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Vacuum interrupter, high reliability component of distribution switches, circuit breakers and contactors

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Abstract: The use of vacuum interrupters (VIs) as the current interruption component for switches, circuit breakers, reclosers and contactors operating at distribution voltages has escalated since their introduction in the mid-1950's. This electrical product has developed a dominating position for switching and protecting distribution circuits. VIs are even being introduced into switching products operating at transmission voltages. Among the reasons for the VI's popularity are its compactness, its range of application, its low cost, its superb electrical and mechanical life and its ease of application. Its major advantage is its well-established reliability. In this paper we show how this reliability has been achieved by design, by mechanical life testing and by electrical performance testing. We introduce the "sealed for life" concept for the VI's integrity. We discuss this in terms of what is meant by a practical leak rate for VIs with a life of over 30 years. We show that a simple high voltage withstand test is an easy and effective method for monitoring the long-term vacuum integrity. Finally we evaluate the need for routine inspection of this electrical product when it is used in adverse ambient environments.

Key words: Vacuum interrupter (VI), Reliability, Mechanical life, Electrical life
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INTRODUCTION

The vacuum interrupter (VI) was introduced in the 1950's as a voltage distribution, load-break switch (Jennings *et al*., 1956). In the late 1950's and into the 1960's the General Electric Corporation (USA) began its R & D effort to produce a VI that would interrupt fault currents (Lee *et al*., 1963). Eaton Corporation (formerly Westinghouse) began its development of VIs suitable for use in distribution circuit breakers and reclosers in 1960. We introduced our first designs into the US recloser market at the end of the 1960's. Thus we have had over 45 years of experience in manufacturing and applying VIs. When the VI was first introduced into switching and circuit protection products the end users expressed two major concerns:

(1) What is the reliability of the VI's performance over its service life?

(2) How reliable is the vacuum vessel over its design life; i.e. will the VI maintain the required vacuum in the life of the switching product?

After a very slow acceptance by the end user community, products containing VIs have gradually gained a dominant position in the voltage distribution market (Slade, 1997), as shown in Fig.1. Vacuum circuit breakers are now employed at system voltages from 1 kV (Fink and Renz, 2002) to 145 kV (Himi *et al*., 1978). They can also interrupt fault currents up to 75 kA and are being used in an ever-widening range of application (Long and Smith, 2003). In this paper we will address the second concern. We will show how the design, testing and manufacture of the VI assure an extremely reliable product. The modern VI provides excellent service throughout its design life.

DESIGN FOR LIFE

Mechanical life

Vacuum circuit breakers and vacuum contactors

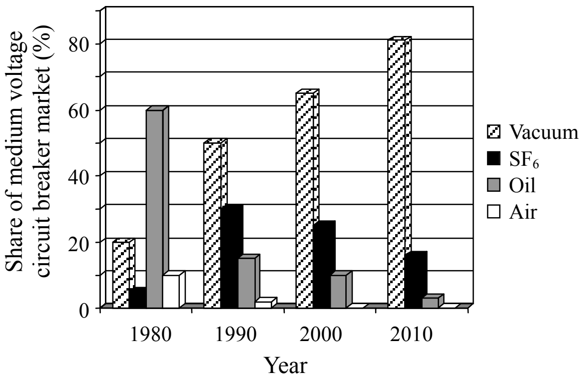


Fig.1 Sales of different medium voltage circuit breaker technologies by year

are required to mechanically open and close for a large number of operations. A bellows made from thin stainless steel allows the contacts to open and close while retaining vacuum inside the interrupter. The fatigue performance of the bellows limits the mechanical life of the VI. The contact opening and closing operations stress the bellows, particularly the convolutions closest to the ends. In addition to the direct motion from the operation, the bellows oscillates after the contact motion stops, further adding to the wear on the bellows. The critical contact motion parameters that affect mechanical life are:

(1) steady state contact stroke or gap;

(2) opening and closing speed;

(3) motion damping at end of opening and closing stroke;

(4) overshoot and rebound on opening;

(5) mounting resilience;

(6) contact bouncing on closing.

The mechanical life of Eaton Electrical VI's was evaluated by performing opening and closing operations on sample VIs in a specially constructed life-test apparatus designed to simulate the operation of any mechanism that a VI may use in practice; e.g. that of a switch, a circuit breaker or a contactor. The opening and closing speeds reflect values recommended for use in these mechanisms. For example, a VI that is to be used in a vacuum circuit breaker will have its contact gap set to the circuit breaker's nominal gap, plus the gap tolerance, plus the amount of overtravel. The opening and closing speeds are adjusted towards the maximum values. This gives the maximum deflection stress on the bellows. The testing pauses after every 100 operations, opens the contacts and applies a 7.5 kV AC voltage. Failure to hold off this voltage indicates that the VI has started to leak from a crack in the bellows. This voltage is generally below the breakdown voltage of the open contact gap at atmospheric pressure; therefore it depends on the breakdown voltage dropping through the minimum of the Paschen curve as air leaks into the VI. For an excellent compilation of Paschen curve data, see (Dakin *et al*., 1974).

VIs need to have no or very low chance of mechanical failure below their rated number of close-open operations. Mechanical life tests were performed on a set of VIs, and the distribution of the life data was analyzed using three-parameter Weibull distribution (Bruning *et al*., 1996) given by:

$$f(x) = 1 - \exp\left[\left(\frac{x - x_0}{\alpha - x_0}\right)^{\beta}\right], \quad (1)$$

where $f(x)$ is the cumulative probability of failure, x is the mechanical life, α is the life where the fraction of 1/e units have failed, β is the shape parameter of the distribution, and x_0 is the threshold value below which the probability of failure is effectively zero. Fig.2 illustrates an example of this analysis. The plot shows the cumulative probability of failure as a function of the number of operations. This probability is the percentage that has failed at of before a particular mechanical life. The three-parameter Weibull distribution reproduces the behavior of the data, and gives a threshold value of 43770, which is just slightly below the lowest mechanical life measurement of 44096.

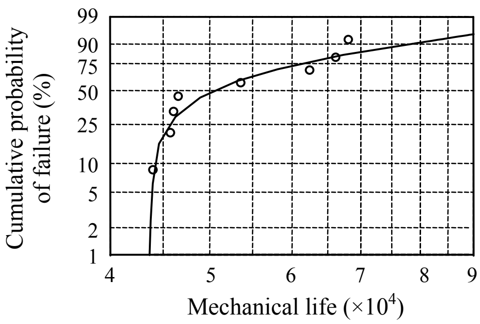


Fig.2 Cumulative percentage of VIs experiencing mechanical failure as a function of the number of operations. These results are for a particular bellows design and circuit breaker parameters. The threshold value is 43770 operations

Most VIs are seldom operated. The electrical and mechanical wear the interrupters experience in service is usually only a small fraction of their actual capability. Table 1 gives an overview of the expected life for a number of common VI applications. In general the VI will certainly perform its switching and protection function for most applications in excess of the expected life of the equipment in which it resides. It is possible to develop bellows for mechanical requirements beyond the VI life given in Table 1. For those applications where very frequent switching is needed, the number of operations should be monitored and a regular maintenance schedule developed. The long-term reliability of the VI while switching current has permitted these frequent switching applications to be implemented.

Electrical life

Since the first introduction of the VI it has demonstrated an exceptional electrical switching life. The major advantage of the contact in vacuum is that throughout its switching life the contact resistance remains nearly constant. There is no gas inside the VI to change the chemical composition of the contact. Slade and Smith (2006) explored this life over the whole current range expected for VIs used in vacuum circuit breakers. These VIs are designed to interrupt the diffuse vacuum arc that results during load currents switching (for currents ≤6 kA) and the high current vacuum arc that results when switching fault currents (for currents >6 kA). In order to control the high current vacuum arc two contact structures were successfully developed (Slade, 1984). The first, named the Transverse Magnetic Field (TMF) contact, forces the high current vacuum arc to move rapidly around the periphery of the contacts. The second, called the Axial Magnetic Field (AMF) contact, forces the high current columnar vacuum arc into a high current diffuse mode.

When switching the diffuse vacuum arc that occurs when normal load currents (e.g. 630 A to 3150 A) are interrupted, it is important to consider the deposit of material eroded from the cathode and deposited on the anode. Schulman *et al*.(1999) showed that when this is taken into account the effective erosion of the VI contacts in an ac circuit is considerably reduced. They determined the effective erosion as a function of the contact gap $<g>$ divided by the contact diameter $<\phi>$ as well as the effect of slots cut into the contact's surface. For example, a 62 mm diameter Cu-Cr contact with $<g>/<\phi>$ and slots in 28% of the contact surfaces has an effective erosion of 13×10^{-7} cm^3/C. The life of this contact is given as a function of load current in Table 2. This contact life is much larger than the 30000 operations expected from the normal operating life of a vacuum circuit breaker. VIs developed for vacuum contactors have been designed with switching lives of up to 5 million electrical switching operations.

A 62 mm diameter TMF contact switching 25 kA (RMS) has a switching life of 100 operations (Slade and Smith, 2006). For currents >6 kA the life of this contact is inversely proportional to the square of the current. The contact life as a function of current is shown in Fig.3. The AMF contact of the same diameter has a much lower erosion rate for the same high current interruption. A comparison of the two contact designs is shown in Fig.4 for a 35 mm di-

Table 1 The expected life of switching equipment using VIs

Application	VI mechanical life (operations)	Expected operation frequency in field	Expected VI service life
Vacuum circuit breaker (VCB)	3×10^4	(1~2)/year	>40 years
Vacuum recloser	3×10^4	<100/year	>40 years
Capacitor switching VCB	3×10^4	≤2/d	>40 years
Capacitor switching switch	5×10^4	≤4/d	>30 years
Arc Furnace VCB	3×10^4	≤100/d	<1 year
Contactor (≥7.2 kV)	1×10^6	≤100/d	>30 years
Contactor (≤3.3 kV)	5×10^6	≤100/d	>30 years
Contactor: jogging (≤3.3 kV)	5×10^6	≥100/d	<3 years

Table 2 Life of a 62 mm TMF contact switching load currents until 3 mm of erosion is reached

Circuit current (RMS) (kA)	Switching to reach 3 mm contact erosion
0.63	953835
1.25	480733
1.60	375572
2.00	300458
2.50	240366
3.15	193532

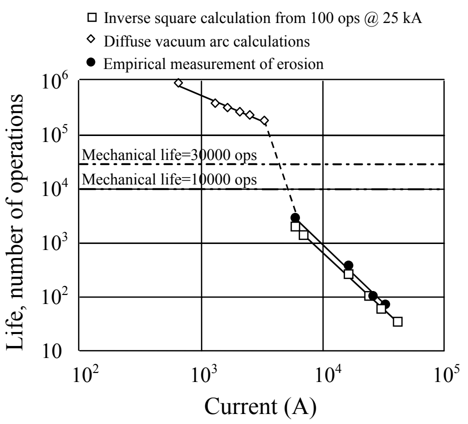


Fig.3 The contact life vs current (RMS) curve for 62 mm diameter TMF contacts inside a 102 mm diameter vacuum interrupter

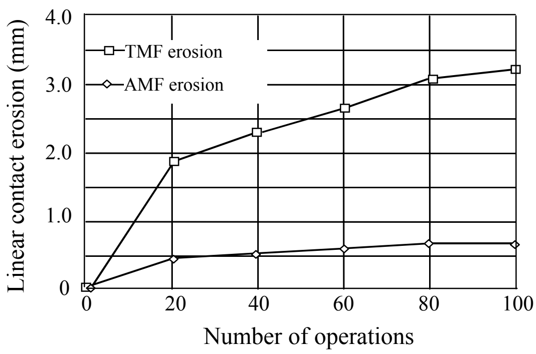


Fig.4 Erosion of 35 mm diameter TMF and AMF contacts switching 12.5 kA (RMS)

ameter Cu-Cr contact. For the AMF contact the eventual limit to the number of high current operations it can achieve is its ability to withstand high voltage, which gradually deteriorates after about 200 high current operations as metal vapor is deposited on the interior walls of the VI's ceramic body (Slade and Smith, 2006). It is thus possible to design VIs to have an outstanding operating life performance, which is greatly in excess of any former and any competing interrupter technology.

Vacuum integrity, sealed for life

In the early days of application of VIs, there was genuine concern about vacuum integrity. This might have been the result of the glass envelope used in the manufacture of these early VIs. Glass is vulnerable to permeation of both hydrogen and helium. At that time some end users were told that the life expectancy of a VI was 20 years. In the last few years we have heard some utility customers replacing perfectly good VIs in their switchgear simply because it has been 20 years since the panel boards were installed. Our own experiences in seeing our VIs used in the field all over the world, in vastly different environments, for well over 40 years, showed that with proper vacuum quarantine testing carried out in the VI manufacturing plant, VIs are "sealed for life". A VI can and should continue to be used for as long as it passes a high voltage AC withstanding test, showing that it still has an acceptable vacuum. As far as we know, those VIs we manufactured in 1968 are still operating reliably. In fact, an analysis in 1998 of an Eaton (formerly Westinghouse) VI that had been in the field since 1970 showed an internal pressure of 1×10^{-3} Pa.

Once the VIs have gone through the final assembly, evacuation and brazing process, the completed product has a vacuum lower than 10^{-2} Pa sealed inside it. The usual method for measuring the vacuum level is the magnetron method (Kageyama, 1983a; 1983b). The magnetron method for measuring pressure has been found to be extremely reliable and is easily incorporated into the VI manufacturing process. One misconception we have encountered is that the lower the residual vacuum level inside a VI, the better it will perform electrically. In fact, we have purposely manufactured and tested a VI with a high residual pressure of 10^{-1} Pa. Its short circuit current interruption ability and its high voltage dielectric withstanding performance are equal to similar VIs that have a final pressure of 10^{-3} Pa. Thus, if the pressure of the residual gases inside the VI is significantly (~2 orders of magnitude) lower than the Paschen curve's minimum value (10 Pa), the VI will perform perfectly.

Unlike other enclosed interrupting systems such as SF_6 puffer interrupters, the VI must be constructed to have a zero leak rate. There are some publications (Okawa *et al*., 1987) that discuss a leak rate to give a 30-year vacuum life (i.e. reach an internal pressure of 10^{-1} Pa). However, these reports do not take into consideration the unique nature of vacuum seals and vacuum leaks in an external ambient such as atmospheric air. What really matters is to determine what size of leak can be tolerated. No one really knows the true length of time that commercial VIs can retain a vacuum below 10^{-1} Pa. In our own experience with VIs manufactured by Eaton Electrical (formerly Westinghouse) the field experience goes back to 1968. As far as we know, those VIs we manufactured in 1968 are still operating reliably. A greater than 30 year life expectancy certainly imposes a very strict requirement on the leak-tightness of the VI envelope and all the braze joints that are exposed to the ambient environment. If we conservatively assume a maximum allowable VI pressure of 10^{-3} mbar or 10^{-1} Pa (a commonly accepted criterion), then the maximum amount of gas N_{max} allowed to leak into a VI of volume V_{int} is:

$$N_{max}=\Delta P V_{int}=(0.1-P_0)V_{int}\approx 0.1 V_{int} \text{ Pa·L}, \quad (2)$$

where P_0 is the initial vacuum level inside the VI. The amount of gas that can leak into the VI depends upon the size of the leak:

$$N_{max} = \int_{30\text{ years}} Q\mathrm{d}t, \quad (3)$$

where Q is the leak rate.

The Q_{max} for a given time t is:

$$Q_{max} = \frac{\Delta P V_{int}}{t} = \frac{(0.1-P_0)V_{int}}{t} \text{ Pa}\cdot\text{L/s}. \quad (4)$$

Using Eq.(4) it is possible to calculate the Q_{max} for a 30 year life:

$$Q_{max} = \frac{N_{max}}{30} = \frac{0.1V_{int}}{30\times 365\times 24\times 3600} \text{ Pa}\cdot\text{L/s}. \quad (5)$$

Table 3 lists the maximum leak rate allowed for VIs with volumes ranging from 0.5 to 4 L to reach 10^{-1} Pa as a function of time. Thus, to obtain a 30-year lifetime, the Q_{max} allowed is about 10^{-10} Pa·L/s. This is two orders of magnitude beyond the practical detection capability of 10^{-8} Pa·L/s for the typical helium leak detector (ASM 142/ASM 142D Helium Leak Detector, 2005; VVPC, 1996). Table 3 shows that the latter leak rate value would only guarantee a lifetime of about one-month. Why, then, is the practical experience by VI manufacturers of lifetimes in excess of 30 years? Fortunately, nature works in their favor. Leak rates of about 10^{-8}~10^{-10} Pa·L/s may require a bake out to become detectable. Leak rates of about 10^{-9}~10^{-8} Pa·L/s or less are most likely plugged permanently when exposed to open air at one atmosphere (Wilson and Beavis, 1976). Leak rates smaller than about 10^{-8} Pa·L/s are of no practical importance for the vacuum life of the typical VI. A leak check level to that sensitivity is enough to guarantee its vacuum integrity over its required lifetime. From the data given in Table 3, it can safely be said that if a VI with an internal volume of 1 L does not show a pressure of 10^{-1} Pa within one month, it does not have a leak larger than 4×10^{-8} Pa·L/s and will, therefore be unlikely to leak further for its entire application life. This, of course, presupposes that the

Table 3 Maximum leak rate for VIs to achieve a given life-time

Internal VI volume (L)	Q_{max} (Pa·L/s)					
	30 years	10 years	5 years	1 years	1 month	1 week
0.5	0.5×10^{-10}	1.6×10^{-10}	3.2×10^{-10}	1.6×10^{-9}	1.9×10^{-8}	8.2×10^{-8}
1.0	1.1×10^{-10}	3.2×10^{-10}	6.3×10^{-10}	3.2×10^{-9}	3.8×10^{-8}	1.6×10^{-7}
2.0	2.1×10^{-10}	6.3×10^{-10}	1.3×10^{-9}	6.3×10^{-9}	7.6×10^{-8}	3.3×10^{-7}
4.0	4.2×10^{-10}	1.3×10^{-9}	2.5×10^{-9}	1.3×10^{-8}	1.5×10^{-7}	6.6×10^{-7}

VI is not subjected to abusive handling or corrosive ambients that can generate unexpected leaks. This analysis leads to a straightforward and effective method for assessing vacuum integrity and expected life of a VI by measuring its high voltage withstand level. The VI should be opened to its design contact gap and the withstanding high voltage value can be measured. The process can be illustrated using the Paschen curve. A typical VI can withstand a voltage of 50 kV (RMS) for a contact gap of 10 mm and a pressure inside the VI of 2×10^{-2} mbar. Thus, a worst case leak or maximum leak rate, Lr_{max} (per unit internal volume) would be:

$$Lr_{max} = \frac{2\times10^{-2}}{y_1} \text{ mbar/year}, \quad (6)$$

where y_1 is the age in years since the VI's manufacture. A VI would have an unacceptable high voltage performance at a pressure of 3×10^{-2} mbar. Thus the minimum time to reach this pressure y_2 would be:

$$y_2 = 3\times10^{-2} / Lr_{max} = 3y_1 / 2 \text{ years}. \quad (7)$$

Now if the VI is tested after a time y_2-y_1 and it still withstands 50 kV (RMS) then Eq.(6) and Eq.(7) can be used to calculate a new minimum life for this VI. Table 4 shows that it only takes 7 test sequences to ensure the VI's integrity for 30 years. In fact in our experience if a VI has been in the field for 5 years without showing any sign that it has a small leak, it will never leak.

Table 4 Life time calculation integrity of a VI using a high voltage withstand test

V	Lr_{max}	Y_1	Y_{min}	Y_2
1	2.0×10^{-2}	0.5	1.50	2
2	1.0×10^{-2}	1.0	3.00	3
3	6.7×10^{-3}	1.5	4.50	5
5	4.0×10^{-3}	2.5	7.55	8
8	2.5×10^{-3}	4.0	12.00	12
12	1.7×10^{-3}	6.0	18.00	20
20	1.0×10^{-3}	10.0	30.00	30

V: withstands 50 kV high voltage after y_1 years after manufacture (pressure $\leq 2\times10^{-2}$ mbar); Lr_{max}: leak rate (mbar/year) to reach 2×10^{-2} mbar since manufacture; Y_1: years to reach 3×10^{-2} mbar after the HV withstand test; Y_{min}: minimum years after manufacture to reach 3×10^{-2} mbar; Y_2: years after manufacture for the next HV withstand test

There are three advantages in using this high voltage test method:

(1) It is relatively easy to perform.

(2) The mechanism only has to be isolated from the circuit and the voltage can be applied across each VI in turn. The VI does not have to be removed from its mechanism.

(3) The test also measures the insulation integrity of the circuit breaker/switch system and not just the vacuum integrity of the VI.

It is important to note that an insulation resistance test normally applies a test voltage of 5~10 kV, which is too low to assess the vacuum integrity of VIs.

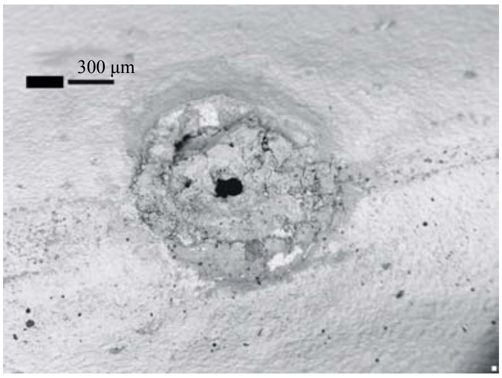
Ambient effects

One consequence of the VI's proven high reliability and its property of being maintenance free for its operating life is that it can be incorporated into sealed chambers. Once installed in such chambers the VIs are usually inaccessible. At distribution voltages of 24 kV and higher compact switchgear have been developed that surround the VI with SF_6 gas (Lav *et al*., 2004) or encapsulate it in a solid dielectric material such as cyclo-aliphatic epoxy (Leusenkamp *et al*., 1996). Each of these developments is successful, because the VI is sealed for its life and does not require replacement once it has been installed.

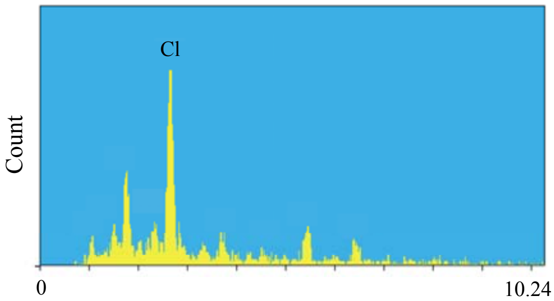
There are some characteristics of the interrupter that can lead to failure if care is not taken. Most if not all of the cases of vacuum integrity failures are caused by a new leak generated later once the VI has been installed as a result of either mishandling, e.g. twisting the bellows, or fatigue failures of the braze joints by inadequate mounting of the VI in the breaker or misuse of the breaker.

VIs are generally assembled from high purity metal, such as OFHC copper and stainless steel, which are susceptible to corrosion in certain environments. For example, in paper mills and wastewater treatment facilities, hydrogen sulfide gas is commonly found. The silver used in the braze joints can react readily with this gas until the integrity of the braze joint is compromised, leading to a loss of vacuum. In order to protect against this type of corrosion, many VI manufacturers apply a protective coating to these joints. If the VI is to be used in a corrosive environment, care must be taken to not scratch or remove this protective coating. Likewise, if the VI is to be used in a corrosive environment, it is a good idea to perform an annual visual inspection of the VIs to look for corrosion, in addition to a yearly high voltage test.

In the aftermath of the flooding caused by Hurricane Katrina in New Orleans in the US, it was apparent that VIs that have been submerged were also at risk. Coastal floodwaters often contain salts, which have chlorine as one component. The stainless steel used to make the bellows and the copper component of the braze material are susceptible to chlorine-based corrosion (Fig.5). Even if the VI is externally cleaned after being immersed, it should not be used, as chlorine-containing water can become trapped in the bellows of the interrupter leading to corrosion of the stainless steel bellows. Even relatively "clean" waters, such as municipal water supplies should not be allowed to come into contact with the interrupter, as they frequently have up to 4×10^{-6} of chlorine added to control the growth of microbes.



(a)



(b)

Fig.5 (a) Example of a hole in a bellows from chlorine corrosion; (b) The surface spectra of the area around the hole, showing the presence of chlorine

CONCLUSION

(1) The modern VI using state-of-the-art processing techniques ensures a vacuum tight construction for the greater than 30 year life of the VI.

(2) The VI provides a reliable maintenance-free operation for its full electrical life.

(3) The VI is used in long-life reclosers, vacuum circuit breakers, load break switches and contactors.

(4) The VI can be matched to all types of operating mechanisms and its opening can be precisely controlled.

(5) The VI proven versatility will result in its having an even wider role in the control and protection of electrical circuits.

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