THE IMPACT OF LINE PROTECTION OPERATE TIME ON CIRCUIT BREAKER WEAR

Sinisa Zubic[1*], Zoran Gajic[1], Davor Kralj[2]

[1]Hitachi Energy, Grid Automation and Communication, Vasteras, Sweden
[2]Svenska Kraftnat, Stockholm, Sweden
**sinisa.zubic@hitachienergy.com*

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Abstract

In this paper the impact of relay operate time on circuit breaker wear, is analysed. The presented results show that the proposed concept of a *fixed relay operate time* (equal to half fundamental frequency cycle) is arguably the most beneficial, from an overall power system perspective. When ultra-fast relay operation (below 3 ms) is compared to the fixed operate time (10 ms), it causes >20% increase in circuit breaker wear. On the other hand, having a 3-6 times faster relay operate time brings only a very modest improvement in the average fault clearing time; of just around 13%. This leads us to question the main paradigm of transmission line protection, declaring that "faster is better"; particularly when considering circuit breaker wear and power system stability aspects. The analysis supports the thesis from the International standards for circuit breakers that the initiation of circuit breakers operation while fault current asymmetry is high is damaging to the circuit breakers.

1 Introduction

The main elements of a fault clearance system in power transmission networks comprise a protective relay and a circuit breaker. The relay operate time and the circuit breaker interrupting time together, result in the fault clearing time, which is important from the power system perspective (Fig.1, [1]). Achieving ultra-high-speed fault clearing time has been an open objective for many decades, mostly due to the need for improvements in power system stability [2]. The relay operate time was reduced to a few milliseconds back in 1976 [3], but improvements in the circuit breaker interrupting time, from near 2 cycles (40 ms in 50Hz systems) to ¾ cycle has not yet been achieved, despite promises to be commercially viable by 1981 [4]. Without the forthcoming circuit breaker improvements, full focus became placed on the relay operate time, where a "need for speed (faster is better)" became the dominant goal when designing new protection algorithms (albeit in evolving relay technologies). Contrary to common opinion, in [1] it is shown that a reduction in relay operate time does not directly improve the fault clearing time and has even lesser impact on the power system stability, due to the complex physics behind the circuit breaker current interruption process.

In this paper another important aspect of the interaction between relays and circuit breakers is analysed. Circuit breakers are designed to interrupt fault currents only if the interruption process is not initiated in a time shorter than the half cycle period [5,6]; which implies that a protection operate time of less than half cycle can negatively affect circuit breakers; a fact that is neglected in the "faster is better" approach. The reason is related to the possible high content of direct current component in the fault current, which is hard to interrupt and prolongs the time to the next zero-crossing instant. In such a case a circuit breaker should be derated [7], alternately, the breaker type testing process should be repeated, to ensure its proper operation.

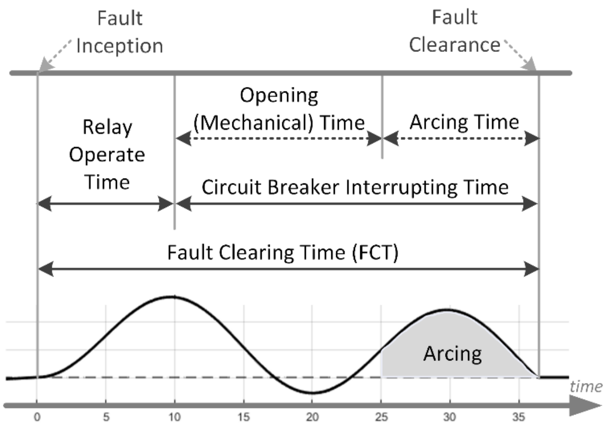

Fig. 1 Definition of Fault Clearing Time (FCT), Relay Operate Time and Circuit Breaker Interrupting Time [1]

In this paper a new methodology to evaluate circuit breaker wear as a function of the relay operate time, is proposed. The methodology is based on type test data of a commercial circuit breaker that is used worldwide. It considers the circuit breaker opening time (mechanical time) and the minimum arcing time, for varying conditions. The circuit breaker wear is calculated as a value proportional to the area below the fault current from the moment of opening its contacts until the zero-crossing instant when the fault current is interrupted [8]. As a reference scenario, a half cycle relay operate time (fixed operate time) is considered as the fastest operate time that does not violate limitations of the circuit breaker design. This reference wear is compared to other types of relays (phasor, time and traveling wave based). The calculated additional circuit breaker wear can be used by network operators to better estimate circuit breaker maintenance intervals.

2 Circuit breaker wear estimation

The manufacturing improvements in high-voltage circuit breakers has significantly decreased the rate of major failures over the years. According to the surveys from CIGRE working groups the major failure frequency decreased from 1.6 to 0.3 failures per 100 CB-years during a more than 30 years period (1974-2007) [8]. Beyond the savings associated with this reduction in failure frequency, utilities are anticipating further savings by transitioning from time-based maintenance to a condition-based maintenance of their circuit breakers [8]. The goal is to perform costly maintenance only on circuit breakers with the highest priority. There are different subcomponents of circuit breakers and different techniques for their condition evaluation, but in this paper the focus is on the CB interruption chamber, the parts of which are shown in Fig.2 [9].

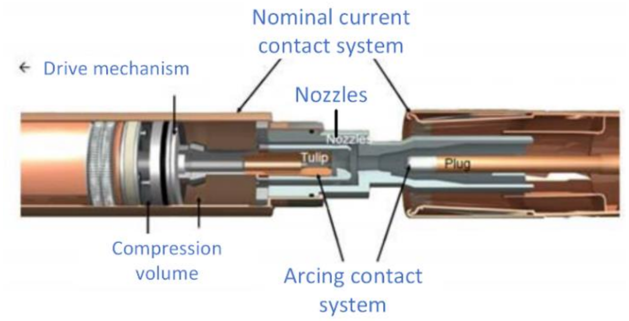

Fig. 2 Arc zone of a typical HV self-blast CB in open contact position [9]

After being triggered by a relay operate signal, a circuit breaker starts opening its contacts. This process is referred to as the "opening time" (Fig.1). When arcing CB contacts start being physically separated the arcing process starts, within the interrupting chamber. Current continues to flow, and the final fault clearing happens when the arc is extinguished, which can occur only at one of the current's natural zero-crossing points. The circuit breaker interrupting time is the interval of time between the beginning of the opening time and the end of the arcing time.

During the arcing process the dissipated energy is absorbed by the contacts and nozzles, causing a degree of deterioration through melting and vaporization (contact erosion and nozzle ablation [9]). The length of the arcing contacts gradually decreases which affects the ability of the CB to interrupt the current. Failing to interrupt the fault current causes prolonged fault current clearing time, since the breaker failure scheme needs to initiate opening of the surrounding circuit breakers in the power system. For this reason, monitoring of the state of the components within the interruption chamber is important.

There are several approaches to estimating the degree of contacts degradation, including vibration analysis, contact resistance or by simply counting the number of faults; although the latter does not provide sufficient accuracy since different fault currents and arcing times have different impacts on the contacts degradation. Other methods that require offline state estimation and additional measurements, such as resistance measurements or additional sensor inputs are not practical for wider use. In [8] are presented experimental results where mass loss of contacts during the interruption process is measured and correlated to instantaneous current values during the arcing and to the arc energy based on availability of arc voltage. The conclusion is that the most accurate prediction of the amount of mass erosion is obtained if the arc energy and transferred electrical charge (calculated from instantaneous current values) are used as input parameters. However, since online arc voltage measurements are not available, the method based on the transferred electrical charge measurements is proposed as that which is preferred, as it provides adequate accuracy in evaluating mass erosion [8]. The proposed method is widely applicable since it can be applied as a non-invasive, online method for monitoring of the interruption chamber aging. The transferred electrical charge measurement is based on equation (1):

$$\Delta m_c = C \times \int_{\tau_{arc}} |i(t)|\, dt \tag{1}$$

where Δm_c represents the mass loss, C is specific erosion depending on the root mean squared value of the current i, and the arcing time, τ_{arc}. The current waveform and the arcing time are illustrated in Fig.1. The integral in the equation (1) is proportional to the gray area below the current waveform in Fig.1. In this paper the integral from eq. (1) is calculated for different fault current waveforms to compare the circuit breaker wear for different relay operate times.

2.1 Minimum arcing time

When it comes to arcing time, it is important to note two things:

- The CB can interrupt the fault current only at one of the zero-crossing instances.
- To interrupt the fault current at a particular zero-crossing instance, a minimum arcing time is required (example from Fig.3 shows minimum arcing time of 7.6ms).

For a given fault current waveform, CB opening time and minimum arcing time, the total arcing time depends on the relay operate time. As shown in Fig.3, Fig.4, Fig.6 and Fig.7, for the same current interruption instance (i.e. the same fault clearing time, FCT) the shorter relay operate time causes longer arcing time. Since it is not possible to avoid the minimum arcing time, a very useful variable to track is the additional arcing time as a function of the relay operate time.

3 Relay operate time

To evaluate the impact of the relay operate time on the CB wear, five different scenarios are proposed for comparison.

3.1 Ideal relay operate time

In [1] is proposed a concept of an *ideal protective relay*. Such a relay would have an operate time that causes the fastest possible fault clearing time (FCT) and at the same time would cause minimum contact erosion of the circuit breaker. That means that for a given fault current waveform, CB opening and minimum arcing time, it would always initiate the CB interruption process at the moment before the targeted zero-crossing that leads to the minimum arcing time, as shown in Fig.3 [14]. Such a predictive relay operation would require high accuracy estimation of the CB opening and minimum arcing time, as well as fast prediction of all zero-crossing instances. Such a level of precision is not possible for the existing technology of circuit breakers used in high-voltage networks, but it can be used as a reference scenario.

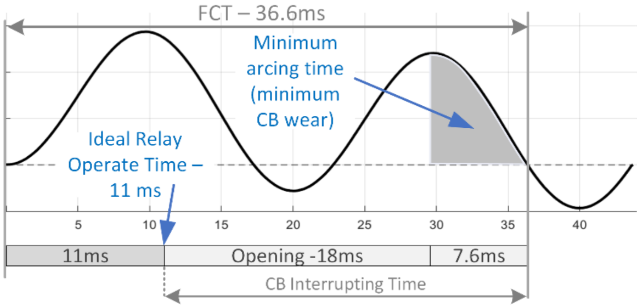

Fig. 3 Ideal relay operate time leading to the FCT and CB arcing time

3.2 Fixed relay operate time

In [1] is also proposed a *fixed relay operate time* as an alternative to the "*faster is better*" philosophy. The fixed half-cycle operate time (10 ms at 50 Hz or 8.33 ms at 60 Hz) is proposed for two reasons:

- To comply with International Standards [5,6] for circuit breakers where relay operate times shorter than a half cycle are not considered, due to the negative affects these have on CB service lifetime, by increasing the amount of cumulative interruption stresses.
- To reduce the probability of protection maloperation and blackouts in the case of disturbances that do not develop into permanent faults in power system.

This paper is intended to determine if this proposal has positive effects on circuit breaker lifetime, when compared to the "*faster is better*" philosophy. In Fig.4 is illustrated the amount of the additional arcing time and consequently, additional circuit breaker wear, when compared to the ideal situation from Fig.3.

3.3 Phasor-domain (PD) relay operate time

The phasor-domain based relays [10,11] could be considered as the first generation of numerical protective relays, and these rely on low sampling frequency (from <1kHz to few kHz). Operate times in the range of 8 ms – 20 ms are assumed, as proposed in [1]. In Fig. 5, an example is shown demonstrating an operation where current interruption is not achieved at third zero-crossing, since the arcing time was not long enough to allow current interruption. The arcing before the third zero-crossing is contributing to the additional CB wear.

3.4 Time-domain (TD) relay operate time

The time-domain based relays could be considered as the second generation of numerical protective relays, and that rely on higher sampling frequency (4 kHz – 10 kHz). They are usually based on incremental quantities and differential equations instead of a phasor approach [12,13]. Operate times in the range of 3 ms – 8 ms are assumed, as proposed in [1]. In Fig. 6, an example is shown demonstrating fault clearing time and additional CB wear.

3.5 Traveling-wave (TW) relay operate time

The traveling-wave based relays could be considered as the third generation of numerical protective relays; and these rely on high sampling frequency (≥1 MHz) [13]. Operate times in the range of 1.5 ms – 3 ms are assumed, as proposed in [1]. In Fig. 7, an example is shown, demonstrating fault clearing time and additional CB wear.

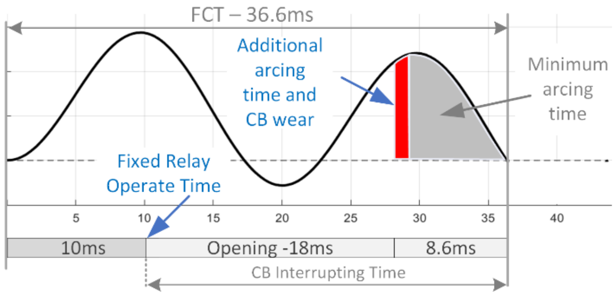

Fig. 4 Fixed relay operate time leading to the FCT and CB arcing time

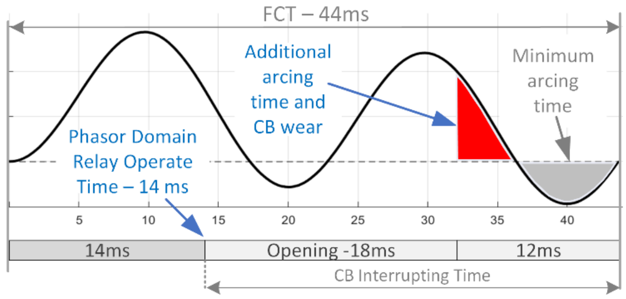

Fig. 5 Phaser domain (PD) relay operate time leading to the FCT and CB arcing time

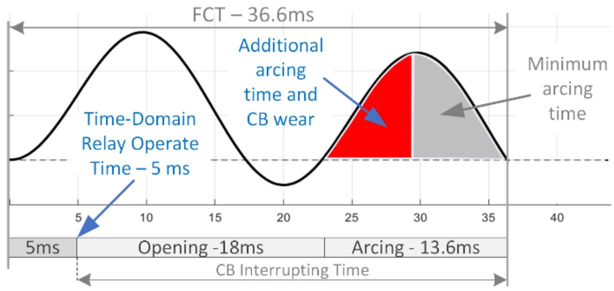

Fig. 6 Time domain (TD) relay operate time leading to the FCT and CB arcing time

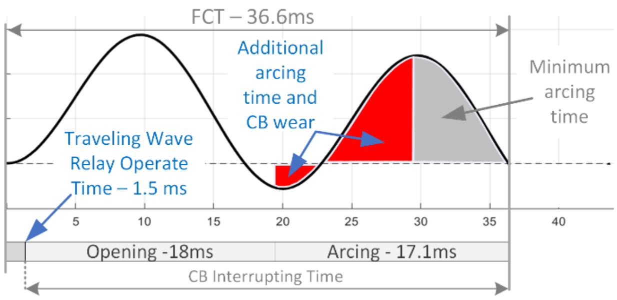

Fig. 7 Traveling wave (TW) relay operate time leading to the FCT and CB arcing time

4 Methodology

The circuit breaker wear estimation, presented in this paper, relies on a model of a widely used SF6 live-tank circuit breaker [1]. It is one of the best SF6 high-voltage circuit breakers (420 kV, 63 kA) and has been used in transmission networks worldwide for 30+ years. The type test results performed in an independent and ISO/IEC 17025 accredited laboratory are used for CB modelling. The rated opening time of this circuit breaker is 18±2 ms, while minimum arcing times are summarized in Table 1. Reference type tests were deemed sufficient to cover almost all possible fault cases in transmission grids and hence provide the relevant insight into the true contribution of relay time to circuit breaker wear.

The CB model used in this paper is based on 10000 random values of minimum arcing time and CB opening times, assuming a uniform distribution (Fig.8). The selected range of minimum arcing time is between the smallest and the largest value from Table 1 (7.6-11.8ms). There are also 10000 values for each of 5 proposed relay operate time scenarios, as shown in Fig.10. The same ranges for PD, TD and TW relays are used as in [1]. The last required input is a fault current waveform. CB wear depends highly on fault current asymmetry levels and for that reason 12 fault current waveforms have been generated as possible fault scenarios (the fault inception angle was selected from 0° to 330°, Fig.9).

Table 1 Minimum arcing time ranges in different type test scenarios

Type of test	Min. arcing time [ms]
L75–1PhG Fault current=100% In	11.8
L90–1PhG Fault current=100% In	10.1
T100a–3Ph Fault current=100% In	10.4
T100s–3Ph Fault current=100% In	11.1
T60 – 3Ph Fault current=60% In	11.4
T30 – 3Ph Fault current=30% In	10.0
T10 – 3Ph Fault current=10% In	7.6

In the first step, an ideal relay operate time is calculated (with the lower limit to 1ms). The algorithm's steps are:

- Take the first out of 12 fault current waveforms;
- Take random values for CB opening time and for minimum arcing time (fig. 8) and calculate CB interrupting time;
- Find the smallest zero-crossing time on the selected current waveform that is larger than the CB interrupting time;
- Calculate ideal relay operate time as the difference between the selected zero-crossing time and the CB interrupting time;
- Repeat this for all 10000 values;
- Repeat this for all 12 fault current waveforms.

The distribution of the ideal relay operate time is shown in Fig. 10a.

In the second step the fault clearing time distribution is calculated for all 5 relay operation scenarios. The algorithm's steps are:

- Take the first out of 12 fault current waveforms;
- Take random values for CB opening time, minimum arcing time and relay operate time – add these three numbers to get *minimum possible FCT*
- Find the smallest zero-crossing time on selected current waveform that is larger than the *minimum possible FCT*;
- Record the selected zero-crossing instance as the Fault clearing time (FCT) and find the same for all types of relays, all 10000 random values and all 12 current waveforms.

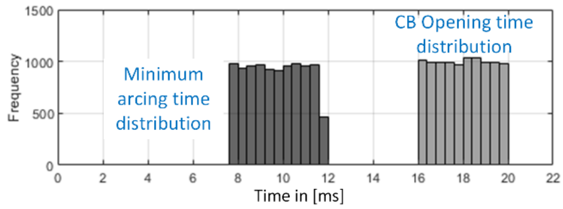

Fig. 8 Distribution of CB opening time and minimum arcing time based on type testing of a widely used SF6 high-voltage circuit breaker [1]

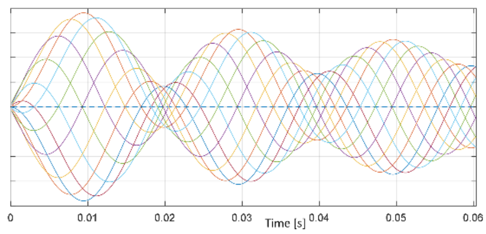

Fig. 9 Fault current waveforms and their zero-crossing instances used for calculation of FCT and CB wear

The distribution of all FCTs are shown in Fig. 11. The last step is to calculate the CB wear. Once the exact zero-crossing instance, and the minimum and total arcing times are known, the equation (1) is applied, and the grey and red surfaces (as illustrated in Fig. 3-7) are calculated. What really matters for the comparison of different relay operation scenarios is the red area which represents the additional CB wear due to prolonged arcing time. The results are presented in Fig.13. It can be noted that the proposed methodology is slightly different from the one presented in [1]. The reason is that in this paper it is important to estimate the precise CB wear and the differences between the minimum and the total arcing times. This causes differences in average FCTs, but differences between PD, TD and TW relays are very close in both approaches.

5 Results

The first fact that can be noticed when Fig.10 and Fig.12 are compared is that even a major reduction in relay operate time brings only a very minor reduction in the real fault clearing time. For example, TW operates 3-6 times faster than the *fixed relay* and still brings a very modest improvement of average FCT of just 13.22%. The main reason for this is the limitation in the circuit breaker technology which dictates that fault current interruption may only occur at a few discrete instances in time; i.e. at a zero crossing, subsequent to a minimum required arcing time. Such a minor FCT improvement is paid by >20% increase in CB wear (Fig.13), not to mention the potential risk of maloperation and possible blackout in case where the disturbances do not develop into real faults in the power system [1].

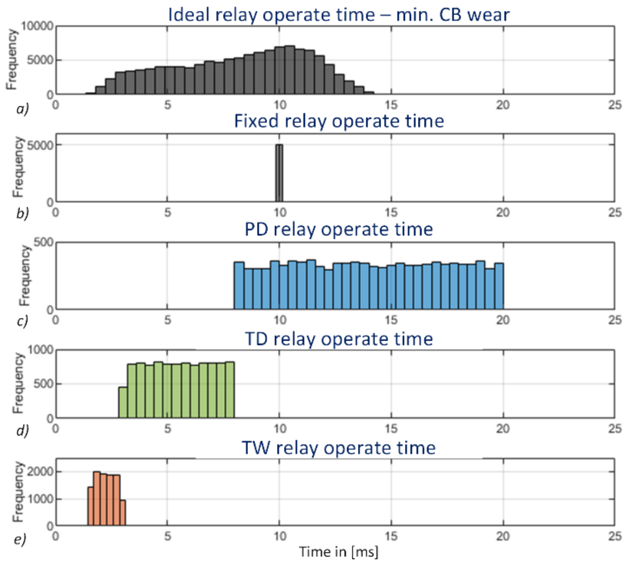

Fig. 10 Distribution of relay operate time: (a) Ideal relay, (b) Fixed relay, (c) PD relay, (d) TD relay, (e) TW relay

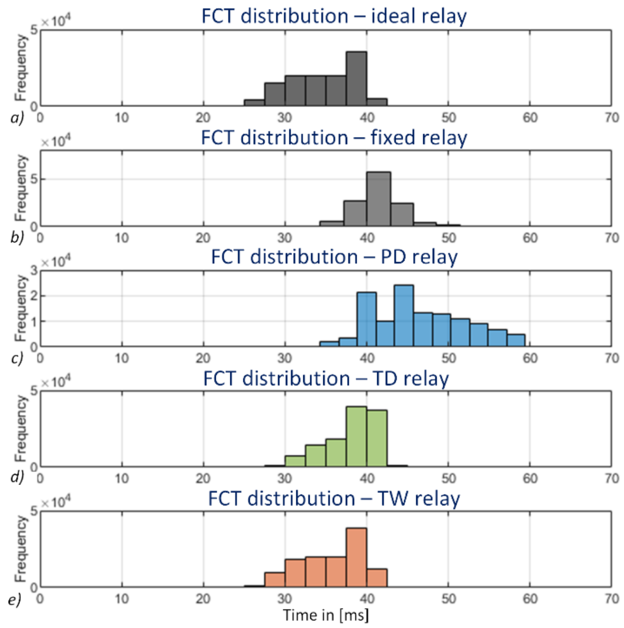

Fig. 11 Distribution of Fault clearing time: (a) Ideal relay, (b) Fixed relay, (c) PD relay, (d) TD relay, (e) TW relay

In Fig.11 the distributions of fault clearing times for all 5 types of relay operations are shown. It can be noted that the average FCT (Fig.12) of traveling wave relay is very close to the average FCT of an ideal relay. It is interesting to notice that such an ideal FCT is achieved with quite different distribution of the relay operate time (Fig. 10a,e). The ideal relay rarely operates in the TW operation interval from 1.5-3 ms. Most of the ideal relay operate time is concentrated around the half-cycle value and it is even slower than the time-domain relay. So, the TW relay, despite having the near perfect FCT, it has the worst impact on the circuit breaker wear. Such a large difference of TW operate time from the ideal relay operate time causes substantially increased arcing time during the high fault current asymmetry. Fig. 13 shows that the TW relay causes over 30% more CB wear than the minimum required value (in an ideal case).

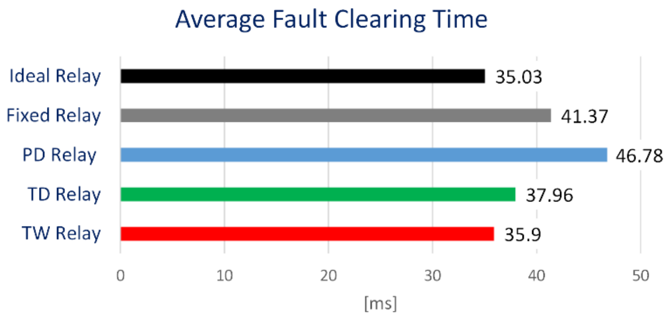

Fig. 12 Average fault clearing time comparison

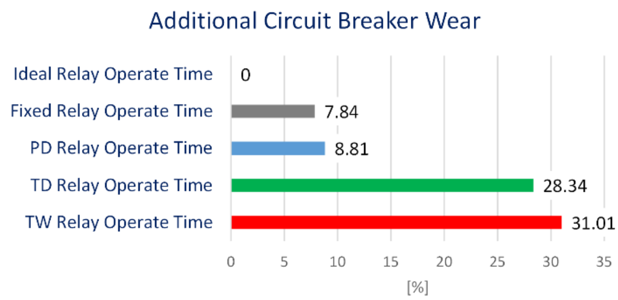

Fig. 13 Additional circuit breaker wear comparison

One might argue that an ideal scenario is not possible and as such is not relevant in real applications. For this reason, it is useful to compare the proposed fixed relay operate time scenario to the PD, TD and TW approaches, which are all possible. In Table 2 the results of the comparison are summarized. It is shown that PD relay does not have advantages over the fixed relay operate time. The PD has prolonged tripping time and yet has not resulted in reduced CB wear, since it has some operations below 10 ms. Those slower operate times do not contribute to a further reduction of CB wear, since the majority of decaying DC offset has already disappeared.

Table 2 Comparison of the common relay technologies to the approach based on the fixed relay operate time

Fixed relay as a reference scenario	FCT difference	CB wear difference
PD relay	+13.08% (+5.4ms)	+0.97%
TD relay	-8.24% (-3.41ms)	+20.50%
TW relay	-13.22% (-5.47ms)	+23.17%

TD and TW relays are causing CB arcing to catch still high asymmetry of the fault current (as illustrated in Fig.6 and Fig.7). This consequently increases the CB wear by more than 20% and shows why it is not recommended to operate in such a short time. On the other hand, the benefits in FCT are just around 8-13% or several milliseconds of reduced average fault clearing time, which is not relevant for power system stability concerns [1].

6 Conclusion

In the domain of transmission line protection, a dominant paradigm for many years has been the “need-for-speed” and “faster is better”. It is claimed that each millisecond of reduced relay operate time contributes to maintain the power system stability. The authors argue that this approach is too simplistic since it ignores the existence of the circuit breakers as equally important components of the fault clearance chain. Such a simplification has two consequences:

- Wrong assumption that the relay operate time, alone, is important, instead of the fault clearing time (which depends on the complex physics of the fault current interruption process in circuit breakers).
- The impact of relay operate time on circuit breaker lifetime is completely ignored and not brought into discussion when different protection solutions are presented.

In this paper the impact of relay operate time on the circuit breaker wear is analysed. The presented results show that the proposed concept of *fixed relay operate time* (equal to half cycle, 10 ms in 50Hz systems and 8.33 ms in 60 Hz systems) is arguably the most beneficial from an overall power system perspective. When the ultra-fast operation of a traveling wave relay is compared to the fixed operate time, TW causes 23% higher circuit breaker wear. On the other hand, having 3-6 times faster relay operate time brings only a very modest improvement, of just around 13%, to the average fault clearing time. These results bring into question the main paradigm, in which “faster is better”; especially when other power system stability aspects are considered [1].

In the paper, the concept of an ideal relay operate time it is also shown. Despite not being feasible, it is interesting to notice that an ideal relay very rarely operates in times below 3 ms, while most of the time its operation is concentrated around the half cycle. The analysis supports the thesis from the International standards for circuit breakers that initiation of circuit breaker operation while fault current asymmetry is high, is damaging to the circuit breaker [5,6]. In [1] is shown that it is not beneficial from a power system stability perspective, as well. Reduction in relay operate time does not offer satisfactory improvement in fault clearing time since existing circuit breaker technology is limiting the potential gain. The emphasis must be placed on the improvement of circuit breaker technology, as was correctly assumed 40 years ago!

7 References

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