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Circuit Breaker Cost Reduction Technique: Guide for the Manufacture of Minimum Cost Circuit Breakers

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Abstract – **The key parameters that determine the operating mechanism energy requirement for circuit breakers are discussed in this paper. The effect of these key parameters on the cost of circuit breakers are also presented to guide manufacturers of circuit breakers in producing cost effective circuit breakers. The symbols used in this work and there meanings include the following: $\propto$, >>, $\approx$, $\sqrt{\ }$, x, and %; meaning: directly proportional to, much greater than, approximately equal to, square root of, multiplied by, and percentage, respectively. The following abbreviations and acronyms were also used in this work: A, A_A, $\frac{di}{dt}$, $\frac{dv}{dt}$, i, M, N, ΔP, P, P_o, RRRV, t_{BR}, t_o, V, W_{KIN}, and W_{COMP}; meaning: Cross-sectional area, Arc cross-section, Current slope, Rate of Rise of Re-striking Voltage, Fault current, Moving contact mass, Number of breaks, Blast pressure necessary for arc quenching, Pressure, Filling pressure, Rate of Rise of Re-striking Voltage, Circuit breaker ready time, Total break time, Velocity, Kinetic energy requirement, and Compression work requirement, respectively.**

Keywords **– Cost-Effective, High Voltage, Manufacture, Operating-Mechanism, Parameter, Circuit Breaker.**

I. Introduction

The Circuit Breakers (CBs) are essential component of the entire high voltage (HV) switchgear portfolio. They are important part of live tank breakers, dead tank breakers, gas insulated switchgear, any hybrids, for example, mixed technology switch system and generator CBs. CBs consist of the interrupter unit, post insulator, control system, operating mechanism and the base frame (pillar) [1]-[3].

In very simple terms, the level of arc anticipated determines the size of the operating mechanism stored energy of a circuit breaker. However, the costs of the actual operating mechanism of a circuit breaker rise with the stored energy required for the operating mechanism. The costs of all moving parts and to some extent the costs of the stationary parts of a circuit breaker, also rise with the operating mechanism energy. The cross-sections of electrical secondary control cables or the pressurized air pipes, the rating of the station battery and the volume of pressure vessels all increase with the operating mechanism energy of the circuit breaker [4].

The meaning of this is that the cost of any circuit breaker is determined by the operating mechanism energy requirement of the circuit breaker. In view of the above, both the manufacturer and the user of circuit breakers are interested in ensuring that the operating mechanism energy is low. However, this interest is opposed to system requirements which demand higher rated short-circuit fault current breaking capabilities and shorter breaking times. Both system requirements would have large influence in the requisite operating mechanism stored energy if the circuit breaker operating mechanism is not modified.

II. Operating Mechanism Energy Requirement of Circuit Breakers

Contacts of a circuit breaker move over certain strokes during closing and tripping. The contact travel must be completed within a specified maximum duration. For instance, such durations are: the interval between the instant at which maximum pre-striking occurs and the instant of contacts touching during a closing operation which is very decisive for contact erosion during making on to a short-circuit fault and during the opening operation; the interval between the instant of initiation of the trip command and the instant of attaining the shortest gap distance at which extinction is possible [4].

Minimum speed can be determined from the strokes and the maximum durations, and thence, in conjunction with the moving masses, the kinetic energy which the operating mechanism has to supply can be deduced [5].

The kinetic energy is recuperative; it can be converted into compression work during the opening operation of a puffer type circuit-breaker. The re-utilization of kinetic energy during the closing operation during which large part of the kinetic energy is converted into potential energy stored in the trip springs for a subsequent opening is a special feature of the spring operated mechanism.

The re-utilization of a large part of the energy expended during closing cannot be accomplished in hydraulic and pneumatic operated mechanisms which employ the same energy store for both ‘closing’ and ‘opening’. However this has been in use for decades in the high voltage low oil content circuit breakers and SF_6 gas circuit breakers.

The energy requirement of the operating mechanism of a circuit breaker is dependent on the type of operating mechanism employed. Spring stored energy operating mechanisms require less operating energy than hydraulic and pneumatic drives [6], [7].

The energy stored in the closing spring consists of the following:

- The energy required to trip the circuit breaker.
- The inevitable friction losses which occur during a closing operation.
- Defined amount of excess energy which is required to overcome the electro-dynamic forces set up by the pre-striking arc during making on to a short-circuit

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fault and to warrant reliable latching of the main contacts under all climatic conditions.

It is pertinent to note that friction losses and surplus energy are directly associated with the tripping energy so that any reduction of tripping energy automatically results in a reduction of closing energy. Measures to reduce operating mechanism energy must therefore be applied to the tripping procedure.

III. Key Cost Parameters for a Circuit Breaker

The key cost parameters for a circuit breaker are as follows:

- The kinetic energy requirement, W_{KIN}
- The blast pressure, ΔP, necessary for arc quenching
- The moving contact cross-sectional area, A.
- The compression work requirement, W_{COMP}.

3.1. The total Break Time and the Kinetic Energy W_{KIN}

The reliability of circuit breakers is directly related to the number of moving parts. Switching of high short-circuit currents involves high reliability and shortest operating times. A short break time as well as short make-break time is necessary to reduce the electro-dynamic stresses of switch gears and generators. If the total break time t_o of a circuit breaker is reduced, the minimum arc-gap distance would have to be attained in an approximately reduced duration [8]. The breaker ready time, t_{BR}, is given as

$$t_{BR} = t_o - (2f)^{-1} \qquad (1)$$

Where

f = the system frequency.

Since the speed of contact travel increases in inverse proportion to the breaker ready time, t_{BR},

(Minimum arc gap distance / t_{BR}) = velocity, V (2)

The kinetic energy W_{KIN}, of the circuit breaker moving contact relates with its mass, M, and its velocity, V, as follows:

$$W_{KIN} = (MV^2/2)$$

This implies that $W_{KIN} \propto V^2$, (M being constant).

From (2), with minimum arc-gap distance being constant,

$$V \propto (1/t_{BR})$$

Or

$$V^2 \propto (t_{BR})^{-2}$$

Hence with the mass of moving contact, M being constant,

$$W_{KIN} \propto (t_{BR})^{-2}$$

Such that

$$W_{KIN} = [t_o - (2f)^{-1}]^{-2} \qquad (3)$$

From (3) it can be observed that for example reducing t_o from, say 50ms to 33.3ms for a 50Hz circuit breaker, gives the following result:

Using (1) at t_o = 50 ms, f = 50 Hz $t_{BR} = 50 \times 10^{-3} - (2 \times 50)^{-1} = 0.05 - 0.01 = 40$ ms.

Using (3)

$$W_{KIN} = (t_{BR})^{-2}$$
$$= (40\times10^{-3})^{-2}$$
$$= 625\text{Joules.}$$

For t_o = 33.3ms

$$t_{BR} = 33.3\times10^{-3} - (2\times50)^{-1}$$
$$= 0.0233 = 23.3\text{ms}$$

$$W_{KIN} = (t_{BR})^{-2}$$
$$= (23.3 \text{ X } 10^{-3})^{-2}$$
$$= 1842 \text{ Joules.}$$

The response curve of a circuit breaker (CB) kinetic energy (W_{KIN}) against the total break time (t_o) is shown in figure 1.

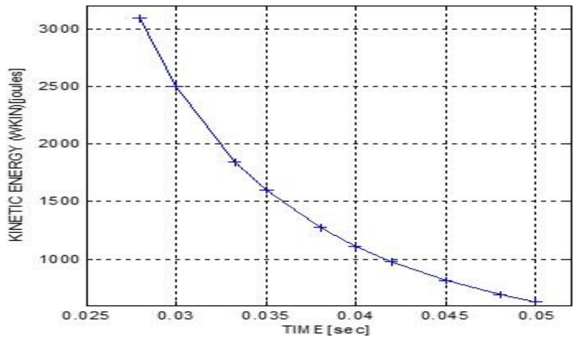

Fig. 1. Response curve of CB total break time (t_o) against the kinetic energy requirement (W_{KIN})

However, keeping t_o constant while minimum arc-gap distance is maintained constant, reducing the mass of the moving contact rod, M, which is the result of this study, reduces the value of W_{KIN}. This is a desirable result.

3.2. The Rated Short-Circuit Breaking Currents and Blast Pressure ΔP.

The rated short-circuit breaking current i, exercises its influence on the required operating mechanism energy mainly through the blast pressure ΔP which is necessary to warrant reliable arc-quenching under short-line fault conditions. Experimental results show the relationship between the required blast pressure ΔP and the current slope $\frac{di}{dt}$ as:

$$\Delta P \propto \left[\frac{di}{dt}\right]^a \qquad (4)$$

Where:

The constant 'a' assumes a value between 1.1 and 1.42, depending on the filling pressure P_o in the circuit breaker [1].

However, as already confirmed by many authors, blast pressure ΔP can be reduced by increasing the number of breaks N. With the well known relationship between current slope $\frac{di}{dt}$ and the rate of rise of re-striking voltage (RRRV), $\frac{dv}{dt}$,

$$\frac{dv}{dt} \cdot \left[\frac{di}{dt}\right]^n = \text{constant} \qquad (5)$$

With large varying values between 1 and 7 as is always the case, specified for n, the effect of N on ΔP can be obtained as follows:

$$\Delta P \propto i^a . N^{-a/n} \qquad (6)$$

If a value of 1.4 is substituted for 'a' and a value of 5 for 'n' in (6), the following results:

$$\Delta P \propto i^{1.4} . N^{-0.28} \qquad (7)$$

The response curve arising from (7) is as shown in figure 2.

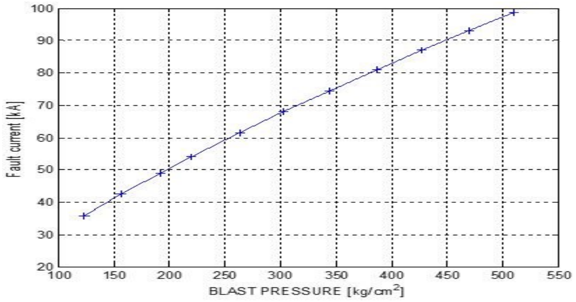

Fig. 2. Response curve of blast pressure against fault current

3.3. The Rated Short-Circuit Breaking Currents and the Piston Area, A.

The rated short circuit breaking current also has effect in the required blast volume, or if the contact stroke is not modified, the piston area, A, will be influenced because the nozzle cross-section has to be adapted to the arc cross-section A_A. As a first approximation, the following relationship can be assumed:

$$A \propto A_A \propto \frac{i}{\sqrt{P}} \quad (8)$$

As the pressure $P = P_0 + \Delta P$ depends again on the current, the dependence of the nozzle cross-section and the Piston area on current is less than one would expect. For large blast pressure, ΔP is much greater than P_0, i.e.

$$\Delta P >> P_0$$

And thus,

$$P \approx \Delta P$$

Where,
P = pressure.
A = piston area.
ΔP = blast pressure.
P_0 = filling pressure.
A_A = arc cross-section.

Substituting equation (7) in (8), gives the following result [6]:

$$A \propto \frac{i}{\sqrt{(i^{1.4}.N^{-0.28})}}$$

This implies

$$A \propto \frac{i}{i^{0.7}.N^{-0.14}}$$

i.e.

$$A \propto i \text{ x } i^{-0.7} \text{ x } N^{0.14}$$

Or

$$A \propto i^{0.3} \text{ x } N^{0.14} \quad (9)$$

(9) gives rise to the response curve shown in figure 3.

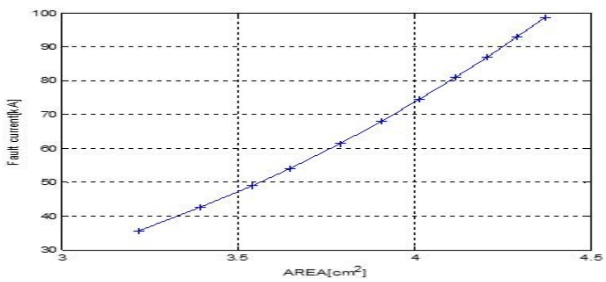

Fig. 3. Response curve of the moving contact area against the fault current

3.4. The Blast Pressure ΔP and the Compression work, W_{comp}.

The relationship between blast pressure ΔP and compression work, W_{comp}, is not simple since one part of the blast pressure is produced by the arc through heating up. Assuming a linear relationship as a rough approximation [4], [9], ΔP relates with the compression work, W_{COMP} thus:

$$W_{COMP} \propto N.A.\ \Delta P \quad (10)$$

But

$$\sqrt{P} \propto \frac{i}{A}$$

And

$$P = P_0 + \Delta P \quad (11)$$

But for large blast pressure: $\Delta P \gg P_0$ and so $P \approx \Delta P$.

From (9),

$$A \propto i^{0.3}.N^{0.14}$$

Substituting (7) and (9) in (10) gives

$$W_{COMP} \propto N.i^{0.3}.N^{0.14}.i^{1.4}.N^{-0.28}$$

OR

$$W_{COMP} \propto N^{0.86}.i^{1.7} \quad (12)$$

(12) results in the response curve shown in figure 4.

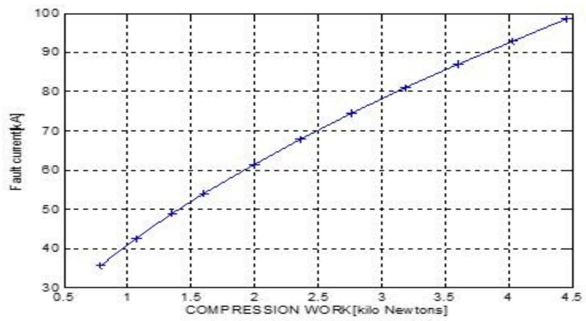

Fig. 4. Response curve of compression work against fault current

IV. Discussions

4.1. The Extent to which the Key Parameters Affect the Cost of Power Circuit Breakers.

4.1.1. The Blast Pressure, ΔP, Necessary for Arc Quenching

From (7), for number of breaks, N, being 2,

$$\Delta P \propto 0.82 \text{ x } i^{1.4} \quad (13)$$

(13) shows that:

5% reduction in the current, i, will amount to 7.3% reduction in the blast pressure, ΔP, i.e.

$$\Delta P \propto 0.82 \text{ x } 0.95^{1.4}$$

= 0.76, meaning 7.3% reduction in ΔP (from 0.82 to 0.76)

i.e. $$[1 - (\frac{0.76}{0.82})] \text{ x } 100 = 7.3\%$$

Or $$\frac{0.82-0.76}{0.82} \text{ x } 100 = 7.3\%$$

10% reduction in the current, i, will amount to 13.4% reduction in the blast pressure, ΔP, i.e.

$$\Delta P \propto 0.82 \text{ x } 0.9^{1.4}$$

= 0.71, meaning 13.4% reduction in ΔP (i.e. from 0.82 to 0.71).

15% reduction in the current, i, will amount to 21% reduction in the blast pressure, ΔP, i.e.

$$\Delta P \propto 0.82 \times 0.85^{1.4}$$

= 0.65, meaning 21% reduction in ΔP (i.e. from 0.82 to 0.65).

20% reduction in the current, i, will amount to 27% reduction in the blast pressure, ΔP, i.e.

$$\Delta P \propto 0.82 \times 0.8^{1.4}$$

= 0.6, meaning 27% reduction in ΔP (i.e. from 0.82 to 0.6).

The above situation means that 1% reduction in the fault current, i, averagely results in a corresponding reduction of 1.4% in the blast pressure.

From (7) and figure 2, it is very glaring that even a very little reduction in 'i' reduces the blast pressure ΔP far more than a large increase in N (which may not even be realistic).

4.1.2. The Circuit Breaker Moving Contact Cross-Sectional Area, A.

From (9), for total number of breaks, N, being equal to 2,

$$A \propto 1.1 \times i^{0.3} \qquad (14)$$

(14) shows that:

5% reduction in the current, i, will amount to 1.8% reduction in the moving contact area, A, i.e.

$$A \propto 1.1 \times 0.95^{0.3}$$

= 1.08, meaning 1.8% reductions in A (i.e. from 1.1 to 1.08).

10% reduction in the current, i, will amount to 3% reduction in the moving contact area, A, i.e.

$$A \propto 1.1 \times 0.9^{0.3}$$

= 1.066, meaning 3% reductions in A (i.e. from 1.1 to 1.066).

15% reduction in the current, i, will amount to 4.5% reduction in the moving contact area, A, i.e.

$$A \propto 1.1 \times 0.85^{0.3}$$

= 1.05, meaning 4.5% reductions in A (i.e. from 1.1 to 1.05).

20% reduction in the current, i, will amount to 6.4% reduction in the moving contact area, A, i.e.

$$A \propto 1.1 \times 0.8^{0.3}$$

= 1.03, meaning 6.4% reductions in A (i.e. from 1.1 to 1.03).

The above situation means that on the average, 3.2% reduction in the fault current, i, results in a corresponding reduction of 1% in the moving contact cross-sectional area.

From figure 3 and (9) it is clear that increasing the number of breaks N, increases the moving contact area A, (which is unacceptable as it should increase the cost of the circuit breaker) whereas reducing the fault current i, reduces A (a desirable result as this lowers the arc involved to a very easily manageable level and as well leads to reduction in CB costs).

4.1.3. The Compression work Requirement of the Circuit Breaker

Again, taking the value of the total number of breaks, N, equal to 2, (12) becomes:

$$W_{COMP} \propto 1.8 \times i^{1.7} \qquad (15)$$

(15) shows that:

5% reduction in the current, i, will amount to 8.3% reduction in the compression work, W_{COMP}, i.e.

$$W_{COMP} \propto 1.8 \times 0.95^{1.7}$$

= 1.65, meaning 8.3% reductions in W_{COMP} (i.e. from 1.8 to 1.65).

10% reduction in the current, i, will amount to 16.7% reduction in the compression work, W_{COMP}, i.e.

$$W_{COMP} \propto 1.8 \times 0.9^{1.7}$$

= 1.5, meaning 16.7% reductions in W_{COMP} (i.e. from 1.8 to 1.5).

15% reduction in the current, i, will amount to 24% reduction in the compression work, W_{COMP}, i.e.

$$W_{COMP} \propto 1.8 \times 0.85^{1.7}$$

= 1.37, meaning 24% reductions in W_{COMP} (i.e. from 1.8 to 1.37).

20% reduction in the current, i, will amount to 31.7% reduction in the compression work, W_{COMP}, i.e.

$$W_{COMP} \propto 1.8 \times 0.8^{1.7}$$

= 1.23, meaning 31.7% reductions in W_{COMP} (i.e. from 1.8 to 1.23).

30% reduction in the current, i, will amount to 45.6% reduction in the compression work, W_{COMP}, i.e.

$$W_{COMP} \propto 1.8 \times 0.7^{1.7}$$

= 0.98, meaning 45.6% reductions in W_{COMP} (from 1.8 to 0.98)

i.e. $[1 - (0.98/1.8)] \times 100 = 45.6\%]$

The above situation means that on the average, 1% reduction in the fault current, i, results in a corresponding reduction of 1.6% in the compression work, W_{COMP}, requirement of the circuit breaker.

From (12), any increase in the number of breaks N, leads to increase in compression work, W_{comp} (this means more cost and so not desired) while reduction in the fault current i, means reduction in W_{comp} (a desired result as the cost of the circuit breaker shall be reduced as well as reduced fault-current resulting in lesser arc which is easier to manage).

Considering (9), (10) and (12) it could be observed that in all the cases, a reduction in 'N' gives good result. However, recent work from others have yielded circuit breakers in which the required Piston travel characteristics can be achieved with a two-fold change of direction instead of four-fold change of direction (i.e. reducing N from 4 to 2). Hence, even if it is possible that the length of the links and the position of the pivoting points can be varied to achieve the required Piston travel characteristic in one-fold change of direction, the result shall be insignificant when compared to the effect of reducing the rated short-circuit fault current as seen in the results.

V. Conclusions

For the cost of circuit breakers, the key parameters that determine the cost are:

(A) The kinetic energy requirement W_{KIN}.
(B) The blast pressure, ΔP, necessary for arc quenching.
(C) The moving contact cross-sectional area, A, or the mass, M.

(D) The compression work requirement, W_{COMP}.
From the expression:

Mass = volume (i.e. area x height) x density,

Mass is proportional to the area i.e.

$$M \propto A \qquad (16)$$

From the expression:

$$\text{Kinetic energy} = \frac{\text{mass x (velocity)}^2}{2}$$

And with the velocity maintained constant,

$$W_{KIN} \propto \text{mass}$$

i.e. $$W_{KIN} \propto M \qquad (17)$$

Combining (16) and (17) means that

$$W_{KIN} \propto A \qquad (18)$$

And from (10)

$$W_{COMP} \propto N.\ A.\ \Delta P$$

Meaning that the kinetic energy requirement W_{KIN}, the blast pressure, ΔP, the moving contact cross-sectional area, A, and the mass, M, of the moving contact, are all embedded in the compression work requirement, W_{COMP}, of the circuit breaker, meaning that the cost determinant for a circuit breaker is the compression work requirement, W_{COMP}. This paper has presented reduction in the compression work requirement, W_{COMP} via reduction in the available short-circuit level as a way of reducing circuit breaker costs. The use of forked moving contacts and the relay-operated adapters [10], [11], to couple circuit breakers and short-circuit current limiting reactors at no constant power losses is a perfect way to achieve this.

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