The study of directional overcurrent relay and directional earth-fault protection application for 33 kV underground cable system in Malaysia

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A B S T R A C T

Differential protection scheme is based on comparison of measured variables such as current and voltage at the two ends of a line via a communication channel such as pilot wire. This scheme is preferred and extensively used in distribution feeder protection system in Malaysia due to its fast operation. However pilot-wire differential scheme has its own drawbacks especially on the maintenance of the pilot-wire. Once the plot-wire is out of service, the feeder protection is jeopardised. One of the options to overcome such maintenance issue is to adopt directional relay as the feeder protection. This paper investigates a suitable relay connection and the maximum torque angle for the directional relay for 33 kV underground network. In this study, a section of 33 kV underground network in Kuala Lumpur (KL) city has been analysed. All faults types have been simulated at all possible location in the network. The obtained voltage and current were then used to determine the operation of directional overcurrent and earth-fault relay. The simulation results indicate that 30°/C176C176C176 relay connection with 0°/C176C176C176 maximum torque angle (30°/C176C176C176/0°/C176C176C176) is the most suitable setting to be applied for 33 kV underground network in KL, as against the best general and most versatile setting, 45°/C176C176C211211.

1. Introduction

One of the main objectives of most utilities is to provide secure and reliable supply to their customers. However, the occurrence of short-circuit fault affects the reliability and quality of power supply. In the event of electricity outage due to fault, fast isolation and restoration are required to minimise customers minutes lost and to reduce electrical and thermal stresses on system equipment, especially on cables, switchgears and transformers. Also, the stability of power system depends on fast fault isolation [1–6].

The types of short circuits commonly occur on 33 kV network can be categorised into insulation failure, electrical, thermal and mechanical or any combination of these. Even though fast restoration can be achieved through state of the art technologies such as Supervisory Control Acquisition Data Automation (SCADA) with automatic re-closing facilities and Automatic Transfer Scheme (ATS), the precondition is to isolate the faulty section effectively and quickly. Hence, the key to secure reliable and quality supply is to use appropriate protection system.

Pilot-wire differential scheme is extensively used in distribution feeder protection system in Malaysia. This scheme is preferred due to its fast operation. The principle of this protection scheme ensures no discrimination problems [3]. However pilot-wire differential scheme based on circulating current or balanced voltage theory has its own drawbacks that can affect the operation of relay. The common encountered problems are [7,8]

i. Open circuit of the pilot-wire.
ii. Short circuit of the pilot-wire.
iii. Crossed connection after maintenance.

Although the faulty section of the pilot-wire can be located and repaired or replaced, the pilot-wire scheme has to be temporarily defunct while waiting to be repaired. At certain area, the pilot-wire scheme is abandoned due to the difficulties to locate, repair or replace new pilot cable. This result in loss in feeder protection reliability thus compromising the line protection once the pilot-wire is no longer in operation. One of the options to overcome such maintenance issue is to adopt Directional Overcurrent Relay (DOC) and Directional Earth-Fault Relay (DEF) as the feeder protection. Furthermore, DOC and DEF are inexpensive compared to pilot wire protection scheme [9].

Abbreviations: LLLGF, Three Phase Fault to Ground; LLLF, Three Phase Fault; LLGF, Double Line to Ground Fault; SLGF, Single Line to Ground Fault; LLF, Line to Line Fault; DOC, directional overcurrent relay; DEF, Directional Earth-Fault Relay; MTA, maximum torque angle.

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This paper examines the effectiveness of DOC relays performance as a feeder protection in a 33 kV distribution network. An actual 33 kV distribution network in Kuala Lumpur with underground cable system is assessed. The study also investigates the most suitable type of relay connection and suitable maximum torque angle setting to be used in the distribution network.

2. Relay connection and maximum torque angle

2.1. Relay connection

Relay connection refers to the angle between voltage applied to the relay and current applied to the relay at system unity power factor and with the system voltages balanced. There are many possibilities to energise the voltage coil of a directional relay. Therefore, relay connection is a matter of suitable phase selection in power system. Table 1 summarises different relay connection angles used [10].

2.2. Maximum torque angle

Contrast with bidirectional relay, directional relay is actuated from two different independent sources which are current and voltage. Hence, the phase angle between these two quantities is subject to change and must be considered in the application of this relay. Since mechanical relay elements were first used for directional protection, the activating angle is called torque angle. When voltage leads current, it is capacitive torque angle and when the current leads the voltage, it is inductive torque angle. MTA is the angle which the protection element will have the maximum affect. The torque angle width is the range of torque angles where the directional element is operational. It is specified at both positive and negative MTA ±90° and a total torque width of 180°. There is no tripping for fault currents detected outside the torque width as shown in Fig. 1. The common MTA settings are 0°, 30°, 45° and 60°. MTA termed is replaced by Relay Characteristic Angle (RCA) for static, digital and numerical relays [10].

3. Modelling of operating zone verification

A program is developed to verify the operating zone of DOC and DEF. The program is written based on different set of equations, which depends on two factors, the relay connection and relay phase. The selected relay connection and phase for operation is shown in Table 1.

3.1. Operating zone verification for DOC program

For 90° connection and relay phase A, the polarising voltage would be V_{BC}. Hence, the inputs required are the voltage from phase B and phase C. Applying trigonometry right angled triangle definitions, the magnitude and angle of V_{BC} is calculated.

\[ |V_{BC}| = \sqrt{(V_{pol}^2 + V_{pol}^2)} \]  
\[ \theta_{B-C} = \cot(V_{pol}/V_{pol}) \]

where

\[ V_{pol} = V_{B} - V_{C} \]
\[ V_{B} = |V_B| \cos \theta_B \] and \[ V_{C} = |V_C| \cos \theta_C \]
\[ V_{pol} = V_{Bx} - V_{Cx} \]
\[ V_{Bx} = |V_B| \cos \theta_B \] and \[ V_{Cx} = |V_C| \cos \theta_C \]

For 30° connection, relay phase A; the polarising voltage is V_{BC} and the input are the voltage from phases A and C. For the operating region (90° connection and relay phase A),

Limit 1 = θ_{B-C} + MTA + 90°

Limit 2 = θ_{B-C} + MTA - 90°

where MTA is the phase shift for the polarising voltage.

To determine the operation of DOC relay, the applied current is checked against the operating region angles. If it falls between Limit 1 and Limit 2, the relay will operate. In this case (90° connection and relay phase A), I_A is compared with Limit 1 and Limit 2. For relay phases B and C, I_B and I_C data are utilised. The snap shot of the program for verification of DOC operating zone is shown in Fig. 2.

3.2. Operating zone verification for directional earth-fault relay

For Directional Earth-Fault Relay (DEF), residual current and residual voltage signals are used. To obtain the residual values, input from all three phases are required.

For residual voltage (polarising voltage),

\[ |V_{res}| = \sqrt{(V_{res}^2 + V_{res}^2)} \]
\[ \theta_{res} = \cot(V_{res}/V_{res}) \]

where

\[ V_{res} = V_{B} + V_{C} \] and \[ V_{res} = V_{A} + V_{B} + V_{C} \]

Table 1

<table>
<thead>
<tr>
<th>Type of connection</th>
<th>Relay phase</th>
<th>Applied current</th>
<th>Applied voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>A</td>
<td>IA</td>
<td>VBC</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>IC</td>
<td>VCA</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>IB</td>
<td>VAB</td>
</tr>
</tbody>
</table>

| 60°               | A           | IA              | VAC + VBC      |
|                   | B           | IB              | VBA + VCA      |
|                   | C           | IC              | VCB + VAB      |

| 30°               | A           | IA              | VAC            |
|                   | B           | IB              | VBA            |
|                   | C           | IC              | VCB            |
\[ V_{AR} = |V_A| \cos \theta_A \]
\[ V_{AX} = |V_A| \sin \]
\[ V_{BR} = |V_B| \cos \theta_B \]
\[ V_{BX} = |V_B| \sin \theta_B \]
\[ V_{CR} = |V_C| \cos \theta_C \]
\[ V_{CX} = |V_C| \sin \theta_C \]

For residual current, 
\[ |I_{res}| = \sqrt{I_{resX}^2 + I_{resR}^2} \]
\[ \theta_{res} = \cot(I_{resX}/I_{resR}) \]

where
\[ I_{resX} = I_{AR} + I_{BR} + I_{CR} \] and \[ I_{resR} = I_{AX} + I_{BX} + I_{CX} \]
\[ I_{AR} = |I_A| \cos \theta_A \]
\[ I_{AX} = |I_A| \sin \theta_A \]
\[ I_{BR} = |I_B| \cos \theta_B \]
\[ I_{BX} = |I_B| \sin \theta_B \]
\[ I_{CR} = |I_C| \cos \theta_C \]
\[ I_{CX} = |I_C| \sin \theta_C \]

And the operating range,
\[ \text{Limit 1} = \theta_{res} + \text{MTA} + 90° \]
\[ \text{Limit 2} = \theta_{res} + \text{MTA} - 90° \]

In DEF, the residual current is compared with the polarising voltage and the operating limit angles. The relay will operate if the residual current falls within Limit 1 and Limit 2, otherwise the relay will restrain its operation.

The snap shot of the program that has been developed based on the above equations to verify the DEF operating is shown in Fig. 3.

4. Study cases

In order to verify the relay connection and the maximum torque angle, study involves short circuit simulation to obtain the fault current data. This data is then applied into the program developed to verify the operation of the Directional Overcurrent (DOC) and Directional Earth-Fault (DEF) Relays.

Fig. 2. Snap shot to verify DOC operating zone. (Near source side diagram shows relay on phase A will operate and far source side diagram shows relay on phase A will not operate.)
Power system software, PSSAdept (Version 5.3.2) by SIEMENS Power Transmission & Distribution Inc. was chosen to simulate load flow and short circuit fault on the 33 kV network. The chosen test system is 33 kV distribution system in KL. The snap shot of the studied network is depicted in Fig. 4.

In this study, the common models (PI-model for a cable and constant power load for load) are used and parameters for all elements are based on actual site data. The only custom model built up for use in this simulation is Neutral Earthing Resistor (NER).

4.1. Short circuit simulation

A fault study is conducted for relay applications to ensure adequate protection. In the simulation, all factors that affect fault currents are considered. These factors include (i) type of fault, (ii) location of the fault, (iii) configuration of the network-parallel lines in service, minimum or maximum generating conditions and (iv) neutral earthing.

To study the sensitivity and selectivity of a directional relay, the fault should be located inside the protection zone. Three locations are simulated, near end source, middle of the feeder and far end source, as illustrated in Fig. 5.

All types of faults, which are Three Phase to Ground (LLLG), Single Line to Ground (SLGF), Double Line to Ground (LLGF), Line to Line Fault (LLF) and Three Phase Fault (LLLF) are considered at each location.

The relay operation is also tested for two cases; (1) Case A-all breakers closed and (2) Case B – breakers at either end is open.

5. Test results

The obtained results are presented based on percentage of the total numbers of relays that operate, not operate and at border for each tested feeder. The total tested feeder is 13 feeders, with two DOCs at each of the feeder. For three phase to ground fault (LLGF) and Three Phase Fault (LLLF) the total number of relays simulated is 26 (13 feeders × two relays/feeder). For other type of fault, the total relays considered are 78 (13 feeders × two relays/feeder × three phases).

The results are presented for (a) fault near to source end, (b) fault at middle of the feeder and (c) fault at far end, for all types of fault. However, detailed results are presented only for fault near to the source end.

5.1. Fault at location near to source end

5.1.1. Three Phase to Ground Fault (LLLG)

Table 2A shows that in a LLLGF near the source, Directional Earth-Fault (DEF) relay with any of the four relay connections were activated, where the highest operation percentage is 84.62% (22 relays out of 26 relays operated) for 90°/45° and 90°/60° setting at location 1.

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Fig. 3. Snap shot to verify DEF operating zone. (Near source side diagram shows the relay will not operate and far source side diagram shows relay will operate.)
When one of the end is opened (Table 2B), the relay performance operation increases to 100% (all relays operated) for 90°/45°, 90°/30° and 30°/0° connections while only relay with 90°/60° connection does not achieve 100% operation.

5.1.2. Single Line to Ground Fault (SLGF)
When SLGF occurred near the source, relay connection 30°/0° provide the best connection in both topologies as shown in Tables 3A and 3B, with the operation percentage is almost 90%. Whilst relay connection of 90°/45°, 90°/30° and 90°/60° achieved a minor incremental of 2%, which is from 76%, 82% 45% operation in Set A simulation to 78%, 85% 47% operation in Set B simulation respectively.

5.1.3. Double Line to Ground Fault (LLGF)
Similar to SLGF at near end source, relay connection 30°/0° shows the best performance for LLGF as well, with the operation percentage is almost 94% for both sets of simulation as shown in Tables 4A and 4B. For relay connection of 90°/45° and 90°/60°, the relay performance was improved from 74% and 44% to 81% and 46% respectively when the line was disconnected at one end. For 90°/30° connection, the performance remains at 91% in both topologies.

5.1.4. Line to Line Fault (LLF)
From Tables 5A and 5B, it can be observed that two elements DOC relay using 30°/0° connection is the most reliable setting, where the operation percentage is above 67%.

Even when one end of the feeders was disconnected and changed the system topology, it does not cause any effect on the DOC relay performance.

5.1.5. Three Line Fault (LLLF)
From Table 6A, it can be observed that during an ungrounded LLLF at near source end, two elements of DOC relay with 90°/60° and 30°/0° connection were able to operate 100%, whilst 90°/45° and 90°/30° connections achieved 38% operation. In the second

### Table 2A

Test results for LLGF (case A).

<table>
<thead>
<tr>
<th>Relay connection</th>
<th>LLLGF (before opening one end)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DEF operates (%)</td>
</tr>
<tr>
<td>90°/45°</td>
<td>84.62</td>
</tr>
<tr>
<td>90°/30°</td>
<td>80.77</td>
</tr>
<tr>
<td>90°/60°</td>
<td>84.62</td>
</tr>
<tr>
<td>30°/0°</td>
<td>76.92</td>
</tr>
</tbody>
</table>
set of simulation as shown in Table 6B, the relay performance remains the same.

5.2. Summary for fault at middle of feeder

For the case of 3-phase to ground fault in the middle of the feeder, all relay connections offer the same performance results where no relay fails to operate (100% operation). However, relay connection of 30°/0° is superior since it can operate instantaneously once the voltage and fault current were detected by the relay, without having to wait for the breaker to disconnect one end of the line before the relay at the other end can operate. In a single phase to ground fault simulated in the mid of the feeder, relay connection of 30°/0° shows the best performance, with above 91% operation in both sets of simulation.

Results for relay connection of 90°/30°, 90°/45° and 90°/60° show that the earth-fault relay operates in the range of 50–76% in the first set of simulation. In the second set of simulation, the performance improves slightly in the range of 55–86% operation.

Inter-phase to ground fault with 30°/0° also provides another excellent setting for earth-fault relay to operate, where the percentages of operation are 90% and 94% for Set A and Set B topologies respectively. Other relay connections can only provide 40–86% operation for Set A topology but for Set B topology, a small increment of 2% is obtained, where the range is between 42% and 88% operation.

Relay connection of 90° and 30° with different MTA in a two element relay does not offer a satisfactory performance when an interphase fault occurs in the middle of the feeder. All connections only operate correctly less than 54% and only 30°/0° connection achieved 63%. At other time, the DOC relay operates either incorrectly or does not operate at all. The performance for all relay settings is improved to 91% and 83% for 90° and 30° connection respectively when three elements are used in the DOC relay. A relay connection of 90° coupled with any three MTA shows a better result compared to a relay connection 30°.

Only relay connection of 30°/0° performed well with 92% operation during a three-phase fault in the mid of the feeder when two-element setup was used. For other relay connection settings, the DOC relays do not operate most of the time despite one end of the feeders was disconnected, where the relay performance still remained below 47%. The DOC relay operates as expected if three elements were employed. For this configuration, any relay connection setting is suitable to be used.

5.3. Summary for fault at far end

In three-phase to ground fault (LLGF) at far end source, for all relay connections, there is less than 58% of the time the earth-fault relay operates, except for 30°/0° which achieved only 73% operation. From the second set of simulation where one end of the feeders was disconnected, the earth-fault relay performance increases drastically from 58% to approximately 92% and 96% for relay connections of 90°/45° and 90°/30° respectively. The relay connection of 30°/0° achieves 100% operation but only relay connection of 90°/60° does not show any changes on both topologies, where the percentage operation is 54%.

A similar trend in LLLGF can be found in Single Line to Ground Fault (SLGF), but with a slightly better performance. 90°/45° and 90°/30° relay connections achieved 80% and 91% operation respectively. Only 30°/0° relay connection achieved 100% operation. For 90°/60° connection, the earth-fault relay merely activated at 45% of the time while for the remaining 54%, the relay was not activated by the fault current.

It is also similar for inter phase to ground fault. The best relay connection was 30°/0°, with 95% operation in Set A and Set B topologies. For other relay connections such as 90°/45° and 90°/30°, the percentage of operation is better in Set B compared to Set A topology, but still within the range of 70–90% operation. There is no improvement in the performance for relay connection of 90°/60°, where it remains at approximately 45% operation although one end of the feeders was disconnected.

For simulation of phase to phase fault at far end source, DOC relay with two elements configuration using relay connection of 90°/45°, 90°/60° and 30°/0° only achieved a maximum of about 55% operation. For 45% of the time, the relay either operates incorrectly or do not operate at all. Relay connection of 90°/30° achieves the highest percentage operation of 70%. The remaining 30% is either due to the relay operates on the wrong phase or not.

Table 4A
Test results for LLGF (case A).

<table>
<thead>
<tr>
<th>Relay connection</th>
<th>LLGF (before opening one end)</th>
<th>DEF operates (%)</th>
<th>Nonoperation (%)</th>
<th>Border (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°/45°</td>
<td>74.36</td>
<td>24.36</td>
<td>1.28</td>
<td></td>
</tr>
<tr>
<td>90°/30°</td>
<td>91.03</td>
<td>6.41</td>
<td>2.56</td>
<td></td>
</tr>
<tr>
<td>90°/60°</td>
<td>43.59</td>
<td>50.00</td>
<td>7.69</td>
<td></td>
</tr>
<tr>
<td>30°/0°</td>
<td>93.59</td>
<td>5.13</td>
<td>1.28</td>
<td></td>
</tr>
</tbody>
</table>

Table 4B
Test results for LLGF (case B).

<table>
<thead>
<tr>
<th>Relay connection</th>
<th>LLGF (after opening one end)</th>
<th>DEF operates (%)</th>
<th>Nonoperation (%)</th>
<th>Border (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°/45°</td>
<td>80.77</td>
<td>19.23</td>
<td>0</td>
<td></td>
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<tr>
<td>90°/30°</td>
<td>91.03</td>
<td>6.41</td>
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<td></td>
</tr>
<tr>
<td>90°/60°</td>
<td>46.15</td>
<td>53.85</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>30°/0°</td>
<td>93.59</td>
<td>6.41</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 3A
Test results for SLGF (case A).

<table>
<thead>
<tr>
<th>Relay connection</th>
<th>SLGF (before opening one end)</th>
<th>DEF operates (%)</th>
<th>Nonoperation (%)</th>
<th>Border (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°/45°</td>
<td>75.64</td>
<td>24.36</td>
<td>0</td>
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</tr>
<tr>
<td>90°/30°</td>
<td>82.05</td>
<td>12.82</td>
<td>5.13</td>
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</tr>
<tr>
<td>90°/60°</td>
<td>44.87</td>
<td>52.56</td>
<td>2.57</td>
<td></td>
</tr>
<tr>
<td>30°/0°</td>
<td>88.46</td>
<td>11.54</td>
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</table>

Table 3B
Test results for SLGF (case B).

<table>
<thead>
<tr>
<th>Relay connection</th>
<th>SLGF (after opening one end)</th>
<th>DEF operates (%)</th>
<th>Nonoperation (%)</th>
<th>Border (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°/45°</td>
<td>78.21</td>
<td>21.79</td>
<td>0</td>
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</tr>
<tr>
<td>90°/30°</td>
<td>84.62</td>
<td>7.69</td>
<td>7.69</td>
<td></td>
</tr>
<tr>
<td>90°/60°</td>
<td>47.44</td>
<td>52.56</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>30°/0°</td>
<td>91.03</td>
<td>8.97</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 4A
Test results for LLGF (case A).

<table>
<thead>
<tr>
<th>Relay connection</th>
<th>LLGF (before opening one end)</th>
<th>DEF operates (%)</th>
<th>Nonoperation (%)</th>
<th>Border (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°/45°</td>
<td>74.36</td>
<td>24.36</td>
<td>1.28</td>
<td></td>
</tr>
<tr>
<td>90°/30°</td>
<td>91.03</td>
<td>6.41</td>
<td>2.56</td>
<td></td>
</tr>
<tr>
<td>90°/60°</td>
<td>43.59</td>
<td>50.00</td>
<td>7.69</td>
<td></td>
</tr>
<tr>
<td>30°/0°</td>
<td>93.59</td>
<td>5.13</td>
<td>1.28</td>
<td></td>
</tr>
</tbody>
</table>
operating. If the operating zone is simulated for three elements configuration, all four relay connections achieve above 91% operation, where 90°/C176°30° yields the most excellent performance (97%).

During an ungrounded 3-phase fault at far source end, two elements DOC relay with connection 30°/C176°0° was able to operate 100%, whilst 90°/C176°45°, 90°/C176°30° and 90°/C176°60° connections achieved less than 42% operation. When three elements of DOC relay were utilised, the performance was improved to 100% operation for all four relays connection.

6. Conclusion

This study shows that directional overcurrent and directional earth-fault relays can be used effectively in a feeder protection, provided that a correct relay connection and the maximum torque angle are chosen. It was found that for all fault locations and all types of phase and earth-fault conditions, relay connection of 30° and 0° maximum torque angle shows the best performance among different types of connection available. This study also shows that directional protection scheme can provide the same function as pilot-wire differential scheme to isolate fault when a fault occurs in the protected zone. Using directional protection scheme, the feeder protection is not put into risk when there is a communication failure between the two relays. This is because the operation is independent of the input from the other end of the relay.

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