Breaker Monitoring with Numeric Relays

By John Horak and Gerald Dalke
Basler Electric

There is a number of functions that a digital or numeric relay can perform with respect to what is occurring in a power circuit breaker:

- Predictive Maintenance
  - Circuit breaker duty/Contact wear monitoring
  - Number of operations
  - Slow circuit breaker trip
- Circuit Breaker Failure
  - Failure to trip
  - Open trip coil
  - Failure to close
- Recording Capabilities
  - Oscillography
  - Sequence of events
  - metering
  - Demand data and alarms

This paper will focus on the first item in the list, capabilities of numeric protective relays to monitor breaker wear. An acknowledgement is given to the recording capabilities of relays to do "post mortem" analysis of events and perform breaker failure relaying (50BF). Figure 1 shows several such recording features of various events: an oscillographic record, a fault summary, and a phasor representation of different events. Event reports such as these, and the breaker failure function, are expected as a matter of course in modern numerical relays from any serious player in the market, so these features are no longer the "new cool toy" in today's market. This presentation is, instead, aimed at the question, "What are the issues associated with Breaker Duty/Contact Wear Monitoring from the perspective of what the modern numerical protective relay can easily monitor?"

What are the difficulties?

The difficulties can be broken down into three categories:

a) *Unclear Circuit Breaker Ratings:* There is a multitude of circuit breakers on the market with varying interrupter duty ratings as stated by the manufacturer, but it can be difficult to ascertain how these ratings correspond to actual conditions to which the breaker is subjected. While SF6 and vacuum technologies rule in new circuit breaker designs, there is a multitude of air blast, and air-magnetic circuit breaker designs in service, although no longer manufactured, and oil circuit breakers usually only for special applications. Within any one general design, each manufacturer has a unique way of doing things, and breaker design evolves over time.

b) *Older Designs:* If starting a monitoring program of an older design breaker today, it will be very difficult to account for the history of the breaker's maintenance and past application.

c) *Contact Wear Variables*: There are many factors that are not easily determined which are associated with the wear a circuit breaker may experience during an operation. Some factors that affect performance include the following:

- Various circuit breaker designs;
  - o Oil, Air-Magnetic, Air Blast, Vacuum, SF6; each has a different level of internal arcing energy and arcing duration;
  - o Within any one manufacturer's design, there may be additional sub-designs
- Energy in a circuit breaker arc is hard to analyze; protective relays cannot or do not commonly have the ability to determine the following:
  - o Control system voltage effects on mechanism operating speed;
  - o Changing R_{arc} of circuit breaker;
  - o Current magnitude throughout the operation, such as evolving fault effects and faults with some dc offset remaining at point of interruption;
  - o Arcing time (measurement may require data entry from a breaker travel analyzer);
  - o Variations in circuit breaker speed from one operation to next;
  - o Where contacts part in the voltage/current wave;
  - o Power factor of interrupted current;
  - o CT saturation, particularly saturation caused by dc offset;
  - o Fast reclose on heated circuit breaker contacts
  - o Multiple breaks on HV circuit breakers and lack of coordination of multiple break;
  - o Additional wear that may be caused by nonstandard reclosing internals;
  - o For number-of-operations-based maintenance, differentiating between no-load, load at rated current, and fault conditions;
  - o Mechanical condition of the circuit breaker, and its history of previous operations and breaker maintenance.

With this extensive list of things that can confuse a relay that is monitoring circuit breaker wear, it should be apparent that the reports available from a relay are a highly approximated number giving general concepts and, hence, cannot be exclusively relied upon for an accurate measurement of when a circuit breaker needs internal maintenance.
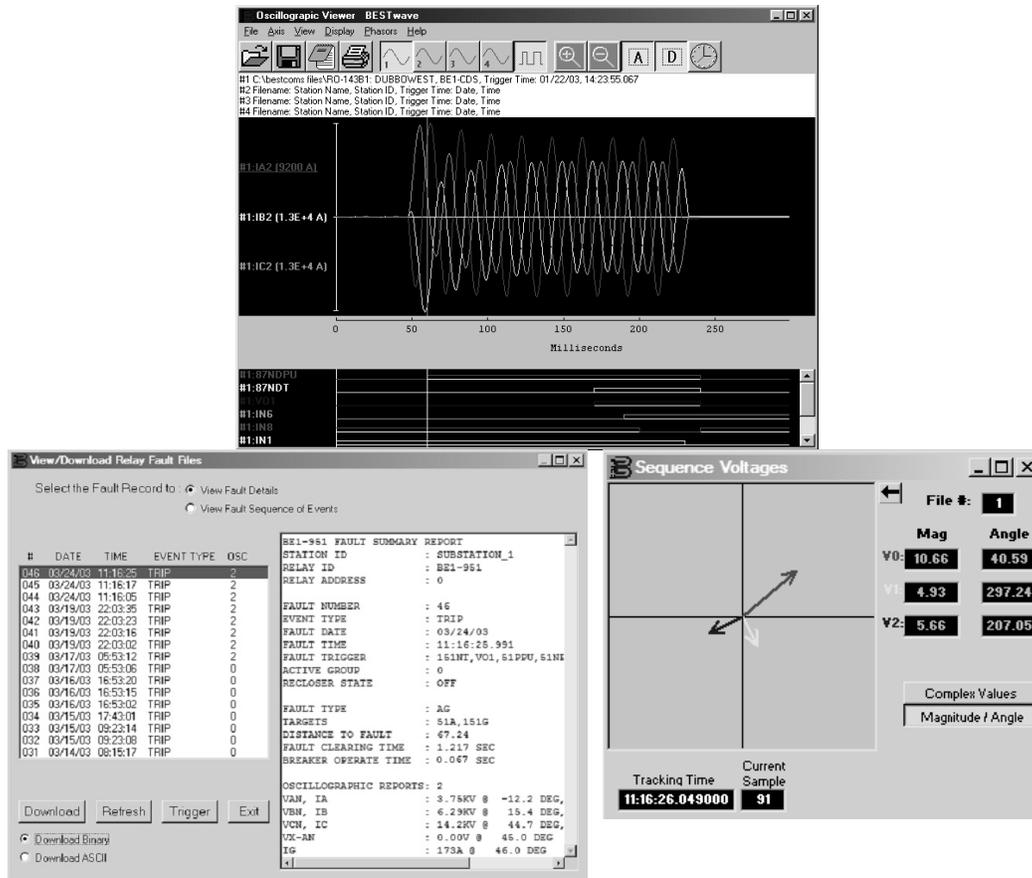
Figure 1a, 1b, 1c: Event Report Formats

Circuit Breaker Designs and Circuit Breaker Wear

Oil Circuit Breakers

Few oil circuit breakers are being manufactured today, but many are still in service. The oil serves two purposes: It is an insulator between energized elements and the grounded portions of the breaker, and it acts to quench the arc. When the contacts part, an arc begins and vaporizes a small portion of the oil. This vaporization absorbs substantial amounts of energy from the arc. The gas that is created is mostly hydrogen, which does not remain in the ionized state easily. Further, the oil cools the arc by thermal conduction to the surrounding bulk oil. The energy required to maintain the gas bubble is large, and the oil can cool and quench the arc at the current zero cross.

The contacts of dead tank oil circuit breakers are enclosed in metal, grounded tanks (Fig. 2A). In the early and lower voltage designs the arc is allowed to occur without any special arc extinguishing scheme except the one provided by the cooling act of the oil surrounding the arc gas bubble. In higher voltage and more advanced designs, arc extinguishing is supplemented with specially-designed arc chutes and directed oil flow surrounding the breaker contacts (Fig. 2B). In cross blast interrupters, the arc is pulled in front of several lateral vents and forced into the vents, which lengthens the arc and shortens the interruption time. The axial blast

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interrupters use a similar principle as the cross blast, but the arc is not as directed, which tends toward poorer performance.

The arc control for the minimum oil breakers is based on the same principle as the arc control devices of the bulk oil breakers, but is designed to reduce oil requirements. This is accomplished by a) utilizing a live tank design; therefore removing the role of the oil as insulation between the conductors and ground, and b) utilizing an oil injection technique to extinguish the arc.

Series Break:

As for all breaker designs, for higher voltages the interrupters are arranged in series. For series break devices, the design must ensure that all breaks occur simultaneously so that the interrupted voltage is divided equally across the breaks during the interrupting process in order to create even wear and high interrupt capacity. A natural voltage division depends on any unreliable stray capacitances between the contacts and to the ground and, therefore, relies on capacitances or resistors in parallel with the interrupting heads to balance the voltages between interrupters. Series break is shown and discussed further later (Fig. 12).
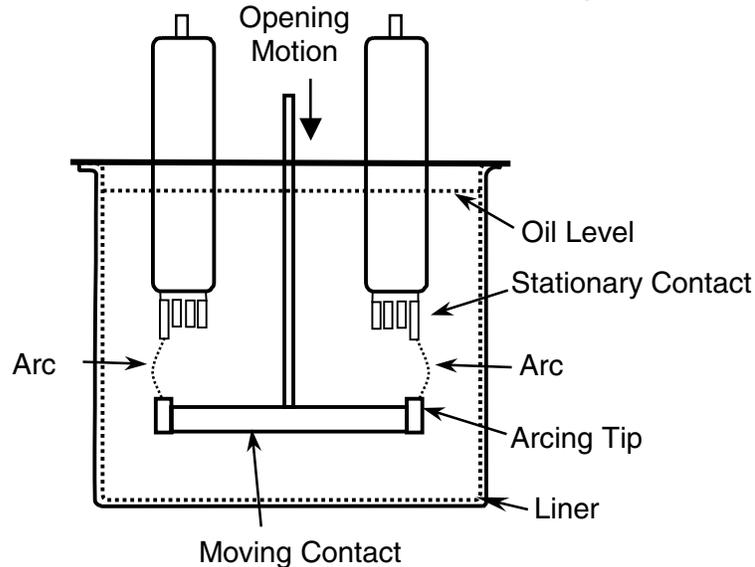

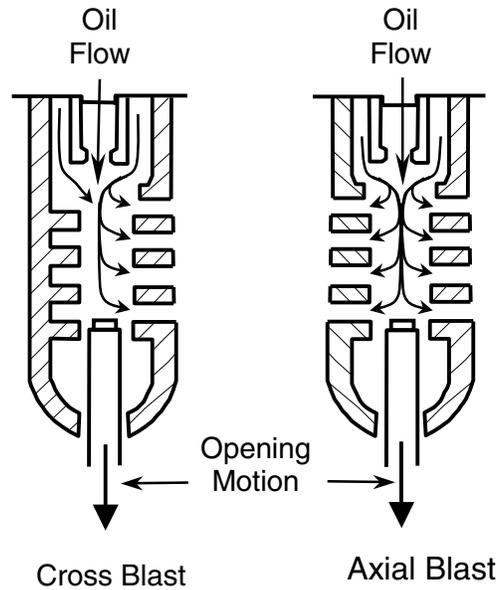**Figure 2A: Plain Break Bulk Oil Breaker**

Figure 2B: Arc Controlled Oil Breaker

Air Break Circuit Breakers

Air-break circuit breakers (sometimes referred to as air-magnetic circuit breakers) extinguish an arc in a normal atmospheric environment by stretching it until the cooling of the gas at the current zero cross can rise fast enough to prevent restrikes. The longer arc has a larger cooling surface, thus cooling increases and deionization of the gap between the contacts improves. The increased length of the arc also increases its resistance and, therefore, decreases the current flow and the amount of heat per unit length of the arc that is created. To increase the length of the arc, the arc is stretched by forcing it into an arc chute with either natural convection of the hot gas, by blowing air through the arc, or by using a magnetic blowout coil. The magnetic blowout coil creates magnetic force on the arc that pushes or pulls the arc into the arc chute. There are two types of arc chutes in air break circuit breakers (Fig. 3). One type is made of insulating material, and its function is to stretch the arc. The other type is made of metal. The metal barriers divide the arc into a series of many smaller arcs. The voltages across these smaller arcs are much lower than the total voltage across the breaker contacts and, therefore, it is easier to extinguish the arcs.
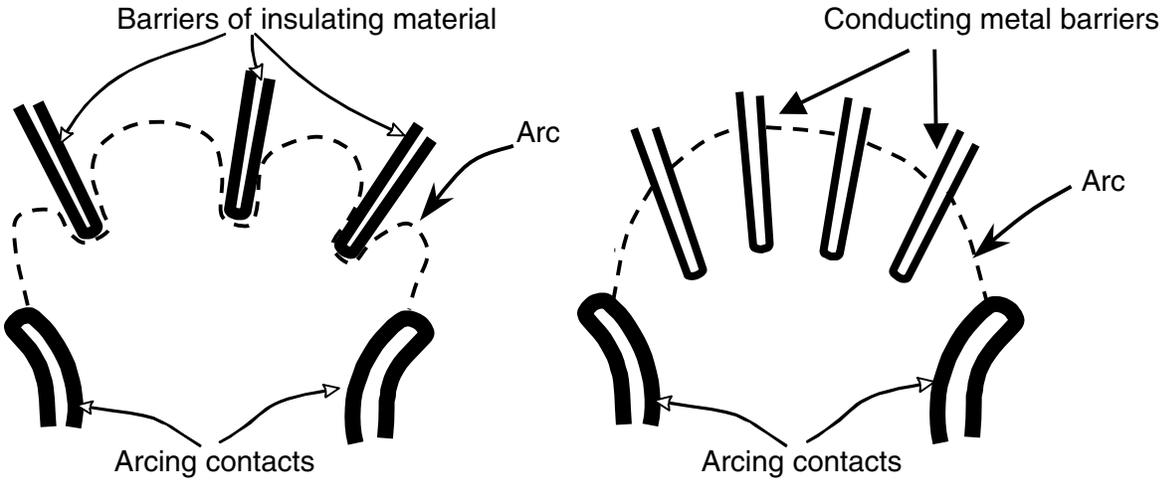
Figure 3: Air Break Circuit Breaker Designs

Air Blast Breakers

A blast of compressed air can be blown into the arc perpendicular to the arc (cross blast Fig. 4A) or along its axis (axial blast Fig. 4B). The cross blast use is limited, because it is difficult to develop the air velocity needed for high voltage breakers across the entire interrupting area. In more recent breakers the axial blast is more common. Air blast breakers have a tendency to chop currents when interrupting low level currents and have subsequent restrikes, adding to contact wear. Unclean or insufficiently dry air will slow arc clearing, increasing contact wear.
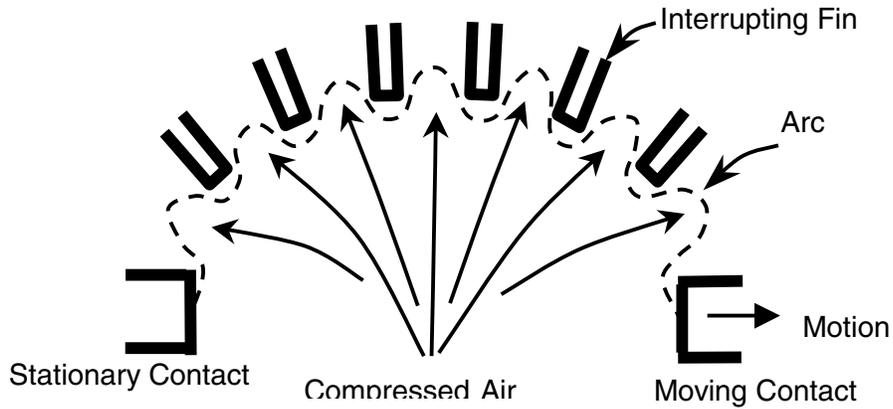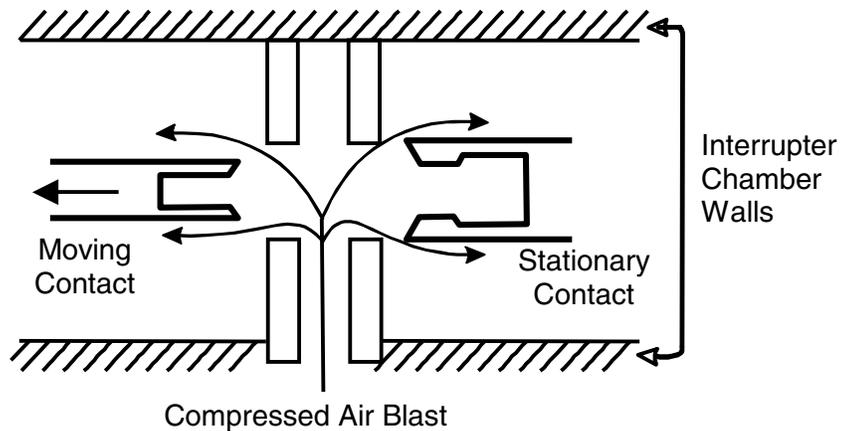

Figure 4A: Cross Air Blast

Figure 4B: Axial Air Blast

Vacuum Breakers

Vacuum circuit breaker interrupters (Fig. 5) are used mostly for medium voltage applications. Vacuum interrupting heads have been developed for up to 38 kV per break. For higher voltages, the interrupters are connected in series, though vacuum breakers are not commonly seen at high voltage.

When contacts separate, a portion of the metallic contact material is vaporized, so the vacuum is partially lost, and this vaporized metal is the conducting media for the arc. At the current zero cross, these vapors rapidly condense on the surrounding surfaces (particularly the contact surfaces) and the vacuum is restored as well as the high dielectric properties of a vacuum. There is a detailed science behind the contact surface material and the shape of the contact. The shape of the contact and the distribution of contact surface materials effects how the current in the arc is distributed as the contacts separate and as the arc progresses. For even wear, one design factor is to attempt to keep the arc diffused over the entire surface area, fighting the tendency of arcs to concentrate at a single point. The earlier copper- bismuth contact material had some tendency to condense too quickly (especially at low arcing levels) and, therefore, break down the conducting arc before a normal current zero, which creates a high di/dt, hence, high transient voltages. Present designs reportedly use a surface material made of sintered copper and chromium powders and do not have current chop issues.
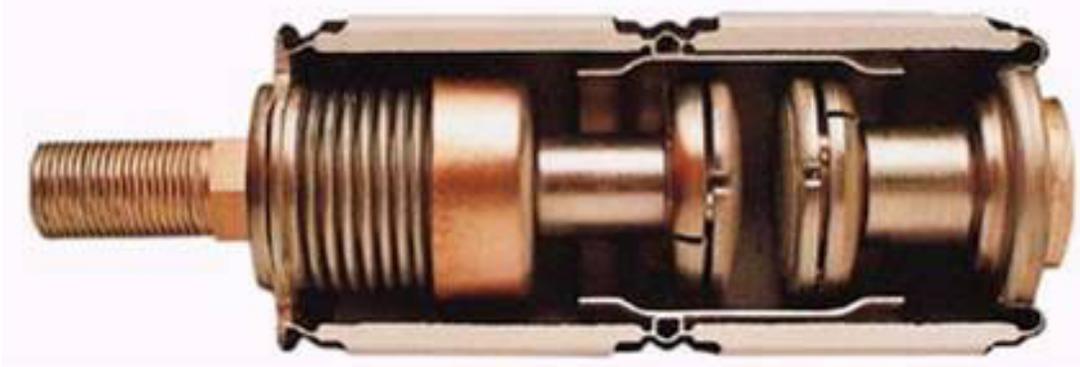

Figure 5: Vacuum Breaker

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SF6 Breakers

In the puffer design (Fig. 6), the arc is extinguished by blowing compressed SF6 gas through the arc via a nozzle near the arcing contacts. The mechanical energy required to compress the gas increases very rapidly with the breaking capacity, and the size of poles and control mechanism tends to be larger, so that 25 kA is a typical upper end design for this technology. While higher interrupting ratings can be achieved with this design, the thermal assist design is a more cost effective means to break high currents.

The thermal assist design (Fig. 6) uses a chamber in which SF6 gas is heated by the energy of the arc, which causes the SF6 gas pressure in the chamber to increase. This gas, when released, extinguishes the arc. This allows the operating mechanism to be smaller because the extinguishing energy comes mainly from the arc. However, for low current interruption a puffer chamber is needed to assist arc interruption due to the low energy that is available in the breaker arc, hence, the low pressures and gas flow rates that are achieved.

A small portion of SF6 will disassociate in the high heat of the interrupting arc, which, in the presence of any moisture and vaporized metal, can create some corrosive chemicals.
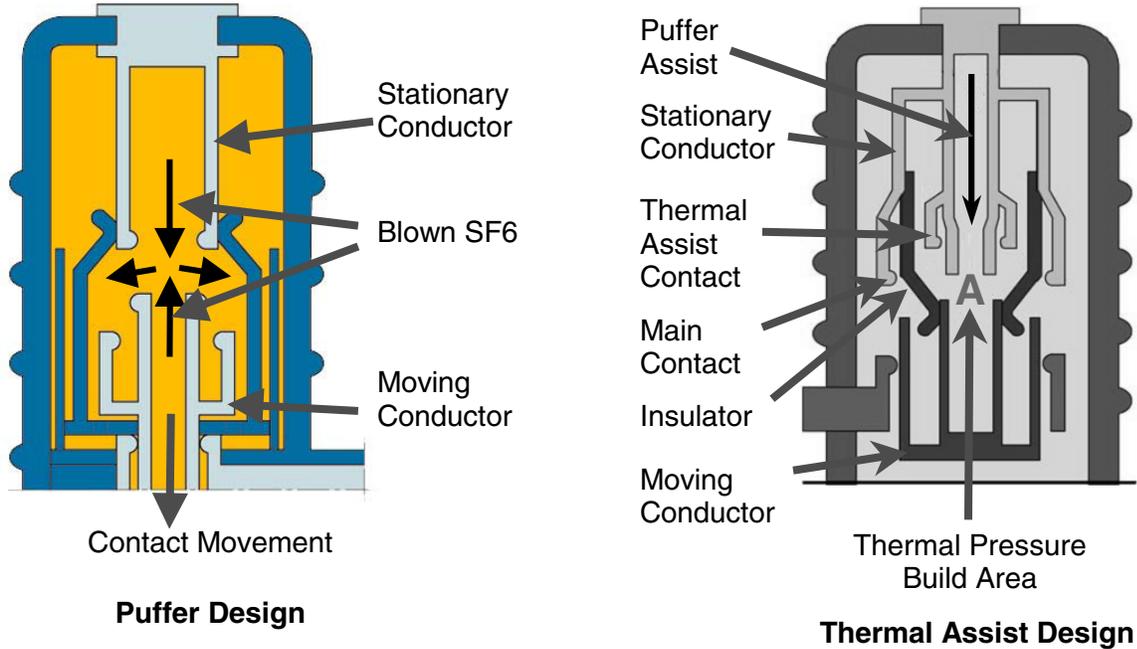

Puffer Design

Thermal Assist Design

Figure 6: Two SF6 Designs

Concept of Contact Wear: Energy in Breaker Arc

A numeric protective relay can supply a value of interrupted current to use in energy calculations. The energy that has been interrupted can be estimated from the interrupted current recorded, but it is not easily done. Neither the voltage across the circuit breaker ($V_{arc-bkr}$) nor the resistance of the arc ($R_{arc-bkr}$) is easily determined. Also, current and voltage are changing more rapidly than the relay is designed to monitor. Values of $R_{arc-bkr}$ vary over time through the interruption process in a nonlinear fashion, discussed further below.

$$Energy_{arc} = \left(I_{arc} \cdot V_{arc-bkr} \right) dt$$

$$V_{arc} = I_{arc} \cdot R_{arc-bkr} \qquad\qquad \text{Eqs. 1-3}$$

$$Energy_{arc} = \left(I_{arc}^2 \cdot R_{arc-bkr} \right) dt$$

A common approach used by numeric relays is to use a value for $I_{fundamental}$ determined just prior to current interruption, and to assume contact wear is proportionate to I^2. Other exponents are sometimes used, ranging from 1 to 2, and some use a different exponent value for different current levels. One reason for confusion about which exponent to use is that $R_{arc-bkr}$ is nonlinear and nonconstant during the interruption process, while the relay measures average, rms, or fundamental frequency current levels.

Changing R_{ARC} During Fault

The diagram of Figure 7 is intended to indicate more clearly the difficulty in determining how much energy is dissipated inside the circuit breaker during the fault. The system impedance and the impedance of interrupted load stays relatively constant and tends to be the ruling component that determines fault current and load current. However, the fault arc impedance and the internal circuit breaker arc impedance may vary during the fault and tend to rise at each current zero crossing, and then goes very high at the fault clearing point. Hence, the voltage across the circuit breaker arc varies as the fault progresses and as the current approaches and departs from the zero crossing point. (See Reference 1)

The humps in arc resistance shown in Figure 7 are intended to show conceptually the tendency of the arc to break down at each zero cross. A circuit is broken when the resistance rises fast enough and high enough to prevent the arc from continuing. In a vacuum or SF6 breaker, the rate of rise to dielectric strength at each current zero cross is tremendous, likely leading to blocking current flow at the first current zero cross after the contacts part. The gradual rise in the circuit breaker arc resistance indicates the increasing arc length as the contacts part such as in older interruption technology. This also is good for conceptually illustrating what is occurring when current is interrupted in any circuit breaker. The final steep rise in the arc breakdown at the final current zero cross represents the rapid rise of dielectric strength as the current flow is blocked. The gradual decrease in fault resistance represents an evolving arc with an increasing amount of conducting ionized gases.
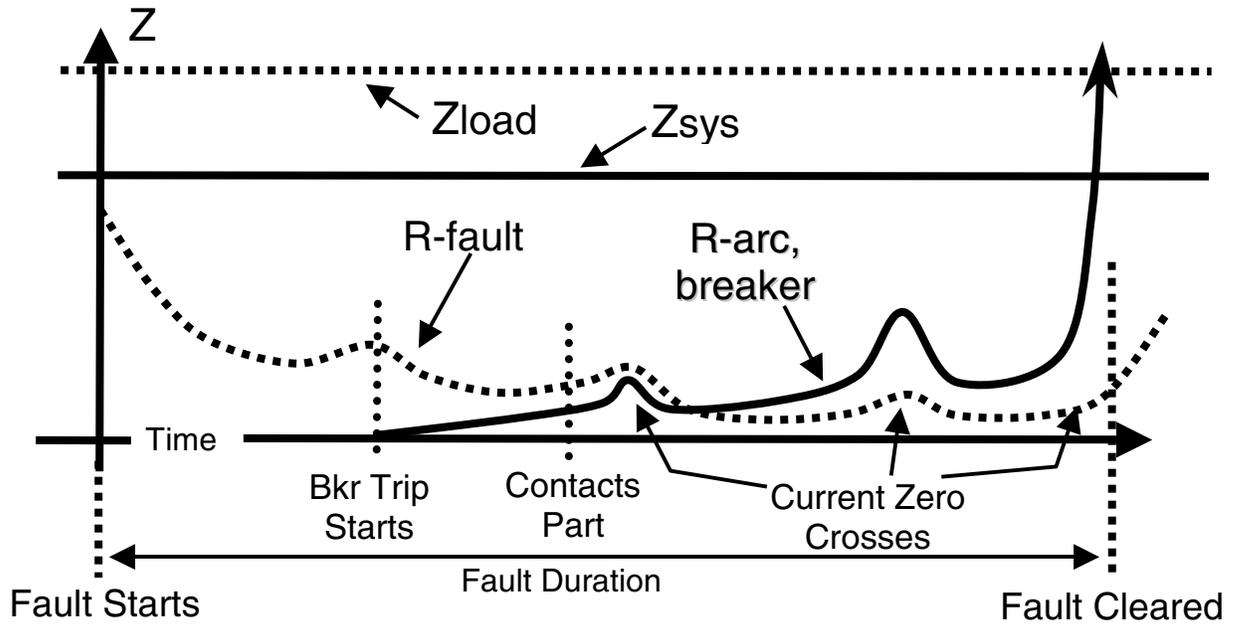
Figure 7: Changing R_{ARC} During Fault

Arcing Time vs. Circuit Breaker Mechanism Travel and 52a/b Contact

The relay may or may not know when a breaker trip command is issued to the breaker. However, for accurate measurement of breaker arc time, the relay needs to know some information that correlates breaker contact parting to some other input to the relay, most commonly a 52a or 52b breaker position indicator. The value Tc in Fig. 8 provides this information. The difficulty is that such data requires a breaker travel analysis that compares main contact travel information as compared to the 52a/b travel. Such data may not be readily available. However, even if a travel analysis were done, there may be some area where grading resistors may be in place that will affect the arc pattern and the contact wear and is yet another confusing point on the energy dissipation in the breaker during the opening process. Relays will also know when current reaches a 0 level. Once the point where the main contacts part is known and the current zero is known, the relay can give an estimate of actual I^2Rt (although R must be an estimate, so only I^2t is all that actually can be collected).
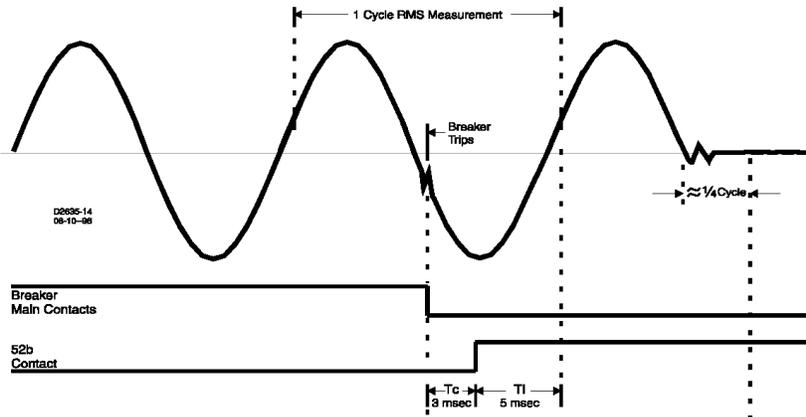
Figure 8: 52a/b vs. Breaker Arcing Time

The point at which the 52a and 52b contacts change state relative to the status of the main contacts varies among circuit breakers. The only common thing is that the 52a and 52b auxiliary contacts will not be closed simultaneously and that the 52a and 52b, because they do not change state simultaneously, are not true inverses of one another (Fig. 9). There are also other types of 52 contacts, variously named 52aa, 52a', 52a'', 52bb, 52b', etc. used in anti-pump circuits and sometimes available for external applications, that have slightly different timing.
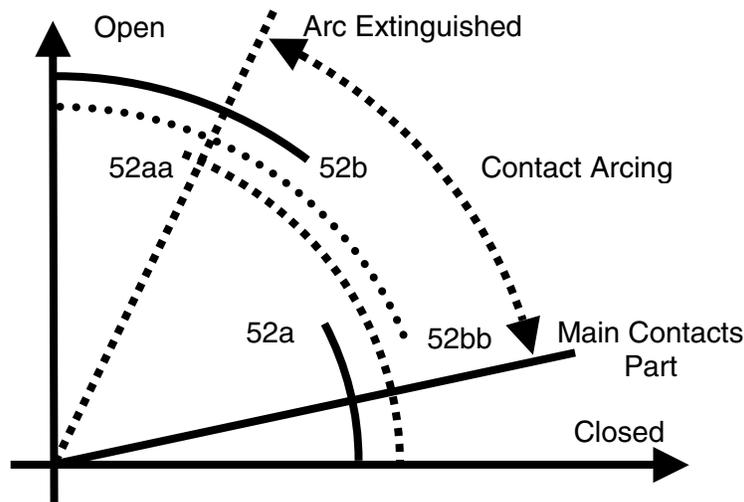
Figure 9: 52a/b vs. Breaker Travel

Circuit Breaker Mechanism Speed Variations

Circuit breaker mechanism operate time is fairly consistent, but there are no guarantees that every mechanical operation will occur at the same speed for each fault cleared over the same time period. Some items that can affect circuit breaker mechanics or clearing time are control system operating voltage, time since last operation, temperature, age, mechanical wear, pneumatic pressure, where in the sine wave the trip command is issued (which affects the time

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to the next current zero cross), and in some circuit breaker designs (particularly air magnetic) the current in the circuit breaker (low currents are interrupted more slowly then high currents).

Power Factor Effects on Contact Wear

The power factor of the load also affects contact wear. At the moment the arc is broken and the current is driven to 0, the system voltage in the circuit must appear entirely across the contacts. In low power factor loads (capacitor banks or inductors) or faults, when a current zero occurs, there is high voltage across the load or system power delivery equipment. To successfully break the arc, this load or equipment voltage must be transferred from the load or equipment to the interrupter very rapidly, hence a high dR/dt is required of the interrupter relative to what would be required to break high power factor loads.

Note that the energy developed in the interrupter is $P = V * I$. At the moment that current is being interrupted (Fig. 10), V is rising higher in low power factor loads relative to the same current in high power factor loads, so there is more energy dissipation in the breaker when interrupting low power factor loads compared to high power factor loads. High power factor loads cause much lower interrupter voltage at the point current is interrupted, so less energy is dissipated in the breaker at the moment of interruption. Also, at high power factor, the breaker is less prone to restrikes, and current is possibly cleared earlier in the interrupter opening process.
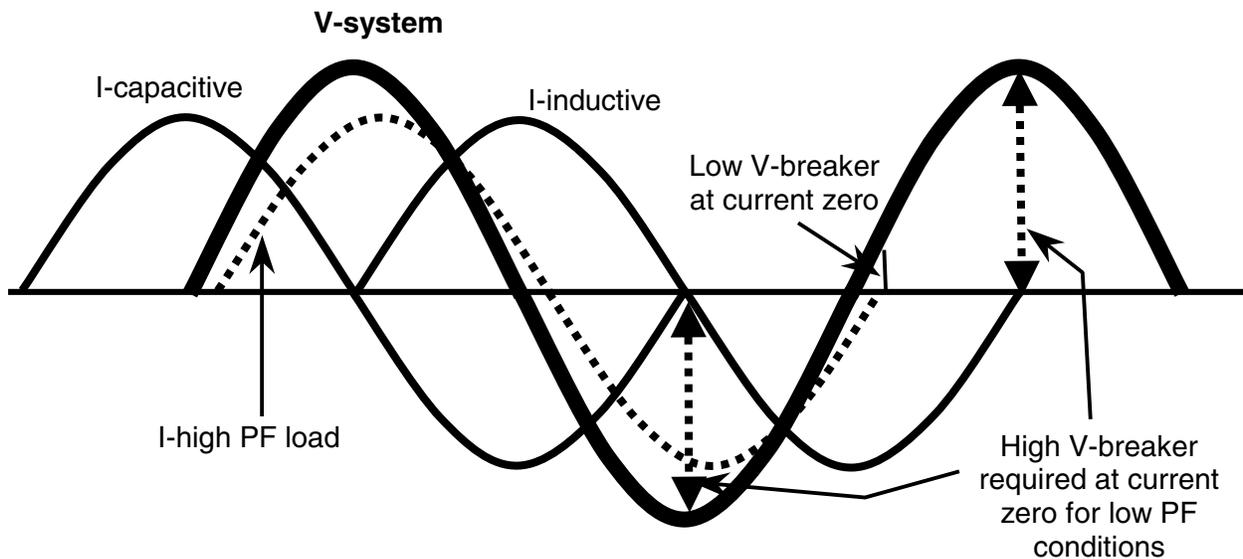
Figure 10: Power Factor vs. Breaker Interrupting Voltage

DC Offset Effects on Breaker Wear

DC Offset increases the current that a breaker carries relative to the symmetrical waveform. Relays that report fundamental current and filter out DC (most relays) give a low report of interrupted current. The first half cycle of a highly offset wave (Fig. 11) will have an RMS equivalent that is about 1.6 times the RMS value of a non-offset wave. By the time a breaker begins its opening process, much of the DC offset has fallen off or decayed, but this may not always be the case.

A couple of slightly related issues that may be good to be aware of are: a) Most short circuit software will give the symmetrical fault level that will be seen in a fault, and some give the RMS symmetrical equivalent of the asymmetrical waveform. Be aware of what the fault study is reporting, and b) Beginning in 1964, ANSI Standards began the change to rating breakers on a symmetrical current basis [2]. This allowed the end user to avoid the confusing aspects of trying to determine the DC offset's equivalent symmetrical current value at the breaker's location or to apply multiplying factors when the breaker interrupting time was faster than a specified interrupting time. Breakers made before the ANSI "Total Current Breaker Rating" Standards of 1953 did not consider the effects of asymmetrical current level.
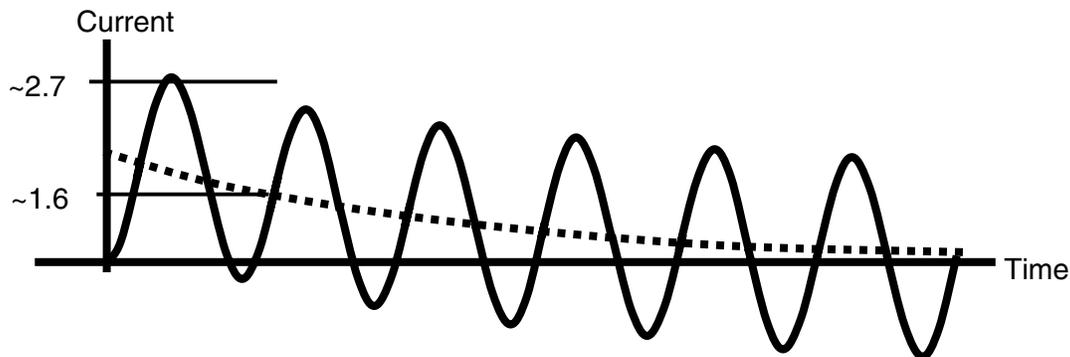

Figure 11: DC Offset Example

Effects of Multiple Series Breaks

Extra High Voltage breakers frequently have multiple breaks, with a grading resistor or capacitor that is held in place until late in the opening process (Fig. 12). Typical relay monitoring of interrupted current can only give one measure of overall interrupter wear. If one contact is worn more than others due to lack of contact opening coordination, breaker wear measurements based on interrupted current will miss the problem. Measuring for uneven wear on multiple break breakers requires high voltage breaker analysis at routine maintenance testing.
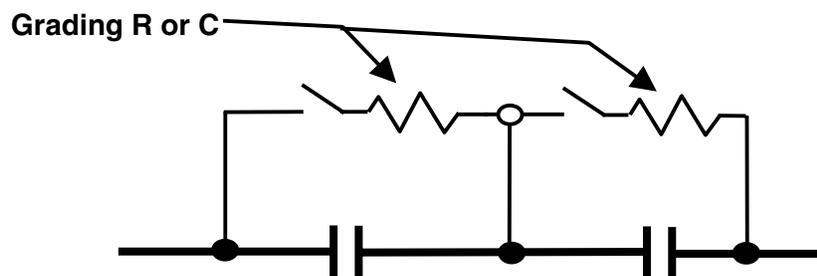

Figure 12: Multiple Series Breaks

Fast Reclosing Effects on Breaker Wear

Since modern circuit breakers have much better heat dissipation, reclosing may not seriously affect contact wear. However, if following IEEE Standard C37.04 guidelines, some derating of

the breaker may be called for. A fault heats up interrupter contacts, so if subsequent rapid operations occur with heated contacts, they are more likely to be damaged. The standard CO duty cycle is, as defined by ANSI/IEEE C37.04-1999, two operations with a time interval of 15 s between operations (CO + 15 s + CO). This means that the circuit breaker should only operate twice at its rated symmetrical interrupting capability current with 15 s of dead time between operations. If reclosing is set to occur faster, then the standards provide a method of calculating derating factors to reduce the rated interrupting current. The effects of unscheduled faster reclosing are not compensated for in the programming of numeric relay duty monitoring.

Close Operation Effects on Breaker Wear

C37 Standards for breaker ratings are based upon the number of Close/Open operations. It is typically assumed that the open operation causes most contact wear, but closing operations also create wear. Protective relays typically are only monitoring the trip operations. If a breaker is always closed into a high load, it will have more wear than the breaker that is always closed into no load. Ignoring the effects of close operations in the relay will affect the accuracy of breaker contact wear measurements. However, since the contact wear calculation in relays is a highly approximated wear measurement, the error in not accounting for the close operation may be considered a negligible increase in the overall inaccuracy issue.

No-Load Operation Considerations

The typical circuit breaker is very highly rated mechanically, and the number of no-load operations is very high. The IEEE Standard C37.06 Operations Endurance Tables vary from 500 to 10,000 no-load operations depending on interrupting current, voltage, and full-load current ratings. Circuit breakers also have a "tighten, adjust, and inspect" requirement after 250-2000 operations. Due to the high number of no-load operations permitted, it is justifiable to ignore no-load operations in the relay duty information; however, the circuit breaker operations counter should be monitored to see when the number-of-operations-based maintenance is required.

Relay Testing Effects on Relay Wear Records

Relay testing will make a change in the accumulated circuit breaker duty that the relay reports, so accumulation of duty current needs to be defeated when applying current to the relay during testing. Numeric relays sometimes have a "Block Circuit Breaker Duty Accumulation" logic input feature that allows a relay to stop circuit breaker duty summation when relay testing is proceeding. If the relay lacks this feature, one must note circuit breaker duty data before starting tests and must reset data at the completion of the testing.

Circuit Breaker Duty Monitoring Capabilities of Numeric Relays

Numeric relays typically only record an rms or fundamental frequency value of the current at the approximate time when the circuit breaker interrupter opens. Thus, the relay can determine:
- Monitor the number of operations;
- Representative value of the total interrupted current;
- Monitor breaker opening time

The variations of total interrupted current found in relays on the market can be I^1, I^2, I^N, and other variations that vary the exponent N for current-level variations.

The next issue is to determine breaker duty settings for the relay. What ratings for the circuit breaker should be used? In order for a company to standardize on a program of planned circuit breaker duty monitoring using relay data, some simplified approach to interpreting circuit breaker duty ratings needs to be developed based upon the circuit breaker rating data that is commonly available, the limited ability of a relay to measure breaker wear, and the limited value of carrying the analysis to a very high degree of accuracy. Maximum circuit breaker short-circuit ratings and continuous current ratings are available from the manufacturer, but the number of allowed interruptions at some intermediate current level may not be available. An alternate position is to use standard values from IEEEC37.04 and ANSI C37.06 circuit breaker standards in lieu of manufacturer's data and then compare this to the current interrupted available from the relay.

Circuit Breaker Duty Rating Approximation

For a given circuit breaker, if one assumes a relatively constant arcing time *t* and a relatively constant R_{arc} in the circuit breaker, then one can assume the energy absorbed by the circuit breaker contacts will be proportional to the current interrupted. If two points of "number of operations at a given current level" can be obtained, then we can find an approximate means to determine when a circuit breaker has absorbed an approximation of maximum wear.

Assume that:
- Average arc time t_{arc} is relatively the same from one operation to the next.
- Averaged over the entire opening process, circuit breaker arc resistance $R_{arc-bkr}$ is relatively the same from one circuit breaker operation to the next.
- The result is energy dissipated in the circuit breaker proportionate to a summation of interrupted current, so we can assume that circuit breaker wear can be estimated from:

$$\text{Bkr Wear} \propto \text{Energy}_{arc-bkr} \propto \quad k \cdot I^N \qquad \text{Eq. 4}$$

The earliest relays and breaker wear concepts were based on energy being proportionate to I^2 but, in some cases, the concept of monitoring only I^1 was available; hence, N=2 or N=1 was used. Therefore, the relay would set k=1 and sum I^2 or I until a user-assigned maximum was reached. The problem is in determining the appropriate maximum. If one can determine a value for "number of operations at a given current level" data for the circuit breaker, then one can determine when a circuit breaker is approaching wear limits and needs internal maintenance. A position that will be taken in the balance of this paper to find these wear ratings is to use ratings from IEEE Standards C37.04-1999 and C37.06-1997 as shown in Table 1.

Rated Continuous Current	2,000A
Voltage Rating	15kV
$I_{sc,max}$ Max Symmetrical Interruption Rating @ max KV	31.5kA
Operations between servicing (lubricating, tightening)	2,000
Rated No-Load Operations	10,000
Full Load C/O at >0.8 pf (Note: This rating will not apply to cap switching, motor starts, highly inductive or capacitive loads, low level faults….)	1,000
Sum of I interrupted that the circuit breaker should be able to withstand as long as each fault is less than 85% of $I_{sc,max}$. *Note 1, 2, 3, 4*	800% of $I_{sc,max}$

Table 1: Sample Breaker Ratings

Note 1: Note the last line in Table 1 is a rating based on I^1, not I^2. Note 800% @ 85% rule from C37.04,1999, section 5.8.2.5 effectively means the circuit breaker shall be able to withstand a calculated value of 9.41 faults at 85% of $I_{sc,max}$ (800% *31.5 kA/85% * 31.5 kA=9.41 operations). This will be important to note when changing to I^2 interruption summations.
Note 2: It should also be noted that in older copies of C37.04, a 400% factor was specified so a 4.7 factor would be used for 85% faults in circuit breakers rated per the older standard.
Note 3: For simplicity, the asymmetrical adjustment factor for high X/R systems called for in section C37.04 section 5.8.2.2 is not used in the following examples.
Note 4: For simplicity, using a K range factor of 1. Higher K range factors are described in older versions of C37.04 and C37.06.

Table 1 effectively provides two measuring points available for wear calculations:
a) Number of operations at rated current =1000;
b) $I_{sc,max}$ rating = 31.5 kA, which implies 26,775 A (85%) can be interrupted 9.41 times.
See Table 1, Note 1, for an explanation of the 9.41 factor.
Now calculate the sum of I^1 and I^2 with these two wear points:

	1,000 ops at I_{FL}, PF>0.8	800% of $I_{sc,max}$, at 85% fault levels:
Sum I Interrupted	1,000 * 2000A = 2,000kA	9.41 * (0.85 * 31.5kA) = 252kA
Sum I^2 Interrupted	1,000 * (2000)^2 = 4,000MA	9.41 * (0.85 * 31.5kA)^2 = 6,747MA

MA = Million Amps; kA = Thousand Amps

Table 2: Sample I and I^2 Interrupted Breaker Ratings

The problem immediately seen is that we have four different wear values: two that might be appropriate if I^1 is accumulated, and two that might be appropriate if I^2 is accumulated. There is no clear answer on how to approach the issue. However, if the relay would allow N to vary from 1 and 2, a resolution to the issue can be found by adjusting the exponent N. If we apply our two wear rating points to equation 4, we can derive a value for N that gives consistent ratings. This gives us the following equality:

$$k \cdot 1000 \cdot 2000^N = k \cdot 9.41 \cdot \left(31500 \cdot 0.85\right)^N \qquad \text{Eq. 5}$$

We can solve this for N. For this example:

$$N = \frac{\log \dfrac{1,000}{9.41}}{\log \dfrac{31,500 \cdot 0.85}{2,000}} = 1.79854 \qquad \text{Eq. 6}$$

Thus, the exponent 1.8 may be more appropriate for wear calculations. The effect will be seen further in the paper, especially in Table 4 discussions.

Breaker Duty Monitoring in Basler Electric Relays

The balance of the paper will explain the different ways Basler Electric implements circuit breaker duty monitoring in its relays, identified as Circuit Breaker Failure Relays BFR1, BFR2 and BFR3. This may or may not apply to how circuit breaker duty monitoring is calculated in other manufacturers' relays but is used for illustration of some of the different methods of estimating breaker duty.

Basler BE1-BPR Relay

In the BE1-BPR circuit breaker failure relay, circuit breaker duty measurement includes the time of the arc. The relay only uses the I^2 exponent; it does not allow other exponents to be used in the equation. It uses a one-cycle rms equivalent of the current at the approximate time of interruption.

The BE1-BPR relay sums I^2t where:
- *t* is taken from monitoring the time between when a 52b changes state, +/- a user offset time ("*Tc*"), until the relay senses current has been interrupted. See Fig. 8.
- *I* is a quasi-rms (low sampling rate) value of one cycle of current at the time the circuit breaker contacts began parting (Fig. 8).

To set *Tc*, one must compare a 52a or 52b to main contact travel, using a circuit breaker travel analyzer. An alarm is set when I^2t sums to greater than a user-defined setting.

The BPR's max I^2t setting ["DMAX" (short for Duty-Max)] is defined by:

$$\text{DMAX} = \left(\text{Max \# Ops @ } I_{SC\,Max}\right) \cdot \left(I_{SC\,Max}^{\ 2}\right) \cdot \left(\text{Typical Bkr Arc Time}\right) \qquad \text{Eq. 7}$$

Typical arc time is hard to define; it is the time that the circuit breaker internal arc is ongoing, from the time of initial contact parting to fault interruption. It should not be confused with published opening time. Not many circuit breaker owners know the internal arc time of their circuit breaker, so this is a notable source of error and makes the calculation of the DMAX setting only a guiding approximation. Assuming the circuit reaker ratings from the earlier example, and assuming a typical arc time of 3/4 cycle (0.0125s):

$$\text{DMAX} = \left(9.41\right) \cdot \left(0.85 \cdot 31,500\right)^2 \cdot \left(0.0125s\right) \approx 84.3E6$$

This is the calculated maximum duty setting.

Basler BE1-851, -951, -IPS, -GPS, and -CDS220 Numerical Relays

Compared to the BE1-BPR, the BE1-851, -951, IPS, -GPS, and -CDS relays discard the inclusion of arcing time in the equation but add the ability to monitor I or I^2 where I is the value of current the relay measured at the time just preceding the circuit breaker opening. While the relay sums both I and I^2, only one of these values can be selected for alarming.

Similar to the BE1-BPR, the Max Circuit Breaker Duty is set in terms of DMAX. If the relay is set to monitor the summation of I^1, DMAX is set by the equation:

$$DMAX = I_{interrupt} \cdot \# \text{ of operations} \qquad \text{Eq. 8}$$

If the relay is set to monitor I^2, then the relay internally uses $(DMAX)^2$. This means you need to calculate and enter a DMAX setting using the equation:

$$DMAX = \left(I^2_{interrupt} \cdot \# \text{ of operations}\right)^{0.5} \qquad \text{Eq. 9}$$

Using our earlier example and Equations 8 and 9, there are four possible settings for DMAX, each valid and suitable depending on the assumptions one makes and the application of the circuit breaker (see Table III).

	1,000 ops I_{FL}, PF>0.8	800% of $I_{sc,max}$, at 85% fault levels:
Sum I Interrupted	1,000 * 2000A = **2,000kA**	(9.41 * (0.85 * 31.5kA) =**252kA**
Sum I² Interrupted	(1,000 * (2000)²)⁰·⁵ = **63.2kA**	(9.41 * (0.85 * 31.5kA)²)⁰·⁵ = **82.1kA**

Table 3: Possible DMAX Settings (bold numbers) for BE1-851, 951, IPS, GPS, CDS220

The variety of values that could be used for maximum I or I^2 means that Basler basically leaves settings recommendations to the good judgment of the end user.

BE1-1051 and BE1-CDS240

These two relays allow the user to set the duty exponent N in Equation 4 between 1.0-3.0. By allowing the user to set the exponent N, the relay offers a better ability for the relay duty measurement to track the two wear data points previously discussed.

These relays sum interrupted I^N, where I is the current value that the relay measured at the time just preceding the circuit breaker opening. Recall earlier calculations using Equation 5 to solve for N, where we determined that N=1.8 would be appropriate.

Similar to the condition for BE1-851, -951, et al when I^2 is used, DMAX needs to be calculated from an equation that backs out the N from the entered value for DMAX. The equation is:

$$DMAX = \left(I_{interrupt}{}^{N} \cdot \# \text{ of operations}\right)^{1/N}$$

The need to include the Nth root function when using the I^N version of circuit breaker duty is caused by Basler's requirement for DMAX to be entered in terms of I, not I^N and because Basler internally uses the Nth power of DMAX for whatever data is entered for DMAX.

Allowing the user to set N gives a circuit breaker duty measurement and DMAX that is consistent across the two duty points (see Table IV):

	1,000 ops I_{FL}, PF>0.8	800% of I_{sc,max_x}, at 85% fault levels:
Sum I^N Interrupted	$(1{,}000 * (2000)^{1.8})^{1/1.8} =$ **93.1kA**	$(9.41 * (0.85 * 31.5kA)^{1.8})^{1/1.8} =$ **93,1kA**

<div align="center">

Table 4: DMAX Settings(bold numbers) for BE1-1051, -CDS240

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Hence, set the relay to N=1.80 and DMAX=93,100.

Other Breaker Monitoring Functions in Numeric Relays

There are other useful features besides circuit breaker wear measuring functions available in numeric relays such as the following.

Circuit Breaker Clearing Time Alarms

A circuit breaker may become just slow enough to create an alarm but still clear a fault. When this occurs, it is an indication that the circuit breaker mechanism needs lubrication or adjustment [3]. The slow breaker clearing time alarm is primarily looking for a clearing time greater than the user's input value, which is based on the manufacturer's stated opening time of the circuit breaker, plus an experience-based margin, indicating a need for maintenance. Another option is to use historical or seasonal operation records to determine typical time to interrupt current. A third approach is to use an anticipated maximum clearing time plus some margin, such as two cycles less than circuit breaker failure relay operate time.

Number of Operations Counter

The operations counter in the relay serves as a means to create an operations-based maintenance interval. It serves the same purpose as a station log that tracks circuit breaker operations but is a value that can more easily be automatically or remotely monitored. The function does not provide any weighting for interrupted current, so it is most useful in indicating a mechanical operations maintenance point has been reached.

Trip Coil Continuity Monitoring

Simple logic is required on the part of the relay to monitor trip coil (TC) continuity, though it does use up some Input/Output capability of the relay. In some unusual circumstances the Trip Circuit Monitor (TCM) has introduced stray unwanted signals in the trip circuit.

In the circuit of Fig. 13, when the circuit breaker is closed, the 52a in the figure will be closed, so voltage across the trip contact should be high, approximately equal to dc power supply. The

"High R" device in the relay allows a trickle current around the trip contact. Normally, this is not enough current to build any substantive voltage across the TC, and the voltage across the trip contact remains nearly equal to the dc supply voltage. However, if either the TC or 52a in series with it fails in an open-circuit mode, the voltage across the trip contact falls to 0. The relay monitors trip contact voltage via device "V" in the diagram, and it alarms if the voltage is low when the circuit breaker is closed.

The TC monitor system must be turned off when the circuit breaker opens, since a 52a in the circuit breaker opens up the trip path. When the circuit breaker opens, the TC is open circuited by the 52a contact. For this purpose, the relay needs to know the status of the circuit breaker, which is supplied from another auxiliary contact not shown in Fig. 13. It should be noted that this would be used in lieu of the common red light in the trip circuit used to show trip circuit continuity.

In occasional cases, the leakage current can be a problem. If the TC itself was actually a high impedance monitoring device that provides trip information rather than being the actual trip coil. The trip coil monitor will see an open circuit and alarm, or the leakage current in the resistor may be enough to tell the high impedance monitor that the trip contact has closed.
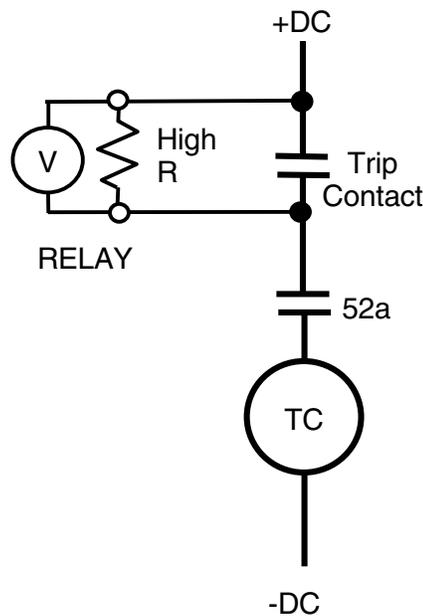

Figure 13: Trip Coil Continuity Monitor Circuit

Relay Recording Capabilities

Some recording features available in most numeric relays are: oscillography records, fault summary records, sequence of events and phasor representation, for each abnormal condition or fault event. These report making functions and the circuit breaker failure function are expected as a matter of course in modern numeric relays.

Conclusion

Numeric relays are useful for monitoring power circuit breakers to obtain predictive maintenance information. However, there is not a universal approach among relay or circuit breaker manufacturers for using interrupted current to measure breaker wear. The instruction manual for each individual relay must be studied to determine the methodology used in applying and setting that relay, since relay manufacturers may not be consistent across their product lines about how duty factor is calculated and set in their relays. When applied properly, the information obtained from the circuit breaker duty monitoring feature of numeric relays is a tool that is waiting to be used for condition-based maintenance scheduling of power circuit breakers.

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