# Motor Control (Vacuum Cleaners)

## Outline:

This application note discusses different types of motors used for vacuum cleaners as well as basic motor circuits. Conventional vacuum cleaners mainly use universal motors powered by a mains supply. Nowadays, brushless DC (BLDC) motors powered by a DC power source are increasingly used for cordless cleaners. BLDC motors are available with three-phase and single-phase configurations, which are controlled in different manners.

This application note describes the drive and control methods (phase control and PWM control techniques) for universal and BLDC motors as well as triac-output photocouplers (also known as phototriacs) and MOSFETs used for motor control drive circuits.

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# 1. Motors for vacuum cleaners

Nowadays, cordless vacuum cleaners (with a DC battery), particularly stick vacuum cleaners, are rapidly becoming more popular than canister vacuum cleaners (powered by a mains AC supply). This trend is being spurred by the development of high-capacity batteries and small high-speed BLDC motors that were realized by improving the trade-off between their rotational speed and torque. As a result, stick vacuum cleaners now provide output power equivalent to that of canister vacuum cleaners.

## 1.1. Suction power of vacuum cleaners versus motor characteristics

Suction power is one of the parameters that indicate the dust suction performance of a vacuum cleaner. Measured in watts (W), it represents the amount of intake air and the power to suck in dust.

An airflow rate (in $m^3$/min) and a degree of vacuum (in pascal, Pa) are measured while suction conditions are varied under prescribed test conditions. Suction power is then determined as the maximum value obtained from the following equation:

**Suction power (W) = 0.01666 (constant) × airflow rate ($m^3$/min) × degree of vacuum (Pa)** ------ Equation 1

**Note: Constant of 0.01666**

Conversion factor (1/60) to convert energy per minute into energy per second

The degree of vacuum determines the power to suck up dust. The greater it is, the heavier the dust a vacuum cleaner can suck up. The airflow rate indicates the capability to carry the dust into the dust container. Suction power is the maximum value obtained from these two parameters. In practice, the dust suction performance depends on nozzle head conditions.

Suction power is proportional to the output power of a motor. The output power of a DC motor is expressed with rotational speed and torque as shown below. To produce high power, high torque is necessary at high rpm. Although a large motor is required to obtain high torque, stick vacuum cleaners have a size constraint. Therefore, a high-rpm motor is commonly used for stick vacuum cleaners to compensate for the size constraint and obtain high output power even with small torque, taking the DC motor characteristics shown in Figure 1.1 into consideration. In Figure 1.1, #1 represents a motor with large torque and low rpm whereas #2 represents a motor with small torque and high rpm.

This indicates that it is possible to compensate for low torque by increasing the rotational speed.

Power, P (W) = rotational speed (rad/s) × torque T(N・m)

Rotational speed (rad/s) = revolutions per minute (r/min) × 2π / 60

= 0.1047 × revolutions per minute (r/min)

**Power, P (W) = 0.1047 × torque T (N・m) × revolutions per minute (r/min)** ------ Equation 2

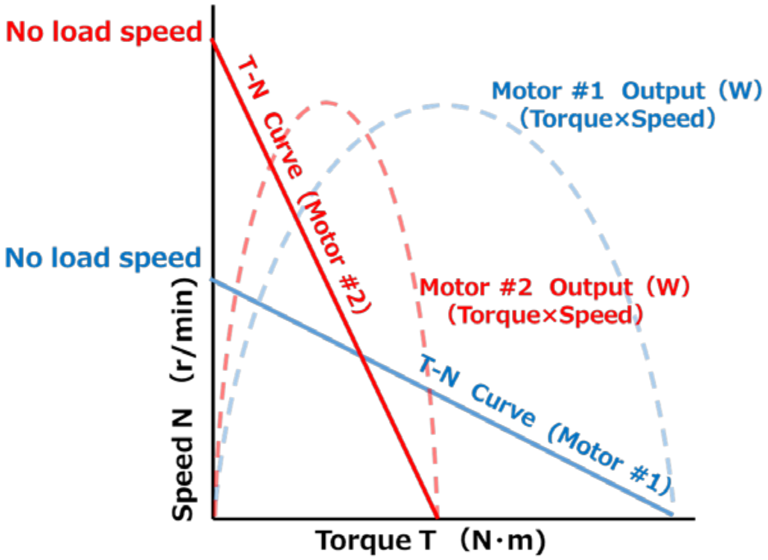


Figure 1.1 DC motor characteristics

## 1.2. Types of motors used for vacuum cleaners

Table 1.1 shows major types of motors commonly used for vacuum cleaners. The majority of corded AC vacuum cleaners for home use are canister models, most of which perform phase control of an AC voltage from a mains supply to drive a universal motor although some models rectify AC power into DC power to run a switched reluctance (SR) or BLDC motor.

Rechargeable DC cordless models use an SR or BLDC motor capable of high-rpm operation to obtain output power equivalent to that of corded models.

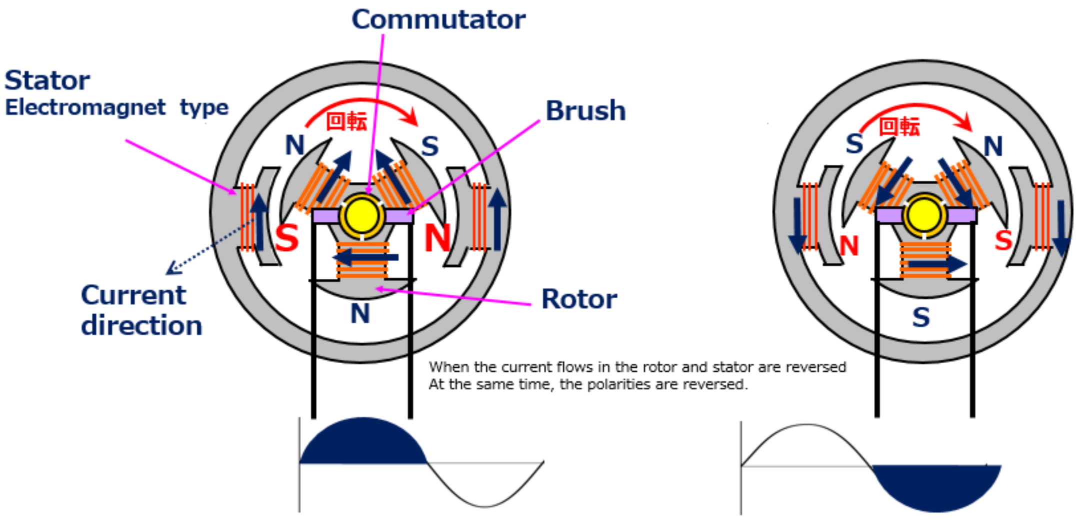
Table 1.1 Types of motors used for vacuum cleaners

| | **Motor** |
|---|---|
| **Corded AC models** | Universal motor |
| **Rechargeable DC cordless models** | Brushed DC motor |
| | SR motor |
| | Three-phase BLDC motor |
| | Single-phase BLDC motor |

### 1.2.1. Overview of different types of motors

**Universal motors:**

The universal motor is a type of AC commutator motor. As is the case with brushed DC motors, universal motors have a commutator and brushes. Although universal motors are mainly used with a single-phase AC power supply, they can also operate on DC power. The universal motor is a series-wound motor in which the rotor windings are connected in series with the stator windings. Since AC current is applied to both the rotor and the stator in series, the stator current also reverses when the rotor current reverses. Therefore, the relative positional relationship between the rotor and the stator remains unchanged.



When the current flows in the rotor and stator are reversed
At the same time, the polarities are reversed.

Figure 1.2 Universal motor

## Switched reluctance (SR) motors

The SR motor is a type of reluctance motor equipped with a rotor having multiple projections to produce variations in reluctance (i.e., magnetic resistance) and thereby multiple poles. The rotor of the SR motor consists only of a ferromagnetic iron core. Notches or air gaps within the iron core provide areas of high reluctance and areas of low reluctance, producing variations in attractive force, depending on the rotor position. This makes it possible for SR motors to move in steps through the attractive force of soft iron without using any permanent magnet or electromagnet on the rotor. As a side note, variants of reluctance motors include synchronous reluctance motors (SynRMs) that do not have projections on the stator to enable sine-wave commutation.

Figure 1.3 illustrates how an SR motor rotates. Current paths, which are highlighted by red lines, are switched to produce a rotating magnetic field. The rotor rotates in the direction opposite to the direction of the rotating magnetic field.

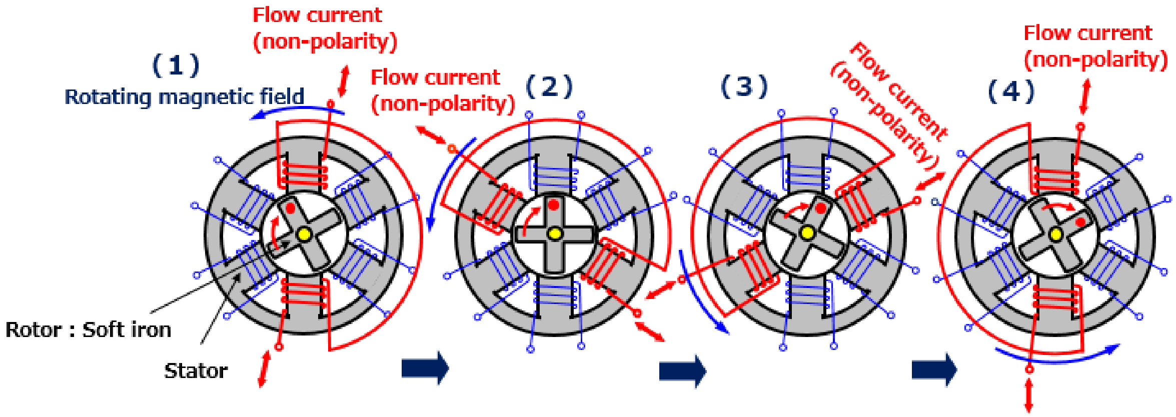


Figure 1.3 SR motor

## Brushed DC motors:

A rotating magnetic field is necessary for a DC motor to rotate. Since DC current does not provide such a magnetic field, mechanical parts (specifically, a commutator and brushes) are necessary to convert DC current into AC current. The brushed DC motor rotates as its commutator physically rubs against brushes to convert the DC current flowing through the rotor into AC current, changing the polarities of the rotor poles. Figure 1.4 illustrates the operation of a two-pole brushed DC motor.

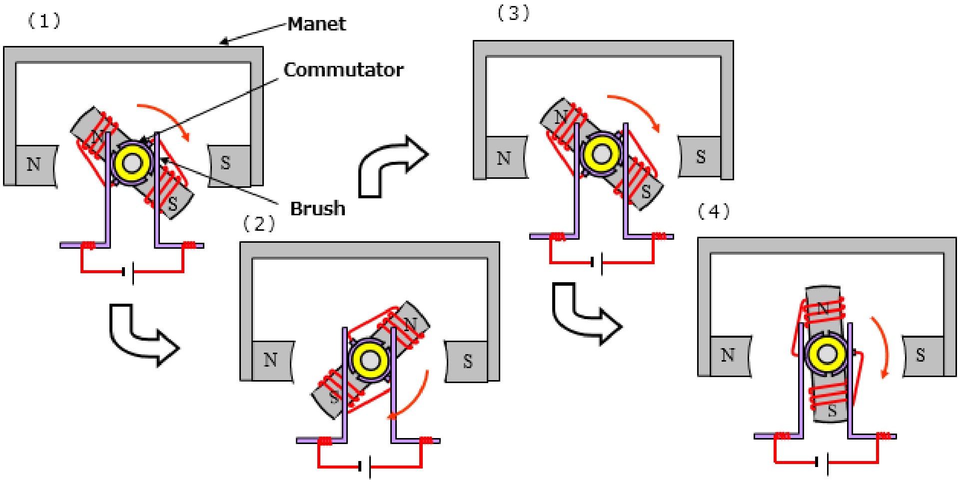


Figure 1.4 Two-pole brushed DC motor

## BLDC motors:

The brushless DC (BLDC) motor is a type of permanent magnet synchronous motor. Unlike brushed DC motors that mechanically switch the direction of coil current using a commutator and brushes, BLDC motors use electrical parts to do this. In order to turn a rotor, the direction of the current flowing through coils is switched to change the direction of magnetic fields generated. External circuitry is used to generate the timing at which to change the current direction according to the rotor position. The rotation of the rotor is controlled by controlling the direction and magnitude of the current applied to the coils.

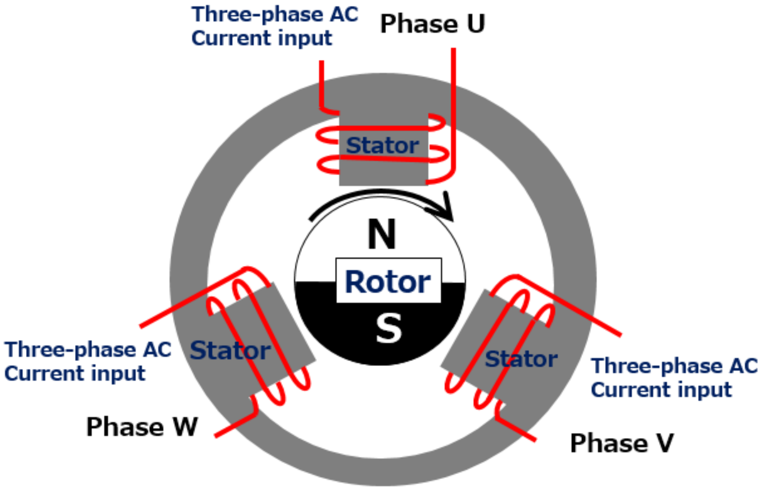


Figure 1.5 Three-phase BLDC motor

# 2. Controlling motors for vacuum cleaners

This section describes the drive circuits for universal motors used in corded AC vacuum cleaners and brushed DC, SR, and BLDC motors used in rechargeable DC cordless vacuum cleaners as well as their operations and control methods.

## 2.1. Corded AC vacuum cleaners

### 2.1.1. Circuits using a universal motor

A universal motor operates on AC voltage. In order to change the suction power of a vacuum cleaner, the power supplied to the motor is controlled through the phase control of a triac. At motor startup, the turn-on phase of the triac is delayed (i.e., the conduction period is reduced) to suppress inrush current.

### 2.1.2. Phase control using a triac

A triac is a switching device capable of directly controlling whether to conduct AC voltage. To control the voltage applied to a motor, control circuitry adjusts the on/off timing (i.e., phase) of the triac every half cycle of the AC input voltage. The triac turns off at the zero-crossing point of AC voltage when the applied current drops below a certain level. It turns on when a trigger signal is applied to the gate and turns off at the zero-crossing point of AC voltage. Figure 2.1 shows a basic phase control circuit using a triac and the waveform applied to a motor.

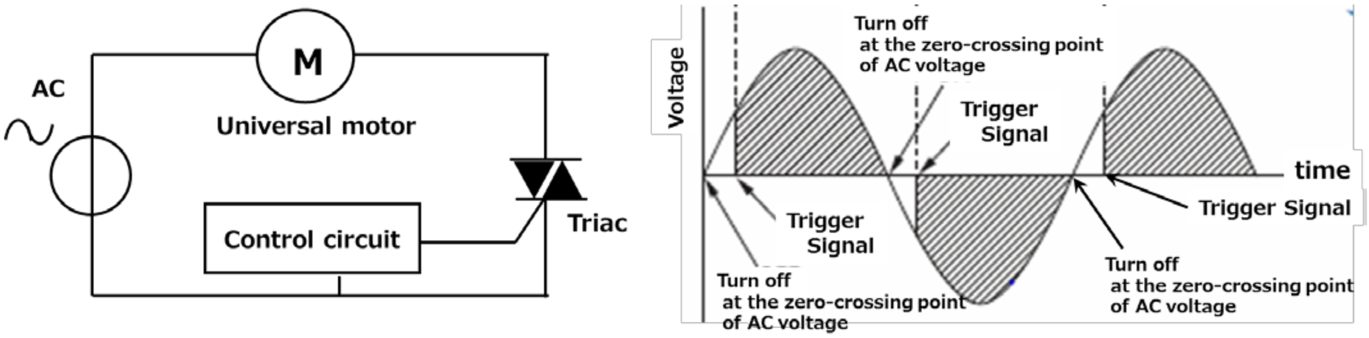
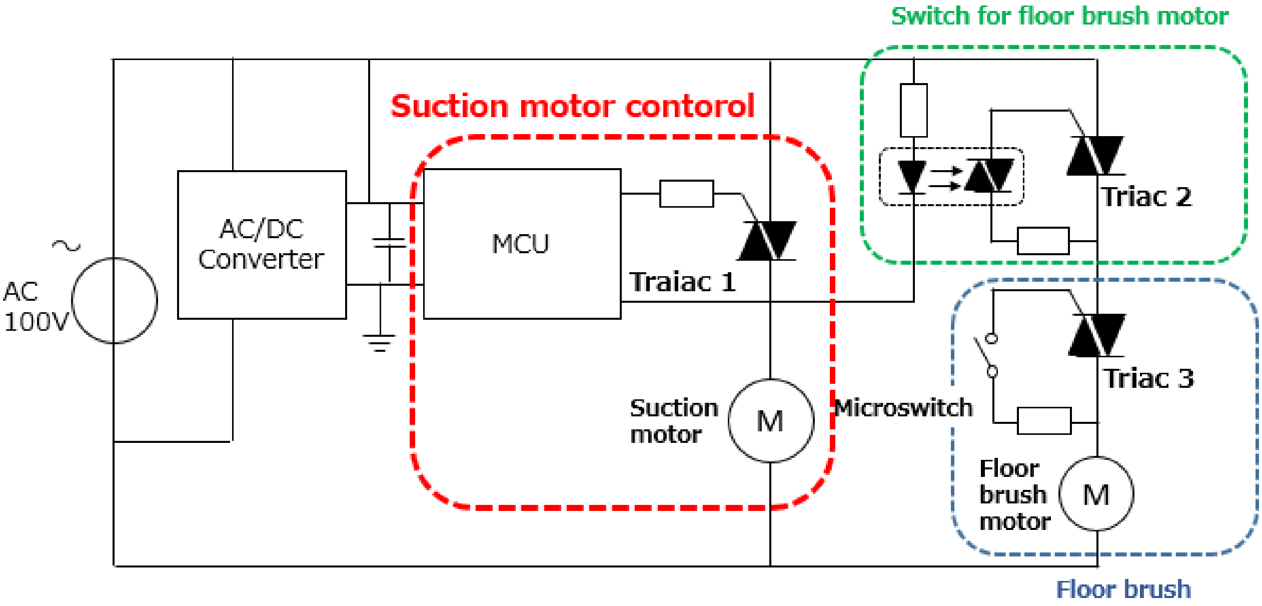


Figure 2.1 Phase control circuit and waveform

### 2.1.3. Triac-based phase control circuit for a vacuum cleaner

Figure 2.2 shows an example of a vacuum cleaner circuit using universal motors. Typically, universal motors are utilized as suction and floor brush motors.



Triac 1: Controls the suction fan motor (universal motor) to control the supplied electric power via phase control
Triac 2: Controls the on/off of the floor brush motor
Triac 3: Turns on a microswitch when the floor brush contacts the floor.

Figure 2.2 Triac-based phase control circuit for a vacuum cleaner

### 2.1.4. Waveforms of phase control using a triac for the vacuum cleaner suction motor

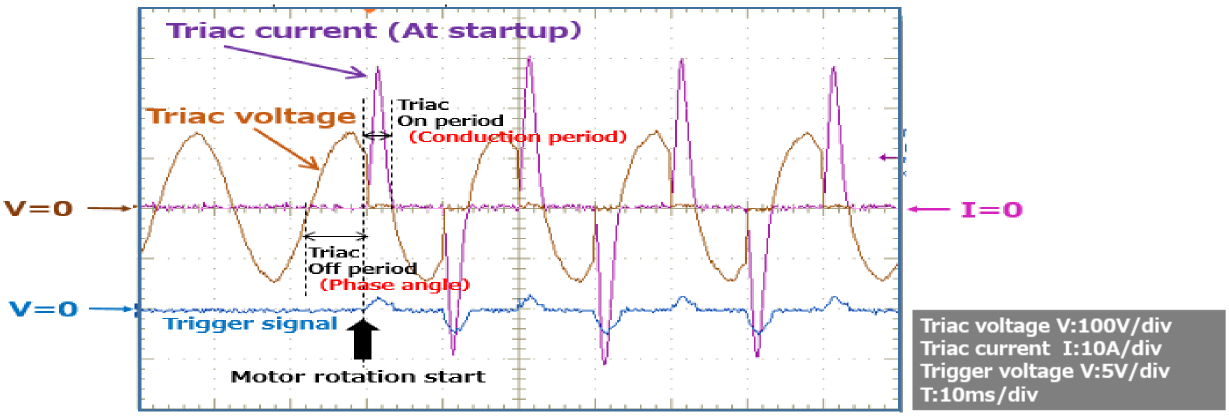
Figure 2.3 shows the voltage and current waveforms of Triac 1 in the circuit of Figure 2.2.

#### 1) At motor startup

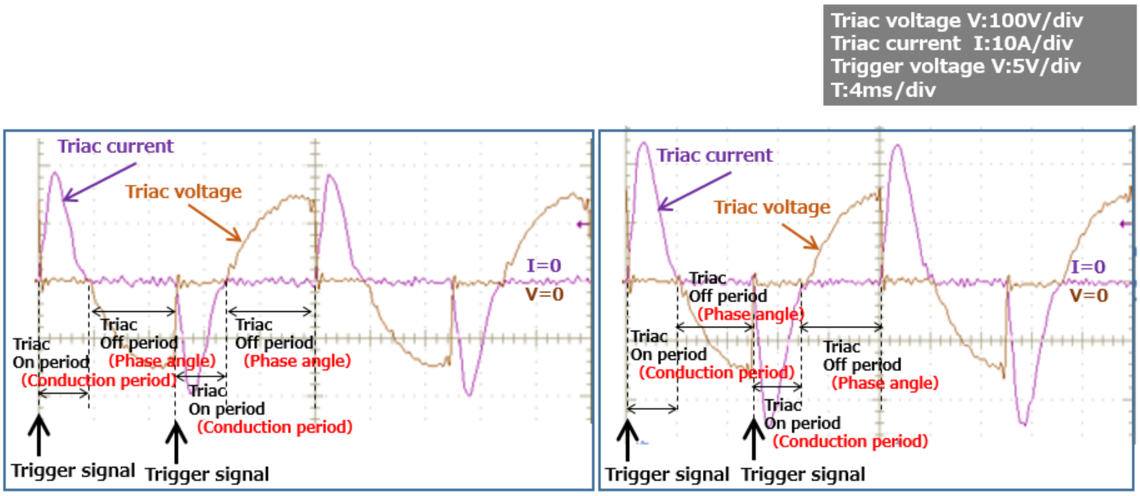
At motor startup, inrush current occurs. Its magnitude is five to six times higher than that of typical motor current. To suppress inrush current, the “on” period of the triac is reduced at motor startup as shown in Figure 2.3 a).

#### 2) During motor operation

Figure 2.3 b) and Figure 2.3 c) compare the phase control waveforms, depending on the turn-on timing, phase angle, and “on” period of the triac when the motor is running at low and high suction levels. At the high suction level, the “on” period of the triac is increased to supply more electric power to the motor.



a) At motor startup



b) At a low suction level

c) At a high suction level

Figure 2.3 Examples of phase control waveforms for a triac

### 2.1.5. Drive voltage and current for the floor brush motor

The on/off of the floor brush motor is controlled using two triacs as shown in Figure 2.2: Triac 2 in the hand grip switch and Triac 3 in the floor contact detection switch. Figure 2.4 shows the voltage and current waveforms of the floor brush motor. Since the floor brush motor is not phase-controlled, its startup current is five to six times higher than the typical motor current.

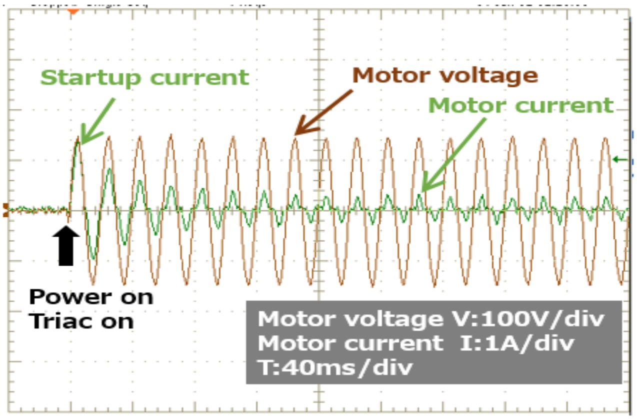


**Figure 2.4 Voltage and current waveforms of the floor brush motor**

### 2.1.6. Triac drive circuit

In some cases, the trigger signals for the triacs for motor drive are applied directly from a microcontroller unit (MCU). In other cases, however, a phototriac coupler is used to transmit a trigger signal to a triac. Figure 2.5 shows an example of a basic triac drive circuit using a phototriac coupler. In Figure 2.5, Rs and Cs form a snubber circuit that absorbs surge voltage to protect the triac. The varistor absorbs surge voltage on the power line.

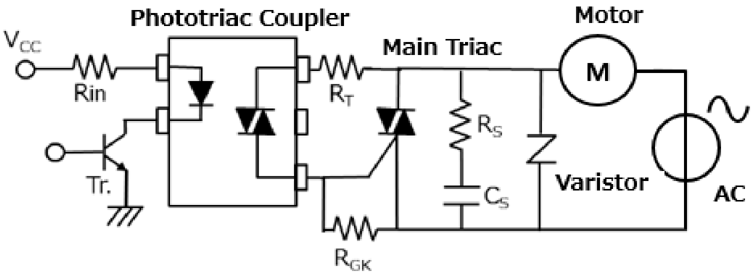


**Figure 2.5 Example of a motor drive circuit using a phototriac coupler and a main triac**

There are two types of phototriac couplers: zero-crossing (ZC) and non-zero-crossing (NZC) phototriac couplers. While the AC supply voltage is high, ZC phototriac couplers do not turn on in order to prevent undesired noise. However, phototriac couplers of this type cannot control the phase angle of a triac. Use an NZC phototriac coupler to perform phase control. Both NZC and ZC phototriac couplers can be used to perform simple on/off control of a triac.

The following describes the basic operations of ZC and NZC phototriac couplers. In most cases, a phototriac coupler is used in combination with a main triac. However, for the sake of brevity, only circuits with a phototriac coupler are discussed in the following.

## ZC phototriac couplers

Figure 2.6 shows a drive circuit with a ZC phototriac coupler for a resistive load and its operating waveforms.

(In the case of an inductive load, the current phase lags behind the voltage phase.)

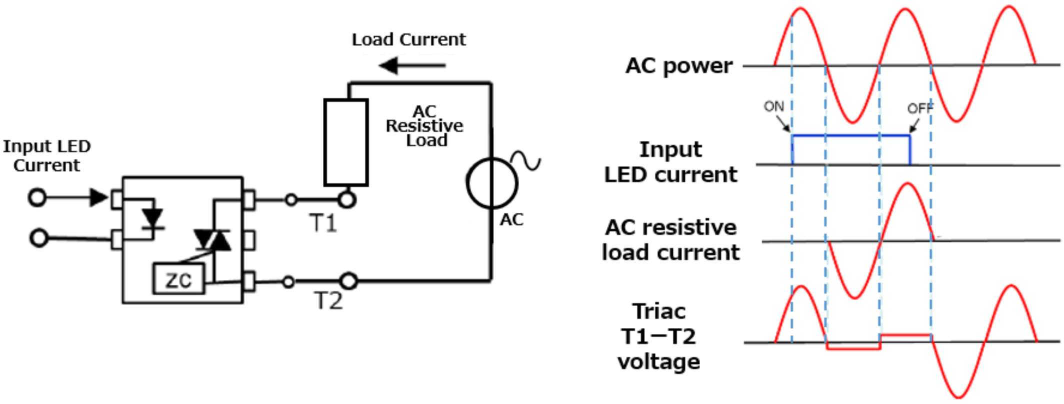


Figure 2.6 Operations of a ZC phototriac coupler

Turn-on operation:

If the AC supply voltage is higher than the zero-crossing voltage (known as the inhibit voltage), the phototriac coupler does not turn on even when current is flowing through the input LED. The phototriac coupler turns on when the AC supply voltage drops close to the zero-crossing point.

Turn-off operation:

When current stops flowing through the input LED and the supply voltage drops close to zero, the load current becomes extremely low. When it drops below the holding current, the triac turns off, unable to maintain the “on” state.

Holding current: Minimum current required to keep a triac in the “on” state

## NZC phototriac couplers

Figure 2.7 shows a drive circuit with an NZC phototriac coupler for a resistive load and its operating waveforms.

(In the case of an inductive load, the current phase lags behind the voltage phase.)

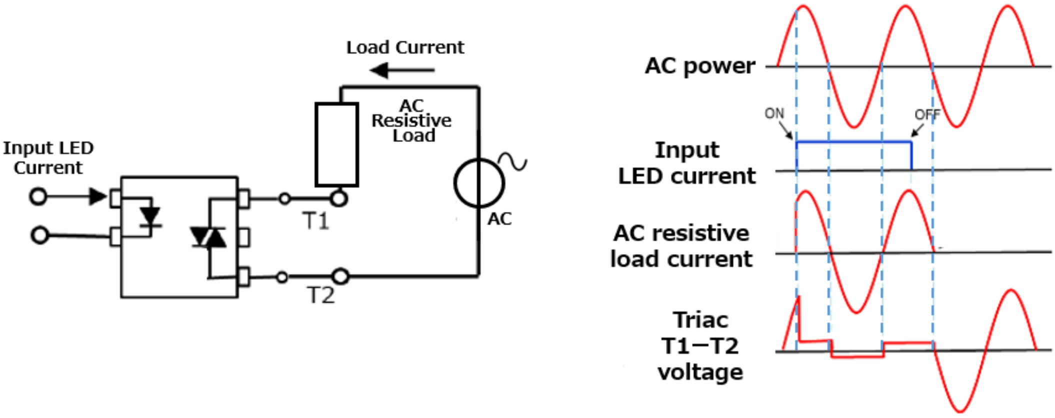


Figure 2.7 Operations of an NZC phototriac coupler

Turn-on operation:

When current flows through the input LED, the phototriac coupler turns on.

Turn-off operation:

When current stops flowing through the input LED and the supply voltage drops close to zero, the load current becomes extremely low. When it drops below the holding current, the triac turns off, unable to maintain the "on" state.

### Phase control using an NZC phototriac coupler

Figure 2.8 shows the waveforms for phase control using an NZC phototriac coupler to drive a resistive load.

(In the case of an inductive load, the current phase lags behind the voltage phase.)

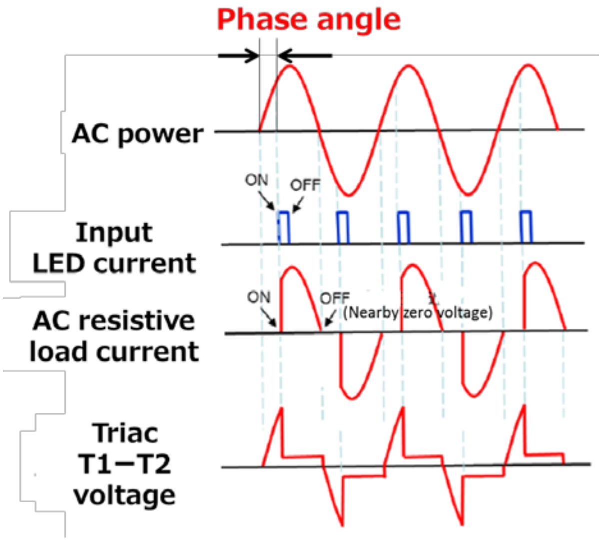


**Figure 2.8 Waveforms of phase control using an NZC phototriac coupler**

Turn-on and turn-off operations:

When the input signal reaches the specified phase angle, the input LED turns on, causing the phototriac coupler to turn on. When the input LED signal turns off, the supply voltage drops close to zero. The phototriac coupler remains on for some time and then turns off when the load current drops below the holding current of a triac. The amount of output power is controlled by applying a signal to the input LED of the phototriac coupler with a phase angle of a half cycle of the sine-wave AC power supply.

### 2.1.7. Considerations for using a phototriac coupler

Read the precautions and usage considerations for phototriac couplers and take their electrical characteristics and performance curves provided in the datasheet into consideration when creating a circuit design. Ensure that all the absolute maximum ratings specified in the datasheet are observed, including the input current ($I_F$), off-state output terminal voltage ($V_{DRM}$), RMS on-state current ($I_{T(RMS)}$), peak non-repetitive surge current ($I_{TSM}$), and isolation voltage ($BV_s$). Other considerations include the following:

- The input voltage range in which ZC phototriac couplers turn on is constrained by the inhibit voltage ($V_{IH}$). In order to ensure that the input LED turns on, it is necessary to take into consideration the amount of current applied to the input LED and the period of time during which it is applied.
- ZC phototriac couplers do not turn on at a voltage higher than $V_{IH}$ even when current is applied to the input LED. However, this situation causes leakage current (called inhibit current, $I_{IH}$) to flow. It should be noted that when a phototriac coupler is used to drive a main triac, the inhibit current ($I_{IH}$) causes an increase in the power loss of the phototriac coupler. It is also necessary to insert a resistor for bypassing the inhibit current to the gate circuit of the main triac in order to prevent its malfunction.
- If the maximum rated off-state output terminal voltage ($V_{DRM}$) is applied across the output triac of a phototriac coupler with no current being applied to the input LED, leakage current (called peak off-state current, $I_{DRM}$) flows during the T1-T2 period. $I_{DRM}$ increases exponentially as temperature increases. An increase in $I_{DRM}$ might cause a false turn-on of the main triac and the load. To avoid this situation, it is necessary to bypass this leakage current or take other countermeasures.
- When an NZC phototriac coupler is used for phase control, it might not turn on if the pulse width of a square-wave signal applied to the input LED is shorter than the turn-on switching time ($t_{ON}$) of the output triac.
- If a rapidly rising voltage is externally applied to a phototriac coupler for some reason when it is off, it might malfunction. This limit is specified as a critical rate of rise of off-state voltage (dv/dt) in the datasheet. In practical applications, it is necessary to add a snubber or other circuit to slow the rise in voltage in order to ensure that it does not exceed the specified dv/dt.
- When an on-state phototriac coupler turns off in the next reverse half cycle of AC voltage, the rate of change of this voltage is specified as a critical rate of rise of commutating voltage (dv/dt(c)). A false turn-on occurs if a voltage with a slew rate higher than dt/dt(c) is applied to the phototriac coupler. To avoid this, insert a snubber circuit to slow the rise in voltage. Particular care should be exercised when driving a reactive load.

## 2.2. Rechargeable DC cordless vacuum cleaners

### 2.2.1. Brushed DC motor drive

A brushed DC motor uses brushes to change the direction of current supplied to the commutator, thereby providing turning force to a motor's rotor shaft. Brushed DC motors are most widely used because of their excellent controllability, high efficiency, and ease of size reduction. They are mainly utilized for handheld vacuum cleaners with relatively small power that are used as a second or third cleaner. A simple chopper circuit is used to control brushed DC motors.

### 2.2.2. Chopper circuit

In a chopper circuit, a switch (MOSFET) is inserted in series with a motor. The motor input voltage is PWM-controlled to control the motor's rpm and torque. Figure 2.9 shows an example of a typical chopper circuit. The diode connected in parallel with the brushed DC motor freewheels the back-EMF generated by the motor when the MOSFET switches off. Without a diode, the back-EMF would be superimposed on the battery voltage immediately after the turn-off of the MOSFET, causing excessive voltage to be applied across the drain and source terminals of the MOSFET. The diode's freewheeling operation short-circuits both ends of the motor at its forward voltage ($V_F$), applying a short-circuit brake to the motor.

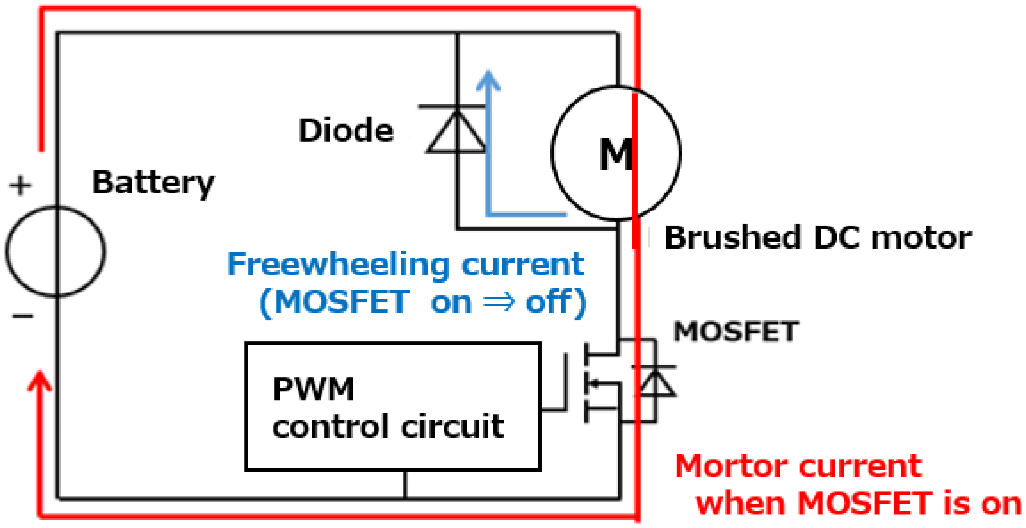


Figure 2.9 Basic chopper circuit for controlling a brushless DC motor

### 2.2.3. SR motor drive

Figure 2.10 shows a basic SR motor circuit. Turning on two switches of each phase causes current to flow through the corresponding phase winding as highlighted by red lines. Switches are turned off in the event of excessive current. Current continues flowing through each phase winding via a diode in the same direction (as shown by blue lines) until the energy stored in the phase winding is completely released. An SR motor rotates as this switching pattern is repeated for each phase. Each phase is controlled independently. The rotor of an SR motor consists only of a ferromagnetic iron core, which, unlike a magnet, is attracted toward a magnetic field irrespective of its polarity. Therefore, the SR motor operates regardless of the current polarity of the windings that generate an external rotating field.

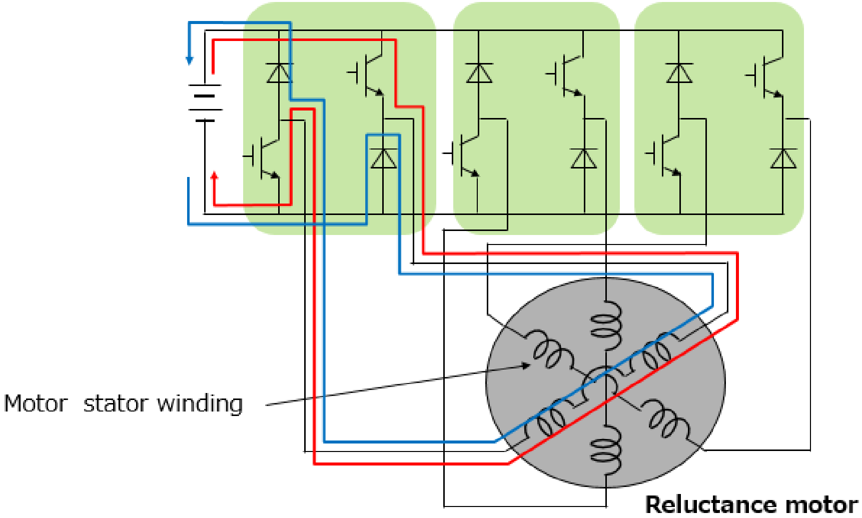


Figure 2.10 Basic circuit for controlling an SR motor

The following describes the operation of an SR motor and its waveforms using a circuit equivalent to the one used in an actual cordless vacuum cleaner shown in Figure 2.11.

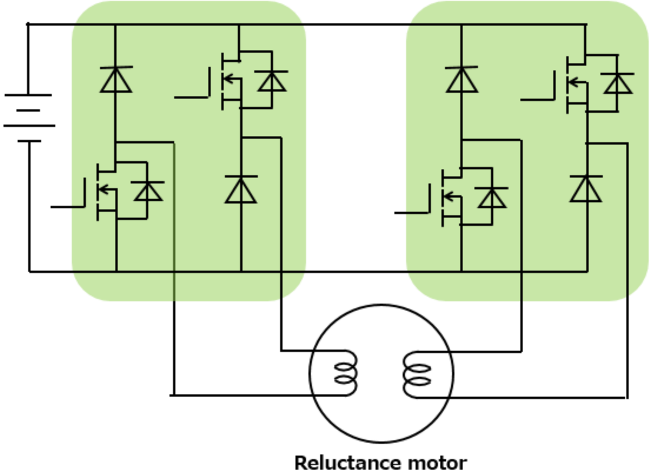


Figure 2.11 Drive circuit for an SR motor

Figure 2.12 illustrates the operation of each phase of the SR motor. Figure 2.13 shows the winding current waveforms.

## Phase A

Period (a): Both switching devices ($SW_1$ are $SW_2$) are turned on, causing current to flow through the Phase-A winding of the motor.

Period (b): As $SW_1$ and $SW_2$ are turned off, the energy stored in the winding returns to the power supply via $D_1$ and $D_2$, causing current to drop to zero.

During (c), (d), and other periods, both $SW_1$ and $SW_2$ are off. No current flows through the phase winding since no energy is stored in it.

## Phase B

Period (c): Both switching devices ($SW_3$ and $SW_4$) are turned on, causing current to flow through the Phase-B winding of the motor.

Period (d): As $SW_3$ and $SW_4$ are turned off, the energy stored in the winding returns to the power supply via $D_3$ and $D_4$, causing current to drop to zero.

During (a), (b), and other periods, both $SW_3$ and $SW_4$ are off. No current flows through the phase winding since no energy is stored in it.

The current flowing in each phase is controlled by alternating these voltage application patterns.

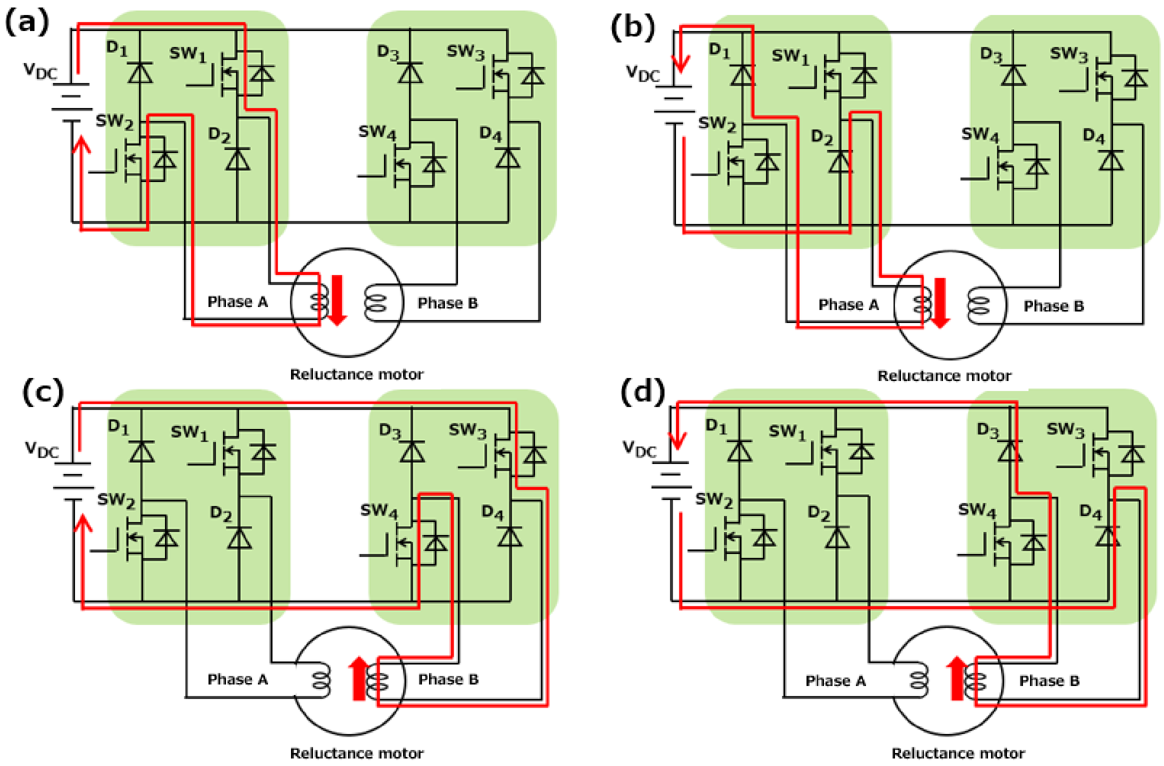


Figure 2.12 Operations of the drive circuit for the SR motor

Figure 2.13 shows the waveforms of the phase currents that flow during the circuit operations illustrated in Figure 2.12.

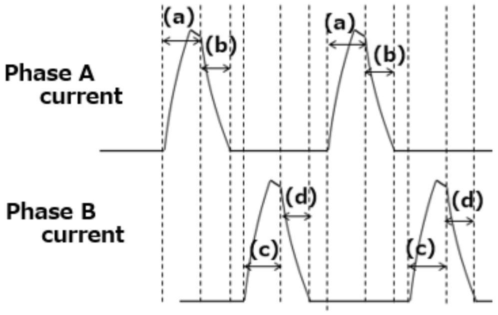


**Figure 2.13 Phase currents in the SR motor**

### 2.2.4. BLDC motor drive

Universal motors are commutated via mechanical contacts between a commutator and brushes whereas BLDC motors are electronically commutated with an inverter circuit composed of power devices. Without mechanical contacts, BLDC motors are free from brush wear and electric noise due to the brushes while providing the advantages of brushed DC motors (such as small size and ease of controlling the rotor speed and position).

BLDC motors used in vacuum cleaners are broadly divided into three-phase and single-phase versions. Single-phase BLDC motors are generally used for high-rpm vacuum cleaners.

### 2.2.5. Three-phase BLDC motor drive

Figure 2.14 shows a basic drive circuit for a BLDC motor. An inverter circuit generates current signals for rotating a motor based on the rotor position detected by a Hall IC (magnetic sensor) in the motor.

BLDC motors are controlled through sine-wave (180°) commutation using two- or three-phase PWM, square-wave (120°) commutation, etc. As an example, the following describes a three-phase PWM for sine-wave commutation.

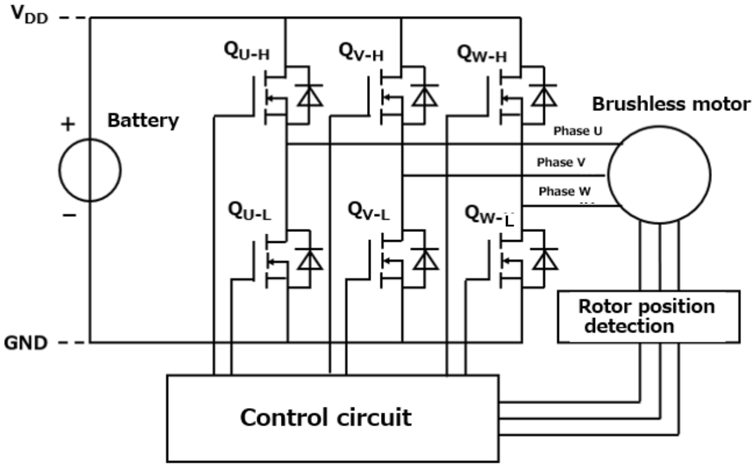
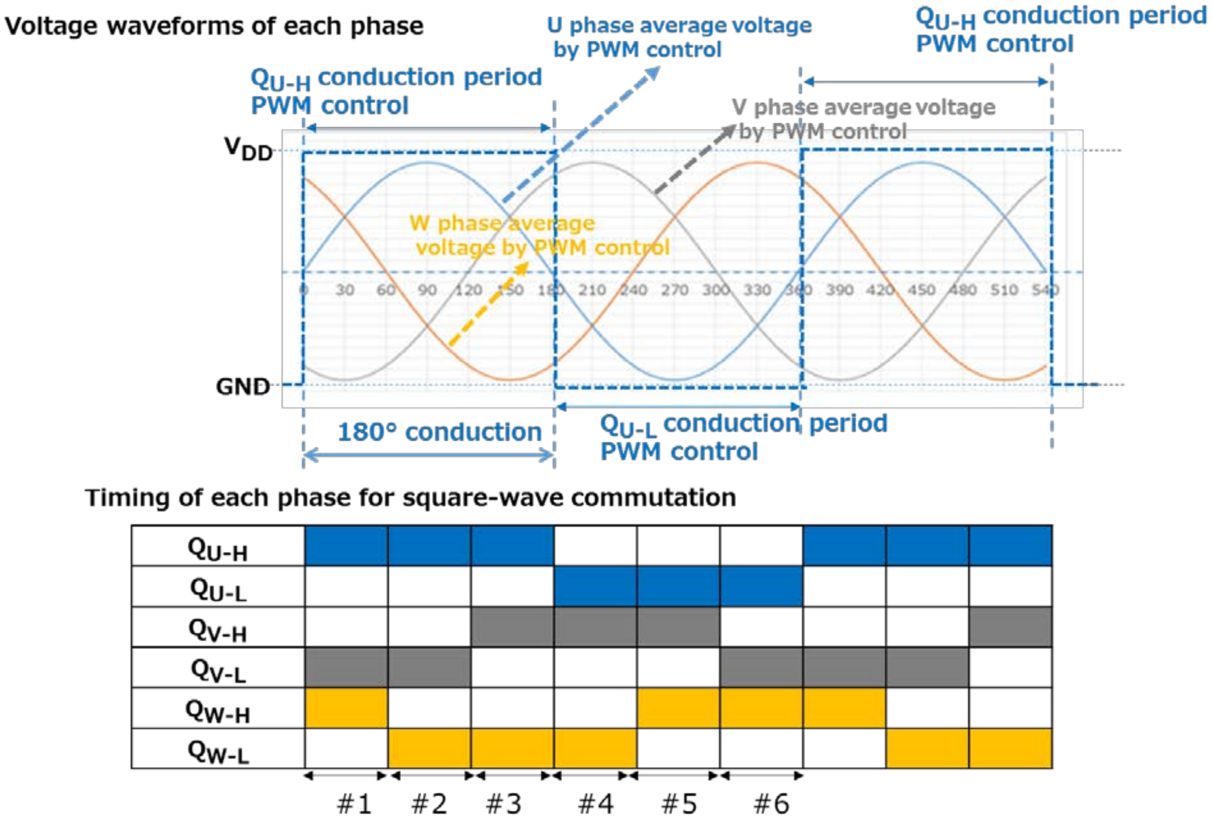


**Figure 2.14 Drive circuit for a three-phase BLDC motor**

This commutation technique switches on and off six switching devices of a three-phase bridge circuit (inverter circuit) to generate three-phase AC waveforms for a motor. Figure 2.15 shows the commutation pattern for the six switching devices of an inverter circuit for sine-wave commutation and the waveforms of the average voltage of each phase. (The switching devices are PWM-controlled in such a manner that they are alternately turned on and off.) In this commutation scheme, three switching devices are conducting (PWM-controlled) at any given time. (The high-side and low-side devices of the same phase never turn on simultaneously.)

Figure 2.16 shows the operations of the six switching devices of the inverter circuit for sine-wave commutation and the motor current paths.



Timing of each phase for square-wave commutation

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $Q_{U-H}$ | 🟦 | 🟦 | 🟦 | | | | 🟦 | 🟦 | 🟦 |
| $Q_{U-L}$ | | | | 🟦 | 🟦 | 🟦 | | | |
| $Q_{V-H}$ | | | ■ | ■ | ■ | | | | ■ |
| $Q_{V-L}$ | ■ | ■ | | | | ■ | ■ | ■ | |
| $Q_{W-H}$ | 🟨 | | | | 🟨 | 🟨 | 🟨 | | |
| $Q_{W-L}$ | | 🟨 | 🟨 | 🟨 | | | | 🟨 | 🟨 |
| | #1 | #2 | #3 | #4 | #5 | #6 | | | |

Figure 2.15 Three-phase BLDC motor drive

Figure 2.16 illustrates the current paths during the periods #1 to #6 shown in Figure 2.15 (Phase U: blue, Phase V: gray, Phase W: orange). The switching devices alternately turn on and off. The solid lines indicate the current paths when they are on whereas the dashed lines indicate the paths of the currents that freewheel through a diode. (When opposite signals are applied to the high-side and low-side devices, the freewheeling currents indicated by dashed lines flow through each MOSFET in synchronous rectification mode.)

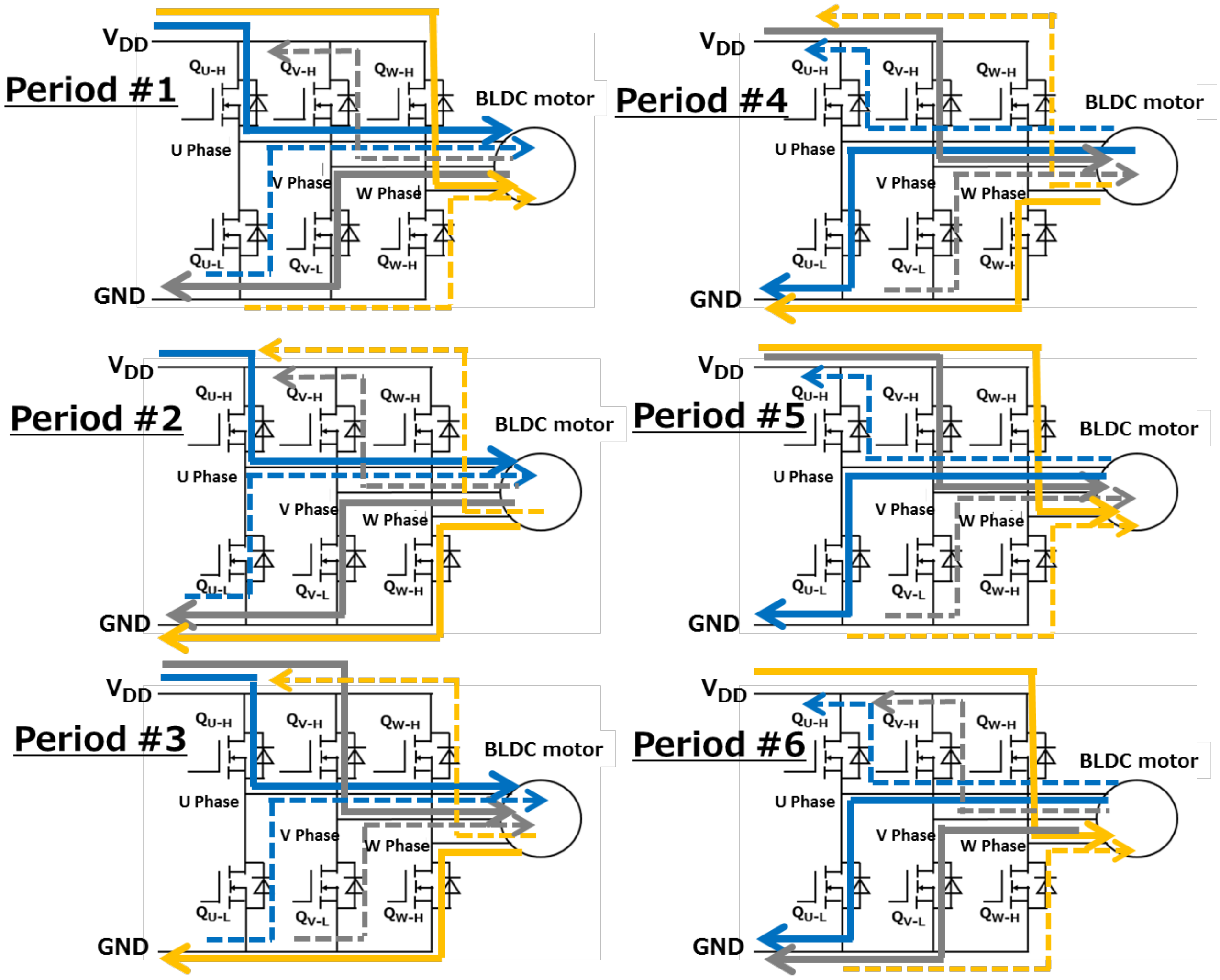
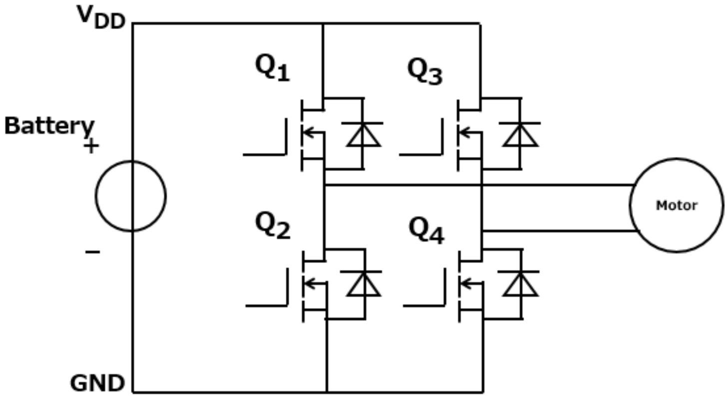


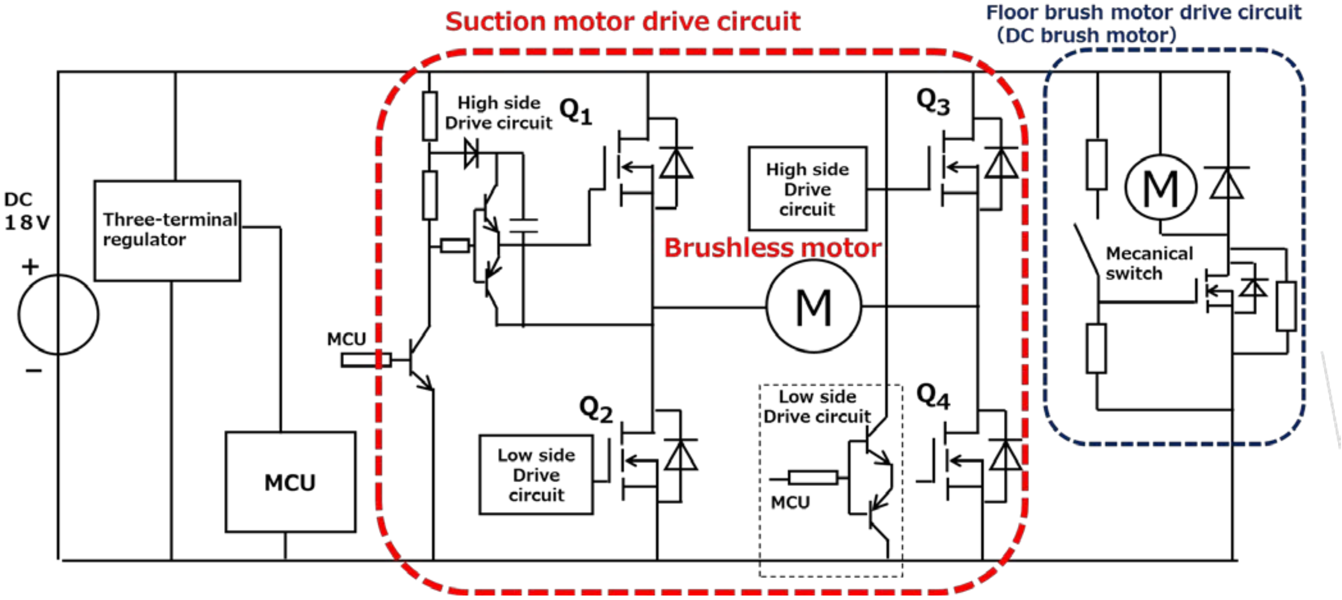
Figure 2.16 Operations of a switching circuit

### 2.2.6. Single-phase BLDC motor drive

Figure 2.17(a) shows a basic drive circuit for a single-phase BLDC motor, and Figure 2.17(b) shows a motor circuit for an actual vacuum cleaner, which uses a single-phase BLDC motor to achieve high-rpm operations. A brushed DC motor is utilized for the cleaner's floor brush. Detailed descriptions of the brushed DC motor are omitted here.



(a) Basic drive circuit



(b) Vacuum cleaner circuit with single-phase brushless motor

Figure 2.17 Example of a drive circuit for a single-phase BLDC motor

The following provides an example of how to control a single-phase BLDC motor. To control a three-phase BLDC motor, an inverter circuit is PWM-controlled to generate a sine-wave AC input for a motor. In the case of a single-phase BLDC motor for a vacuum cleaner, the duty cycle of a square AC input is varied to control the motor output. Figure 2.18 shows the gate input signals for each of the MOSFETs in the circuit of Figure 2.17. The amount of power supplied to the motor is controlled via the pulse width of the input signals to the high-side MOSFETs ($Q_1$ and $Q_3$) of the H bridge. Their inverse signals are applied to the low-side MOSFETs ($Q_2$ and $Q_4$).

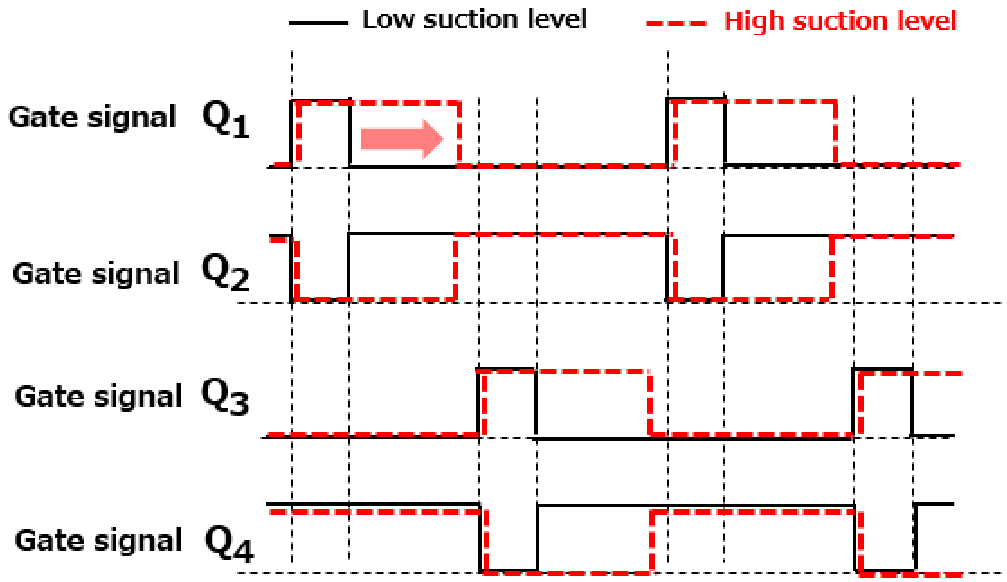
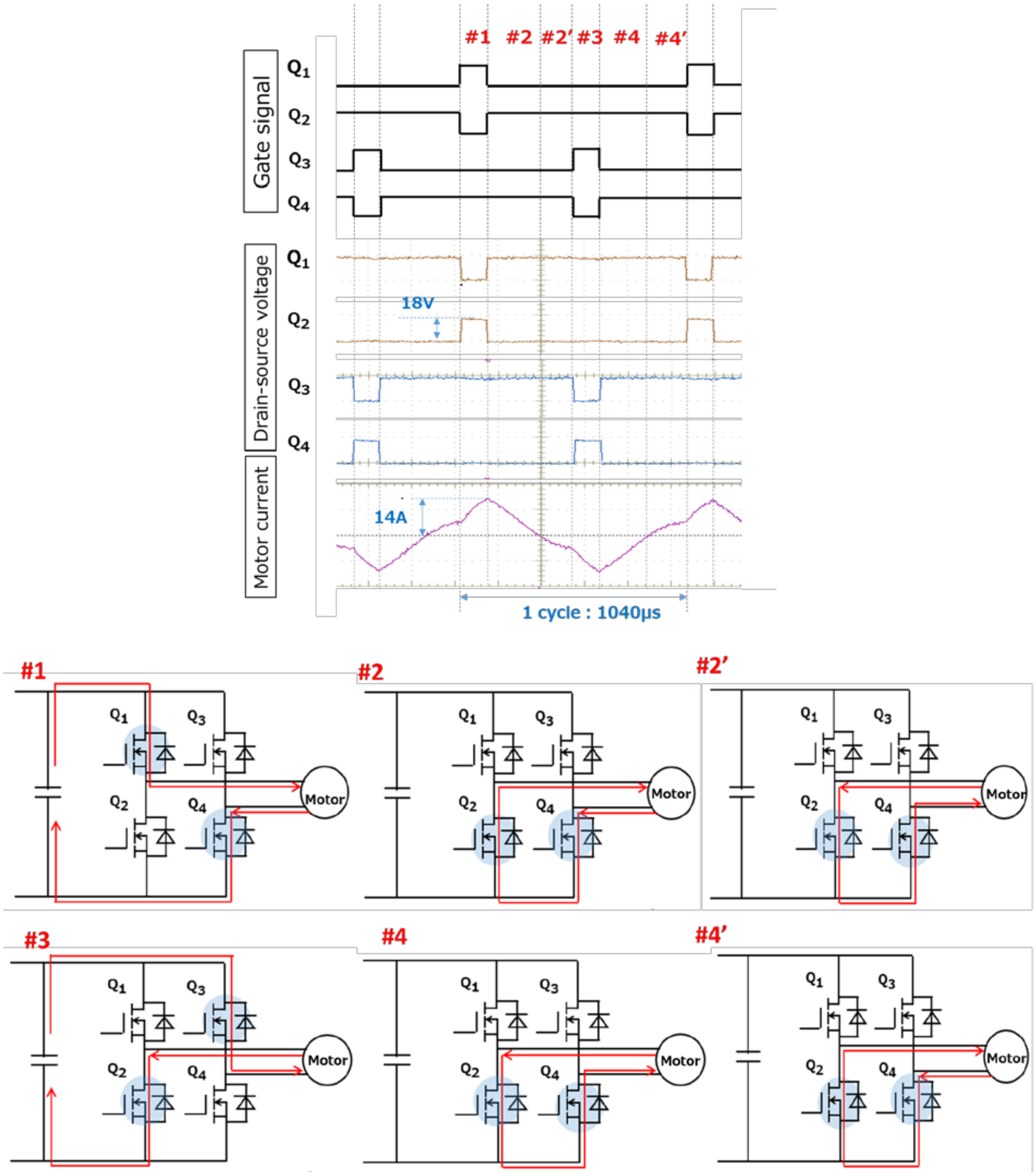
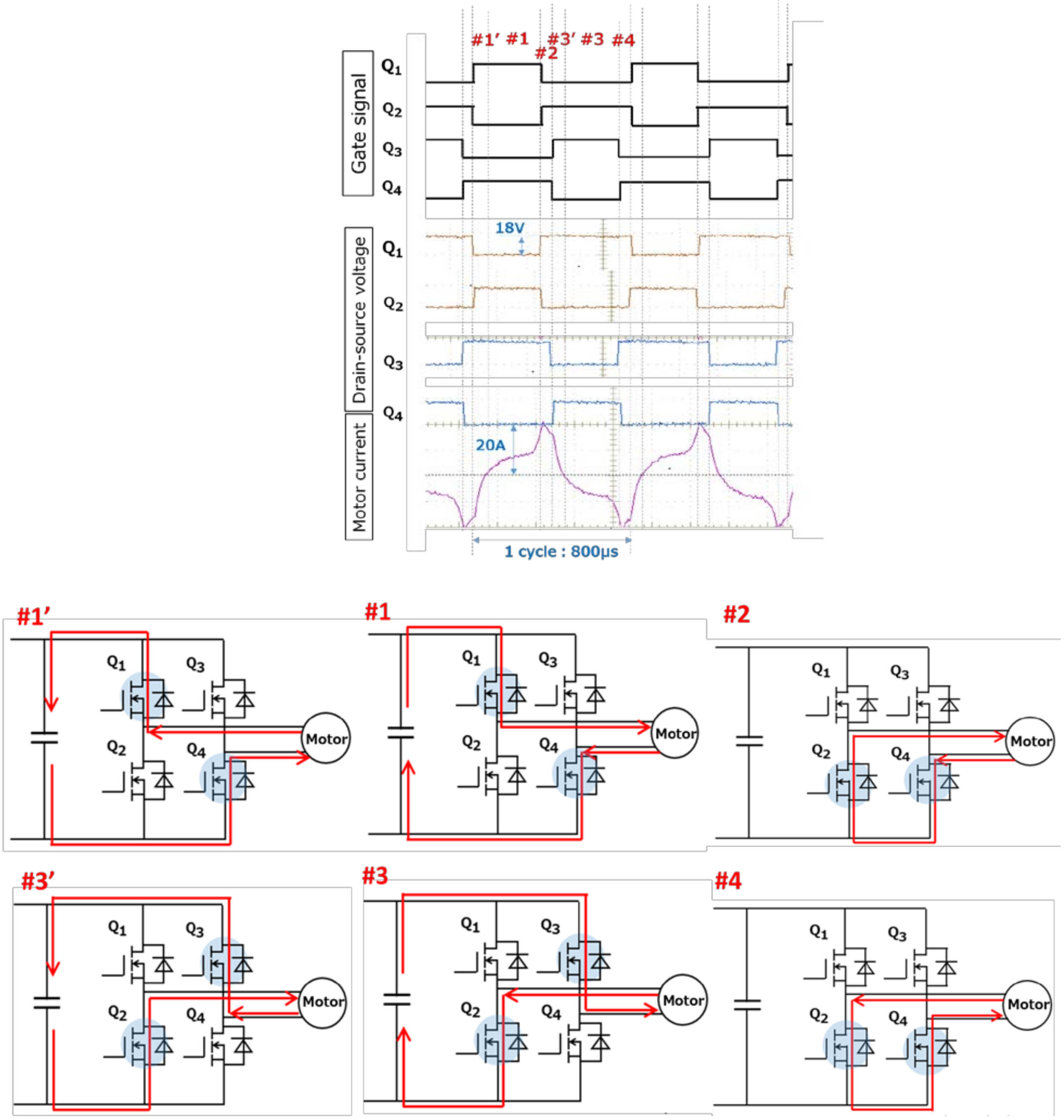


Figure 2.18 Input signals to the drive circuit for the single-phase BLDC motor

Figure 2.19(a) shows the waveforms of the switching signals and drain-source voltages of the MOSFETs as well as the motor current when the vacuum cleaner is running at low suction level and Figure 2.19(b) shows these of high suction level. They also illustrate the circuit operations and current paths that occur when the voltages of the gate signals change.



(a) Basic circuit operations and waveforms at a low suction level



(b) Basic circuit operations and waveforms at a high suction level

**Figure 2.19 Input signals and operations of the drive circuit for the single-phase BLDC motor**

The single-phase BLDC motor for this vacuum cleaner is a two-pole motor, which rotates once every cycle of the motor current. The MOSFET switching frequency is calculated to be 0.96 to 1.3 kHz from the cycle period. The motor speed is calculated to be 57,000 to 75,000 rpm. In the case of PWM control for a three-phase BLDC motor, the requirement for the MOSFET switching frequency is roughly 20 kHz. However, in the case of square-wave control for this single-phase BLDC motor, the MOSFET switching frequency is roughly 1/20th of that. This means that conduction loss constitutes a larger proportion of the overall loss than switching loss. Therefore, MOSFETs with low conduction loss are required for the drive circuit. Figure 2.19 also shows that the high-side and low-side MOSFETs do not operate exactly in the same manner and therefore cause different amounts of loss.

## 2.3. MOSFETs for an inverter circuit for rechargeable DC cordless vacuum cleaners

### 2.3.1. Selection of the withstand voltage of MOSFETs (low-$V_{DSS}$ MOSFETs)

One of the most important parameters in selecting MOSFETs is drain-source voltage ($V_{DSS}$). When voltage higher than $V_{DSS}$ is applied, a MOSFET enters the breakdown region where an increase in internal leakage current might lead to the destruction of the MOSFET. In inverter applications, MOSFETs are switched at high speed to reduce their switching loss. At turn-off, MOSFETs are subject to surge voltage higher than the applied bus voltage. It is therefore important to trade off switching loss for surge voltage. Because of this surge voltage, it is also necessary not only to allow sufficient margin in relation to the battery voltage but also to take surge voltage into consideration for the selection of $V_{DSS}$. It should be noted, however, that MOSFETs with high $V_{DSS}$ have large on-resistance. In some cases, surge voltage is absorbed through the MOSFET avalanche operation in order to use low-$V_{DSS}$ MOSFETs. However, since the avalanche operation places excessive stress on MOSFETs, it is necessary to consider their tolerance for avalanche current and avalanche energy. Toshiba's U-MOSVIII, U-MOSIX, and U-MOSX are effective since these MOSFET series provide a function for suppressing turn-off surge voltage.

### 2.3.2. Inverter PWM control (sine-wave commutation) and synchronous rectification in freewheeling mode

Pulse-width modulation (PWM) is a method of controlling the output power delivered by a signal by repeatedly switching on and off power devices. PWM modulates a constant voltage as a series of pulses with a constant cycle while changing the period during which the pulse is on. PWM provides an output voltage proportional to the width of the "on" pulse.

As an example, Figure 2.20 shows the input signals for synchronous rectification applied to the high-side and low-side MOSFETs of Phase U in the circuit of Figure 2.14 and the resulting output voltage. PWM control signals are produced in such a manner as to turn on and off the MOSFETs at the intersection of a reference sine wave and a triangular signal. (The reference sine wave is compared with a triangular signal. When the latter is less than the former, the PWM signal is in the high state. Otherwise, it is in the low state.)

When the high-side MOSFET of Phase U ($Q_{U\text{-}H}$) is switching in PWM mode in Figure 2.20, the load current flows in freewheeling mode while $Q_{U\text{-}H}$ is off. Normally, the load current flows through the body diode of the low-side MOSFET ($Q_{U\text{-}L}$). In some cases, the inverse signal of the PWM signal for the high-side MOSFET ($Q_{U\text{-}H}$) is used to turn on the low-side MOSFET ($Q_{U\text{-}L}$) at the timing of the freewheeling operation of $Q_{U\text{-}L}$. This is effective in reducing the conduction loss since the freewheeling current flows to the MOSFET having an on-state voltage lower than that of the body diode. While the low-side MOSFET ($Q_{U\text{-}L}$) is switching in PWM mode, the high-side MOSFET ($Q_{U\text{-}H}$) also operates in the same manner.

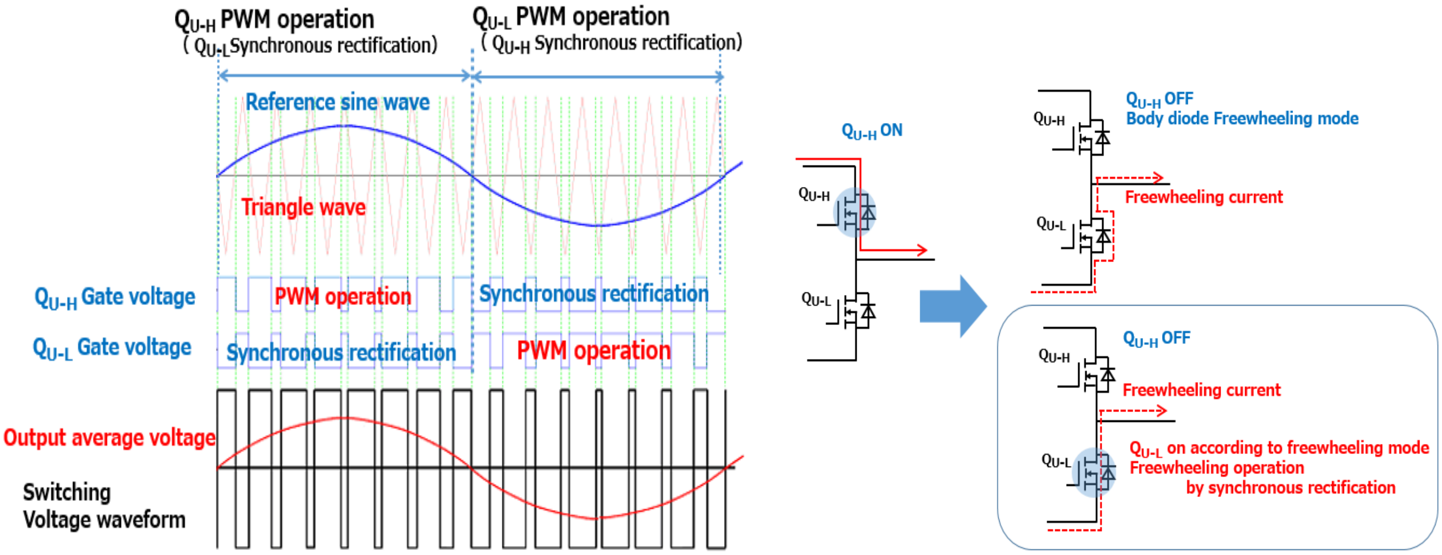


Figure 2.20 PWM control and synchronous rectification in freewheeling mode

### 2.3.3. Setting the dead time of an inverter circuit

It is necessary to allow a dead time between the turn-on of the high-side MOSFET and the turn-off of the low-side MOSFET, and vice versa.
Without a dead time, both the high-side and low-side MOSFETs conduct for a brief period during their switching transitions. Cross conduction provides a direct short-circuit across the power supply lines, causing an excessive current to flow. To prevent cross conduction, a dead time should be determined based on a difference between the turn-on and turn-off times of the MOSFETs. It is also necessary to take the drive conditions into considerations when calculating the turn-on and turn-off times.

### 2.3.4. Power loss of the MOSFETs in an inverter circuit

MOSFETs can be regarded as resistors while they are on. The conduction loss of a MOSFET can be calculated as $I_D{}^2 \times R_{DS(ON)}$. The power loss of the MOSFETs for the PWM control of an inverter circuit is approximated as the sum of 1) MOSFETs' loss during the conduction period and body diodes' loss during the freewheeling period (or MOSFETs' conduction loss in synchronous rectification mode) and 2) MOSFETs' switching loss (= (turn-on loss + turn-off loss) × switching frequency). To be exact, diodes' reverse recovery loss should also be taken into consideration. It is necessary to select MOSFETs that will not cause a power loss higher than the permissible power dissipation under their actual operating conditions.

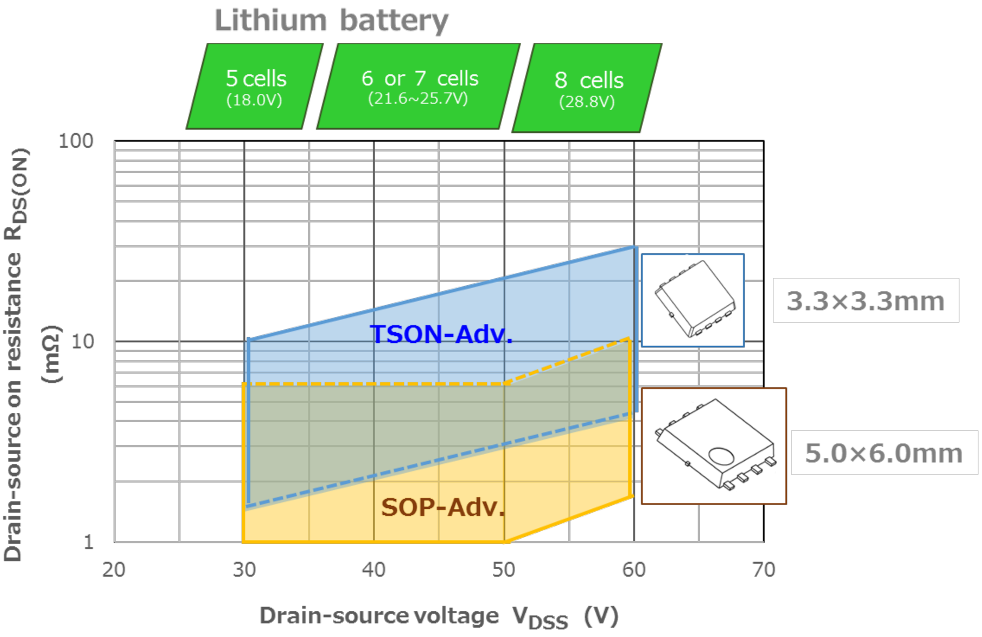
### 2.3.5. Battery voltage of a cordless vacuum cleaner versus MOSFETs

The battery voltage of some cordless vacuum cleaners is as low as 7.2 V. However, the typical battery voltage of cordless vacuum cleaners with a BLDC motor is 18.0 to 28.8 V. BLDC motors are classified into single-phase and three-phase versions. Single-phase BLDC motors are used at higher rpm than three-phase BLDC motors. The rotation speed of the BLDC motor is determined by each phase voltage applied to the motor, the motor current frequency, and the number of motor poles. In the case of a two-pole motor, its rotational speed is calculated as input frequency × 60 (rpm).

The output of an inverter circuit for a single-phase BLDC motor is controlled by changing the duty cycle of a square-wave signal. Its switching frequency is roughly 1 kHz. In contrast, three-phase BLDC motors are generally driven with a sine wave at a frequency of 20 to 30 kHz using PWM.

In the former case, conduction loss constitutes a large proportion of the total loss of MOSFETs. Therefore, MOSFETs with low on-resistance are required. In the latter case, it is necessary to take both on-resistance and switching performance into consideration when selecting MOSFETs. The single-phase BLDC motor places a greater burden on each of the MOSFETs than the three-phase BLDC motor.

Switching devices suitable for vacuum cleaners depend on the output power required. Figure 2.21 shows the drain-source voltage ($V_{DSS}$) and on-resistance ($R_{DS(ON)}$) ranges and the packages of the recommended MOSFETs according to the battery voltage.



TSON-Adv and SOP-Adv are Toshiba package names.

**Figure 2.21 $V_{DSS}$ and $R_{DS(ON)}$ ranges and packages of recommended power MOSFETs according to the battery voltage**

Note: Figure 2.21 is based on the latest lineup of Toshiba’s power MOSFETs available as of June 2020. It is subject to change due to the development of new products. Visit Toshiba’s semiconductor website for the latest information about Toshiba’s MOSFETs, their part numbers, and detailed electrical characteristics, or contact Toshiba’s sales representatives or business partners.

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