2. BASICS OF INVERTER

2.1 Basic Configuration

2.1.1 Inverter

The basic configuration of an inverter is as follows.

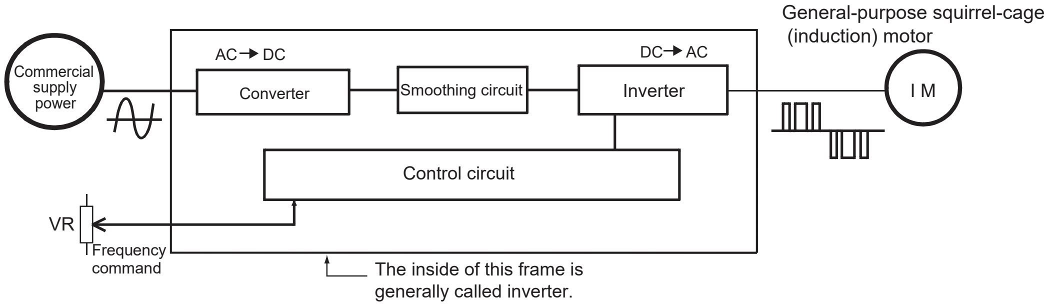


Fig. 2.1 Basic configuration of inverter

Each part of an inverter has the following function.

- Converter ･･････････ Circuit to change the commercial power supply to the DC
- Smoothing circuit ･･･ Circuit to smooth the pulsation included in the DC
- Inverter ･･･････････ Circuit to change the DC to the AC with variable frequency
- Control circuit ･････ Circuit to mainly control the inverter part

2.2 Principle of Converter Operation

The converter part consists of the following parts as Fig. 2.3 shows:

1) Converter
2) Inrush current control circuit
3) Smoothing circuit

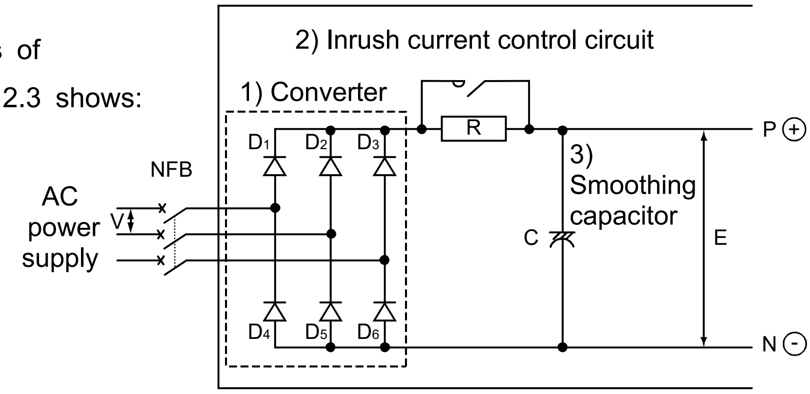


Fig. 2.3 Converter part

2.2.1 Method to create DC from AC (commercial) power supply

A converter is a device to create the DC from the AC power supply. See the basic principle with the single-phase AC as the simplest example.

Fig. 2.5 shows the example of the method to convert the AC to the DC by utilizing a resistor for the load in place of a smoothing capacitor.

Diodes are used for the elements. These diodes let the current flow or not flow depending on the direction to which the voltage is applied as Fig. 2.4 shows.

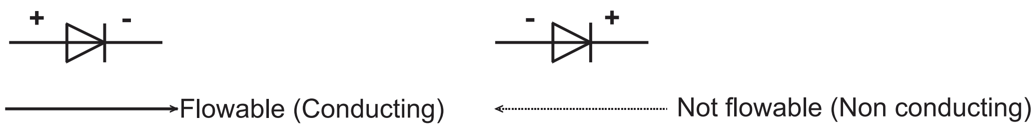


Fig. 2.4 Diode

This diode nature allows the following: When the AC voltage is applied between A and B of the circuit shown in Fig. 2.5, the voltage is always applied to the load in the same direction shown in Table 2.1.

That is to say, the AC is converted to the DC.

(To convert the AC to the DC is generally called rectification.)

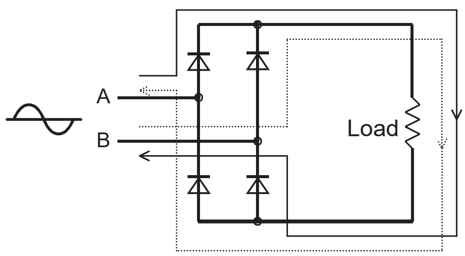


Fig. 2.5 Rectifying circuit

Table 2.1 Voltage applied to the load

AC voltage	AC flowing direction	Voltage applied to load
	Direction of solid line	Same direction
	Direction of dotted line	

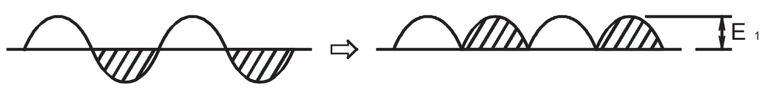


Fig. 2.6 (Continuous waveforms of the ones in Table 2.1)

For the three-phase AC input, combining six diodes to rectify all the waves of the AC power supply allows the output voltage as shown in Fig. 2.7.

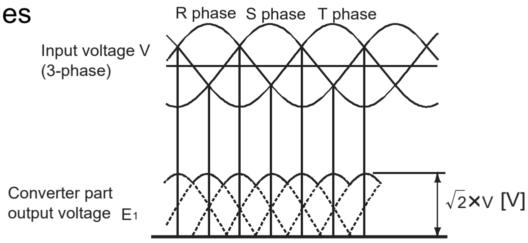
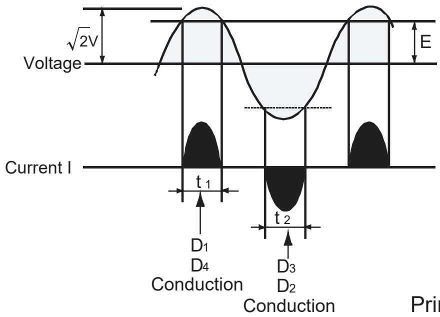
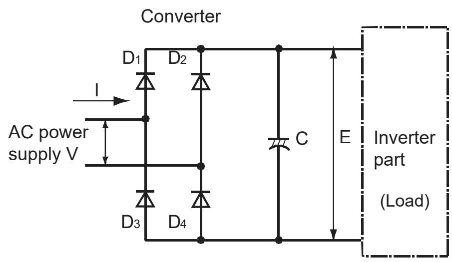


Fig. 2.7 Converter part waveform

2.2.2 Input current waveform when capacitor is used as load

The principle of rectification is explained with a resistor. However, a smoothing capacit or is actually used for the load. If a smoothing capacitor is used, the input current waveforms become not sine waveforms but distorted waveforms shown in Fig. 2.8 since the AC voltage flows only when it surpasses the DC voltage.





Principle of converter

2.2.3 Inrush current control circuit

The principle of rectification is explained with a resistor. However, a smoothing capacitor is actually used for the load. A capacitor has a nature to store electricity. At the moment when the voltage is applied, a large inrush current flows for charging a capacitor.

To prevent rectifying diodes from being damaged by this large inrush current, make a forcible series connection to capacitors for approximately 0.05 second from the power on to control the inrush current value. After that, short the both ends of these resistors with a magnetic switch to configure a resistor-bypassed circuit.

This circuit is called an inrush current control circuit.

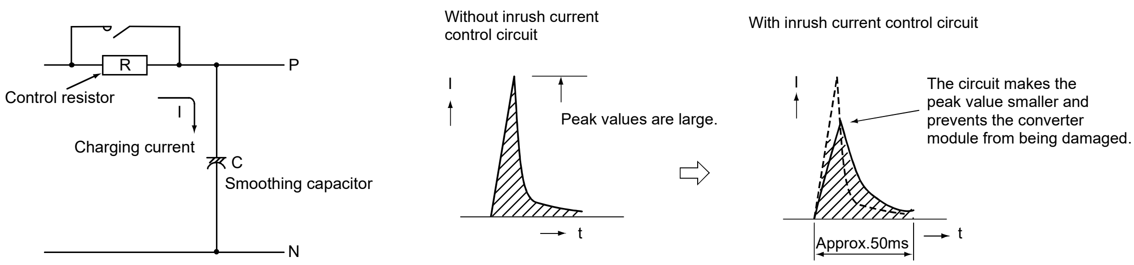


Fig. 2.9 Inrush current

2.2.4 Principle of smoothing circuit operation

The smoothing circuit creates the DC voltage E_2 with little pulsation from the rectified DC voltage E_1 using a smoothing capacitor.

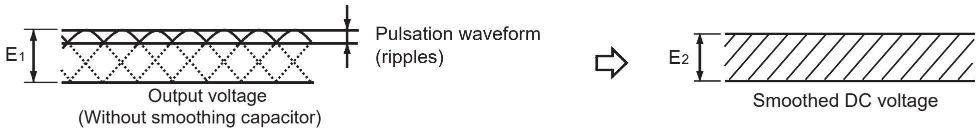


Fig. 2.10 DC smoothed waveform

2.3 Principle of Inverter Operation

2.3.1 Method to create AC from DC

An inverter is a device to create the AC from the DC power supply. See the basic principle with the single-phase DC as the simplest example.
Fig. 2.11 shows the example of the method to convert the DC to the AC by utilizing a lamp for the load in place of a motor.
When four switches, S1 to S4, are connected to the DC power supply, S1 and S4 and also S2 and S4 are respectively paired and the pairs are alternatively turned ON and OFF, the AC flows as shown in Fig 2.12.

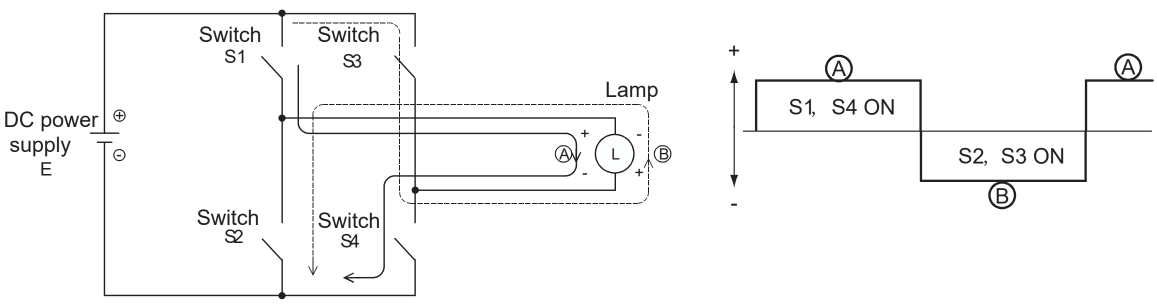


Fig. 2.11 Method to create AC

- When the switches S1 and S4 are turned ON, the current flows in the lamp in the direction of A.
- When the switches S2 and S3 are turned ON, the current flows in the lamp in the direction of B.

  If these operations are repeated by a certain period, the AC is created since the direction of the current flowing in the lamp alters.

2.3.2 Method to change frequency

The frequency changes by changing the period to turn ON and OFF the switches S1 to S4.
For example, if the switches S1 and S4 are turned ON for 0.5 second and S2 and S3 for 0.5 second and this operation is repeated, the AC with one alternation per second, i.e., the AC with a frequency of 1[Hz] is created.

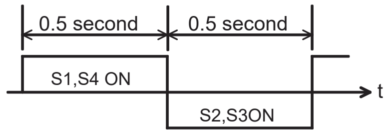


Figure 2.13 1Hz AC waveform

Generally, if S1/S4 and S2/S3 are respectively turned ON for the same period and the total time for one cycle is t0 second(s), the frequency f becomes f=1/t0 [Hz].

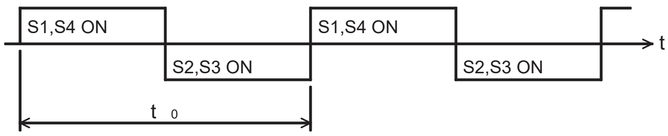


Fig. 2.14 Frequency

2.3.3 Method to change voltage

The voltage changes by turning ON and OFF the switches with a shorter period.
For example, if the switches S1 and S4 are turned ON for the half period, the output voltage is E/2, half of the DC voltage E.
To obtain a higher voltage, turn ON for the longer period. To obtain a lower voltage, t urn ON for the shorter period.

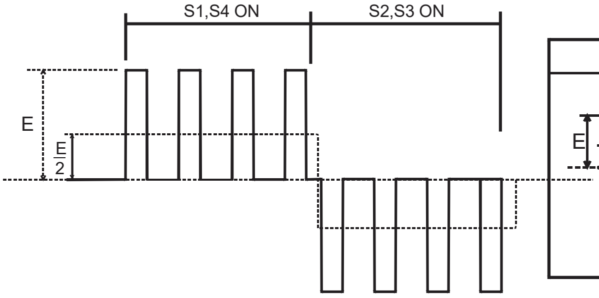


Figure 2.15 Voltage waveform of E/2

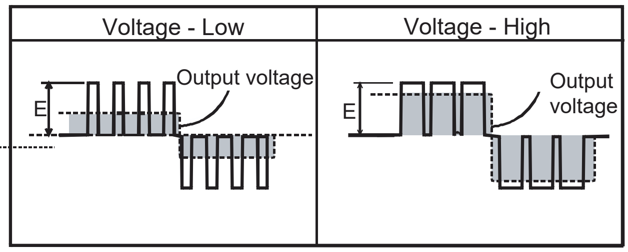


Fig. 2.16 Method to change voltage

This control method is generally used and called PWM (Pulse Width Modulation) since it controls pulse width. The frequency to be referenced to determine the time for pulse width is called a carrier frequency.

2.3.4 Three-phase AC

The basic circuit of the three-phase inverter and the method to create the three-phase AC are shown in Fig. 2.17 and 2.18.

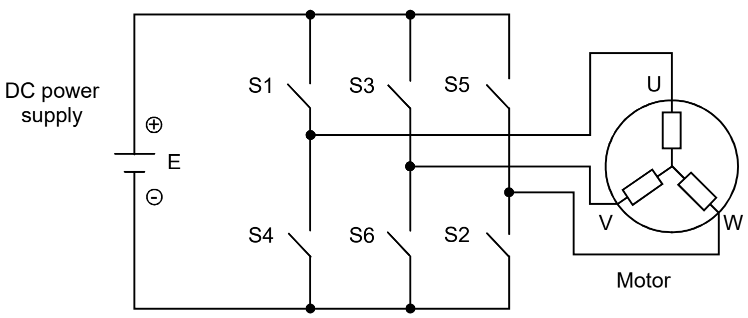


Fig 2.17 3-phase inverter basic circuit

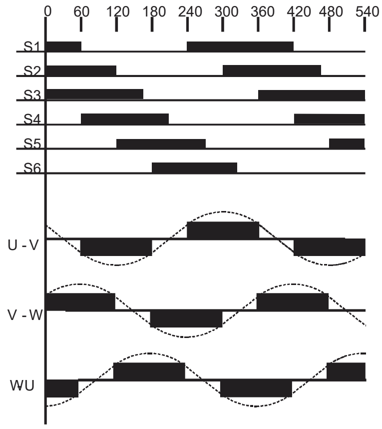


Fig. 2.18 Method to create 3-phase AC

To obtain the three-phase AC, connect the switches S1 to S6 to the circuit and simultaneously turn ON/OFF all the six switches at the timing shown in Fig. 2.18.
If the order of turning ON/OFF six switches is changed, the phase order is changed between U-V, V-W and W-U and the rotation direction can be changed.

2.3.5 Switch element

For the switch element in the explanation above, a semiconductor called IGBT (Insulated Gate Bipolar Transistor) is used.

2.3.6 V/F pattern

Changing the motor speed is enabled by changing the frequency as shown in Formula 1.2. When the output frequency of an inverter is changed, the output voltage must be changed.
The output torque of a motor is expressed as the product of the magnetic flux inside the motor (Φ) multiplied by the current flowing in the coil (I). (Refer to the principle of induction motor operation and the Fleming's left-hand rule.)

$$\text{Torque TM} = K \times \Phi \times I = K \times \frac{V}{F} \times I$$

The relationship between the magnetic flux (Φ), the voltage applied to a motor (V) and the frequency (F), is expressed as Φ=V/F. If the voltage is fixed (e.g. 200V) and only the frequency is decreased, the increased magnetic flux (Φ) causes the iron core to be magnetic saturation and then the increased current causes overheat and burnout.
Changing the voltage applied to a motor (V) and the frequency (F) with their relationship kept constant allows the motor output torque to be constant even if the motor speed is changed. For these two reasons, the output voltage must be controlled low when the inverter output frequency is low, and controlled high when the frequency is high.
This relationship between the output frequency and the output voltage is called V/F pattern.

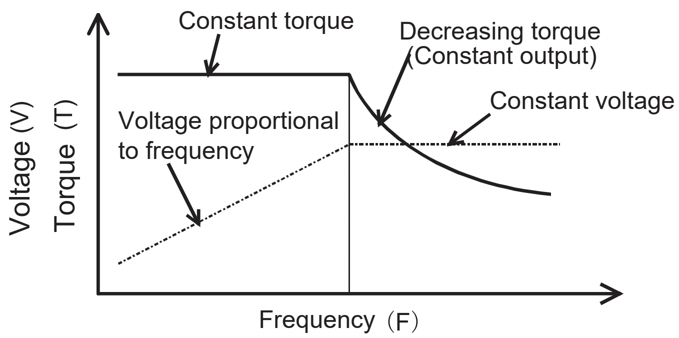


Fig. 2.19 V/F pattern and motor output torque

2.4 Regenerative Brake

When the motor speed surpasses the inverter output frequency (speed command from an inverter) such as the situation where an elevator goes down, a motor works as a generator and the generated electricity (energy) returns to an inverter. This status is called regeneration.

When the electricity returns to an inverter, the DC voltage of the inverter (Fig. 2.20 E1) increases. If this DC voltages surpasses a certain specified value (370VDC for 200V class), rectifying diodes or IGBT of the inverter part are damaged.

To prevent this, insert a resistor and a power capacitor for a switch element in series in the DC voltage circuit (between P and N) as shown in Fig. 2.20. This prevents the DC voltage increase by turning ON the power transistor to consume the current as heat when the DC voltage surpasses a certain specified value. See Fig. 2.21.

This resistor is called a regenerative brake resistor and this power capacitor a regenerative brake capacitor.

For a large capacity inverter that needs a large regenerative brake resistor, the power return system, which returns the regenerative energy to the power supply side, is adopted to prevent the heat influence to the ambience.

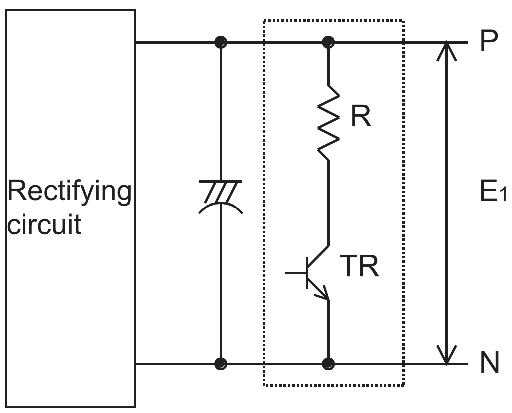


Fig. 2.20 Regenerative brake circuit

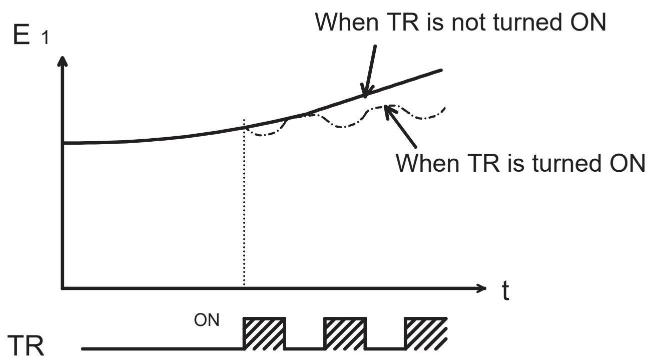


Fig. 2.21 DC voltage (between P and N)

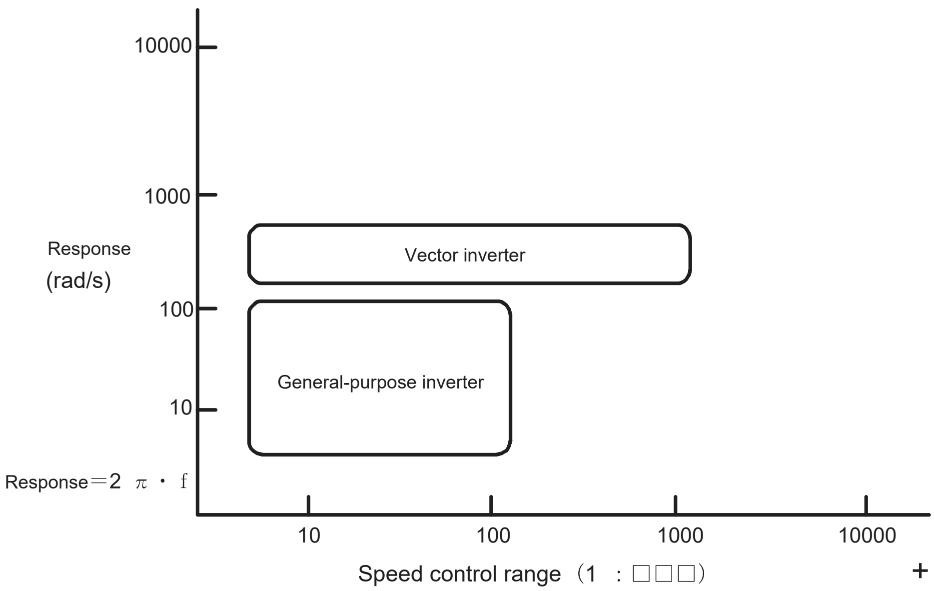
2.5 Control

2.5.1 Difference between general-purpose inverter and vector inverter

Although the same main circuit is used between a general-purpose inverter and a vector inverter, the following differences exist in outline according to the used control circuit or the presence/absence of an encoder, which depends on the applied motor.

Table 2.2 Difference between general-purpose inverter and vector inverter

Item \ Type	General-purpose inverter	Vector inverter
Output	100W to 560kW	1.5 to 250kW
Transmission gear ratio (approx.)	1:10 to 1:20 to 200	1:1000 to 1:1500
Speed fluctuation percentage (%)	3 to 4% (1% or less for advanced magnetic flux vector control and real sensorless vector control)	0.03% (Load fluctuation between 0 to 100%)
Frequency response	Low 1 to 19Hz	30 to 125Hz
Guideline of start/stop frequency	Approx. 15 times/min.	Approx. 100 times/min.
Positioning accuracy	Approx. 1 to 5mm	Approx. 10μm to 100μm
Torque characteristics	Constant torque (Torque decreased for a base frequency or more)	Constant torque (0 to rated speed)
Applied motor	General-purpose motor (Induction motor)	Dedicated motor (Motor with encoder)
Remarks (Mitsubishi inverter main series)	Main series FR-E500 FR-A024 FR-A700 FR-A500 FR-F700 FR-F500 FR-S500	Main series FR-V500



2.5.2 Control method

There are three methods to control an inverter: speed control to control the motor speed mainly with the analog voltage, position control to control the motor rotation amount with simple limit switches, a high accuracy encoder or others and torque control to control the current flowing into a motor for a constant torque value.
The detailed account is given below.

(1) Speed control

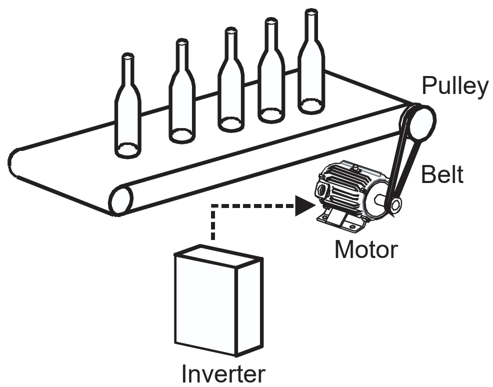
1) Open loop control

This control method does not feed back the speed as general-purpose inverters adopt it.

The command system is analog voltage command, which is used for many applications such as the conveyor speed control, fan wind amount control, pump flow amount control, etc. The slip at the rated torque depends on the characteristics of a motor. Approximately 3 to 5% speed fluctuation occurs.

The recent inverters are resistant to temperature drifts for the digital control that allows setting the speed data internally and for the digital command (pulse train, parallel data and communication). In addition, the inverters of advanced magnetic flux vector control or real sensorless vector control are available with the speed fluctuation of 1% or less.

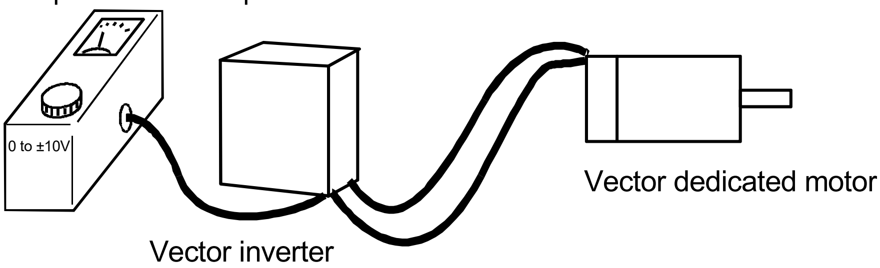
This speed control method is used for almost all general-purpose inverters.



2) Closed loop control

To ensure the change of the motor speed, an encoder must be installed to detect the actual speed and feed it back to a control circuit. This method is called a closed loop control.

To detect the speed, TG (tachogenerator), encoder, etc. are used. Encoders are mostly used these days. For the closed loop control too, the analog voltage or current is used for the speed command. However, inputting pulse trains or using the digital input allows a high accuracy speed control for the draw operation or continuous speed control operation.

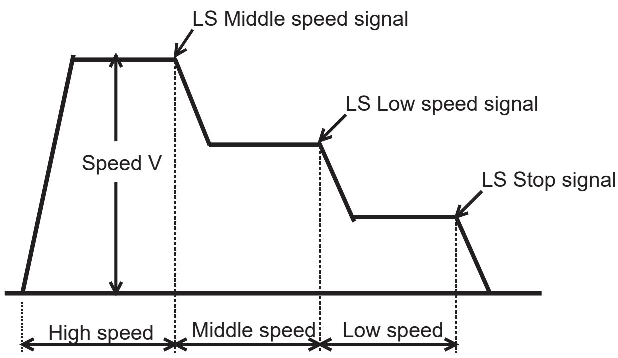


(2) Position control

The position control allows not only the control of the motor speed but also the control to stop at the target stop position. There are many control methods from the simple method to stop at the target position by taking the external sensor signals into the stop signal, to the method to perform a high accuracy positioning with an encoder installed to the motor, and to the advanced method to perform a positioning to always-changing target stop positions by tracking or synchronization.

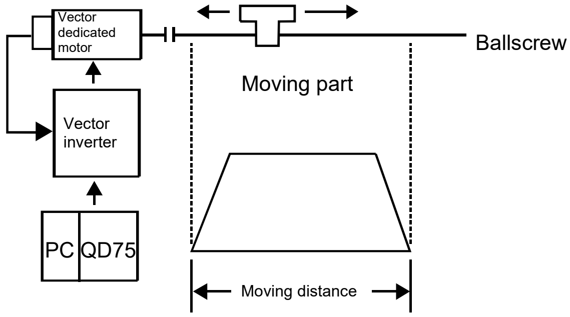
1) Open loop control

This control is used for the applications that do not need high accuracy for stop. The motor decelerates to stop with signals from the limit switches installed before the target stop position for deceleration command. This is the simplest and most reasonable method although the fluctuation of the deceleration points affects the stop positions in accuracy.



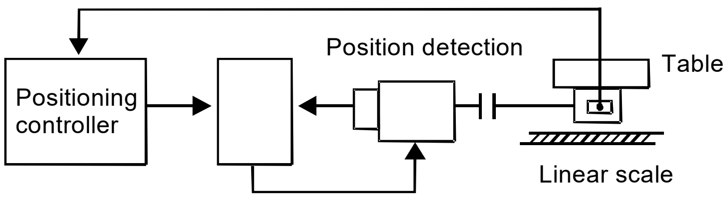
2) Semi-closed loop control

An encoder installed to a motor performs feedback. For example, a vector dedicated motor operates for the command input to a vector inverter when the feedback is looped back. At this moment, the speed command is calculated to zero the difference between the input command amount and the feedback amount for rotating the motor.



3) Full-closed loop control

This control is performed by the feedback from a linear scale or encoder installed to the machine side.
Installing a linear scale or encoder to the final machine edge allows a high accuracy positioning free from backlashes or mechanical system errors. Instead, it is required to heighten the machine rigidity. This control is sometimes used for machine tools part of which requires a high accuracy control.



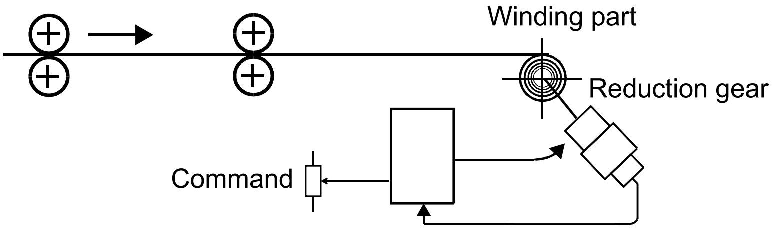
(3) Torque control

The torque control indicates controlling the torque (current) output from a motor and it must be distinguished from the torque limit. However, both of them are available depending on the application. The most appropriate method should be selected. The torque control performs a control of the torque (current) against the torque command value. Therefore, the speed automatically increases when the load torque is smaller and decreases when larger. If the load torque is equal to the torque command value, both torque values are balanced and the speed becomes zero. That is to say, the motor stops. In short, the same principle as a tug of war is working.
On the other hand, the torque limit is used when a machine can be damaged for unnecessary torque to control the position or speed, when the stop is performed by pressing the machine, or when the mechanical lock is performed.
For the torque control, the current flowing in the motor must be detected and controlled. Therefore, the torque control can be supported by the vector inverter or the inverter of real sensorless vector control, which perform current detection.

1) Open loop control

This control is used for the applications that do not require high torque accuracy such as an unwinding or winding axis. The analog command is generally used for the torque command.

For this control, it must be taken into account that the torque accuracy (temperature drift) varies depending on the temperature and machines have losses.



2) Closed loop control

This control is used for the applications that require high tension accuracy such as an unwinding or winding axis (for paper, film, etc.).

This control feeds back the tension applied to the actual products to a tension control device.