

Instantaneous protection scheme for backup protection of high-voltage transmission lines

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Received: 01.11.2015

Accepted/Published Online: 30.12.2016

Final Version: 30.07.2017

Abstract: The protection scheme focused on in this study is a typical protection system used in high-voltage systems such as 132 kV, 275 kV, and 500 kV. The research will analyze the existing protection scheme for transmission lines that the power utility has implemented and will propose a new protection scheme to improve the performance of the existing scheme. The existing protection scheme currently implemented by the power utility for backup protection operation has a longer fault-clearing time and no restoration time, and it does not utilize support relays. This study will focus on a backup protection operation on high-voltage overhead transmission lines, which take up communication when the main protection has failed to communicate, the relay has failed due to loss of DC supply, or the relay function itself has been blocked. Moreover, all the support relays will be utilized in order to improve the protection system. The improvement will consider three elements, which are the fault-clearing time, fast restoration time, and relay utilization. Each improvement to the protection system will have its own philosophy and concrete rationale, which have advantages or disadvantages for the transmission line. The effect of the improvement scheme will also consider the outcomes in other schemes to ensure that time coordination does not overlap. Every possibility of a fault will be analyzed in order to have a clear understanding of the effects of the three elements. CAPE software will be used as a tool for simulation and to analyze its compatibility with real applications. CAPE software is able to model a real-life transmission line and is also able to simulate faults in the tested area. The results of the simulation show that the backup protection operation improved fault-clearing time and restoration time. It also increased the network's system stability, particularly during the occurrence of maximum fault currents.

Key words: Transmission line protection, backup protection, fault-clearing time, fast restoration, relay utilization

1. Introduction

A protection scheme is a vital provision that can have a massive impact on system operation. The effect of a malfunction of the scheme may cause the wrong tripping sequence and can ruin the system, affecting customers. Small setting discrepancies may even cause an increase in the fault-clearing time and cause system feeding to the fault to be longer than the system design [1]. Unit protection is typically used as the main protection, such as pilot wire and current differential relays, due to its capability to detect faults in a certain area. Meanwhile, nonunit protection is used as backup protection, including distance and overcurrent relays, which have the capability to detect faults in-zone and out-zone that are differentiated by time coordination. A current differential relay at the transmission line relies on communication between substations to detect faults, which will disable the protection for both substations during a loss of communication [2]. However, a distance relay has its own benefits, unlike the existing differential relay; the failure of a distance relay on one side does

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not result in failure of the protection on the other side [3]. The value of the distance relay is that it provides engineers with the tools and flexibility to design more secure and dependable protection schemes [4].

Protection schemes for transmission lines are currently equipped with backup protection, although the design scheme does not have a similar impact to that of the main protection. In this study, the standard scheme implemented by the power utility in Malaysia will be used since it is a very practical scheme that has been in use for a long time. The existing scheme will be based on the TNB Transmission System Protection and Control Code of Practice booklet [5].

1.1. Project background

Transmission lines are the typical medium used to transmit power from generation to distribution. In Malaysia, transmission lines are designed for high-voltage levels such as 132 kV, 275 kV, and 500 kV, depending on the estimation of the system's needs. The main reason behind this principle is to reduce losses during transmission of bulk power [5].

A study regarding the power utility in Malaysia was conducted to define the capability of the system to feed faults in order to protect the high-voltage apparatus and the system as a whole. The protection scheme design must be in line with the competency of the apparatus and the system. Competency consists of the minimum requirements needed in the design of the protection schemes. For example, the fault-clearing time for a 132-kV system must be below or equal to 150 ms [5], while the fault-clearing time for 275-kV and 500-kV lines must be below or equal to 100 ms [5]. These levels are used as a limit for the main protection.

Using the fault-clearing time as a reference will help the designer to coordinate a time for the breaker to be opened during a fault as required. Rather than only affecting the coordination time, it will also cause an increase in the specification for breaker time opening, relay detection, and much more in order to satisfy the fault-clearing time requirement. The voltage level on the transmission line, its length, its distance to sources, load flows, and also the stability parameters are examples of the effects of the protection scheme for typical transmission lines [6].

In addition, transmission lines are normally equipped with an autoreclose function that is designed to minimize the restoration time during a transient fault, such as one caused by lightning. Normally, in high-voltage applications, the utility will only tolerate a single reclose because the outcome of the fault current can cause a major voltage dip, and this will reduce the lifecycle of a sensitive high-voltage apparatus such as a circuit breaker [7]. However, the autoreclose scheme is only available during the main protection operation and remains idle during backup protection operations [5]. This causes a long restoration time for transmission lines, even when faced with a transient fault that can supposedly be reduced if an autoreclose function is embedded in the backup protection operation.

2. Literature review

The protection scheme is designed based on the overall system, which considers many parameters such as the fault current level, equipment rating, and power system stability. Each power system is designed to withstand some fault level depending on preliminary studies. Hence, each primary apparatus is equipped with protection schemes that protect the apparatus from failing. Certain protection schemes have been designed to maintain stability, and users are trained to make a proper decision in restoring the system to normal conditions after a fault [8]. The protection schemes that are generally implemented in transmission lines are equipped with appropriate autoreclose facilities that enable fast restoration and power system stability. The fault-clearing

system is a system that detects faults and isolates them. The system design needs to take into consideration that the failure of any component in a fault clearance system should not result in a complete failure to clear the power system fault or abnormalities. This can be achieved when considering the backup protection, which can be a local backup or a remote backup for every possible component failure. The new proposed protection scheme will focus on the fault-clearing time, fast restoration, and relay utilization. The best backup protection for all three criteria will be designed. In addition, time coordination will also be taken into account when dealing with these three parameters. The protection scheme that is implemented by the power utility in Malaysia consists of current differential protection (87CD), distance protection (21Z), autoreclose relay (79AR), and synchronous relay (25SYN).

2.1. Current differential protection

Current differential protection is a unit protection. The philosophy of unit protection is related to Kirchhoff’s current law, which states that the value of current leaving a circuit must be equal to the value of that entering the circuit. Current differential protection is also immune to the power swing phenomenon, which causes the protection to be more stable and reliable during mass changing of the load flow in the system [9]. For a fault within its zone of protection, a relay will instantaneously operate the scheme in order to isolate the fault through the dedicated circuit breaker. Nevertheless, this scheme should remain stable or inoperative for faults outside of its zone. This type of zone of protection is demonstrated in Figure 1. As previously mentioned, both vector currents are meant to cancel each other out in order to have zero differential, but this summation will create a larger current if a fault occurs.

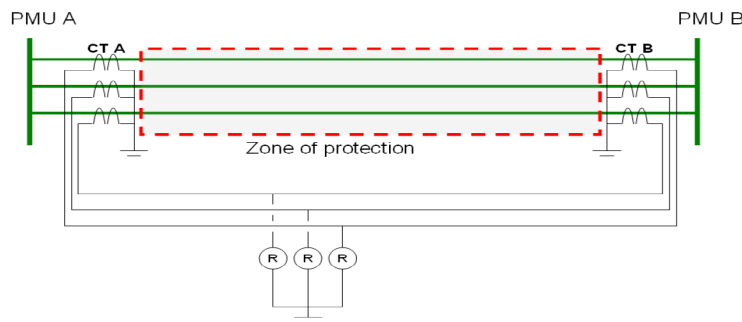


Figure 1. Protection zone for unit protection.

2.2. Distance protection

Distance protection is currently a nonunit protection, one that protects transmission lines by separating them into zones. All inputs are therefore stand-alone only on one side. Distance protection relay is used as backup protection due to the measurement inaccuracy of the impedance during faults, especially when dealing with high-resistance faults that may cause an increase in impedance and lead to an incorrect zone of operation. The distance relay for zone 1 requires permission input from the main protection relay to be activated. The input from the main protection relay only functions with the availability of DC supply to the main relay, during relay function failure, or when a communication failure occurs between both ends [5].

The distance relays algorithm is capable of measuring the impedance between the relay and the fault location. However, it depends on the resistance occurring at the fault. If there is a low resistance fault, the impedance is approximately similar to the distance from the relay to the fault location, but for a higher

resistance fault, it may cause an inaccurate assessment of the distance. Current and voltage inputs from the dedicated transmission lines are required for the distance relay to quantify the impedance. A distance relay is designed to be segregated into several zones, which are differentiated by the impedance value range. Every zone has its own timer that is coordinated based on the application for the transmission lines. The relay will be operated according to the respective zones and a dedicated timer, which can indirectly separate the fault locations, making it easy for faultfinders to find the fault locations [1].

Distance zones are practically divided into four parts; three zones are dedicated for forward zone protection while the other one is for reverse zone protection [5]. The zones' protection is illustrated in Figure 2. The protection for dedicated transmission lines consists of the whole of zone 1 and a part of zone 2, which are differentiated by a timer. Normally, 70% to 85% of line length is covered by the protection from zone 1 [5] due to the inaccuracy of the apparent impedance and protection relay measurements to operate the remote transmission line fault. The remaining length will be concealed by another zone, which will also cover a part of the remote transmission line. This is known as zone 2, which has a timer delay that is designed to be inactive during faults that must be cleared by the distance protection of zone 1 at local and remote sides. This coordination delay depends on system stability, where current practice for the power utility in Malaysia is 0.45 s [8].

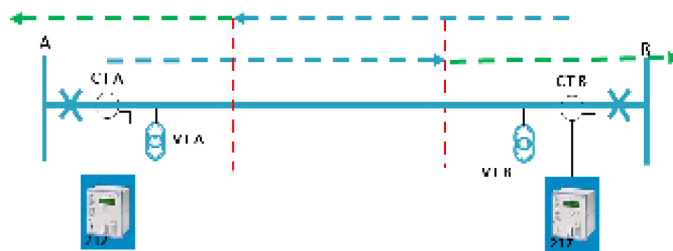


Figure 2. Coordination distance relay zones for the transmission line.

2.3. Autoreclose scheme

High-voltage transmission lines will deliver a bulk supply from the generation to the customer. Disturbance on the transmission lines may contribute stress to the overall system even if it only involves one transmission line. When the transmission line experiences a fault, the circuit breaker will open and isolate the fault. Normalizing of the transmission line needs to be done manually, which will take longer. Generally, autoreclose schemes help to maintain system stability and synchronism. In fact, most faults on overhead transmission lines are transient faults. Malaysia, which has a high keraunic level of about 180 thunder days per year, suffers a high-transient fault rate, and 70% of the faults are transient in nature, indirectly affecting the reliability and quality of supply to customers [7]. Faults can be divided into two types: transient and permanent. An example of a transient fault is lightning, which, as mentioned earlier, is a major contributor to fault statistics. From the analysis, a transient fault occurs for a short duration. Transient faults can therefore be cleared by temporarily isolating the transmission line to tolerate the clearance of the fault [10]. The autoreclose relay generally functions to reclose the circuit breaker after considering some parameters engaged by the synchronous relay. Figure 3 shows the relay coordination when dealing with a transient fault. As a result, autoreclosing can reduce the outage time arising from faults with fast restoration of the transient fault, resulting in only short power interruptions for customers [10].

Permanent faults are those that are not yet cleared, even after the reclosing process. Permanent faults will not be discussed in this study since they take a longer time to remove. Figure 4 shows the relay coordination

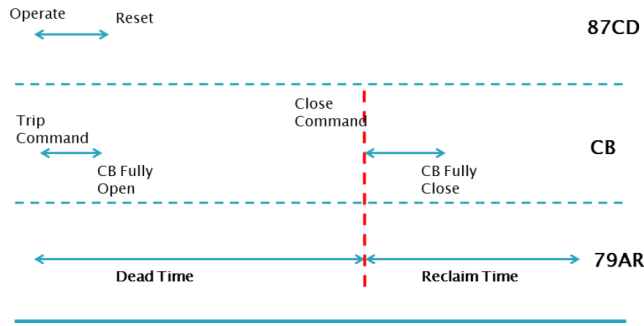


Figure 3. Relay coordination during transient fault.

during a permanent fault, resulting in the circuit breaker being permanently opened even after an autoreclose operation.

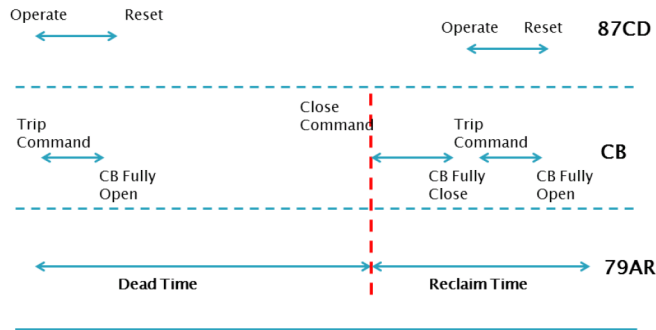


Figure 4. Relay coordination during permanent fault.

2.4. Existing protection scheme

In this study, the existing scheme implemented by the power utility in Malaysia will be used and analyzed. The transmission line protection scheme contains a main protection that is supported by additional relays such as autoreclose and synchronous relays. Figure 5 clearly shows the types of protection scheme in use.

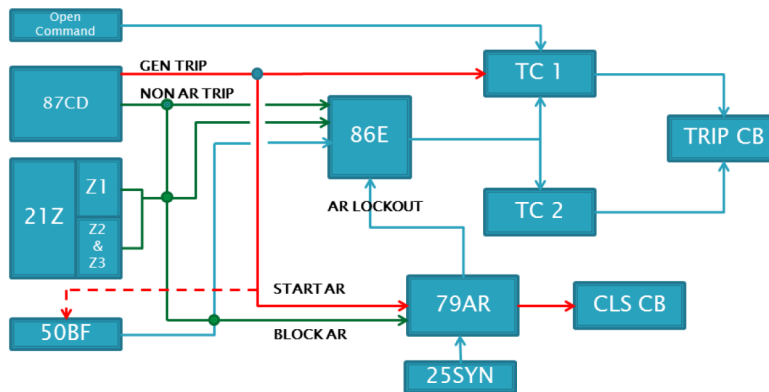


Figure 5. The protection scheme implemented in Malaysia.

The main protection operation can be divided into a general trip and a nonautoreclose trip. The general trip will directly trip the circuit breaker and start the autoreclose operation and the breaker fail's timer.

It will next reclose the circuit breaker after considering the synchronous relay output. The nonautoreclose trip represents any triggered fault that should not start the autoreclose relay such as a switch-on-to fault or three-phase fault. Besides this, backup protection uses the distance relay, where it can be divided into three zones. Current implementation for backup protection only permits all tripping directly to the master trip (lockout), which will block the autoreclose operation. This will mean no restoration during the backup protection operation. Zone 1 generally covers about 75% to 85% of the line length while zone 2 covers up to 110% to 130%. The operation in zone 1 will always be blocked until it acquires permission from the main protection relay. Permission from the main protection will be picked up after the main protection is blocked due to DC supply failure, communication failure, or failure of the relay function itself.

3. Proposed protection scheme

In this study, the proposed improved protection scheme will focus on three aspects: the fault-clearing time, fast restoration, and relay utilization. The transmission line protection scheme contains a single main protection that is supported by additional relays, such as autoreclose and synchronous relays. However, during the main protection block, the backup protection relay will stimulate zone 1 protection after gaining permission through physical contact from the main protection. Permission is dependent on the integrity of the physical contact, but it is very challenging to monitor the condition of the conductor; therefore, this study proposes that the backup protection scheme should not only depend on input from the main protection. The proposed backup protection for zone 1 has already considered the effect of input contact failure, which can lead to an incorrect fault isolation that may depend on remote backup. It will also cause the activation of many high-voltage circuit breakers. The proposed scheme will lead the operation of the main protection and the backup protection to pick up together in order to isolate the fault, which theoretically does not affect the overall scheme. In fact, it will make the system more reliable and stable in protecting the transmission lines.

Backup protection uses a distance relay that can be divided into three zones. The present implementation of backup protection only tolerates the tripping to be directed into the master trip, which will block autoreclose operations. This prevents fast restoration during backup protection operations. The proposed protection scheme will allow the distance relay of zone 1 protection to start the autoreclose operation similar to the main protection. However, zone 2 and 3 protection will retain their functions in order to trigger the master trip directly and to block the autoreclose operation. The effect of triggering the start for autoreclose by the distance relay of zone 1 may cause approximately 60% of the fault along transmission lines, which can be applied for using the proposed scheme during a backup protection operation. The proposed protection scheme does not involve the installation of any new protection relays in the system since it will utilize all of the existing relays that were used during the main protection operation. The overall features of the proposed protection scheme can be seen in Figure 6.

4. Summary

The new proposed protection scheme for transmission lines has been designed without interrupting the existing relay function and time coordination between all timers. The network model has been set up in order to simulate a practical transmission line using CAPE software. The modification of the scheme is based on the need to improve the fault-clearing time, restoration time, and relay utilization.

5. Results and discussion

This section will highlight the output of the simulation procedure in order to analyze three important elements: the fault-clearing time, fast restoration time, and relay utilization of the high-voltage transmission lines. The

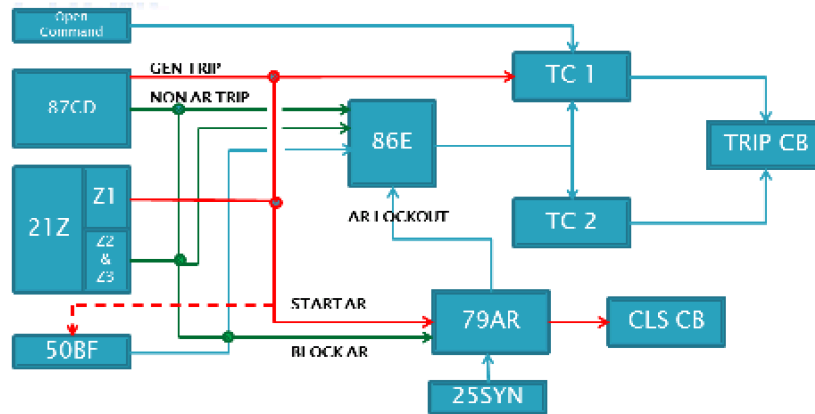


Figure 6. Proposed protection scheme for the transmission line.

analysis will become clear with the summary of the operation produced with CAPE software as an applied practical condition.

5.1. Simulation during main protection in good conditions

This section will focus on the existing protection scheme with a good working condition of the current differential relay. The main protection will offer the best safeguard for the power system network in terms of fault-clearing time, restoration time, and relay utilization without any discrepancy in time coordination. The mockup will react to faults on the transmission lines according to the type of fault, such as single-phase-to-ground, phase-to-phase, phase-to-phase-to-ground, and three-phase-to-ground. For simulation purposes, only a single-phase-to-ground fault will be used because a requirement of this research is to understand the protection scheme operation at different fault locations. The simulation process will generate faults at 10%, 50%, and 90% of the line length to show the area of protection for the dedicated relay. The simulation for the current differential relay shows that the protection covers the entire transmission line with instantaneous protection, as demonstrated in Figure 7. The time of operation recorded is 60 ms for all three cases. Moreover, the scheme also permits the circuit breaker to reclose after dead time. The dead time set in PSAK is 3.5 s while in TLST it is 3 s. From the simulation, the operation summary can be constructed to display the impact of the main protection on the transmission lines. Table 1 shows the summary of the operation for all three different locations. The operating times for the circuit breaker to isolate all of the faults are similar, representing the time for the electrical operation (30 ms) and the circuit breaker opening time (30 ms). The operation time correspondingly indicates that the fault-clearing time is within an acceptable tolerance level to protect the network. Moreover, the restoration time during the main protection operation for the transient fault is around 3 to 4 s, depending on the dead time setting at the site. The restoration time for the main protection can be considered as sufficiently fast enough to renormalize the system. Usage of the support relay is very important in order to assist the main protection relay for safe normalizing.

5.2. Simulation during main protection in blocking mode

The backup protection scheme will take over the protection system if the main protection is in blocking mode. Conditions for initiation of the blocking mode are caused by an interruption of supply, a telecommunication failure, or failure of the relay. During the simulation process, the current differential relay will be positioned

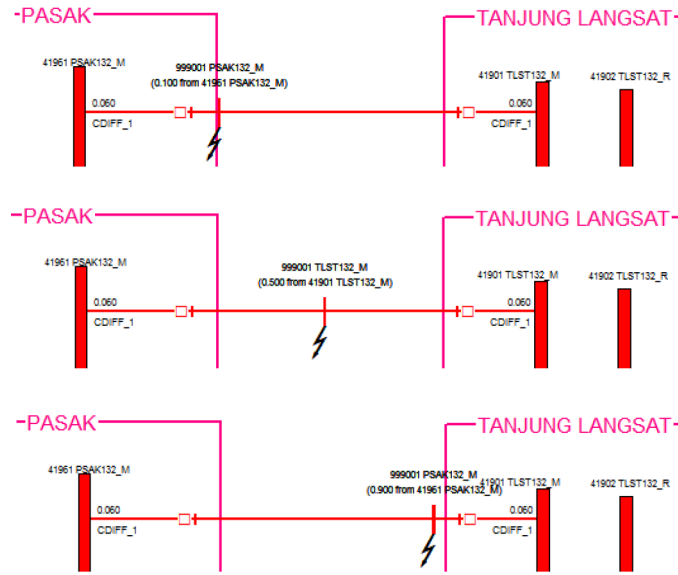


Figure 7. Operation for the main protection at three different fault locations.

Table 1. Summary of operation for main protection.

Case	Fault condition	Fault location (% of line length)	Fault clearing time (s): PSAK	Fault clearing time (s): TLST	Restoration time (s): PSAK	Restoration time (s): TLST	A/R & sync
1	Transient	0.1	60	60	3.57	3.07	Active
2	Transient	0.5	60	60	3.57	3.07	Active
3	Transient	0.9	60	60	3.57	3.07	Active
4	Permanent	0.1	60	60	-	-*	Active
5	Permanent	0.5	60	60	-	-*	Active
6	Permanent	0.9	60	60	-	-*	Active

*: Circuit breaker recloses but trips back.

in disable mode, and contact for the activation being sent through the hard wire will be assumed to be always picking up. The simulation process will focus on two zones: zone 1 and 2. Every zone will have its own timer before dispensing a trip. The timers for both zones are 150 ms and 450 ms, respectively, as implemented in the Malaysian power utility. Since the backup protection does not trigger the autoreclose relay, no reclosing occurs during the operation of the backup protection. The mockup will use an identical method to that used in the previous study, which performed faults at three different locations to comprehend their impact on the backup protection system. After the simulation, a summary of the operation can be created to demonstrate the impact of the backup protection on the transmission lines. Table 2 summarizes the operation for the different locations. The operating time for the circuit breaker to isolate the faults for all three locations can be subdivided into two operating times: 230 ms and 530 ms. The 230-ms timer represents zone 1’s operating time while 530 ms represents zone 2’s operating time, as demonstrated in Figure 8. The operating time consists of the fault detection time, the zone timer, and the circuit breaker operation time. The operation time means that the fault-clearing time is more than 100 ms, which does not meet the grid’s requirement. Moreover, there is no

restoration time facility during the backup protection operation, even for a transient fault. The support relay will be inactive during backup protection for safe normalizing.

Table 2. Summary of operation for backup protection for the existing scheme.

Case	Fault condition	Fault location (% of line length)	Fault clearing time (ms): PSAK	Fault clearing time (ms): TLST	Zone of operation: PSAK	Zone of operation: TLST	A/R & sync
1	Transient	0.1	230	530	Zone 1	Zone 2	Not active
2	Transient	0.5	230	230	Zone 1	Zone 1	Not active
3	Transient	0.9	530	230	Zone 2	Zone 1	Not active
4	Permanent	0.1	230	530	Zone 1	Zone 2	Not active
5	Permanent	0.5	230	230	Zone 1	Zone 1	Not active
6	Permanent	0.9	530	230	Zone 2	Zone 1	Not active

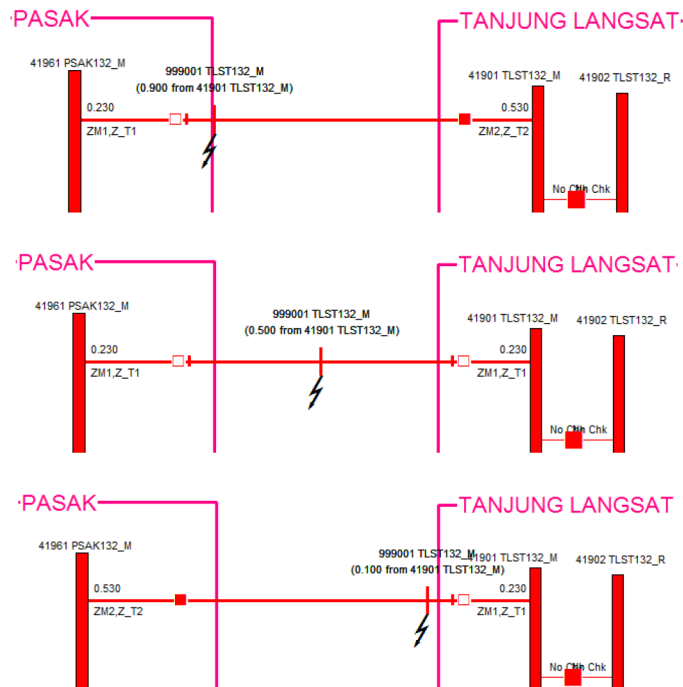


Figure 8. Operation for the backup protection at three different fault locations.

5.3. Simulation for proposed new scheme

As mentioned earlier, the proposed protection scheme will highlight the performance during the blocking mode of the main protection scheme. The backup protection scheme for the proposed protection scheme will use the distance relay but will be supported by the autoreclose and synchronizing relays. The role of the support relays is to assist the distance relay in making the decision to reclose the circuit breaker during zone 1 operation. The simulation process for this part will also focus on zone 1 and zone 2 operations during fault occurrence. The timer for zone 1 is instantaneous while for zone 2 it is maintained at 450 ms. The simulation procedure will

also analyze the impact on all three fault locations, as demonstrated in Figure 9. The support relays will be set in an active mode to support any relevant operations. They will also undergo fast normalization with dead times of 3 and 3.5 s, as illustrated in Table 3. The dead time fixed in PSAK is 3.5 s while in TLST it is 3 s. From the simulation procedure, the fault-clearing time during zone 1 operation is 80 ms while for zone 2 it is 530 ms. Moreover, the time of operation for the second tripping process due to the permanent fault after the circuit breaker has reclosed is at 3.19 s. The circuit breaker is successfully closed during zone 1 operation for both ends.

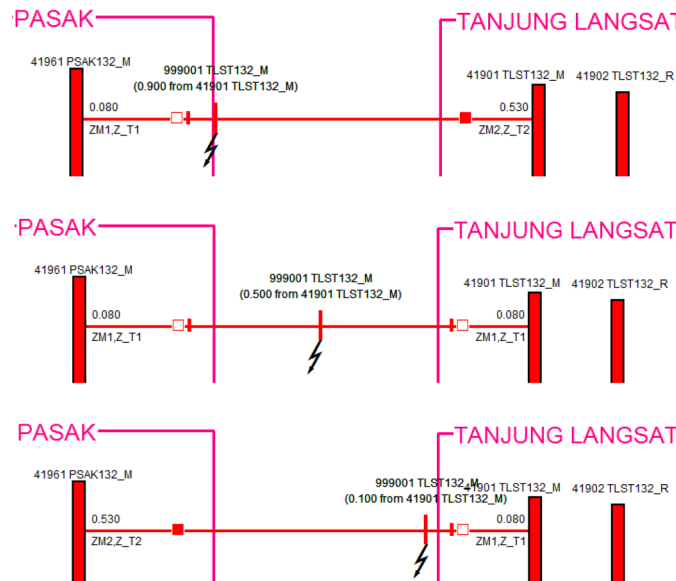


Figure 9. Operation for the proposed new scheme for backup protection.

Table 3. Summary of operation for backup protection.

Case	Fault location	Fault location (% of line length)	Fault clearing time (s): PSAK	Fault clearing time (s): TLST	Restoration time (s): PSAK	Restoration time (s): TLST	A/R & sync A/R	Zone of operation: PSAK	Zone of operation: TLST
1	Transient	0.1	80	530	-	-	Not active	Zone 1	Zone 2
2	Transient	0.5	80	80	3.61	3.11	Active	Zone 2	Zone 1
3	Transient	0.9	530	80	-	3.11	Active	Zone 1	Zone 1
4	Permanent	0.1	80	530	-	-	Not active	Zone 1	Zone 2
5	Permanent	0.5	80	80	-*	-*	Active	Zone 1	Zone 1
6	Permanent	0.9	530	80	-	-*	Active	Zone 2	Zone 1

*: Circuit breaker recloses but trips back.

5.4. Summary

From the analysis of the simulation and after modification of the backup protection schemes, it appears that there is significant influence on the protection system of the transmission lines. The modification also contributes to the positive control of the overall protection system to deal with certain types of faults. In addition to this, it also enhances the possibility of normalizing the system in a shorter period. The benefits of the proposed new backup protection scheme can be seen through three elements: the fault-clearing time, fast restoration,

and relay utilization. It is clear that with the proposed scheme, the fault-clearing time has been significantly improved, especially during zone 1 operation, compared to the existing scheme as tabulated in Table 4. This has the benefit of enabling the system to react to the fault as fast as it can, even during the backup protection operation, compared to the existing scheme, which required 230 ms to isolate the fault. The proposed scheme also strengthens the network system stability, particularly during the occurrence of the maximum fault current.

Table 4. Fault-clearing time comparison.

Case	Fault condition	Fault location (% of line length)	Existing scheme's fault clearing time (ms): PSAK	Existing scheme's fault clearing time (ms): TLST	New scheme's fault clearing time (ms): PSAK	New scheme's fault clearing time (ms): TLST
1	Transient	0.1	230	530	80	530
2	Transient	0.5	230	230	80	80
3	Transient	0.9	530	230	530	80
4	Permanent	0.1	230	530	80	530
5	Permanent	0.5	230	230	80	80
6	Permanent	0.9	530	230	530	80

Furthermore, the fast restoration time has also been improved, mainly during the transient fault, in nearly 60% of the transmission lines, as demonstrated in Figure 10. Restoration time for 60% of the total transmission lines shows a similar effect, identical to the main protection operation. Another 40% of the transmission lines were not equipped with a restoration facility as zone 2 coverage is beyond its own transmission lines, and it is difficult to identify the exact location of the faults. This will upsurge to 60% of the transmission lines to acquire a greater possibility of being restored. However, the permanent fault will not have a restoration time because the circuit breaker will trip back for the second time after fault detection. The results of the simulation procedure demonstrate that the supporting relays will also be utilized during the backup protection operation. Utilization of the supporting relays results in a positive improvement to the entire control, as the existing scheme will not support the backup protection operation. Moreover, the scheme addresses the shortcomings of the system. The user of this scheme requires a good understanding of the usage of relays as a typical zone 1 fault will trigger the main and the backup protection to operate simultaneously. This might interrupt the user's ability to make a correct analysis of the fault during fault investigation.

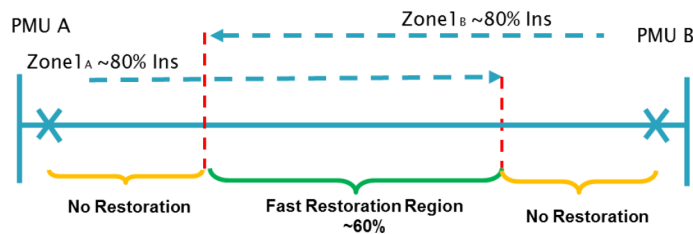


Figure 10. Restoration region for transient fault using the proposed scheme.

6. Conclusion

The fault-clearing time under the proposed scheme has been significantly improved, especially during zone 1 operation. Fast restoration time has also been improved, mainly during transient faults, in nearly 60% of the transmission lines, even though this occurred during backup protection operations. All of the relays installed were fully utilized during the backup protection operation, and there were no discrepancies in time coordination between the main, backup, and support relays. Simulation and analysis using CAPE software also shows the capability of the proposed scheme to be adopted in real application.

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