LINE PROTECTION OPERATE TIME: SPEED VS. CIRCUIT BREAKER WEAR, POWER SYSTEM STABILITY AND SECURITY

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Abstract

The improvements in power system stability and power transfer capability have been the main drivers for achieving faster transmission line protection. The decades of advancements of protection devices (from electromechanical to modern numerical relays) have allowed a significant reduction in protection operate time, from tens of milliseconds down to almost zero. However, overfocusing solely on the protection speed can be misleading and at the end increase the risk of maloperation and blackout, instead of contributing to power system stability. The main reason is a wrong assumption that relay operation directly contributes to power system stability, while operation of circuit breakers is not considered in most of the studies. In reality, power systems can only sense a physical interruption of fault current, which happens after the circuit breaker interruption process, while relay operation has only an indirect impact. In other words, a faster relay operate time is not a guarantee of faster fault current clearing time and for this reason circuit breaker operations must be considered. In this paper the impact of relay operate time on the total fault clearing time is calculated based on circuit breaker models. Additionally, a trade-off between the speed and security of protection relays and how a shorter trip decision time can lead to misclassification of disturbances as genuine faults is analysed. This can lead to disconnection of a healthy transmission line from the system and to further domino effect leading to a blackout. 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.

1 Introduction

An uninterrupted electrical energy supply is one of the highest priorities in today's world. Almost all crucial systems (such as the telecommunication networks and the health care systems) have high dependency on electrical power supply. For these reasons a power system blackout, where a large portion of transmission network is disconnected from the power system, has severe consequences on human lives, and it is connected to high financial loses. To maintain the power system stability under all circumstances is one of the most important challenges across different areas, one of which is the power system protection.

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 (FCT), 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 half a cycle [5,6], which implies that a protection operate time of less than a 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, or alternatively the breaker type testing process should be repeated, to ensure its proper operation [7,15].

In this paper the impact of the protection operate time on the transient stability of power systems is analysed. The relay operate time affects the Critical Clearing Time (CCT) margin, but also has impact on the overall protection system security. The protection speed and security represent conflicting requirements where trade-offs are inevitable [1]. The benefits of the ultra-fast relay operate time, in terms of increased critical clearing time margin, are confronted to the risks of relay maloperations in case of non-faulty conditions that can lead to power system blackout. The concept of a “fixed half cycle relay operate time” is proposed as an optimal solution to minimize the relay maloperation risks and circuit breaker wear, with no practical impact on the critical clearing time margins [1,7].

2 Fault Clearing Time (FCT) definition

Fig.1 shows a part of a substation where protection of a power line is illustrated. In order to protect the line (or any other power system element) it is necessary to have:

- instrument transformers – to provide measurements of the most important variables related to the protected element (currents and voltages),
- circuit breaker (CB) – to interrupt the fault current (to allow physical separation of the protected element),
- protection equipment (protective relay) – to recognize abnormal operating conditions of the protected element and to trigger the circuit breaker operation when needed.

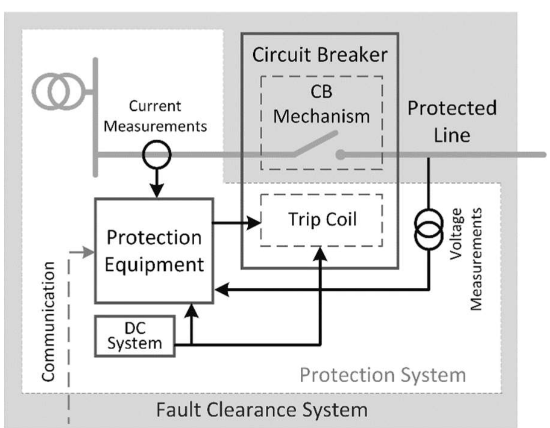

Fig.1 Illustration of a Fault Clearance System (FCS) that consists of instrument transformers, protection equipment and circuit breaker

The trip coil and DC control voltage are also parts of the protection system, while all of them together make the Fault Clearance System (FCS) [16]. The protection system complies with N-1 requirement since each element is typically duplicated for HV lines, while this is only partially true for the circuit breaker. On the power system level, the performance of the fault clearance system is relevant, not performance of the protection equipment or circuit breaker itself.

The total fault clearing time (Fig.2) is the time between the fault inception and the moment when fault current is interrupted. It consists of the relay operate time and the circuit breaker interrupting time (if the CB operates correctly, otherwise it prolongs until a breaker failure scheme opens adjacent CBs). The relay operate time is the time between the fault inception and the moment when the relay operate signal triggers the CB to interrupt the current.

The circuit breaker interrupting time is the interval of time between the beginning of the opening time and the end of the arcing time. The opening time is the time between the moment when the relay signal appears to the CB trip coil until the moment when the CB arcing contacts physically start to separate. Vendors usually provide some average value and variation interval for the opening time. After the arcing contacts start to separate, the current continues to flow and final fault clearing happens when the arc is extinguished, which can occur only at one of the current’s natural zero-crossing points. The time interval during which current continues to flow is called the arcing time and thermal and dielectric stresses require a minimum arcing time prior to successful interruption at a fault current zero-crossing [14].

Due to all mentioned factors, there is an embedded uncertainty in the circuit breaker interrupting time. An even more important fact is that the nature of that time is discrete since current can be interrupted only in the fault current zero-crossing moments.

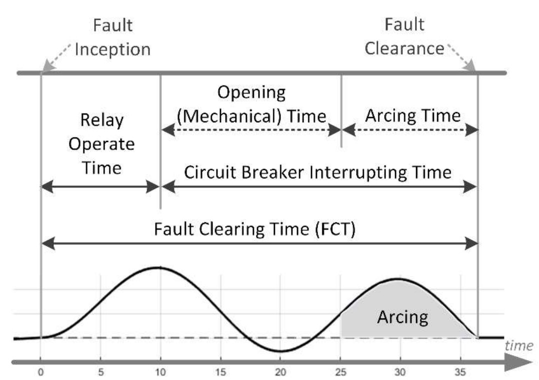

Fig.2 Definition of Fault Clearing Time (FCT), Relay Operate Time and Circuit Breaker Interrupting Time [1]

3 Impact of Relay Operate Time (ROT) on the fault clearing time

In Fig.3 is shown an example of a fault current waveform where possible current interruption moments are analysed. In this example, current can be interrupted only in a set of discrete time instances shown in Table 1:

Table 1 Zero-crossing instances of the fault current waveform from Fig.3

Zero-crossing (ZC)	ZC1	ZC2	ZC3	ZC4	ZC5	ZC6	ZC7
Time [ms]	17.4	22.9	36.6	43.7	55.9	64.1	75.6

Since circuit breakers have their limitations (opening and arcing time), not all the zero-crossing instances from Table 1 are the candidates for the current interruption. In this paper a model of a SF6 live-tank circuit breaker (420kV, 63kA) is used [1]. This CB model is selected since this CB has been used in transmission networks worldwide for 30+ years. The rated opening time of this circuit breaker is 18±2 ms, while minimum arcing times are summarized in Table 2 [1,2]. 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.

Table 2 Minimum arcing time ranges in different type test scenarios [7]

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 Fig.3 example it is assumed that CB opening time is 18 ms and the minimum arcing time is 7.6 ms. This means that, even in principle, the fault current cannot be interrupted by this circuit breaker in a time shorter than 25.6 ms, which excludes the first two zero-crossing instances from Table 1. In other words, no matter how fast the protection operate time is, the fault clearing time (FCT) cannot be shorter than 36.6 ms, which is the third zero-crossing instance. All the relay operate times from zero to 11 ms would have the same outcome, a FCT of 36.6 ms. Only when the relay operate time exceeds 11 ms will the FCT go to the next discrete point which is ZC4=43.7 ms.

In Fig.4 are shown possible fault clearing times as a function of the relay operate time under given condition (fault current waveform and the circuit breaker model). It is shown that relay operate time matters only around several discrete points such as 11 ms, 18 ms and 30 ms. At such points a millisecond of relay operate time can make a difference in the fault clearing time of around 7-10 ms. Otherwise, it does not make any difference from the power system perspective and claims that each millisecond of reduced relay operate time matters and directly contributes to power system stability are misleading.

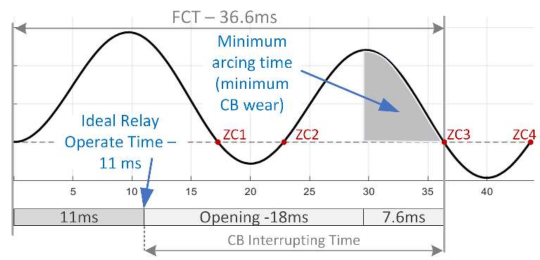

Fig.3 Ideal relay operate time leading to the FCT and CB arcing time

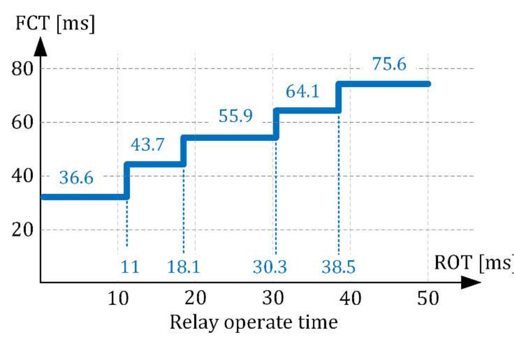

Fig.4 Fault clearing times as a function of the relay operate time under given condition

4 Impact of relay operate time on the circuit breaker wear

If relay operate times from zero to 11 ms do not make any difference in the fault clearing time, do they make any difference in other aspects of power systems? Yes, they affect the circuit breaker lifetime, as shown in [7], and the power system stability aspects, which are discussed in sections 5 and 8 [1].

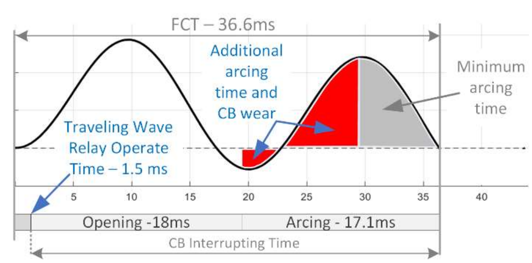

Fig.5 Ultra-fast relay operate time leading to additional CB arcing time

In Fig.5 it is shown the CB arcing time in case of an ultra-fast relay operate time. Since there is not enough arcing time before the second zero-crossing, the fault current can be interrupted only at the third zero-crossing at 36.6 ms. This means that after the circuit breaker opening time, there would be a very long arcing time of more than 17 ms, which is far more than the required minimum arcing time of 7.6 ms. The circuit breaker would experience additional wear due to the nearly 10 ms of additional arcing, while the system would get the same fault clearing time as if the relay operated in 11 ms. In this case there was no benefit to the system due to a faster relay operate time, while the circuit breaker lifetime was penalized as shown in [7].

5 Impact of relay operate time on the protection system security

In most of the publications in the field of transmission line protection, the shortening of the relay operate time is presented only in a positive context, as helping to maintain the power system stability. But the ultra-fast relay operation can lead to the opposite effect, where power system stability is affected due to unnecessary relay operation for a non-faulty condition. A protection device operates securely if it does not trip the circuit breaker in case of faults outside of the protected line, or in case of other non-faulty disturbances [1]. False tripping, or maloperations, are unacceptable in HV and UHV grids, as they can lead to system blackouts with high economic loss. The protection speed and security represent conflicting requirements, fundamentally limited by the Heisenberg's Uncertainty Principle. This fundamental law of physics limits our knowledge about particle's momentum if we know its location with high precision and vice versa. The same law applies to the signal processing area that shortening the time window of the measured signal (to reduce operate time) makes the response of the filter more spread in the frequency domain. The consequence is that the filter output is more sensitive and affected by different harmonics and transients and the likelihood of the relay making a wrong decision is increasing.

This uncertainty is illustrated in Fig.6. It is obvious that by reducing the time window between a disturbance inception (or relay starting instant) and the relay decision (Fig.6a), it becomes very hard to anticipate in which way the disturbance will develop in the future (Figs.6b-6g). It can develop into a permanent fault within the protected zone that requires the relay to operate and the circuit breaker to interrupt the fault current, as in Fig.6b. But it can also develop into an "incipient fault" or a short disturbance that is not harmful to the power system and does not require circuit breaker operation. Some of the situations whereby disturbances could wrongly be interpreted as genuine faults within the protection zone are [1,17,18]:

- parallel line faults that induce traveling waves in the protected line,
- lightning strikes,
- operation of surge arresters,
- operation of the bypass breakers on series capacitors,
- contamination of isolators (organic or chemical),
- encroaching vegetation,
- brush fires.

Such events occur even on the highest voltage levels, where unnecessary relay operation can be very harmful. Fig.6c shows a record from a 765kV network where a certain disturbance caused a very high spike in the phase A current. However, the condition disappeared by itself, and the current returned to normal load level. The network operator does not want the UHV line to be disconnected from the system in such a case. That means that too fast relay operation might negatively affect the power system stability and availability.

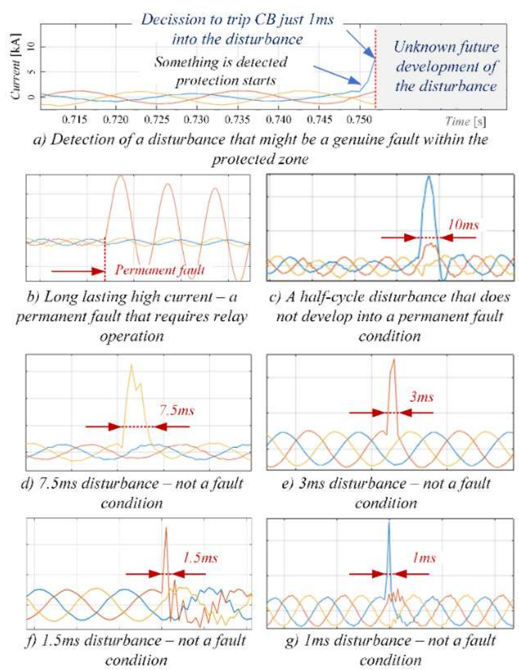

Fig.6 Impact of relay decision window on the protection security; a) example of a short relay decision window, b-f) current waveforms of different types of disturbances recorded on 400kV-765kV overhead transmission lines

How a particular relay would react on any of the scenarios from Fig.6 highly depends on the type of the protection algorithm and the details of the implementation. Slower, phasor-based algorithms would most likely stay secure on all the disturbances (Figs.6c-6g). A faster algorithm, incremental quantity (time-domain) based, could have a problem with the longer lasting transients (Figs.6c & 6d) if the decision is made without a bit longer security check. The ultra-fast algorithms based on traveling waves might recognize most of the transients as genuine faults if they originate from the protected zone. The main challenge for the ultra-fast algorithms is that they are designed to detect traveling waves, not faults. All the current waveforms from Fig.6 contain traveling waves, but not all of them are real faults. If a relay is forced to decide in a very short time, the knowledge about the disturbance is so limited that the probability of unsecure operation rises and puts into question the potential benefits of fast operation. The fast operation benefits are very questionable if the circuit breaker operation is taken into consideration, as illustrated in Figs.3-5.

The examples given in sections 3, 4 and 5 are illustrative and cannot cover the entirety of the situations in real networks. For this reason, statistical models of the operation of different types of relays and a commercial circuit breaker are taken into consideration to evaluate the real impacts of the relay operate time on the fault clearing time and circuit breaker wear. The results of the statistical analysis are presented in section 7.

6 Methodology

In Fig.3 a situation is illustrated where the relay operate time from zero to 11 ms did not change the total fault clearing time. It is obvious that for different zero-crossing moments and/or circuit breaker characteristics, the impact of relay operate time will differ. To have a fair evaluation of the impact of the relay operate time on the total fault clearing time, a wide range of fault current asymmetry levels were used, resulting in a different time spread of fault current zero-crossings [7]. The set of 12 asymmetrical fault current waveforms and corresponding zero-crossings were obtained from simulations of power line faults, as shown in Fig.7.

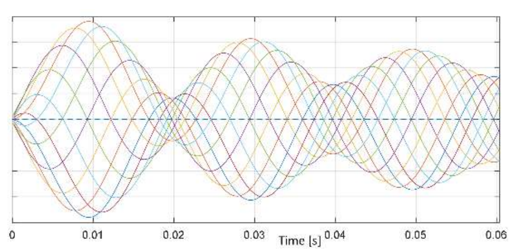

Fig.7 Fault current waveforms having variable zero-crossing instances used for calculation of FCT and CB wear

The CB model used in this paper is based on the type test results of a SF6 live-tank circuit breaker (420kV, 63kA) performed in an independent and ISO/IEC 17025 accredited laboratory [7]. It is shown in Table 2 that the required minimum arcing times are in the range 7.6-11.8 ms, while the rated opening time of this circuit breaker is 18±2 ms.

In Fig.8 are shown 10,000 random values of minimum arcing time and CB opening times, assuming a uniform distribution, to be used in the evaluation.

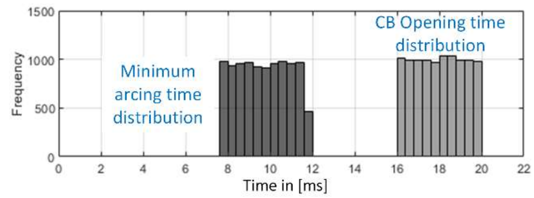

Fig.8 Distribution of CB opening time and minimum arcing time based on type testing of a widely used SF6 high-voltage circuit breaker [7]

Modelling of the relay operate time is a bit more of a challenging task since it depends on a number of factors: the protection algorithm type, hardware and software limitations (algorithm execution interval, bandwidth of internal filters, speed of output contacts), accuracy of measurement chain (CT saturation, CVT transients, noise) and a number of external factors (fault inception angle, fault location, power flow, fault resistance, etc.). To get exact values it would be required to use products from different vendors with correct settings and test them in a hardware-in-the-loop setup with a large number of test scenarios, which is not practical.

The proposed approach is to divide all numerical relays into three generations [1,7], which should cover the main algorithm types and hardware limitations.

I generation line protective relays are based on low sampling frequency (from <1 kHz to a few kHz) and phasor-domain (PD) algorithms (or some hybrid with incremental quantities). Operate times in the range of 8 ms – 20 ms are assumed, which should cover the majority of cases.

II generation line protective relays use higher sampling frequency (4 kHz – 10 kHz) and time-domain (TD) algorithms (usually incremental quantities and differential equations instead of the phasor approach). In the analysis operate times in the range of 3 ms – 8 ms are assumed.

III generation line protective relays use high sampling frequency (≥1 MHz) and traveling wave (TW) based algorithms. Operate times in range of 1.5 ms – 3 ms are assumed.

The distribution of relay operate times used in the evaluation of the total fault clearing time are shown in Figs.9c-9e. A uniform distribution of the operate times is assumed and there are in total 10,000 operate time values for each generation of relay to be used in the evaluation.

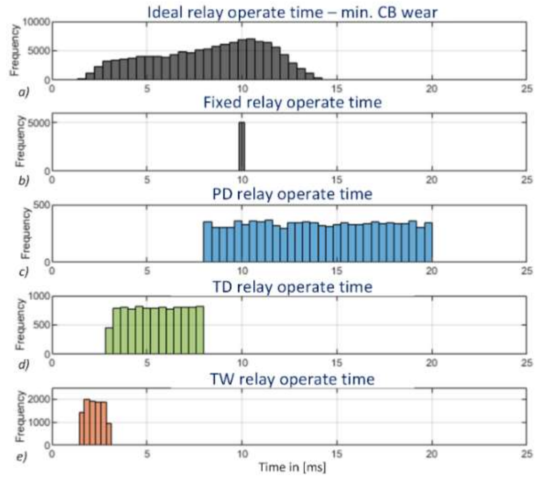

Fig.9 Distribution of relay operate time: (a) Ideal relay, (b) Fixed relay, (c) PD relay, (d) TD relay, (e) TW relay

The evaluation methodology starts with one of the fault current waveforms from Fig.7 and calculates the fault clearing time and the additional circuit breaker wear (red area from Fig.5) for each of the 10,000 examples of CB characteristics (Fig.8) and relay operate times (Fig.9). This is repeated for all 12 fault current waveforms and gives distributions of 120,000 FCTs for each of the three relay generations (Fig.10). Additionally, two more scenarios are calculated, based on the ideal relay operate time and the fixed half cycle relay operate time.

In [1,7] the concept of an ideal protective relay is proposed. 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 time and required minimum arcing time, it would always initiate the CB interruption process at the exact moment before the targeted zero-crossing that leads to the minimum arcing time (no red area in Fig.5, where the relay operates in 11 ms, which results in just the required minimum arcing time). The calculated ideal relay operate time is shown in Fig.9a. It is worth noticing that the ideal relay rarely operates in the fast operation interval below 5 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.

In [1,7] a fixed relay operate time is also proposed as an alternative to the "faster is better" philosophy. The fixed half cycle operate time (Fig.9b, 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 the power system (Fig.6).

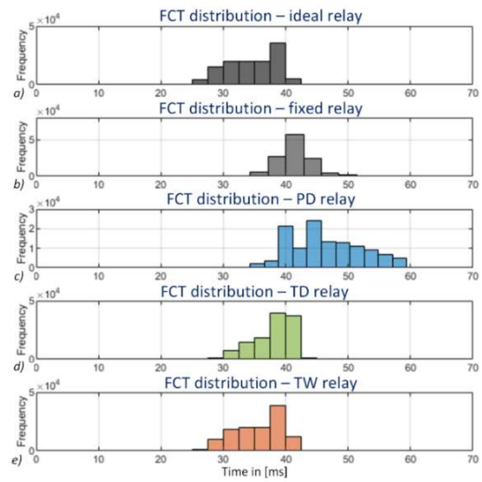

Fig.10 Distribution of fault clearing time [7]: (a) Ideal relay, (b) Fixed relay, (c) PD relay, (d) TD relay, (e) TW relay

7 Results

The first fact that can be noticed when Fig.9 and Fig.11 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, the TW relay operates 3-6 times faster than the fixed relay, yet brings a very modest improvement of average FCT of just 13.22% (Table 3). 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 fault current zero-crossing, subsequent to a required minimum arcing time. Such a minor FCT improvement is paid by >20% increase in CB wear (Fig.12, Table 3), not to mention the potential risk of maloperation and possible blackout in cases where the disturbances do not develop into real faults in the power system (Fig.6).

Fig.11 Average fault clearing time comparison [7]

In Fig.10 the distributions of fault clearing times for all 5 types of relay operations are shown. It can be noted that the average FCT (Fig.11) of the traveling wave relay is very close to the average FCT of an ideal relay, but the ideal relay rarely operates in the traveling wave relay operation interval from 1.5-3 ms. Most of the ideal relay operate time is concentrated around the half cycle value (Fig.9a). Such a large difference of traveling wave relay operate time from the ideal relay operate time causes substantially increased arcing time during the high fault current asymmetry. Fig.12 shows that the traveling wave relay causes over 30% more CB wear than the minimum value (in an ideal case).

Fig.12 Additional circuit breaker wear comparison [7]

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 3 the results of the comparison are summarized. It is shown that the PD relay does not have advantages over the fixed relay operate time. The PD relay has prolonged tripping time, yet has not resulted in reduced CB wear, since it has some operations below 10 ms. The slower operate times do not contribute to a further reduction of CB wear, since the majority of decaying DC offset has already disappeared.

Table 3 Comparison of the common relay technologies to the approach based on the fixed relay operate time [7]

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.3 and Fig.5). 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 [1,7].

8 Impact of the protection operate time on the transient stability of a power system

What is the impact of the protection operate time on the transient stability of a power system? A common criterion for the evaluation of transient angle stability is the Critical Clearing Time (CCT). It is defined as the maximum time during which a disturbance can be applied without the power system losing its stability [19]. As an example, in China Southern Grid, the CCT of some 500kV stations is around 350 ms [20]. The main requirement for the fault clearance system (Fig.1) is to clear faults faster than the critical clearing time (FCT<CCT) (Fig. 13), which leads to two scenarios:

1. Best-case scenario – fault current is interrupted by the closest circuit breaker/s (the current is interrupted at the FCT, Fig.13)
2. Worst-case scenario – the closest circuit breaker/s fail to interrupt the current and the breaker failure protection initiates opening of the adjacent circuit breakers (the current is interrupted after breaker failure fault clearing time, Fig.14)

In the best-case scenario, the fault clearing times are mostly in the interval of 30-50 ms for all generations of protective relays as shown in Figs.10 & 11. This leads to a CCT margin time of approximately 300 ms in the China Southern Grid example [20]. In the case of slower CBs, for FCTs in the range of 70-80 ms, the CCT margin is still significant.

How does the relay operate time affect CCT margin time? Fig.4 shows that relay operate time makes an impact on the FCT (and hence the CCT margin time as well) only at a few discrete moments, otherwise it makes no difference. We propose two relay operate times for the purpose of comparison:

a. relay operates in 1 ms
b. relay operates in 10 ms

In the case of the circuit breaker and fault current from Figs.3 & 4, the fault clearing time would be the same for both relay operate times (since the cutting point is at 11 ms). If other fault current waveforms from Fig.7 are considered, then the 1 ms relay operate time still does not reduce the FCT (nor increase the CCT margin time) in about 33% of cases. In the other 67% of cases, the 1 ms relay operate time reduces the FCT (and thereby increases the CCT margin time) by approximately 10 ms which, from our example, is just a 3.3% increase in the CCT margin time.

These results show that forcing the relay to operate in just 1 ms, instead of 10 ms, does not make any practical difference to the CCT margin time, and as such does not contribute to the power system stability in all situations when the CB/s operate as expected. On the other hand, 1 ms relay operate times impose a greater maloperation risk for cases of longer transient disturbances (as shown in Fig.6). It is very hard to avoid maloperations on such disturbances since their source can originate from within the protected zone. But if the relay has 10 ms to make a decision, most likely it will remain 100% secure even for the cases of longer disturbances (as shown in Fig.6). Therefore, relay operate times of 1 ms can be more likely to negatively affect power system stability than help to maintain it. Additionally, relay operate times of 1 ms negatively affect circuit breaker lifetime, and go against the International Standards that recommend to restrain relay operation until at least a half cycle has elapsed [5,6].

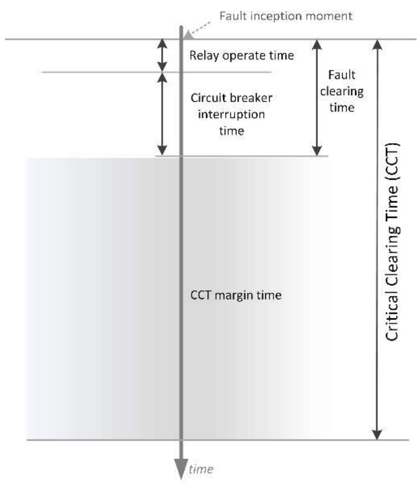

Fig.13 The impact of the relay operate time on the CCT margin time (best-case scenario)

In the worst-case scenario the closest CB/s fail to clear the fault and the breaker failure protection scheme initiates opening of the adjacent circuit breakers, as illustrated in Fig.14.

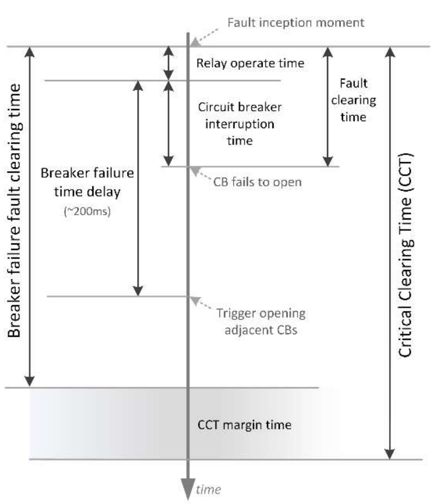

Fig.14 The impact of the relay operate time on the CCT margin time when breaker failure protection initiates the fault clearing (worst-case scenario)

In this scenario faster relay operate time improves the CCT margin time by starting the breaker failure timing earlier. However, if the first relay operation was false it will lead to maloperation on multiple lines which would compromise the overall power system stability. This brings the question if around 10 ms of earlier starting of the breaker failure timer, which is around 20 times longer, is worth the risk. Engineers need to carefully assess the settings of the "breaker failure time delay" against the risks of relay maloperation and its consequences related to power system stability.

9 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 and the fact that protection speed and security represent conflicting requirements. Such a simplification has three consequences:

1. 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).
2. The impact of relay operate time on circuit breaker lifetime is completely ignored and not brought into discussion when different protection solutions are presented.
3. The risk of system blackout due to relay maloperation caused by too short time to distinguish genuine fault states from disturbances (ultra-high speed affects the protection security).

In this paper the impact of relay operate time on the fault clearing time, the circuit breaker wear and the relay security is analysed. The presented results show that the proposed concept of a fixed relay operate time (equal to half a 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.

From the fault clearing time perspective, despite having 3-6 times faster relay operate time, the traveling wave protection brings only a very modest improvement, of just around 13%, when compared to the half cycle operate time. 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!

Such a small improvement in FCT brings a risk of relay maloperation and power system blackout, which is hard to accept. It is obvious that having a security time delay of around half a cycle before releasing the tripping signal can highly reduce the risk of tripping on disturbances even if they are long lasting (Fig.6).

From the circuit breaker lifetime perspective, when the ultra-fast operation of a traveling wave relay is compared to the fixed half cycle operate time, the TW relay causes 23% higher circuit breaker wear. 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].

These results bring into question the main paradigm in transmission line protection, in which “faster is better”, especially when power system stability aspects are considered.

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11 References

[1] Zubic, S., Gajic, Z., Kralj, D.: 'Line Protection Operate Time: How Fast Shall It Be? ' IEEE Access, 2021, vol. 9, pp. 75608-75616

[2] Berglund, R. O., Mittelstadt, W. A., Shelton, M. L., et al.: 'One-Cycle Fault Interruption at 500 kV: System Benefits and Breaker Design' IEEE Transactions on Power Apparatus and Systems, Sept. 1974., vol. PAS-93, no. 5, pp. 1240-1251

[3] Chamia, M., Liberman, S.: 'Ultra High Speed Relay for EHV/UHV Transmission Lines -- Development, Design and Application' IEEE Transactions on Power Apparatus and Systems, Nov. 1978., vol. PAS-97, no. 6, pp. 2104-2116

[4] Katsuhiro Ohse, Shigemi Mitsuhashi: 'Synchronous ABB for one cycle interruption delivered to keeler substation, Bonneville Power Administration, U.S.A.' https://www.fujielectric.com/company/tech_archives/review_19-03.html , accessed 9 November 2021

[5] IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers, C37.04-1999 (R2006).

[6] International Standard on High-Voltage Switchgear and Controlgear. Part 100: Alternating-current circuit breakers, IEC 62271-100, Ed. 2.0

[7] S. Zubic, Z. Gajic and D. Kralj, "The impact of line protection operate time on circuit breaker wear," 16th International Conference on Developments in Power System Protection (DPSP 2022), Hybrid Conference, Newcastle, UK, 2022, pp. 404-409
[8] Mohammadhosein, M., Niayesh, K., Shayegani-Akmal, A. A., et al.: 'Online Assessment of Contact Erosion in High Voltage Gas Circuit Breakers Based on Different Physical Quantities' in IEEE Transactions on Power Delivery, April 2019, vol. 34, no. 2, pp. 580-587
[9] Seeger M.: 'Future Perspectives on High Voltage Circuit Breaker Research', Plasma Physics and Technology
2015, 2, 3, 271-279
[10] Hitachi ABB Power Grids - Grid Automation Products: 'Line distance protection REL670 version 2.2 ANSI - technical manual ABB', https://search.abb.com/library/ Download.aspx?DocumentID=1MRK506369-UUS&LanguageCode=en&DocumentPartId=&Action=Launch, accessed 9 November 2021
[11] Siemens, Manual: 'SIPROTEC 5 Distance and Line Differential Protection, Breaker Management for 1-Pole and 3-Pole Tripping', https://cache.industry.siemens.com/dl/files/440/109742440/att_1040496/v1/SIP5_7SA-SD-SL-VK-87_V08.40_Manual C011-E_en.pdf, accessed 9 November 2021
[12] Dzienis, C., Kereit, M., Blumschein, J., et al.: 'An experimental analysis of high-speed-distance protection' 2010 Modern Electric Power Systems, Wroclaw, Poland, 2010, pp. 1-8
[13] Schweitzer, E. O., Kasztenny, B., Guzmán, A., et al.: 'Speed of line protection - can we break free of phasor limitations?' 2015 68th Annual Conference for Protective Relay Engineers, College Station, TX, USA, 2015, pp. 448-461
[14] Thomas, R.: 'Controlled Switching of High Voltage SF6 Circuit Breakers for Fault Interruption,' PhD thesis, Dept. Elect. Power Eng., Chalmers Univ. of Techn., 2004
[15] Kasztenny, B., Rostron, J.: 'Circuit breaker ratings — A primer for protection engineers' 2018 71st Annual Conference for Protective Relay Engineers (CPRE), College Station, TX, 2018, pp. 1-13
[16] S. Lindahl et al., "Reliable fault clearance and back-up protection," CIGRE Working Group 34.01, Report no. 140, Apr. 1999.
[17] E. O. Schweitzer, B. Kasztenny, A. Guzmán, V. Skendzic and M. V. Mynam, "Speed of line protection - can we break free of phasor limitations?," 2015 68th Annual Conference for Protective Relay Engineers, College Station, TX, USA, 2015, pp. 448-461
[18] B. Kasztenny, M. V. Mynam, T. Yoshi, D. Holmbo, "Preventing Line Faults With Continuous Monitoring Based on Current Traveling Waves," 15th International Conference on Development in Power System Protection 2020 (DPSP)
[19] ENTSOE, "Inertia and Rate of Change of Frequency (RoCoF)," ENTSOE, Version 17, SPD-Inertia TF, [Online]. Available: https://eepublicdownloads.azureedge.net/clean-documents/SOC%20documents/Inertia%20and%20RoCoF_v17_clean.pdf
[20] Yu Jiang, Zhou Hongyang, Chen Zhaohui, Li Jie, Li YiQuan and Zhang Shaofan, "The optimization of 500 kV breaker failure protection," 2014 China International Conference on Electricity Distribution (CICED), Shenzhen, China, 2014, pp. 1755-1758