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PROTECTION TECHNIQUES OF BIPOLAR POWER TRANSISTORS

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1. FOREWORD

In recent years, power transistors have come into wide use in various electronic power converters. A big reason for this is that different from the conventional thyristor, the power transistor is not only self-commutating, but since *di/dt* and *dv/dt* limiting is basically unnecessary, various protection circuits can also be simplified. However, to simplify various protection circuits, the device characteristics and breakdown capacity of the associated power transistor must be known. The VVVF inverter is taken up here as a concrete example.

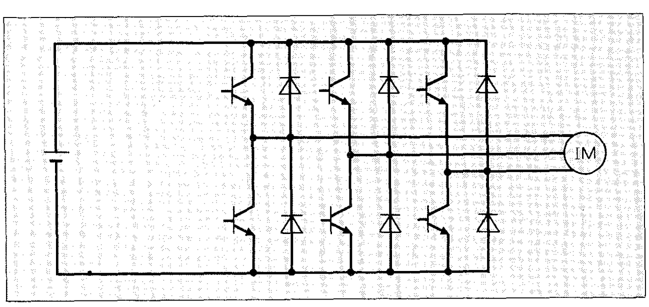
The mechanism which generates the overvoltage and overcurrent which are applied to the power transistor and its related device characteristics, breakdown capacity, and basic protection methods are described centered about:
(1) Problems based upon high capacity switching circuit
(2) Problems based upon inverter circuit

2. OVERVOLTAGE PROTECTION

2.1 Overvoltage generation causes

The basic circuit configuration of a VVVF inverter is shown in *Fig. 1*. In this example, the increase of the DC bus voltage by AC input voltage rise and motor regeneration energy and the surge voltage generated by the device switching operation become overvoltage against power transistor. The method of protecting the power transistor against the surge voltage generated by the device switching operation is described in detail here.

Fig. 1 Example of basic circuit configuration of VVVF inverter



2.2 Switching surge voltage generation mechanism

In an inverter circuit, the following two kinds of switching surge voltage are generated:
- Surge voltage at reverse recovery of free wheeling diode
- Surge voltage at turn-off of power transistor

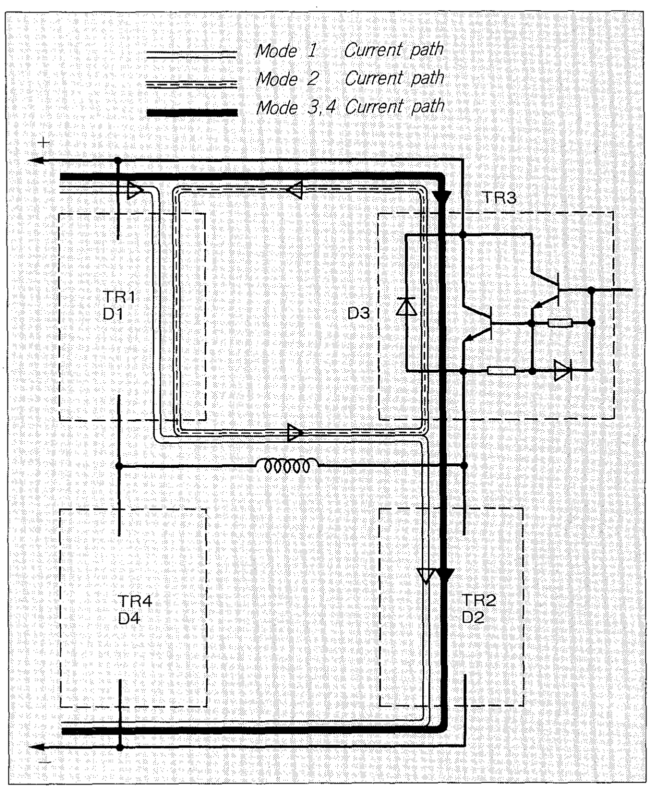
The generation mechanism of these surge voltages is described below.

(1) Surge voltage at reverse recovery of free wheeling diode

Fig. 2 shows the load current path in an inverter circuit. The mechanism which generates a surge voltage at reverse recovery of free wheel diode is explained by using *Fig. 2*.

Mode 1: TR1 and TR2 are on and TR3 and TR4 are off. Load current flows through TR1 and TR2.

Fig. 2 Inverter circuit operation



Mode 2: TR2 is turned off. Load current shifts to the TR2 and D3 path and continues to flow.

Mode 3: When TR2 is turned on again, a short circuit is formed by the D3-TR-2-DC power supply path and the reverse recovery operation of D3 is performed.

Mode 4: After the reverse recovery current of D3 reaches the maximum value, it begins to drop abruptly. A surge voltage is generated by the abrupt current change when the recovery current of D3 disappears and the action of the inductance in the main circuit. This surge voltage is applied to D3 and TR3 connected in parallel with it. This is shown in *Fig. 3.*

(2) Surge voltage at power transistor turn-off

The operation waveforms when the power transistor is turned off are shown in *Fig. 4*. A surge voltage is generated by the abrupt change of the collector current and the action of the inductance in the main circuit during the falling period.

2.3 Operation of power transistor when surge voltage applied

(1) At reverse recovery of free wheeling diode

At the time the surge voltage at reverse recovery of free wheeling diode is applied, the power transistor is in the off state. The withstand voltage of the power transistor differs with the base drive conditions. A snubber circuit is designed to suppress the surge voltage at reverse recovery of free wheeling diode to below the power transistor withstand voltage.

(2) At turn-off of power transistor

An example of the operation locus at turn off of power transistor is shown in *Fig. 5*. Generally, a power transistor is used by applying a reverse bias current to shorten the turn-off time. In this case, the operation locus at turn-off must be within the RBSOA (Reverse Biased Safety Operation Area) as shown in *Fig. 5*. The snubber circuit keeps the operation locus at turn-off within the RBSOA. Details are given latter, but a discharge-restraint type RCD snubber is generally used for various reasons. *Fig. 5* shows the operation locus at turn-off when a discharge-restraint type RCD snubber was used. The operation locus with an ideal snubber circuit is shown by the broken line. The operation locus of an actual circuit has a bulge at the right shoulder as shown by the solid line. Since this bulge approaches the RBSOA, a keypoint of snubber circuit design is that both the part (V_{CESP}) shown by (A) in *Fig. 5* and V_{CEP} remain within the RBSOA.

2.4 Kinds of snubber circuits

Typical snubber circuits are shown in *Fig. 6*. The RC snubber is used mainly with small capacity power transistors and the charge-discharge type RCD snubber and discharge restraint type RCD snubbers are used with large capacity power transistors. Since the charge-discharge type RCD snubber has a *dv/dt* suppression effect at turn-off, it is an effective snubber circuit when a power transistor with a narrow RBSOA can be used. However, since the charge-discharge RCD snubber generates a loss when the charge stored across the snubber capacitor is discharged and this loss increases as the switching frequency of the power transistor is increased, the discharge-restraint type RCD snubber, which does not have this defect, is the most generally used. Since the discharge-restraint type RCD snubber circuit does not have a *dv/dt* suppression effect, it must be used in combination with a power transistor with a wide RBSOA. Recently, however, power transistors with a wide RBSOA have been commercialized with discharge-restraint type RCD snubber use as a precondition. The method of designing the discharge-restraint type RCD snubber circuit most generally used is described here.

Fig. 3 Operation waveforms at reverse recovery of free wheeling diode

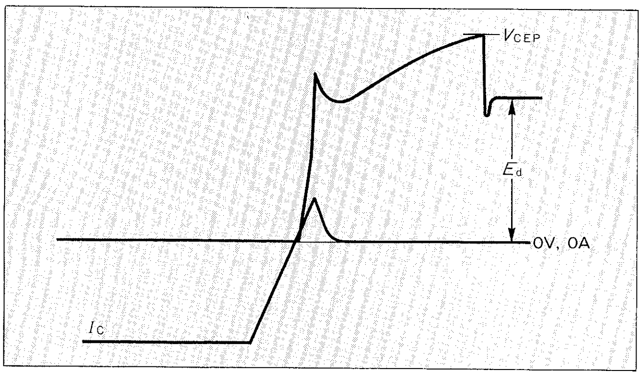


Fig. 4 Operation waveforms at turn-off of power transistor

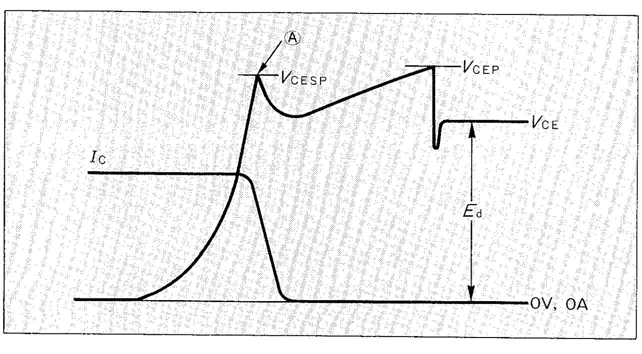


Fig. 5 Operation locus at turn-off and RBSOA

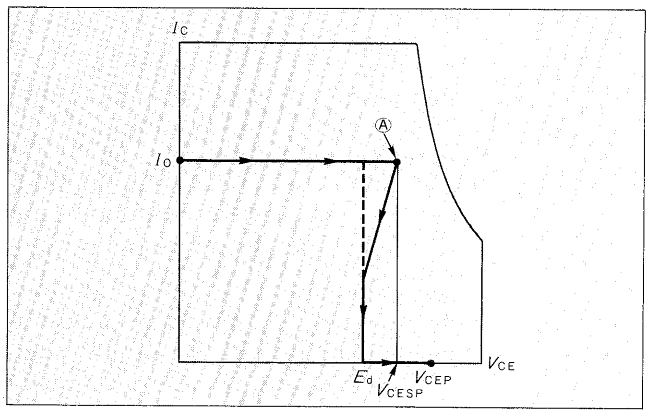
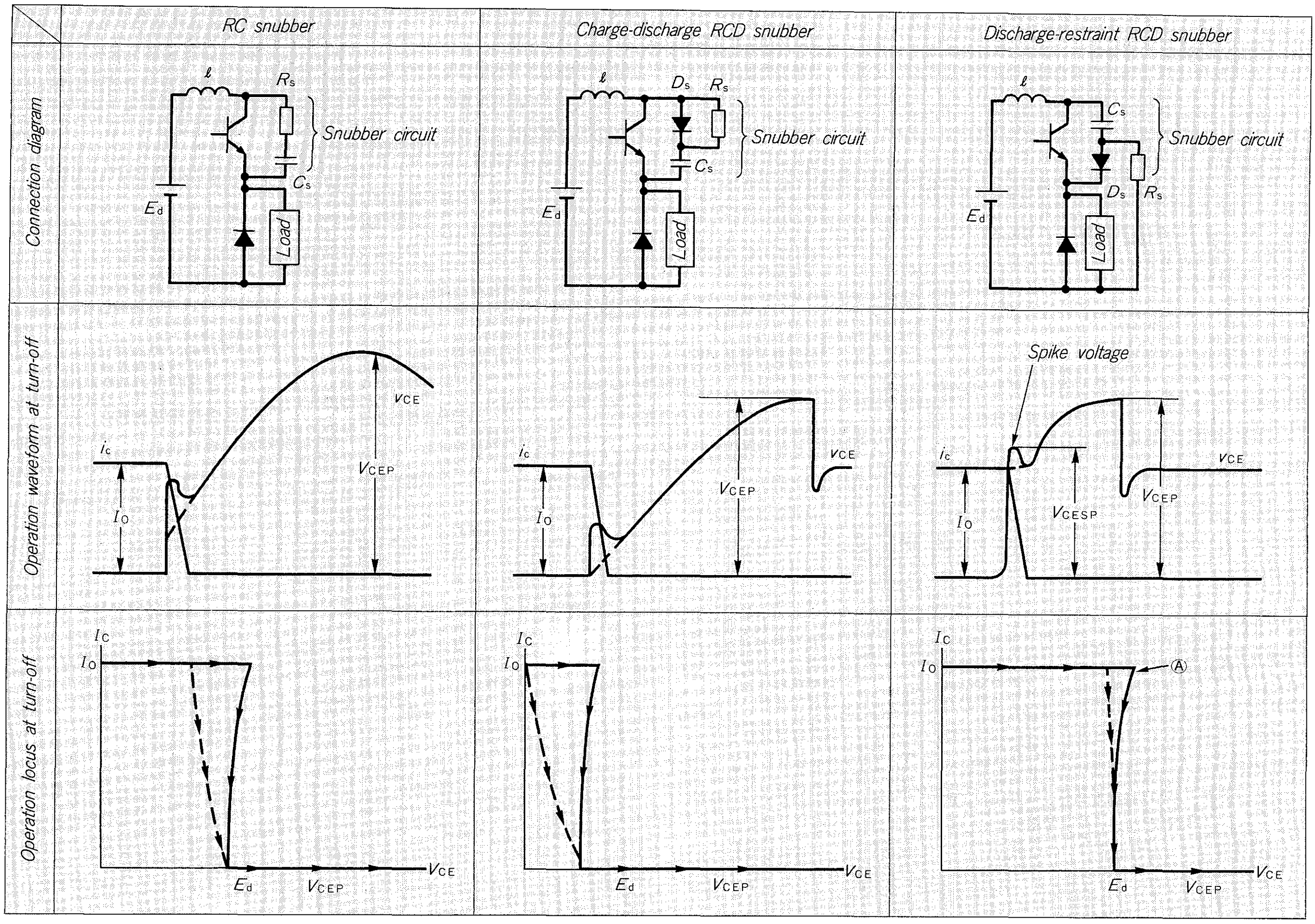


Fig. 6 Typical snubber circuits



----: *Ideal snubber circuit*, ——: *Actual snubber circuit*

2.5 Basic design method of discharge-restraint type RCD snubber circuit

(1) Determinations of snubber capacitor

The voltage designated V_{CEP} in *Fig. 3* and *Fig. 4* is impressed when collector current is not flowing in any power transistor (that is, blocked region). To protect the power transistors against this voltage, the following equations must be satisfied:

(a) When base-emitter reverse biased

$$V_{CEP} < V_{CEX(SUS)} \quad \cdots\cdots (1)$$

(b) When base-emitter not reverse biased

$$V_{CEP} < V_{CEO(SUS)} \quad \cdots\cdots (2)$$

The capacitance of snubber capacitor (C_s) is found from:

$$C_s = \frac{l I_0^{\,2}}{(V_{CEP} - E_d)^2} \quad \cdots\cdots (3)$$

where, l : Main circuit inductance

I_0 : Reverse recovery current peak value of free wheeling diode or maximum value of power transistor collector current

V_{CEP} : Final value of snubber capacitor terminal voltage

E_d : DC intermediate circuit voltage

(2) RBSOA consideration method

The spike voltage V_{CESP} (voltage of the part indicated by (A) in *Fig. 5*) during the power transistor turn-off process is found from the following equation:

$$V_{CESP} = E_d + V_{FM} + l_s \cdot \frac{di_c}{dt} \quad \cdots\cdots (4)$$

where, l_s : Snubber circuit inductance

di_c/dt : Rate of change of collector current during falling period

V_{FM} : Snubber diode forward transient voltage (Generally, 20 to 30V for 500V class high speed diodes and 40 to 60V for 100V class high speed diodes)

Here, part (A) shown in *Fig. 5* must be within the RBSOA. To use a power transistor effectively, ample consideration must be given wiring structure to reduce the inductance of the snubber circuit, a diode with a small forward transient voltage must be selected, etc.

(3) Determination of snubber resistor (R_s)

The following two functions are demanded of the snubber resistor:

(a) Discharging of the charge stored across the snubber capacitor until the next time the power transistor is turned off. The conditional expression when 90% of the charge is discharged up to the next turn-off is given by:

$$R_s \leqq \frac{1}{2.3 \cdot C_s \cdot f} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (5)$$

where f: power transistor switching frequency

(b) Suppression of the current vibrations of the snubber circuit. The conditional expression when the circuit control coefficient is made 1.0 is given by:

$$R_s \geqq 2\sqrt{\frac{l_s}{C_s}} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (6)$$

Since snubber resistor loss (P_s) is given by the following equation and is completely unrelated to the value of the snubber resistor, the snubber resistor should be as large as possible within the range which satisfies Eqs. (5).

$$P_s = \frac{l_s \cdot I_0^2 \cdot f}{2} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (7)$$

3. OVERCURRENT PROTECTION

3.1 Overcurrent generation causes

With the VVVF inverter shown in *Fig. 1*, surge current at motor starting, output short-circuit due to erroneous wiring, etc. may cause an overcurrent to flow in the power transistors. Of these, surge current at motor starting and other overcurrents with a comparatively slow current change are protected against by a current limiting circuit using a PI controller, etc. However, for output short circuits and other overcurrents with an extremely fast current change, a protection approach different from the thyristor is necessary. The method of protecting against overcurrents with an extremely fast current change, such as output short-circuit, etc., is described here. The main causes of generation of short-circuits in a VVVF inverter are shown in *Fig. 7*.

3.2 Power transistor short-circuit capability

An example of power transistor short-circuit capability is shown in *Fig. 8*. *Fig. 8* was obtained by simulating the arm short-circuit shown in *Fig. 7* and shows the protectible region for 50μs short-circuit period. The change of the short-circuit current by DC power supply voltage, with three base current values as the parameter, is also shown in *Fig. 8*. As shown in *Fig. 8*, the collector current at a short-circuit accident becomes the value limited by the output characteristic (DC current gain h_{FE}) of the power transistor and is different than the case of a thyristor or diode in that an it does not reach an extremely high value like that determined by the impedance of the circuit. However, when a short-circuit occurs, the power transistor is responsible for an extremely high voltage and large current and protection by a fuse, such as the thyristor, diode, etc.,

Fig. 7 Main causes of short-circuits

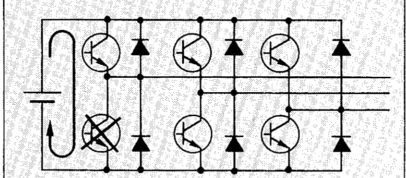
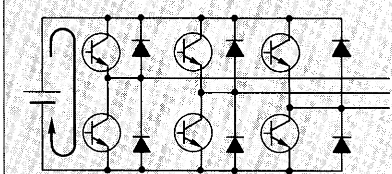
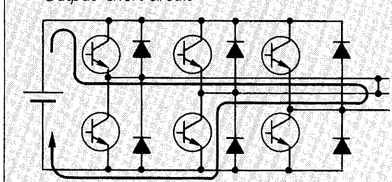
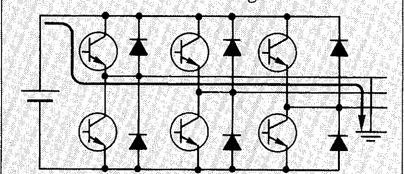
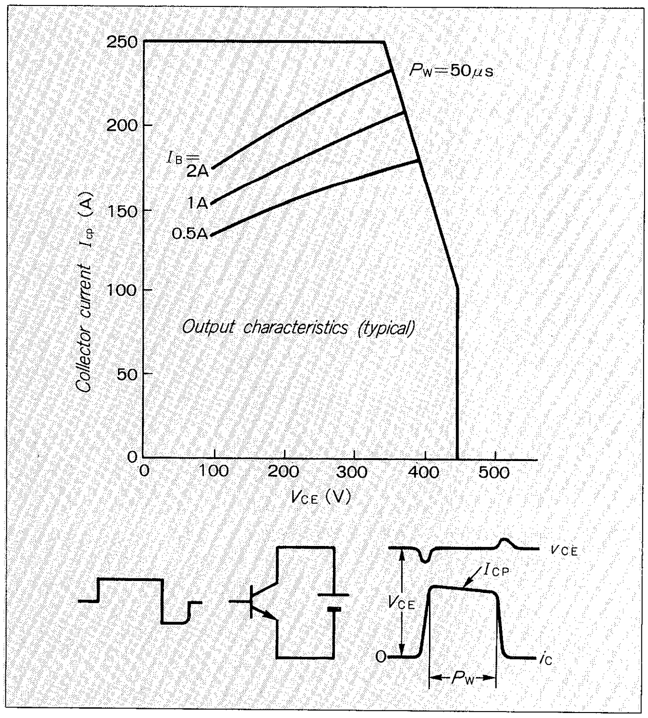
Short paths	Causes
Arm short-circuit 	*Transistor or diode destroyed*
Serial short-circuit 	*Control circuit drive circuit or erroneous operation by noise*
Output short-circuit 	*Wiring work mistake or other human error and load insulation breakdown*
Short-circuit from load to ground 	*Same as above.*

Fig. 8 Power transistor short-circuit capability and measurement circuit



is difficult. For this reason, a method which provides protection by blocking of overcurrents by the device itself is generally used with power transistors. *Fig. 8* is the short-circuit capability of a 500V 50A Darlington transistor. In this example, the power transistor can be protected by blocking an overcurrent in a 50μs period for an arm short-circuit of up to a 350V DC power supply voltage by applying a forward bias current of 2A or less.

3.3 Overcurrent detection method

Overcurrent is detected by a method which combines a resistor, CT (current transformer), and other current detectors and a comparator and a method which detects overcurrent indirectly from the operating state of the power transistor. Since it method has advantages and disadvantages, selection according to the protection objective, range, etc. is necessary.

(1) Method combining a current detector and comparator

With small capacity equipment, a resistor is used as the current detector and with large capacity equipment, an ACCT (AC current transformer) or DCCT (DC current transformer, device using a Hall element, etc.) is used as the current detector. Since the kind of overcurrent that can be detected differs with the current detector insertion position as shown in *Fig. 9* and *Table 1*, the insertion position should be decided by considering the protection objective, range, etc. The overcurrent protection circuit in a VVVF inverter is shown in *Fig. 10*. In the circuit shown in *Fig. 10*, the current detector is inserted at the inverter output line and protection against output short-circuit and short-circuit from load to ground is possible. As shown in *Fig. 10*, there are various circuits which cause a response delay in the overcurrent protection loop. For reliable power transistor overcurrent protection, care must be exercised so that the response delay of these circuit is not too large.

Fig. 9 Insertion of overcurrent detector

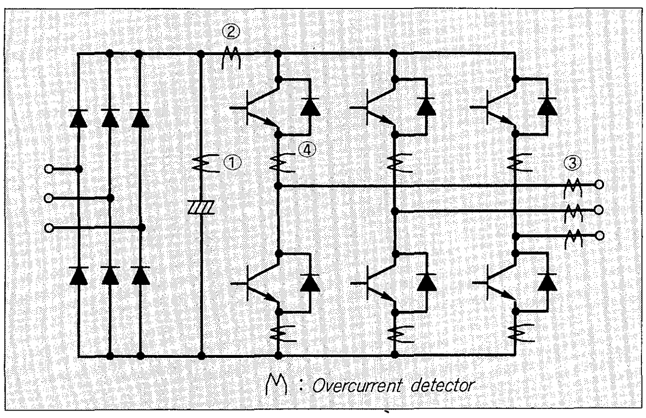


Table 1 Insertion place of overcurrent detector and detection contents

Insertion place overcurrent of detector	Features	Detection contents
(1) Inserted in series with smoothing capacitor	•ACCT available •Low detection precision	•Arm short-circuit •Series arm short-circuit •Output short-circuit •Grounding
(2) Inserted at DC line	•DCCT must be used •Low detection precision	Same as above
(3) Inserted at inverter output	•ACCT can be used in equipment with high output frequency •High detection precision	•Output short-circuit •Grounding
(4) Inserted in series with each device	•DCCT must be used •High detection precision	•Arm short-circuit •Series arm short-circuit •Output short-circuit •Grounding

(2) Indirect detection method

During normal operation, in the on state, the power transistor collector-emitter voltage becomes a low value of several volts or less. On the other hand, in the overcurrent state, the power transistor cannot maintain the saturation state and the collector-emitter voltage increases suddenly. Therefore, when the collector-emitter voltage is abnormal high, even though forward bias base current is supplied, it is judged that an overcurrent is flowing.

Fig. 11 is an example of an overcurrent protection circuit using this principle. Since the state in which the collector-emitter voltage is high occurs at the turn-on period at normal switching operation, this period must not be detected as an overcurrent. In *Fig. 11* this function

Fig. 10 Example of overcurrent protection circuit at VVVF inverter

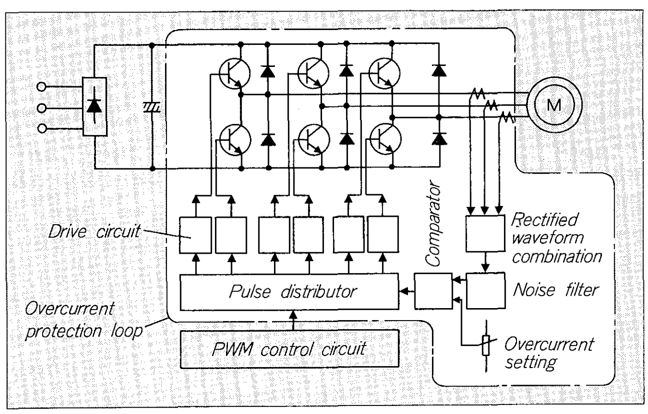


Fig. 11 Indirect overcurrent detection method

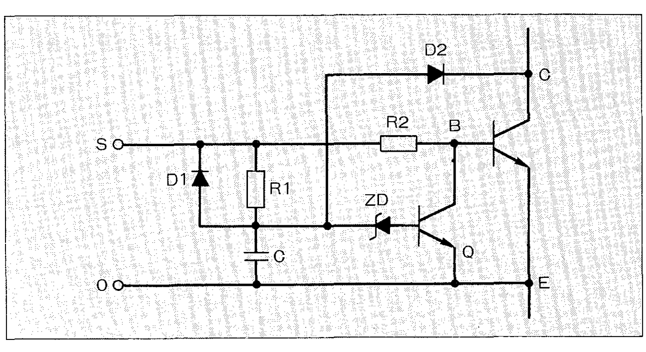


Fig. 12 Example of overcurrent protection

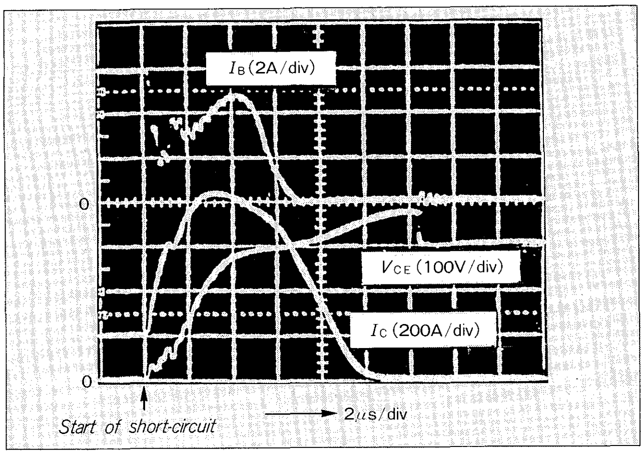
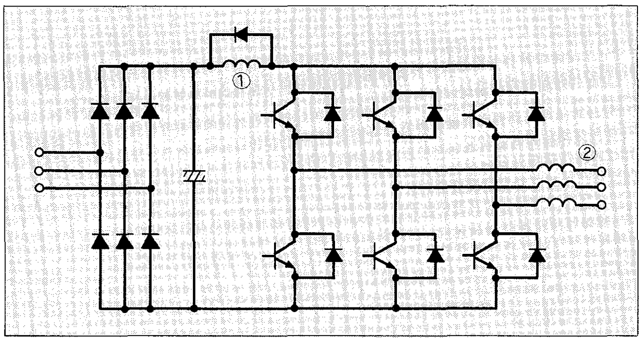


Fig. 13 Insertion place of overcurrent limiting reactor



is provided by the timer consisting of R1 and C.

Fig. 12 shows examples of the operation waveforms of the overcurrent circuit shown in *Fig. 11*. Since the overcurrent protection circuit shown in *Fig. 11* performs the series of protection operations from overcurrent detection to stopping of the forward bias base current in the drive circuit, protection within a short time is possible. However, since the overcurrent protection operation is performed in the drive circuit of each power transistor without going through a control circuit, when stopping of equipment operation and other processing is performed when the overcurrent operation was performed, a feedback loop for the signals from each overcurrent protection circuit to the control circuit is necessary.

3.4 Insertion of reactor for overcurrent limiting

When the overcurrent peak value must be limited because the short-circuit capability of the power transistor is insufficient or for other reasons, a reactor must be inserted into the main circuit as shown in *Fig. 13*. The method which inserts the reactor at the input side of the inverter and the method which inserts the reactor at the output side are shown in *Fig. 13*. Each method has the features described below. However, in any case, enlarging of the equipment, lowering of the conversion efficiency, and other abuses must be avoided.

(1) Insertion at input side of inverter

This method is effective in overcurrent peak value limiting at arm short-circuit, series arm short-circuit, output short-circuit, and grounding short-circuit accidents. To avoid enlarging of the snubber circuit, a feed back diode must be connected in parallel with the reactor.

(2) Insertion at output side of inverter

This method has no effect against arm short-circuit and series arm short-circuit, but a feed back diode is unnecessary. Since the output capacity of the equipment is lowered by the voltage drop across the reactor, a very large reactor cannot be inserted.

As shown in *Fig. 8*, the short-circuit capability of a 500V class power transistor is on a level which allows protection without inserting a reactor. However, with 1000V and 1200V class power transistors, protection without reactor was difficult. The power transistor module "Z series" (1000V, 1200V) developed by Fuji Electric has a substantially improved short-circuit capability and increases the possibility of protection without insertion of a reactor remarkably.

4. CONCLUSION

The VVVF inverter was taken as a specific example and the approach to protection of the power transistor used in it against overvoltage and overcurrent was described. To operate the power transistor stabily for a long time, overvoltage and overcurrent protection technology is extremely important. The authors will be happy if the contents described here are of assistance when designing a protection circuit. We will continue our efforts in developing devices so that the protection circuit can be simplified and its protection range increased.