COMPREHENSIVE ASSESSMENT OF FAULT CLEARANCE TIMES AND GRADING MARGINS IN POWER DISTRIBUTION SYSTEMS

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Abstract

This paper presents an investigation to comprehensively assess the maximum fault clearance time and the minimum time grading margin between reclosers in Powerco's distribution networks, for the purpose of re-evaluating conventional industry practice in the light of advances in technology. On one hand, the conventional maximum fault clearance time of 1 second is assessed to be still applicable for most networks; however, in specific cases, other values may also be used after detailed assessment. On the other hand, a more accurate time grading margin between reclosers, other than the conventional 0.4 seconds, can be worked out by using the comprehensive calculation method developed in this project. If a shorter grading time is confirmed to be applicable, then more reclosers can be placed in a distribution feeder, which forms a more selective protection scheme, i.e. minimises blackout areas during a fault. Based on the theoretical assessment and modelling, a customised computation tool was created to facilitate the calculation of grading margins. Several case studies using real network data were carried out on Powerco's distribution system in order to evaluate the formulation and the computation tool being developed.

1 Introduction

In a power distribution system, protection devices are employed to safeguard the system from a variety of faults. They will trip to isolate the faulty section from the rest of the system, as part of the fault clearance process. A common strategy in overcurrent protection scheme is to deploy more than one protection device in the network. This is to allow one device to offer main protection and the other devices to offer back-up protection. The back-up protection should only operate if the main protection fails to operate. Figure 1 shows a simplified representation of a typical power distribution feeder network[1] protected by two reclosers, namely, Device 1 and Device 2. In normal conditions, normal operating current flows through the network.

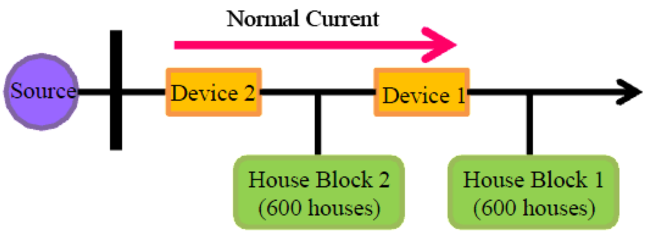

Figure 1: Typical power distribution network

When there is an overcurrent fault occurring downstream of the network, as shown in Figure 2, the current flowing through the network will suddenly increase to be several times larger than normal operating current.

[1] A typical power distribution feeder network refers to a network with a radial configuration in which the current flow is unidirectional.

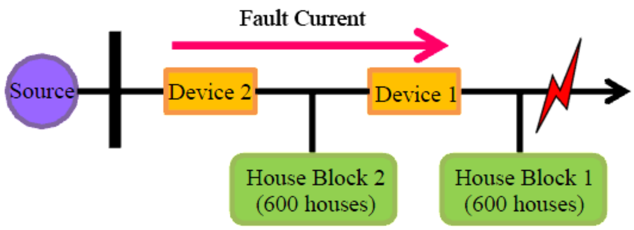

Figure 2: Overcurrent fault in the network

As Protection Device 1 is nearest the fault, it is the one to offer main protection; hence it will trip first to isolate the fault from the rest of the system. The consequence is shown in Figure 3 where the 600 houses in House Block 1 will experience a power outage, but the other 600 houses in House Block 2 will not be affected.

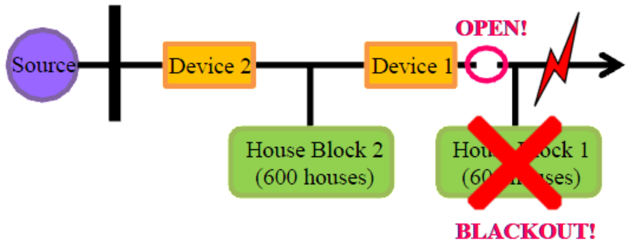

Figure 3: Fault clearance by main protection

However, if Protection Device 1 fails to operate, then Protection Device 2 serving as a back-up has to open. This will still isolate the faulty part and protect apparatus from damage in the power network, but at a higher expense with 1,200 houses experiencing power outages as illustrated in Figure 4.

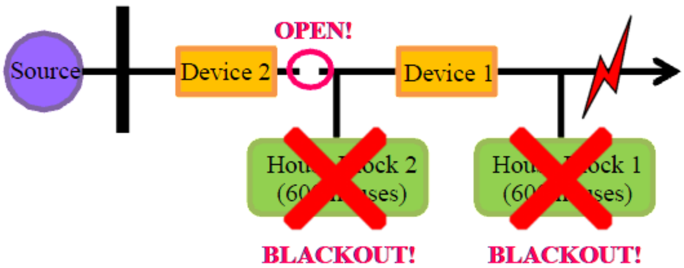

Figure 4: Fault clearance by back-up protection

From a protection engineer's point of view, an ideal protection scheme would deploy several protection devices in the network in order to minimise the power outage area during a fault. Figure 5 shows the same power distribution network as before, but instead, three protection devices are deployed. Since the total number of houses is unchanged, each of the protection devices will only be associated with 400 houses. If Protection Device 2 operates to back up Protection Device 1, only 800 houses in total will experience power outages, compared to 1,200 houses in the previous case where only two protection devices are deployed. It is clear that it will be advantageous to deploy more protection devices in the network in order to minimise the power outage area in a fault condition.

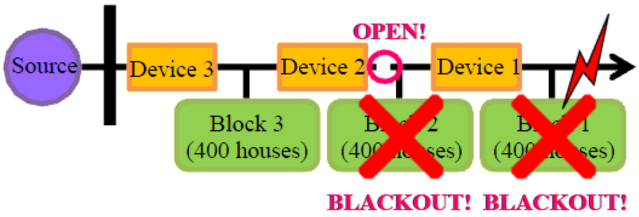

Figure 5: Deployment of three protection devices

A certain time period must be set between the adjacent protection devices to ensure they do not operate at the same time; else role of back-up protection will be compromised. This time period is referred to as the grading margin. Proper grading is crucial for the setting of protection devices. If the grading margin between Protection Devices 1 and 2 is too short, then Protection Device 2 will operate sooner than required. Conversely, if the grading margin is too long, then the maximum number of devices that can be deployed in the network will be under-estimated due to the constraint that the summation of grading margins in the network must not exceed the maximum fault clearance time. This is the reason why it is not possible to deploy numerous protection devices in the network.

1.1. Industry concerns

The current industry practice is to adopt 0.4 seconds [1] to be the grading margin and to set the constraint that the maximum fault clearance time should not be greater than 1 second [2]. Although this industry practice was developed several decades ago, it is still being widely used for the setting of the latest protection device – the recloser. Regarding this, Powerco raised two concerns. Firstly, they would like to explore whether the grading margin between reclosers can be shorter than the traditional recommended value. If a shorter grading margin is possible, then more reclosers can be deployed in the network, which is a preferable protection strategy as discussed above. Secondly, Powerco would prefer to have a more comprehensive calculation method to determine the grading margin and the maximum fault clearance time.

1.2. Project objectives

The objectives of this project were closely formulated to address Powerco's concerns. The first objective is to comprehensively assess the grading margin between reclosers. The second objective is to comprehensively assess the maximum fault clearance time in a power distribution network. Hence, the maximum number of reclosers that can be deployed in the network can be determined. The scope of the investigation in this project is to focus on radial distribution network[2], overhead lines[3], overcurrent faults and the coordination between reclosers.

1.3. Paper structure

In this paper, Section 2 briefly reviews application and functionality of reclosers. Section

[2] A radial distribution network is a unidirectional network with current flowing only in one direction.
[3] Overhead lines refer to power cables suspended on power poles.

3 discusses the developed theory for comprehensively calculating the grading margin between reclosers and the maximum fault clearance time in a power distribution network. Section 4 presents the custom software computation tool being created in this project based on the developed theory. Section 5 evaluates the development through a thorough case study. All the findings are then concluded in Section 6.

2 Recloser

Recloser is a type of switchgear consisting of a circuit breaker and a control unit. With its control unit, a recloser is able to trip during various faults and effectively restore power supply after transient or self-clearing faults have occurred.

Figure 6: NOJA OSM Recloser

Auto-reclosing is preferably used in the following conditions:

- Radial circuit configuration
- Circuits are located in rural areas, away from the public
- Circuits have low risks of damaging the downstream equipment during a fault
- Circuits are located in areas with history of outages resulted from transient faults, or in areas which are prone to wind storm and lightning.

With the application of auto-reclosing, electricity users benefit from the resulting improvement in power systems reliability, and unneccesary power blackouts can be avoided during transient faults.

Different types of recloser or auto-reclose facilities have been extensively used on overhead sub-transmission and HV distribution feeder line circuits. To comply with our project scope, only pole mounted auto-relosers being deployed on HV distribution feeder lines will be assessed and discussed in this report.

When a fault occurs, the recloser will trip and reclose several times until it locks out. This is usually referred to as auto-reclose shots. The typical maximum number of consecutive auto-reclose shots on HV distribution feeders is 3 auto-reclse shots, i.e. 4 trips to lockout.

In the following sections, the discussion will focus on how to coordinate a group of auto-reclosers on an HV distribution overhead line and the maximum fault clearance time in each auto-reclose shot.

3 Theory Development

Comprehensive theories have been developed in this project to determine time grading margin between adjacent reclosers and maximum fault clearance time on HV distribution overhead lines.

3.1 Time Grading Margin

As described in the previous section, a grading margin is applied in an overcurrent protection scheme to ensure that backup protection will only trip when main protection fails.

Before assessing the grading margin, a few key factors that contribute to the grading margin value must be investigated carefully.

- **Circuit breaker interrupting time**

The circuit breaker interrupting time is the maximum permissible time interval between the energising of the trip circuit and the interruption of the current in the main circuit [3]. The preferred values are 2, 3 and 5 cycles in [4]. In New Zealand's 50 Hz power systems, they are correspondingly converted to 40, 60 and 100 ms.

- **Overshoot time**

The overshoot time is defined as the time for which the recloser's relaying function continues to operate a bit longer, even after the overcurrent has been interrupted, until all stored energy has dissipated.

For electromechanical relaying mechanisms, overshoot used to be a main issue due to the moment of inertia of the moving disc inside the electromechanical relay. However, the latest relaying mechanism in electronically controlled reclosers can reduce the overshoot time down to around 20 ms [5].

- **Current transformer accuracy**

A protective current transformer has a standard accuracy class for current measurement. In [6] this accuracy class is specified to be 5P or 10P (5% or 10% error tolerance of the current measured), despite in most recloser manufacturers' user manuals, this accuracy rating is usually much less than 5% [7].

- **Recloser timing accuracy**

Reclosers have errors in their timing compared to the ideal tripping characteristics as defined in [8]. The maximum permissible timing error in [8] is set to be 5% of the time setting value. The timing error rated in most manufacturers' user manuals is consistent with the standard requirement.

- **Safety margin**

In practice, an extra allowance, or safety margin, is added to ensure successful recloser grading. This safety margin can be flexibly decided by protection engineers, but a value between 20ms and 30ms is recommended in some design guides [5].

3.1.1 Definite time characteristics

If a recloser is set to have definite time characteristics, it will operate when the current reaches a predetermined value (as shown in Figure 7). Recloser operating time in this case does not vary with the magnitude of fault current.

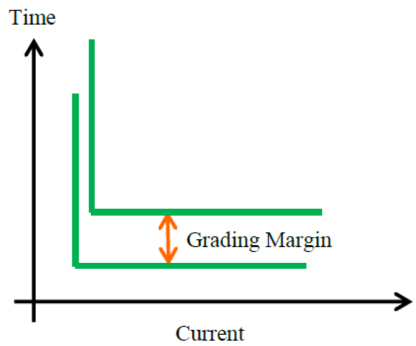

Figure 7: Definite time tripping curve

The grading margin between two reclosers which both have definite time characteristics can be expressed as follows:

$$t_{DT} = 2t_e + t_{ov} + t_{cb} + t_s \qquad (1)$$

Where t_{DT} : grading margin for definite time (sec)

t_e : recloser timing error (sec)

t_{ov} : recloser overshoot time (sec)

t_{cb} : circuit breaker interrupting time (sec)

t_s : safety margin (sec)

3.1.2 Inverse time characteristics

If a recloser is set to have inverse-time characteristics, its tripping time is inversely proportional to the fault current (as shown in Figure 8). The advantage of inverse-time characteristics is that the higher the fault current, the faster the recloser will operate.

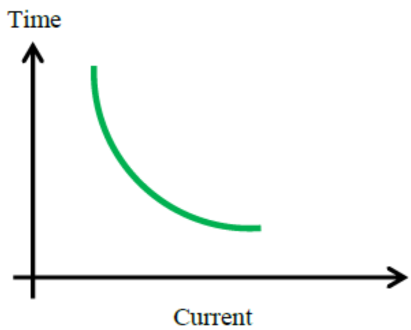

Figure 8: Inverse time tripping curve

Inverse time characteristic curves are generally classified into normal inverse, very inverse, extremely inverse and long-time inverse, according to the steepness of the curve

[8]. The curve can be expressed by using the equation below:

$$t = \frac{k\beta}{(\frac{I_f}{I_s})^{\alpha} - 1} \quad (2)$$

Where t : operating time of device (sec)
k : time multiplier (dimensionless)
I_f : measured fault current (amp)
I_s : setting current (amp)
α, β : curve parameters (dimensionless)

Table 1 shows the α and β values that correspond to the four different curve types:

Table 1: Classification of inverse-time curves

Types	α	β
Normal Inverse	0.02	0.14
Very Inverse	1.00	13.50
Extremely Inverse	2.00	80.00
Long-Time Inverse	1.00	120.00

Inverse time tripping is also referred to as inverse definite minimum time or IDMT tripping.

After comprehensive assessment and investigation by the author's research group, it was found that the grading margin between two inverse-time curves can be calculated as follows:

$$t_{IDMT} = t_1 \times (\frac{1+E_1}{1-E_2} - 1) + t_{ov} + t_{cb} + t_s \quad (3)$$

Where t_{IDMT} : grading margin for inverse time (sec)
t_1: operating time of main protection device (sec)
E_1 : total error of main protection device (%)
E_2 : total error of backup protection device (%)
t_{ov} : recloser overshoot time (sec)
t_{cb} : circuit breaker interrupting time (sec)
t_s : safety margin (sec)

The operating time of main protection device t_1 can be calculated by using Equation (2). Each of E_1 and E_2 is the summation of the recloser timing error and the timing error caused by current transformer measurement error.

The recloser timing error is 5%, in accordance with the earlier discussion in this section. The timing error due to the current transformer measurement error can be calculated using the following equations.

$$error(\%) = \frac{t_e - t}{t} \times 100 \qquad (4)$$

$$t = \frac{k\beta}{(\frac{I_f}{I_s})^{\alpha} - 1} \qquad (5)$$

$$t_e = \frac{k\beta}{\left[\frac{I_f}{I_s} \times (1 + e_I)\right]^{\alpha} - 1} \qquad (6)$$

Where t : operating time without current measurement error (sec)

t_e : operating time with current measurement error (sec)

I_f : measured fault current (amp)

I_s : setting current in recloser (amp)

e_I : current measurement error (%)

α, β : curve parameters (dimensionless)

k : time multiplier (dimensionless)

A diagram which demonstrates the grading margin between two IDMT curves obtained by using the calculation method above can be seen in Figure 9.

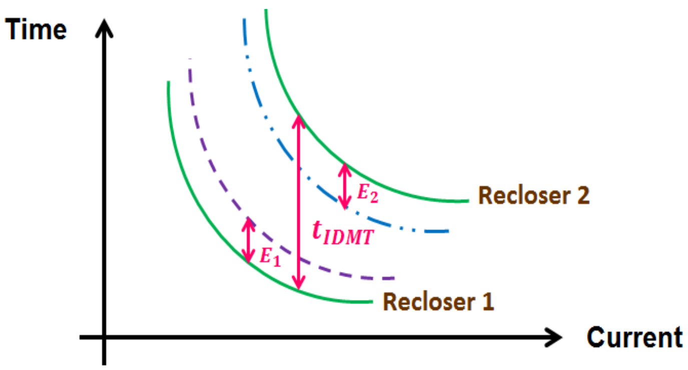

Figure 9: Grading margin of IDMTcurves

3.2 Maximum fault clearance time

The maximum fault clearance time herein is defined as the maximum allowable time period from the fault's inception to the first interruption of the fault. In auto-recloser operations, this is more specifically referred to the maximum allowable time for the fault to be interrupted in each auto-reclose shot. Maximum fault clearance time is constrained by certain components in the distribution network.

3.2.1 Thermal capability of power transformers

The power transformers in a distribution substation (shown in Figure 10) can only withstand a certain thermal load caused by a short circuit current.
The short-time thermal load capability of a liquid-immersed power transformer is summarised in Table 2 [9].

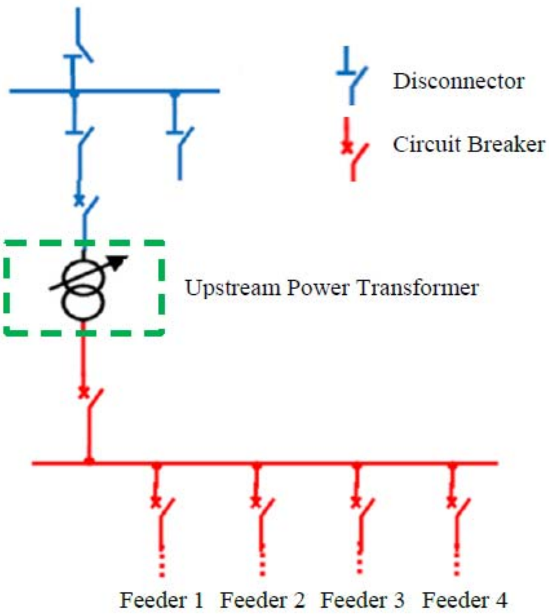

Figure 10: Power transformer in substation

As shown in Table 2, the thermal capability of a power transformer under a faulty condition depends on how many times the fault current is larger than the transformer's rated current.

Table 2: Transformer short-time thermal load capability

Times rated current	Time
25.0	2 sec
11.3	10 sec
6.3	30 sec
4.75	60 sec
3.0	5 min
2.0	30 min

3.2.2 Rated duration of short circuits for reclosers

Switchgears such as reclosers have a rated duration to carry a short circuit current under a fault condition. One second is the standard value for all switchgears as a common specification [10], while 0.5, 2 and 3 seconds are also given in [10] as recommended values. From manufacturers' data, this value is normally rated as 3 seconds.

3.2.3 Conductor short-circuit thermal ratings

Each type of distribution conductor has a maximum temperature rating under a fault condition. Table 3 lists three common conductors used in Powerco's networks and their maximum temperature ratings [11].

Table 3: Maximum temperature ratings of conductors

Conductor	Normal operation: Max. temperature (°C)	Fault conditions: Max. temperatures (°C)
HDCu	50	200
AAC	50	160
AAAC	50	160

The final temperature of a bare conductor can be calculated by using the formula below [12]:

$$T_2 = 20 - \frac{1}{A_r} + \left[T_1 - 20 + \frac{1}{A_r}\right] e^{\left[\frac{J^2 A_r R t}{DC}\right]} \qquad (7)$$

Where T2: final temperature in °C
T1: initial temperature in °C
Ar: temperature coefficient of resistance in $°C^{-1}$
R: resistivity in Ω.mm
D: density in g/mm3 or kg/cm^3
J: current density in A/mm^2
t: duration in seconds
C: specific heat in Jg-1 °C-1
A: cross sectional area of conductor in mm^2

Many parameters in Equation (7), such as Ar, R, D, C and T1 can be found as constants from [11] and [12]. The cross sectional area A of a conductor ranges from 35mm2 to 500mm2: a common value of 95mm2 has been chosen herein for testing purposes. All those parameters mentioned above can be found in Table 4.

Table 4: Parameters of three conductors

	Value		
	HD copper	AAC	AAAC
A	95	95	95
D	8.89×10^{-3}	2.70×10^{-3}	2.70×10^{-3}
C	0.4	0.9	0.9
R	1.78×10^{-5}	2.83×10^{-5}	2.93×10^{-5}
A_r	3.81×10^{-3}	4.03×10^{-3}	3.90×10^{-3}
T_1	50	50	50
J	21.05	21.05	21.05

Note: The units of all the parameters above are compliant with the units in Equation (7).

The fault duration of a recloser is no longer a single time period since the recloser has multiple open-reclose operations. Instead, the fault duration of a recloser is a summation of the initial fault duration and any subsequent fault durations. If the maximum fault clearance time is 1 second, considering the recloser has three operations, the maximum fault duration will be 3 seconds. Similarly, the fault duration will be 6 seconds if the maximum fault clearance time is 2 seconds.

To examine the effect of auto-reclose on the distribution conductor ratings, two final temperature vs. short circuit current diagrams were plotted, with a maximum fault clearance time of 1 second and 2 seconds respectively in Figure 11 and 12.

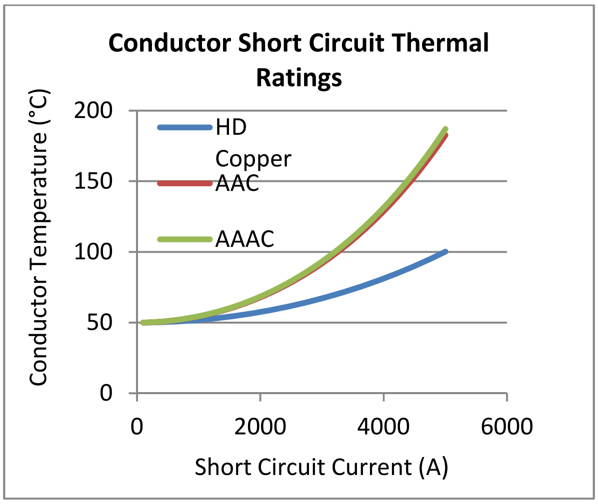

Figure 11: Conductor short-circuit thermal ratings (max. fault clearance time=1second)

In Powerco's networks, that have beend assessed in this work, the maximum fault current that can be reached is around 4000 A. At this current, if the maximum fault clearance time is 1 second, the final temperatures of all three conductors shown in Figure 11, HDCu (High Density copper), AAC (All Aluminium Conductor) and AAAC (All Aluminium Alloy Conductor) are below their short-circuit maximum temperature ratings. Short-circuit maximum temperature ratings of these three conductors can be found in Table 3.

However, if the maximum fault clearance time is 2 seconds, and other parameters remained the same, the final temperature of AAC and AAAC conductors will exceed their short-circuit maximum temperature ratings at 4000 A. This can be seen in Figure 12.

Therefore, it is concluded that 1 second is a reasonable value for maximum fault clearance time, and that 2 seconds and 3 seconds may bring risks of exceeding the maximum thermal ratings of conductors under the fault condition.

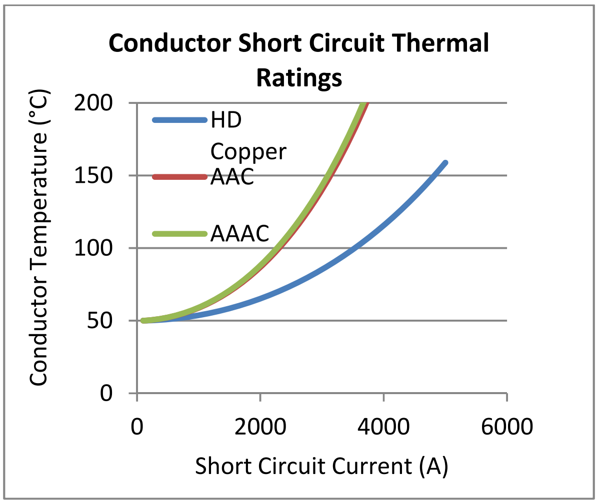

Figure 12: Conductor short-circuit thermal ratings (max. fault clearance time=2 seconds)

4 *Computation Tool Development*

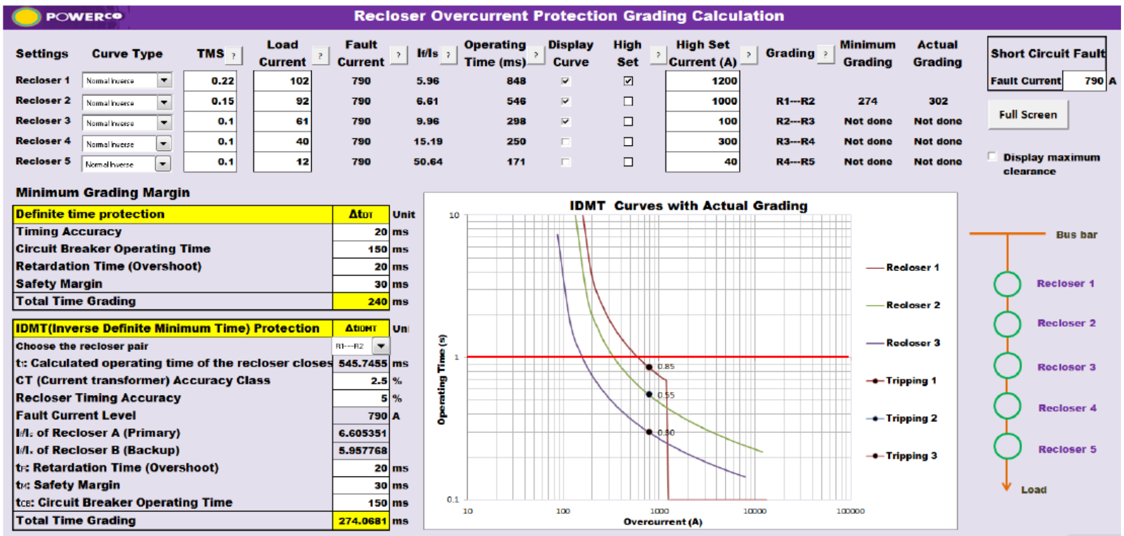

Figure 13: Computation tool

4.1. Motivation of development

The calculation of the grading margin involves a substantial number of variables and parameters as explained in the theory development section. In order to facilitate the calculation process, a piece of software serving as a computation tool was developed in this project. This software is written in Excel VBA (Visual Basic for Application) with advantages of being compact (153kB) and executable in any computer with Microsoft Excel installed. It is applicable in various areas, such as overcurrent protection settings, protection report and assest management planning.

4.2. Inputs

- **Parameters**

The parameters are the recloser settings and their characteristics, such as time multiplier setting, recloser operating curves, recloser timing accuracy and the retardation time etc. The parameters that require user input are represented by the "white cells" on the Excel spread sheet as shown in Figure 13.

- **Variable**

The short circuit fault current is the independent input variable in the calculation of the grading margin between reclosers. It is emphasised with a black border box and is located at the top right corner in the user interface as shown in Figure 13.

4.3. Outputs

- **Grading margin**

The primary output of the computation tool is the grading margin between reclosers, either for reclosers with definite time operating curves or with IDMT operating curves.

- **Coordination graph**

A coordination graph for reclosers with IDMT operating curves is also presented in the computation tool based on the grading results. Users can readily determine the maximum number of reclosers that can be deployed in the network by counting the number of operating curves under the horizontal red line, which represents the maximum fault clearance time of being one second.

4.4. Additional features

- **Error warning for insufficient grading**

By changing the recloser settings such as the time multiplier setting (TMS), the actual grading margin between reclosers will change accordingly. The computation tool will warn the users if the actual grading margin is below the minimum acceptable value and users are advised to modify the recloser settings.

- **High set instantaneous tripping**

The most common types of reclosers are the ones operating with IDMT curves and having a high set instantaneous tripping function. The computation tool supports this function by allowing users to turn on or off the associated check boxes.

- **"Help" function**

This is a user-friendly feature to ease the operation of the calculation tool. Users can click on the "?" buttons as shown in Figure 14 to check out the meaning of the technical terms and seek some advice for recommended input values.

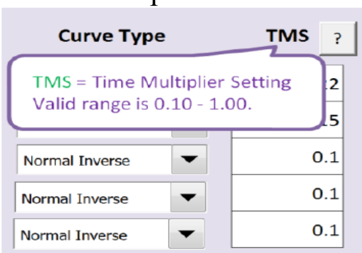

Figure 14: Help function

5 *Case Study*

A case study has been implemented on a feeder (18.16km) in the Powerco Thames Substation. This is to examine how the more comprehensive grading margin can help to improve the reliability of distribution systems.

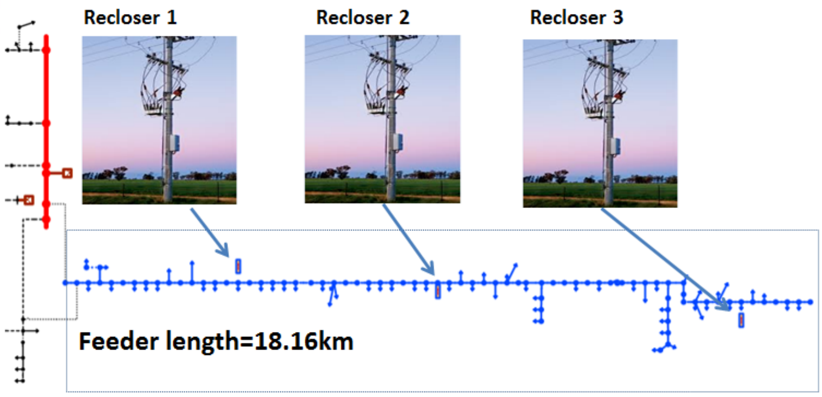

Figure 15: Thames Substation feeder and reclosers

After the simulation in PSS Sincal, the load current and line-to-line fault current were recorded in Table 5. The distances from each of the three points marked in Figure 15 to Thames Substation were also measured in PSS Sincal.

Table 5: Data recorded for case study on Thames Substation feeder

Recloser	Load Current (A)	Fault Current (A)	Distance to substation (km)
1	102	2380	2.64
2	92	1190	9.77
3	61	790	15.11

Using the conventional 0.4 seconds grading margin between reclosers, the maximum number of reclosers that can be put on this feeder is two. In contrast, a more comprehensive calculation method shows that the grading margin between Recloser 1 and Recloser 2 can be decreased to 0.29 seconds and the grading margin between Recloser 2 and Recloser 3 can be 0.25 seconds (grading curves are shown in Figure 16). This shows that it is possible to put three reclosers on this distribution feeder instead of two. Deploying another recloser on the feeder will effectively increase the selectivity of the protection scheme and hence prevent downstream users from unnecessary power outages.

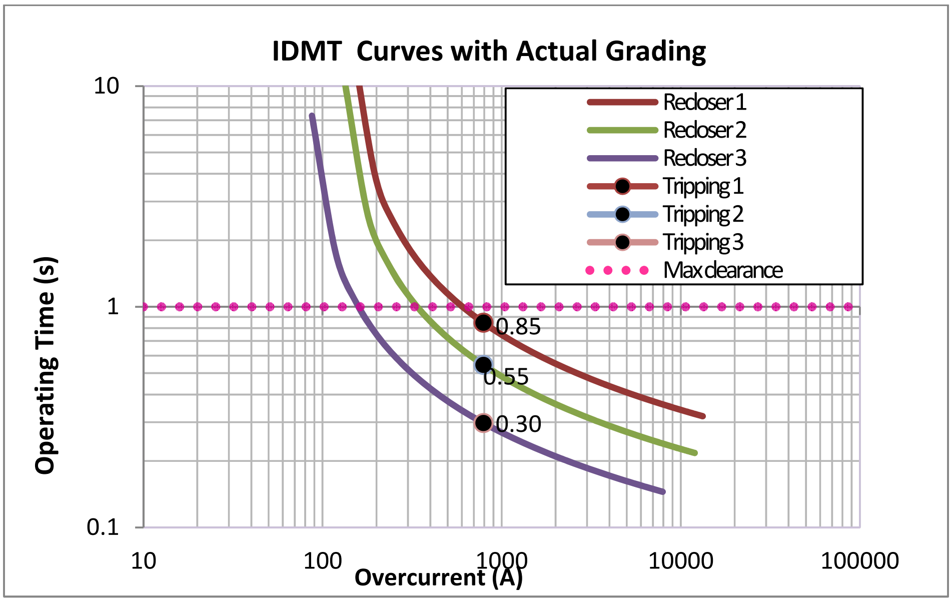

Figure 16: Reclosers' coordination diagram of the case study

6 *Conclusions*

This paper has comprehensively assessed the maximum fault clearance time in power distribution feeders and the corresponding minimum time grading margin between reclosers. The maximum fault clearance time of 1 second in industry practice is still applicable in most cases; however, a more accurate value can be determined after detailed modelling with three constraints: thermal capability of the power transformer, rated short-circuit duration of the protection devices and conductor short-circuit thermal ratings.

A calculation method has been developed to evaluate the grading margin between reclosers. In contrast to following the conventional practice of using 0.4 seconds, this method takes account of the variation of fault current levels and the advances in protection devices.

A software application tool was designed to facilitate the procedure of implementing a more comprehensive grading margin calculation.This paper is expected to assist power protection engineers to implement more robust protection grading margins in power distribution networks.

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8 Authors

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