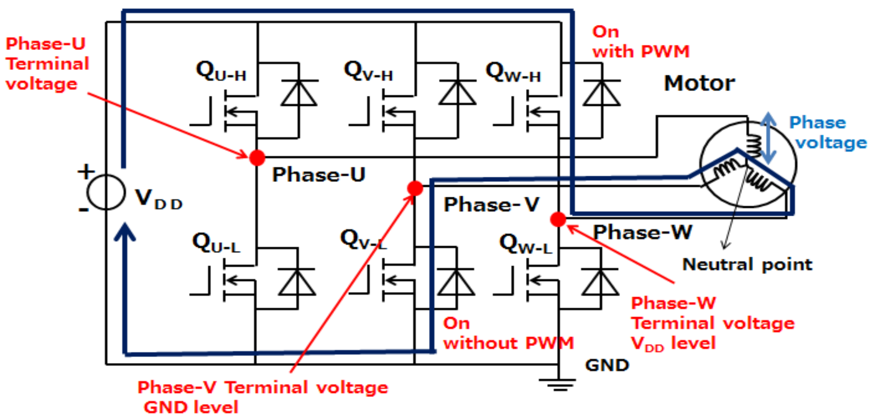


Figure 2.7 Current path when Q_{W-H} is in PWM mode and Q_{V-L} is on

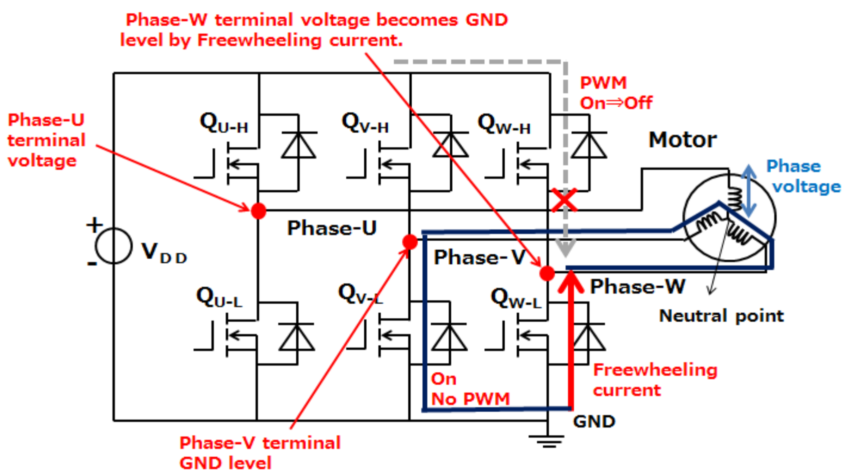


Figure 2.8 Current path immediately after Q_{W-H} switches off

2) Voltage during t2

Period t2 can be considered in the same manner as for t1.

· While $Q_{W\text{-}H}$ 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 $Q_{W\text{-}H}$ is off

The freewheel current flows through the body diode in $Q_{W\text{-}L}$, 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 t3

While $Q_{U\text{-}H}$ is on, the Phase-U terminal voltage equals V_{DD} as shown in Figure 2.9. While $Q_{U\text{-}H}$ is off, a freewheel current flows through the body diode in $Q_{U\text{-}L}$, causing the Phase-U terminal voltage to be equal to GND.

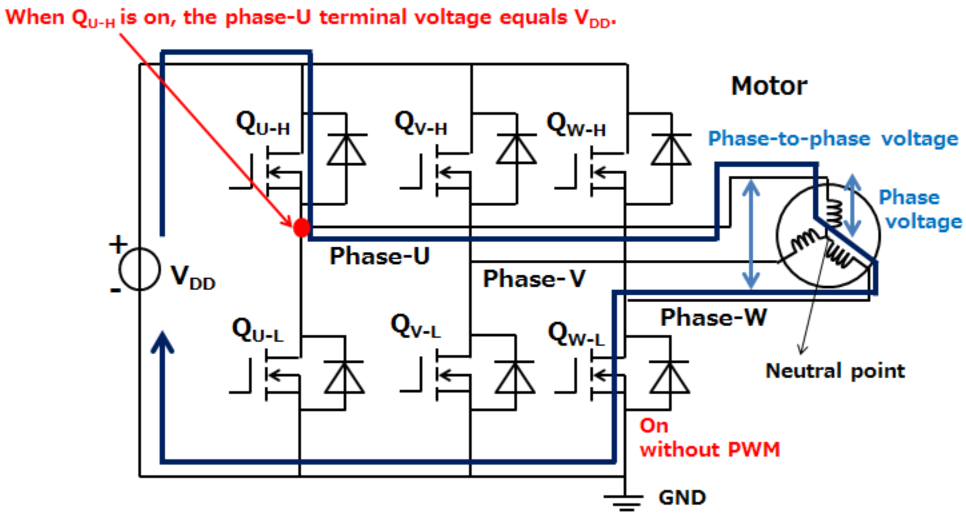


Figure 2.9 Current path when $Q_{U\text{-}H}$ is on

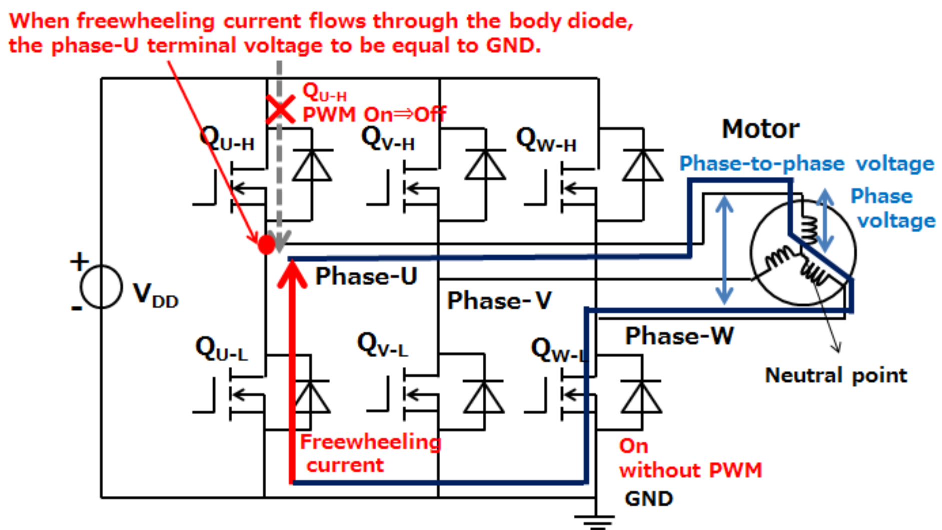


Figure 2.10 Current path immediately after $Q_{U\text{-}H}$ switches off

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, Q_{U-L}, remains on (without PWM), causing the Phase-U terminal voltage to become equal to GND.

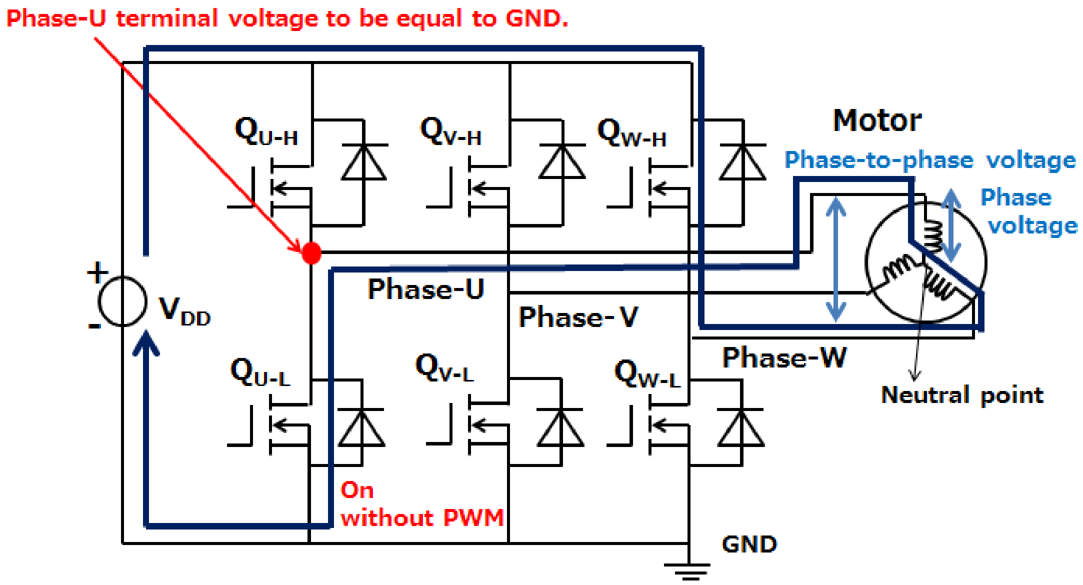


Figure 2.11 Current path immediately after Q_{U-H} switches off

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).

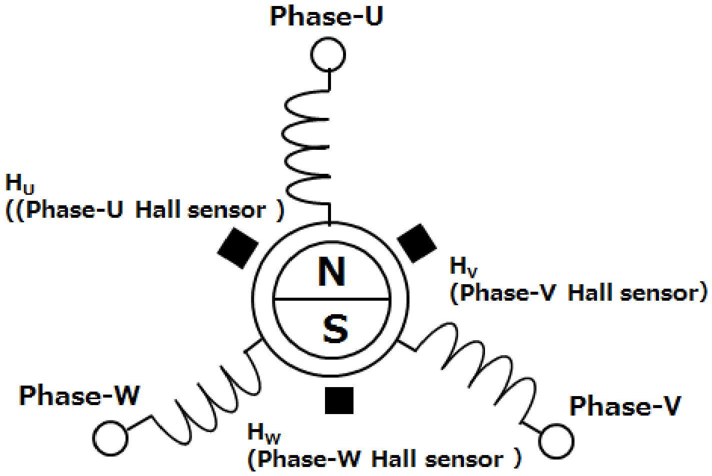


Figure 3.1 Hall sensor positions

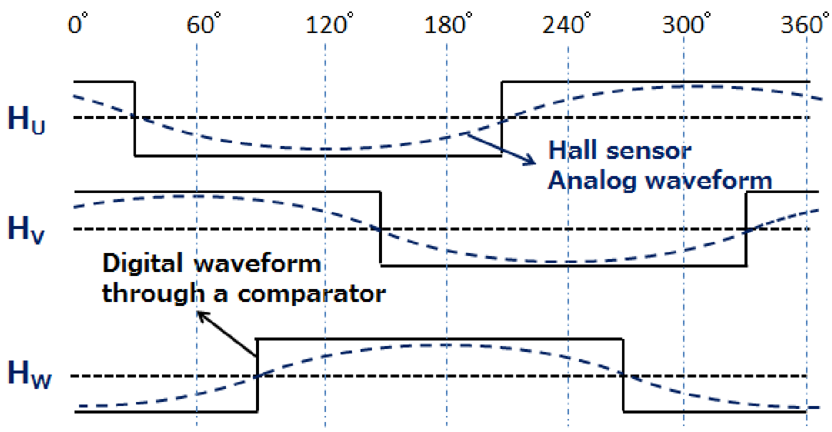


Figure 3.2 Hall sensor waveforms

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.

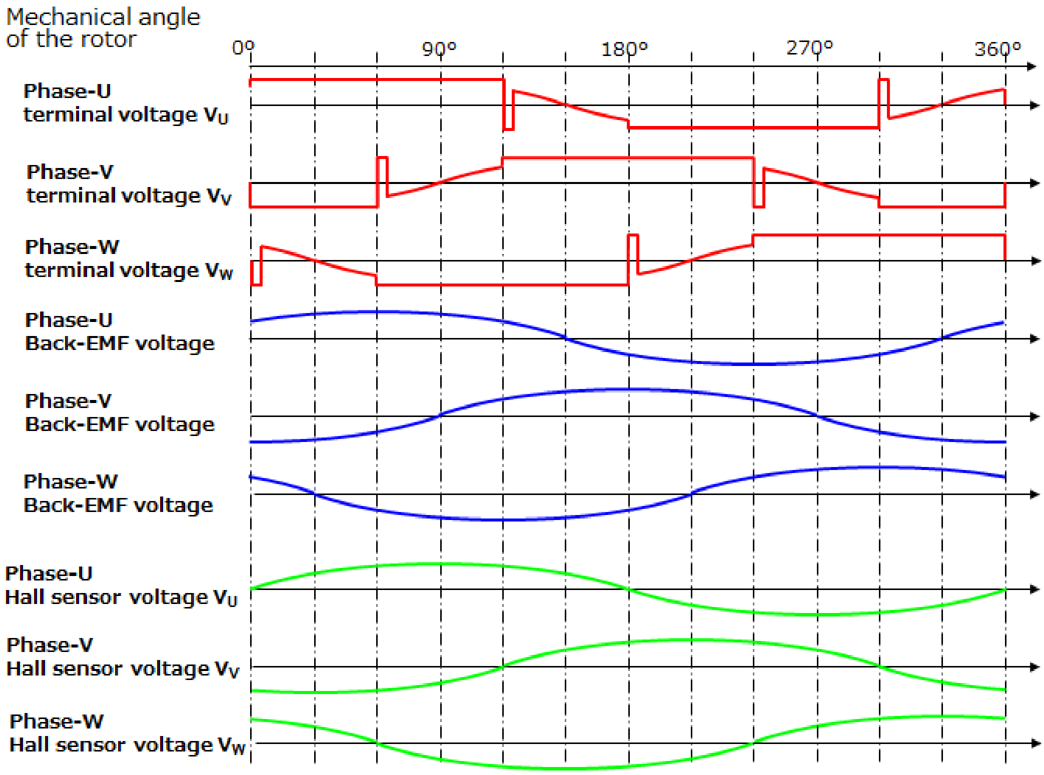


Figure 3.3 Phase terminal voltage, back-EMF voltage, and Hall sensor voltage of each phase

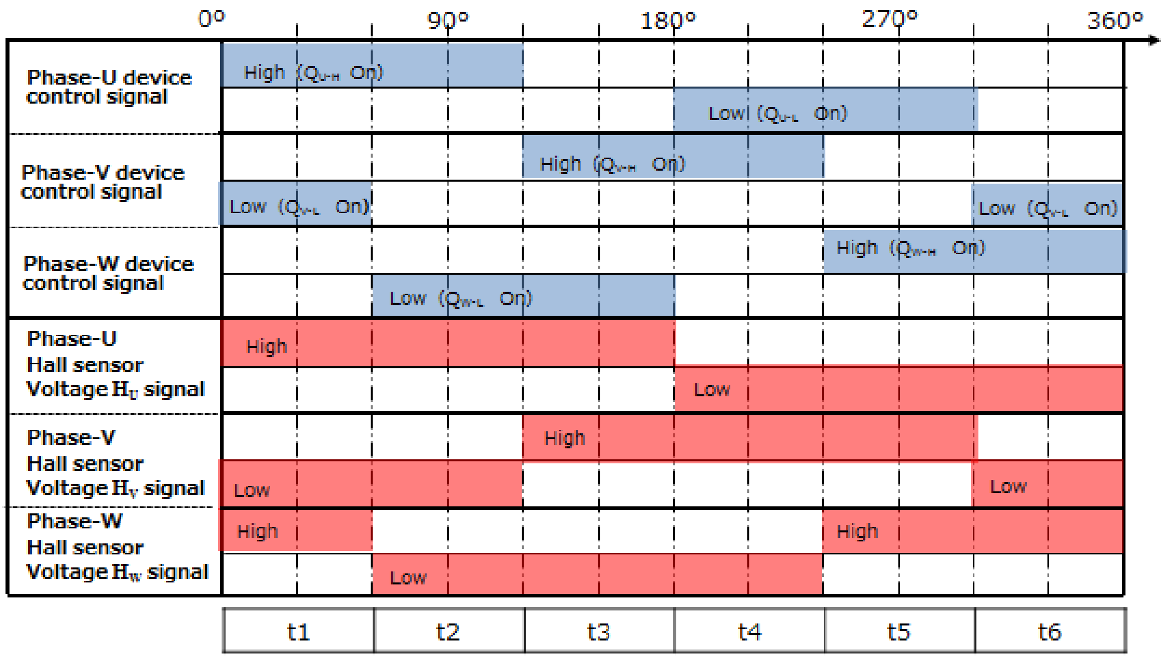


Figure 3.4 Hall sensor signals vs. inverter switching timing

Table 3.1 Truth table

	High-side devices			Low-side devices				Hall sensor output		
Pattern	Q_{U-H}	Q_{V-H}	Q_{W-H}	Q_{U-L}	Q_{V-L}	Q_{W-L}		H_U	H_V	H_W
t1	1	0	0	0	1	0		1	0	1
t2	1	0	0	0	0	1		1	0	0
t3	0	1	0	0	0	1		1	1	0
t4	0	1	0	1	0	0		0	1	0
t5	0	0	1	1	0	0		0	1	1
t6	0	0	1	0	1	0		0	0	1

The Boolean logic for Q_{U-H} to Q_{W-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.

$$Q_{U-H}=H_U\bar{H}_V H_W+H_U\bar{H}_V\bar{H}_W=H_U\bar{H}_V(H_W+\bar{H}_W)=H_U\bar{H}_V$$

$$Q_{V-H}=H_V\bar{H}_W,\ Q_{W-H}=H_W\bar{H}_U$$

$$Q_{U-L}=\bar{H}_U H_V\bar{H}_W+\bar{H}_U H_V H_W=\bar{H}_U H_V(H_W+\bar{H}_W)=\bar{H}_U H_V$$

$$Q_{V-L}=\bar{H}_V H_W,\ Q_{W-L}=\bar{H}_W H_U$$

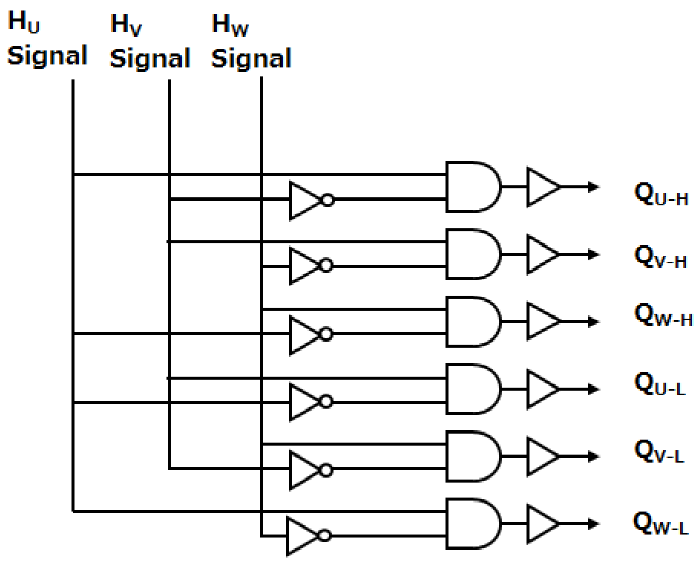


Figure 3.5 Logic circuit that provides the switching signals

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.

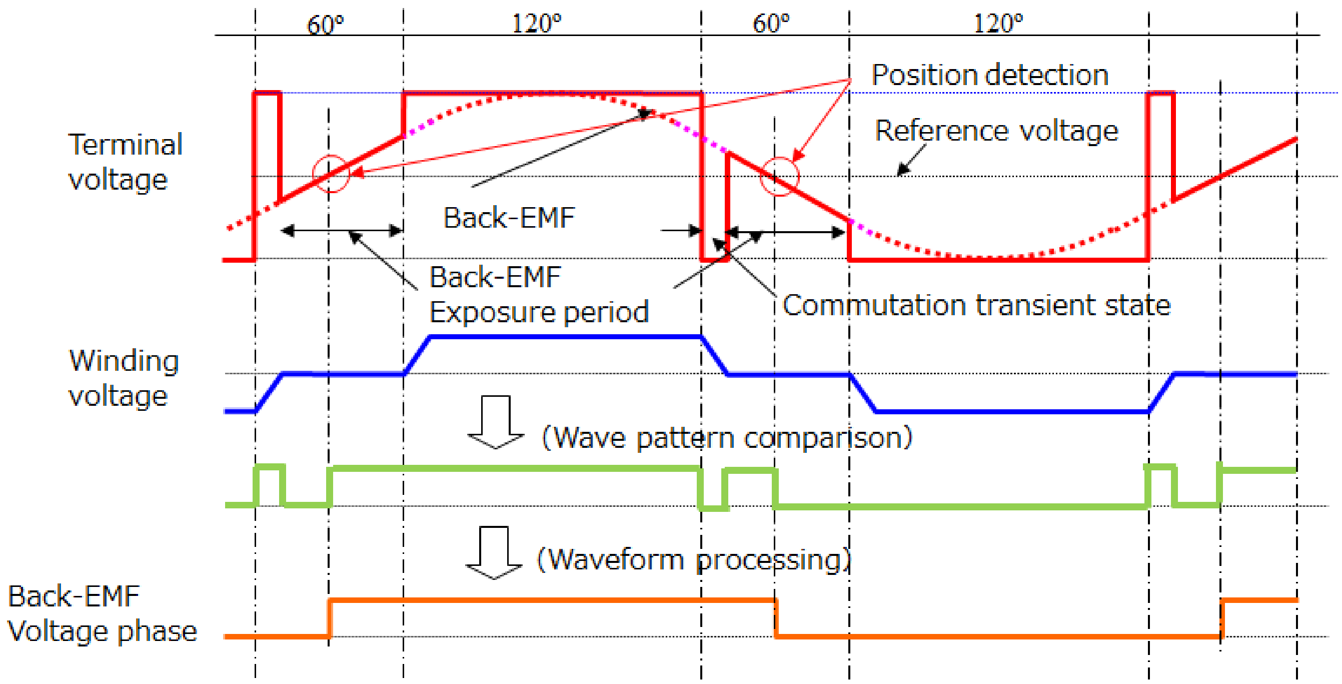


Figure 3.6 Zero-crossing points for rotor position detection

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.

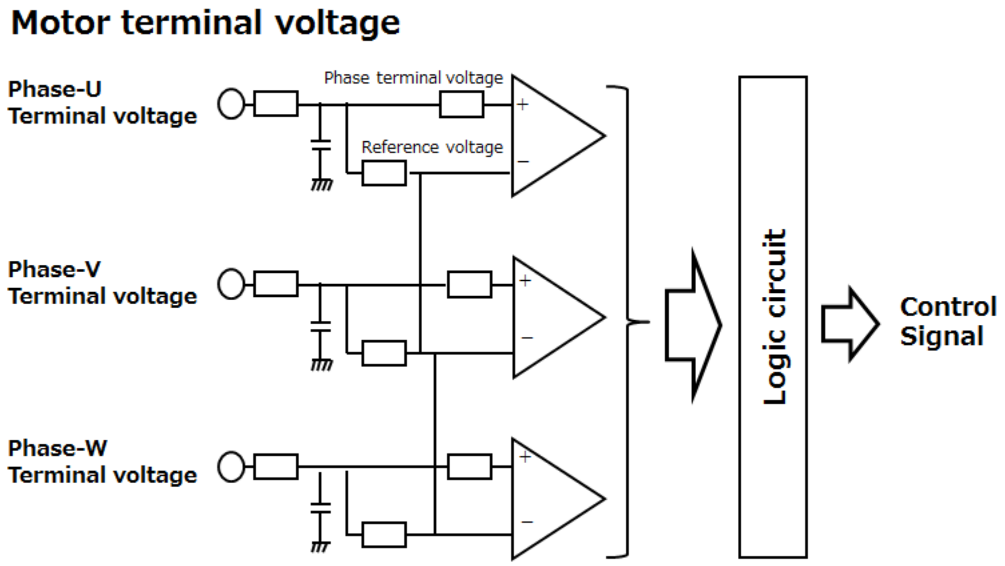


Figure 3.7 Example of sensorless rotor position detection (analog method)

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.

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