AN OVER-CURRENT INDICATOR

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ABSTRACT

The over-current indicator indicates to the user that the current in a circuit is exceeding its rated value as soon as it occurs. The current is sensed by a current transformer (CT) and the rectified and regulated output of the CT is fed to a comparator for detecting over-current. The output of the comparator triggers the indicator circuit that lights up a light emitting diode (LED) when the over-current is detected. The device is designed for operation in 5 A or 10 A rated current circuits, as selected by a toggle switch. The paper describes the device, its principle of operation and the design procedure.

INTRODUCTION

The purpose of the over-current indicator is to immediately indicate to the user that the current flowing in a circuit is exceeding its rated value. The user can then take remedial action before the current increases further and circuit breakers operate due to the over-current to switch off the power supply to the circuit. Most widely used over-current protective device in both industrial and domestic sectors is the miniature circuit breaker (MCB). The tripping factors of MCBs vary from 1.5 to 2.0, which means that they allow a current of 1.5 to 2.0 times the rated value before operating to disconnect the circuit. In contrast, the over-current indicator acts as soon as the current exceeds the rated value and indicates to the user that the rated value has been exceeded. The user can take remedial actions such as not increasing the loads beyond that point or switching off of less important sub-circuits, in order to prevent sudden tripping-off of the entire circuit due to the over-current.

It is very important especially in industrial environments to maintain the processes undisrupted to ensure the quality of products. Sudden shut-off of processes can also seriously affect the productivity of factories. Moreover, certain sensitive components of equipment may be damaged due to a slight over-current that is not sufficient to activate the MCBs. Thus, the use of the over-current indicator along with MCBs can further improve the reliability and protection of a distribution system.

This paper describes the over-current indicator, its principle of operation and the steps in the design procedure.

DESCRIPTION OF THE DEVICE

Figure 1 shows photographs of the exterior and interior of the constructed over-current indicator with the current transformer. The actual dimensions of the unit are 4 cm x 4 cm x 1cm. The unit can be connected in series with the MCBs in a suitable location.

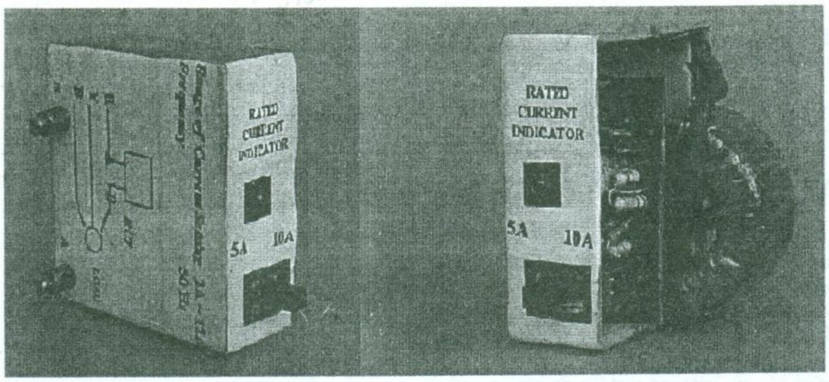

Figure 1. Exterior and interior views of the over-current indicator

PRINCIPLE OF OPERATION

Basic components of the over-current indicator are shown schematically in Figure 2. The current of the circuit is sensed by the use of a current transformer (CT). The output of the CT is rectified and regulated before being fed to the comparator for deciding whether the limit has been reached. When the current exceeds the rated value, the output of the comparator triggers the LED or the alarm to warn the user.

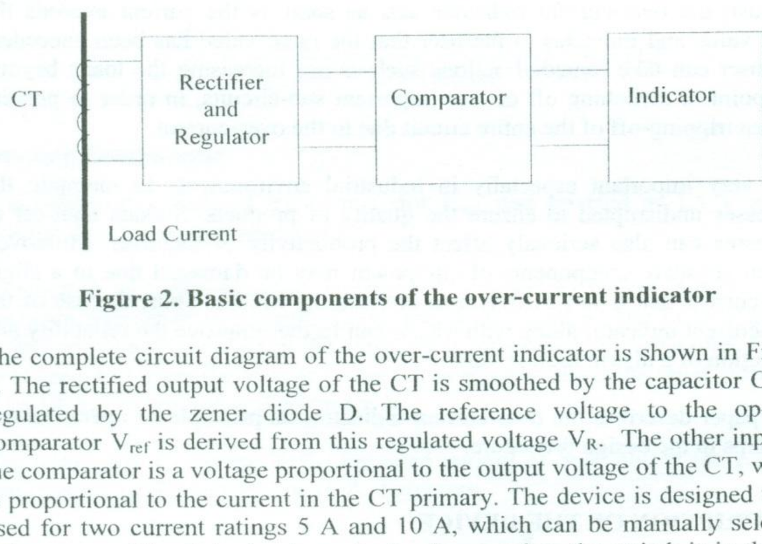

Figure 2. Basic components of the over-current indicator

The complete circuit diagram of the over-current indicator is shown in Figure 3. The rectified output voltage of the CT is smoothed by the capacitor C and regulated by the zener diode D. The reference voltage to the op-amp comparator V_{ref} is derived from this regulated voltage V_R. The other input to the comparator is a voltage proportional to the output voltage of the CT, which is proportional to the current in the CT primary. The device is designed to be used for two current ratings 5 A and 10 A, which can be manually selected using an on-off switch. As shown in the figure, when the switch is in the off position the lower arm resistance is only R_{41}. But when the switch is in the on position, the lower arm resistance is the parallel combination of the R_{41} and R_{42}. Thus the switch operation provides two resistor values for the lower arm

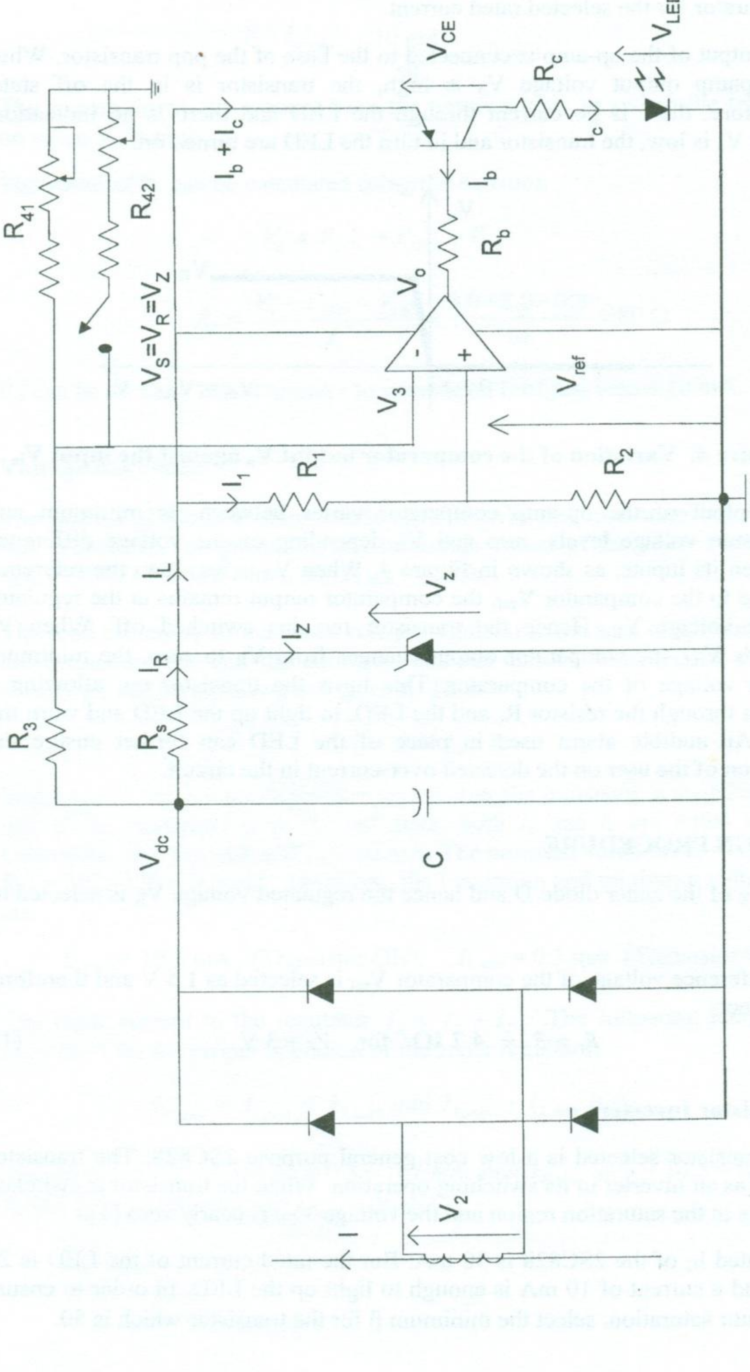

Figure 3. Complete circuit diagram of the over-current indicator

of the potential divider, thereby providing the necessary voltage to the comparator for the selected rated current.

The output of the op-amp is connected to the base of the pnp transistor. When the opamp output voltage V_o is high, the transistor is in the off state. Therefore, there is no current through the LED and there is no indication. When V_o is low, the transistor and in turn the LED are turned on.

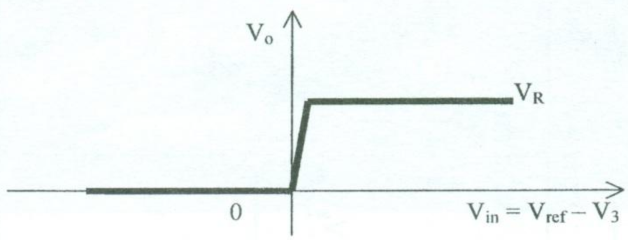

Figure 4. Variation of the comparator output V_o against the input V_{in}

The output of the op-amp comparator varies between its minimum and maximum voltage levels, zero and V_R depending on the voltage difference between its inputs, as shown in Figure 4. When V_3 is less than the reference voltage to the comparator V_{ref}, the comparator output remains at the regulator output voltage V_R. Hence the transistor remains switched off. When V_3 exceeds V_{ref}, the comparator output changes from V_R to zero, the minimum output voltage of the comparator. This turns the transistor on, allowing a current through the resistor R_c and the LED, to light up the LED and warn the user. An audible alarm used in place of the LED can further ensure the attention of the user on the detected over-current in the circuit.

DESIGN PROCEDURE

The V_Z of the zener diode D and hence the regulated voltage V_R is selected as 3 V.

The reference voltage of the comparator V_{ref} is selected as 1.5 V and therefore, we select

$$R_1 = R_2 = 4.7\ k\Omega \quad \text{for} \quad V_R = 3\ \text{V} \tag{1}$$

Transistor Inverter

The transistor selected is a low cost general purpose 2SC828. The transistor works as an inverter in its switching operation. When the transistor is switched on, it is in the saturation region and the voltage V_{CE} is nearly zero [1].

The rated I_C of the 2SC828 is 30 mA. But the rated current of the LED is 20 mA and a current of 10 mA is enough to light up the LED. In order to ensure transistor saturation, select the minimum β for the transistor which is 50.

Therefore,

$$I_b = \frac{I_{c(sat)}}{\beta} = \frac{10\,mA}{50} = 0.2\,mA \quad (2)$$

The opamp draws this current from the power supply to switch the transistor on when V_o is high.

The value of R_c can be calculated using the equation

$$V_s = R_c I_c + V_{LED} + V_{CE} \quad (3)$$

$$R_c = \frac{V_s - V_{LED} - V_{CE}}{I_c} = \frac{3.0-2.0-0.2}{10} = 80\ \Omega$$

R_c can be 82 Ω or 100 Ω in order to provide an I_c of just below 10 mA.

Voltage Regulator

The ratings of the 3 V zener diode are 500 mW and minimum current of 5 mA. Therefore, the maximum and minimum values of the zener current are, $I_{Z,max} = 500/3 = 166.67$ mA, and $I_{Z,min} = 5$ mA.

The load current I_L of the zener voltage regulator is the sum of the currents in the transistor base and the collector, and the current taken by the potential divider R_1 and R_2 as shown in Figure 3. Thus

$$I_L = I_1 + I_b + I_c \quad (4)$$

Values of I_b and I_c vary depending on whether the transistor is switched on or off. If the transistor is in the off state, both I_b and I_c are equal to zero. Otherwise, $I_b = 0.2$ mA and $I_c = 10$ mA. The constant value of $I_1 = V_R/(R_1 + R_2) = 3/(2\text{x}4.7) = 0.3$ mA. Therefore, the maximum and minimum values of I_L are

$I_{L,max} = 10.5$ mA (Transistor ON), $I_{L,min} = 0.3$ mA (Transistor OFF)

The input current to the regulator $I_R = I_Z + I_L$. The following inequalities must hold for the proper operation of the zener regulator:

$$I_{R,\max} - I_{L,\min} \leq I_{Z,\max}\ and\ I_{R,\min} - I_{L,\max} \geq I_{Z,\min} \quad (5)$$

Therefore, $I_{R,\max} \leq 166.67 + 0.3 = 167\ mA$ and $I_{R,\min} \geq 5 + 10.5 = 15.5\ mA$. Select $I_{R,max} = 100$ mA and $I_{R,min} = 20$ mA.

Current Transformer

The maximum and minimum values of the average dc output voltage needed across the capacitor can be calculated as

$$V_{dc,\max} = V_R + I_{R,\max} R_S \text{ and } V_{dc,\min} = V_R + I_{R,\min} R_S \quad (6)$$

The resistance R_s is selected as 68 Ω. Thus, $V_{dc,max}$ = 3.0 + 0.1x68 = 9.8 V and $V_{dc,min}$ = 3.0 + .02x68 = 4.36 V.

Figure 5 shows the voltage across the smoothing capacitor connected across the full-wave diode bridge, which rectifies the output voltage of the current transformer. V_{2p} is the peak value of the CT secondary voltage. The frequency of the waveform is 100 Hz, twice the supply frequency. For the purpose of design calculations this waveform can be approximated to a saw-tooth waveform with zero charging time and constant discharging current indicated by a constant slope as shown in Figure 6 [2].

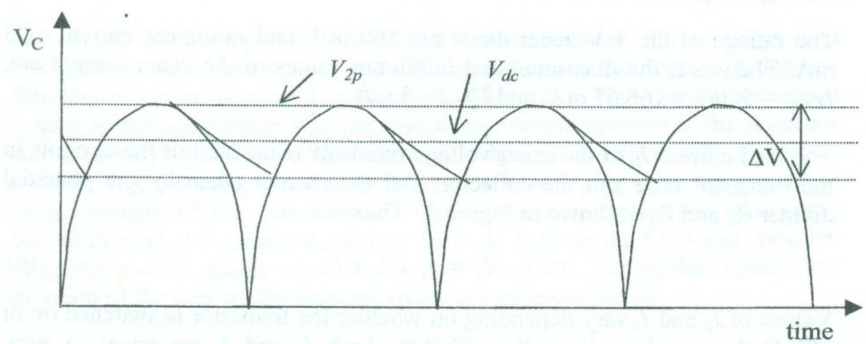

Figure 5. Voltage across the smoothing capacitor

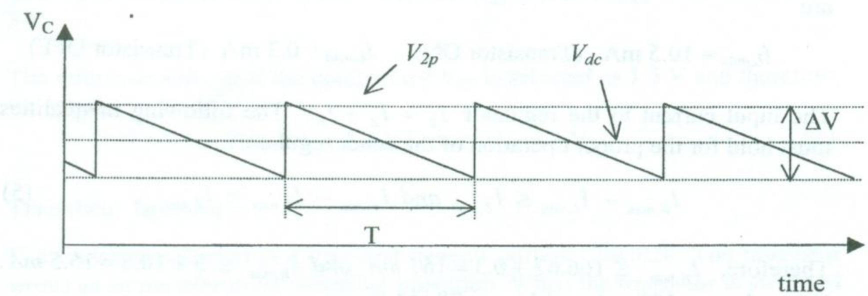

Figure 6. Approximated voltage waveform across the capacitor

It can be seen from Figure 6 that the average dc output voltage of the capacitor $V_{dc} = V_{2p} - \frac{\Delta V}{2}$ and the voltage variation $\Delta V = \frac{\Delta Q}{C} = \frac{I_R\, T}{C}$ that can be combined to obtain

$$V_{dc} = V_{2p} - \frac{I_R\, T}{2C} \qquad (7)$$

where T = 1/100 = 10 ms and the capacitance C is selected as 470 μF.

V_{2p} is determined by the primary current in the CT and is independent of I_R. Therefore, the maximum value of V_{dc} occurs when V_{2p} is maximum and I_R is minimum.

Thus,

$$V_{2p,\max} = V_{dc,\max} + \frac{I_{R,\min}\, T}{2C} = 9.8 + \frac{20x10}{2x470} = 10.0\ V$$

Similarly, minimum value of V_{dc} occur when V_{2p} is minimum and I_R is maximum and therefore,

$$V_{2p,\min} = V_{dc,\min} + \frac{I_{R,\max}\, T}{2C} = 4.36 + \frac{100x10}{2x470} = 5.42\ V$$

The core of the CT is made of Silicon Steel, which has the following maximum values of the flux density B and field strength H:

$$B_{max} = 1.7\ \text{T}, \qquad H_{max} = 200\ \text{A/m}$$

Current flows in the secondary of the CT only during the charging of the capacitor, when the diodes in the CT secondary are forward biased. During other times, the secondary current is zero, and therefore, there is no secondary mmf to balance the primary mmf. Thus the entire primary mmf is used for the magnetization of the CT core. The maximum magnetic field strength occurs during this period when the maximum current flows in the primary [3]. Thus,

$$N_1\, I_{1p,\max} = H_{\max}\, l \qquad (8)$$

where, $I_{1p,max}$ is the peak value of the maximum primary current and l is the mean length of the toroidal core of the CT as shown in Figure 7. N_1 is the number of primary turns of the CT which is 1.

The over-current indicator is to be designed for the rated currents of 5 A and 10 A. A maximum current of 12 A is assumed in the 10 A rated current circuit. Thus, the minimum mean length of the toroidal core can be calculated from equation (8) as

$$l = \frac{N_1\, I_{1p,\max}}{H_{\max}} = \frac{1x12\sqrt{2}}{200} = 8.48\ cm$$

A toroidal core of mean length 9.5 cm was selected for the CT in order to ensure a magnetic field strength of less than H_{max}. The cross sectional area of the core is 1.68 cm^2.

The peak induced voltage of the CT secondary can be expressed as [3]

$$V_{2p,\max} = B_{\max} N_2 A \omega \qquad (9)$$

where A is the cross sectional area of the toroidal core of the CT as shown in Figure 7, N_2 is the number of secondary turns of the CT and $\omega = 2\pi f$ where f is the frequency of the supply voltage.

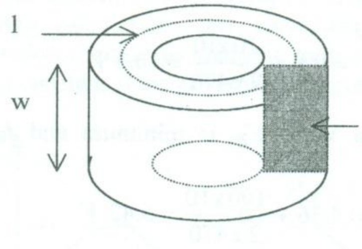

Figure 7. Dimensions of the toroidal core

The maximum number of turns of the CT secondary can now be calculated using equation (9) as

$$N_2 = \frac{V_{2p,\max}}{B_{\max} A \omega} = \frac{10.0}{1.7 x\, 1.68 x 10^{-4} x 100\pi} = 112$$

Op-amp Comparator

The reference voltage of the comparator V_{ref} was selected as 1.5 V at the beginning of the design procedure.

The output of the comparator remains at V_R when V_3 is less than V_{ref}, but becomes zero when V_3 exceeds V_{ref} as shown in Figure 4. The LED lights up to indicate over-current when the comparator output is zero. Therefore, V_3 has to exceed V_{ref} when the current in the CT primary exceeds the rated current 5 A or 10 A. Let this value of V_3 be 1.6 V.

The lower arm resistance is R_{41} for rated current of 5 A, and is the parallel combination of R_{41} and R_{42} for 10 A. Therefore,

$$V_3 = \frac{R_{41}}{R_3 + R_{41}} V_{dc@5A} \quad \text{and} \quad V_3 = \frac{R_p}{R_3 + R_p} V_{dc@10A} \qquad (10)$$

where R_p is the parallel combination of R_{41} and R_{42}.

The actual variation of V_{dc} with the primary load current of the CT is given in Figure 8.

It can be seen from Figure 8 that,

$$V_{dc\,@\,5A} = 4.8\text{ V} \quad \text{and} \quad V_{dc\,@\,10\,A} = 10\text{ V}$$

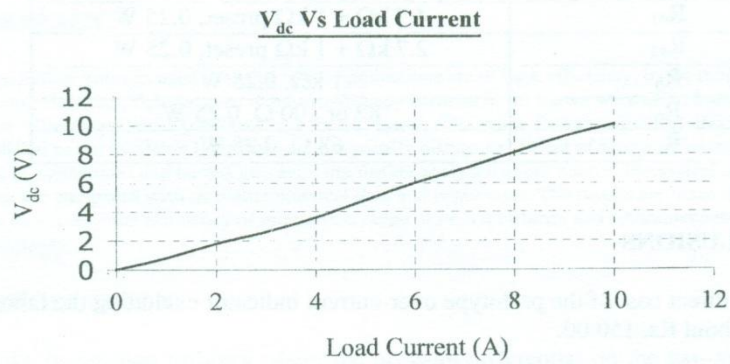

Figure 8. Variation of the Capacitor voltage V_{dc} with load current I_1

Select R_3 = 10 kΩ and the above values can be used in equation (10) to calculate

$$R_{41} = \frac{V_3}{V_{dc\,at\,5\,A} - V_3} R_3 = \frac{1.6}{4.8 - 1.6} 10 = 5\ k\Omega$$

$$R_p = \frac{V_3}{V_{dc\,at\,10\,A} - V_3} R_3 = \frac{1.6}{10 - 1.6} 10 = 1.9\ k\Omega$$

where, R_p is the parallel combination of R_{41} and R_{42}.

Therefore R_{42} = 5x1.9/(5-1.9) = 3 kΩ. A 4.7 kΩ resistor with a 1 kΩ preset for fine tuning can be used for R_{41} whereas, a 2.7 kΩ resistor with a 1 kΩ preset can be used for R_{42}.

Short Circuit Protection

In the case of a direct short circuit of the primary load side of the current transformer, a large current may flow in the CT primary until the circuit breakers operate and disconnect the power supply. Assuming a current of 40 A under short circuit conditions for the 10 A rated circuit, the maximum CT secondary current would be 40/112 = 357 mA. The voltage that may build on the CT secondary could be between 30 to 40 V. A capacitor of rated voltage

Component Ratings

Component	Rating
Zener diode	3 V, 1.3 W
Capacitor C	470 μF, 63 V
R_1, R_2	4.7 kΩ, 0.25 W
R_3	10 kΩ, 0.25 W
R_{41}	4.7 kΩ + 1 kΩ preset, 0.25 W
R_{42}	2.7 kΩ + 1 kΩ preset, 0.25 W
R_b	1 kΩ, 0.25 W
R_c	82 or 100 Ω, 0.25 W
R_s	68 Ω, 0.25 W

CONCLUSIONS

The net direct cost of the prototype over-current indicator excluding the labour cost is about Rs. 150.00.

The prototype was designed for rated currents of 5 A and 10 A. However, with the use of a variable resistor in place of the fixed value resistors in the potential divider, the selector switch can be eliminated and the device can be made to respond to any rated current within the designed range.

The device does not require any external power supplies and the dc power supply needed for the op-amp is obtained from the same CT output voltage which indicates the current level.

The over-current indicator would be very useful in various industrial and commercial applications where maintaining undisrupted operation is important. Various other alarms can be incorporated instead of the LED with additional circuits for their operation as necessary.

REFERENCES

1. *Electronic Devices and Circuits*, Bogart T. F, Universal Book Stall, 1986.

2. *Power Electronics: Converters, Applications and Design*, Mohan N, Undeland T. M., Robbins W. P., John Wiley and Sons, 1989.

3. *Electromagnetic and Electromechanical Machines*, Matsch L. W., Morgan J. D., 3rd Edition, Harper & Row Publishers, 1986.

4. *IC Op-Amp Cookbook*, W. G. Jung, 3rd Edition, BPB Publishers, 1997.