Optimal Coordination of Directional Overcurrent Relays Considering a Modified Objective Function Using Genetic Algorithm

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Abstract: Directional Overcurrent Relays (DOCR) are widely used in meshed distribution and sub-transmission networks to provide inexpensive primary protection and in transmission systems as the second line of protection to distance and/or differential protection relays that serve as the primary protection system. DOCR operation settings (current Pick-up I_{pickup} and Time Multiplier Setting TMS) must ensure that the protection system maintains selectivity during fault isolation at all times. For optimal setting and coordinated operation of DOCR relays, this paper proposes a modified objective function and is tested using a genetic algorithm to obtain the optimal settings for the IEEE 8-bus test grid.

Keywords: DOCR, Optimization, Protection Coordination, Genetic Algorithm, Electrocon CAPE software.

I. INTRODUCTION

Meshed configuration in interconnected power systems (transmission, sub-transmission and distribution) is associated with high fault levels and current flow in either direction of a line segment is possible. The bi-directional current flow pauses a challenge regarding the design of a speedy, selective and reliable protection system that is very essential to limit the duration of fault current flow in such grid. At transmission and sub-transmission voltage, more than one protection scheme is normally used to protect a single component in order to enhance protection security. One of the schemes is designated as a primary scheme and usually has very fast operation speed. In most cases, a unit protection scheme (such as Differential protection) is preferred but due to the high cost and inability to provide backup protection by unit protection schemes, communication aided schemes based on distance protection have also often been used for transmission lines. A second protection scheme is designated as a backup scheme to provide alternative protection in the unlikely event of failure of the primary scheme to clear the fault e.g. due to relay failure or communication failure. The backup protection scheme is usually based on a different protection principle, and Directional Overcurrent Relays have widely been used to inexpensively provide the second line of defence function. The DOCR, in this case, are normally implemented as independent relays (even where numerical relays with the capability of multiple schemes are used) and often use different primary devices to reduce the risk of common mode failure with the Primary protection scheme. On the other hand, meshed distribution system extensively uses Directional Overcurrent relays as the only means to provide protection for distribution lines. [1-3]

Whether used as the only protection scheme or used together with more than one protection schemes, there must be comprehensive protection coordination both among the DOCR relays and with any other relays in order to achieve selectivity [1-5]. In addition, since DOCR relays respond to magnitude (and direction) of current flow, it is important to consider the impact of change in network topology as a result of switching action in arriving at optimal coordination [6,7], since switching is a routine on the power system arising out of maintenance or isolation following successful relay operation; and affects the load flow current distribution and fault levels in the grid; yet the system must continue to operate until the out-of-service equipment is restored.

Different approaches have been used to achieve protection coordination ranging from conventional methods, (such as Trial and error method, Minimum Break Point Relay Set (MBPS)), optimisation techniques (such as Linear Programming(LP)), and nature-inspired and artificial intelligence-based algorithms [8]. The latter category has recently been extensively used since they result in global minimum coordination settings and achieve coordination in a short time. These include Genetic Algorithm (GA), Evolutionary Programming (EP), Particle Swarm Optimisation (PSO), Ant Colony Optimisation (ACO), Teacher Learner Based Optimisation (TLBO), Symbiotic Organism Search Optimisation (SOSO), among others and also includes their variant hybrid algorithms. The key to using recent algorithms is the objective function.

Reference [1,5], highlights an objective function used to achieve optimum protection coordination among overcurrent relays, which is generalised and improved by Reference [9]. This paper proposes a modification to the objective function in [1,5], and the modified function is tested on the IEEE 8-bus test grid simulated using Electrocon CAPE (Computer-Aided Protection Engineering) software. The modified objective function has fewer terms and therefore easier to use. In addition, it produces comparable results in shorter execution time.

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II. OVERCURRENT RELAY COORDINATION

Optimal Overcurrent relay coordination must ensure that a fault is isolated in minimum possible time, as well as back-up overcurrent relays must give sufficient time margin to the main overcurrent relay to extinguish the fault [1-5]. The minimum time margin minimises possible erroneous operation of the back-up relay before the main relay, which is typically associated with isolation of a wider portion of the grid. The minimum time margin has been widely termed as Coordination Time Interval, CTI or grading margin. The grading margin depends on 1) opening time of CB 2) Relay timing errors 3) overshoot time of the relay 4) CT errors and 5) safety margin for completion of operation. Depending on the speed of the equipment used in the protection scheme, the typical value CTI ranges from 0.2s to 0.5s, of which this paper shall adopt an average of 0.3s. [3]

To establish relay coordination, the relay Time-current characteristic must be specified or defined. The Inverse Definite Minimum Time (IDMT) characteristic is widely used by overcurrent relays and has been generalised by the following relationship in (1); as well as Instantaneous and Definite Time delay characteristics are common [5,10,14];

$$t = \left(\frac{A}{\left(\frac{I_f}{I_{pickup}} \right)^{\alpha} - 1} + L \right) \times TMS \qquad (1)$$

where TMS is the Time Multiplier Setting of the relay and I_{pickup} is its pick-up setting in relay Amps. I_f is the actual current (relay Amps) input to the relay from the current transformer. The coefficients A, α and L define the actual relay characteristic and have been defined differently by IEC60255 and ANSI/IEEE standards. In addition to the standard characteristics, manufacturer-specific characteristics exist; as well as it is possible with Numerical Relays for a user to define a special characteristic if it is deemed necessary in order to achieve a specific coordination purpose [3,5]. The values of TMS and I_{pickup} setting can be discrete or continuous depending on the relay [1,5]. The table below highlights some relay characteristics derived from (1); and Fig 1 shows the graphical relatioship of some IEC 60255 standard relay characteristics.

TABLE 1:
OVERCURRENT RELAY CHARACTERISTICS

	Characteristic	**A**	**α**	***L***
1	IEC Standard Inverse	0.14	0.02	0
2	IEC Very Inverse	13.5	1	0
3	IEC Extremely Inverse	80	2	0
4	IEC Long time standard earth fault	120	1	0
5	IEEE Moderately Inverse	0.0515	0.02	0.114
6	IEEE Very Inverse	19.61	2	0.491
7	IEEE Extremely Inverse	28.2	2	0.1217
8	AREVA Short Time Inverse	0.05	0.04	0
9	AREVA Long Time Inverse	120	1	0

It is generally desired that similar characteristic be used when coordinating overcurrent relays and in most cases the use of IEC Standard Inverse curve proves satisfactory. If satisfactory coordination cannot be achieved, a mix of characteristics can be adopted [3].

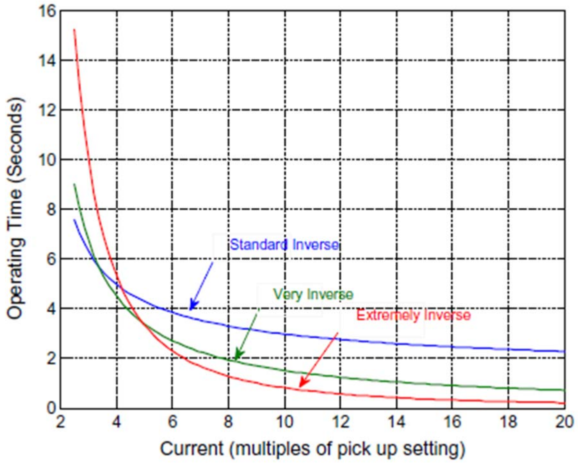

Fig 1. IEC 60255 IDMT Relay Characteristics, TMS=1. (Reproduced from reference [14])

As shown in equation (1), relay operating time in response to current flowing in the grid, as measured and extended to the Relay from the connected Current Transformer (CT), is affected by the choice of settings of TMS and I_{pickup} in addition to the choice of relay characteristic curve.

Whereas it is desired that the relay operates with speed for safety and minimal damage to faulty equipment, we must take care to ensure that when the choice of settings do not compromise the selectivity and reliability of the grid [3].

For a given I_{pickup} setting and current input I_f to the relay, The operating time is adjusted by varying the TMS values between $TMS_{min} < TMS < TMS_{max}$ as allowed by the relay. Typical values of TMS vary between 0.05 – 1.2 [1, 9].

I_{pickup} setting is the minimum current which causes a relay to declare faulty condition. It must satisfy bounds $I_{pickup-min} < I_{pickup} < I_{pickup-max}$ such that

$I_{pickup-min}$ the minimum pick-up setting is

- Greater than the Maximum load current to avoid tripping on normal load (and therefore load currents during contingency switching)
- Must be greater or equal to the minimum pick-up current setting on the relay
- Must be lessthan the maximum allowable overload on protected equipment rating

$I_{pickup-max}$ the maximum pick-up setting

- Must be equal or less than the maximum pick-up current setting on the relay
- Must be less than the minimum fault current on the protected element

I_f is the actual current input to the Relay as derived from the secondary of the CT connected to the relay. For overcurrent protection scheme, the CT sizing should be such that the relay is able to operate unsaturated for all foreseeable faults at its location in order for the relay to respond accurately to the power system conditions. The primary current I_{fp} (actual grid current) of the CT responding to the relay input current can be computed by using the corresponding CT ratio (CTR) from $I_{fp} = I_f \times CTR$. In equation (1), both I_f and I_{pickup} can be referred to the primary side of the CT. The quotient is independent of the CT ratio.

III. GENETIC ALGORITHM

Genetic Algorithm is a type of optimisation algorithm that can seek global maxima or minima of a computation optimisation phenomenon with efficiency. It imitates the biological process of reproduction and natural selection to select the best ('fittest') solution [11]. The problem to be optimised is modelled mathematically in the form of an Objective function. The genetic algorithm has been widely used for the optimisation of DOCR coordination problems including its variants in the form of Hybrid genetic algorithms. The generic flow of processes of a genetic algorithm execution is summarised in [12] and reproduced in the Fig 2. The important input to the genetic algorithm are the control parameters and the Objective function.

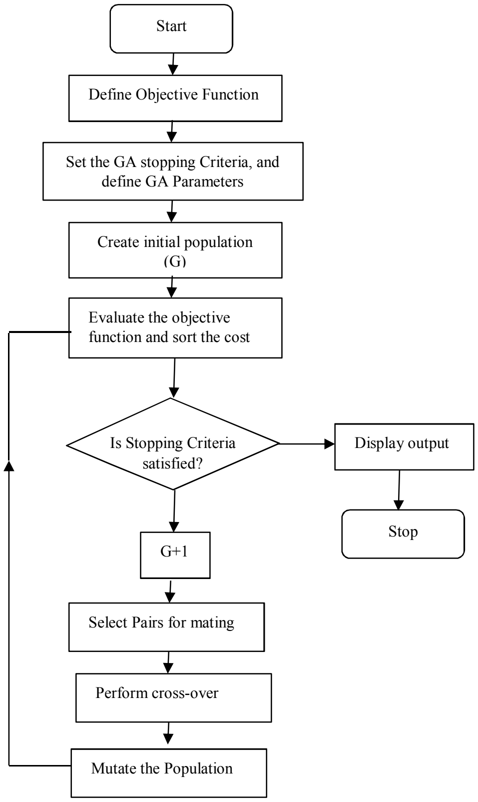

Fig 2. Flow chart for Genetic algorithm execution

III. OBJECTIVE FUNCTION FOR OVERCURRENT COORDINATION

For a set of adjascent bus DOCR in a meshed grid, the relatioship between the relays at adjuscent bus bars is illustrated in Fig. 3. The relays are arranged such that they will only respond to a specific direction of current flow. In fig. 3, the DOCR are related such that R1 pairs and coordinates with R3 (only respond to current flow towards left) while Relay R2 pairs and coordinates with R4 (only respond to current flow to the right). For a line fault near the CB of R1, the main relay is R1 and the back-up relay is R3. R2 and R4 see the fault current flows in their reverse direction and cannot respond to that fault. Similarly, for a line fault near the CB of R4, the main relay is R4 and its backup relay is R3. R1 and R3 see the fault current flow in their reverse direction and cannot respond.

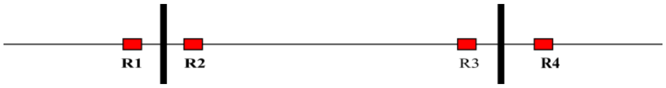

Fig 3. DOCR in a portion of Meshed Network

The first step in solving the coordination problem is identifying the coordinating pairs (Main – Backup relay pairs) for a fault in the zone of the main relay. For a fault close to the Circuit Breaker (CB) of the main relay, the corresponding current flow through the back-up relay must be measured. The corresponding relay operation time t_m for the main relay and t_b for the back-up relay must satisfy the relay coordination constraint i.e. the Main relay must always operates before the Backup relay for faults in the zone of the main relay; and the minimum Coordination Time Interval (grading margin) must always observed. Since the most severe fault current flows through the main relay when the fault is close to its CB (Close-in fault), the Coordination time constraint is set for a close-in fault at the main relay CB. In addition to CTI constraint, the main relay operation time must be minimum in order to achieve fast isolation of the fault.

In reference [1,5], optimal coordination between adjacent DOCR in a meshed grid is achieved by minimisation of the using the objective function of the form

$$\mathrm{OF} = \alpha_1 \sum_{i=1}^{N} {t_i}^2 + \alpha_2 \sum_{k=1}^{P} \{\Delta t_k - \beta(\Delta t_k - |\Delta t_k|)\}^2 \tag{2}$$

$$\Delta t_k = t_{bk} - t_{mk} - CTI \tag{3}$$

where $t_i$is the relay operation time for a close-in fault near relay i; N is the number of relays, $\Delta t_k$is the coordination error for Main – backup relay pair k where P is the total number of main – backup relay pairs; t_{bk} is the operation time for the back-up relay for a fault close-in fault near the Circuit Breaker (CB) of the main relay, t_{mk} is the operating time of the main relay for a fault near its CB. Weights α_1, α_2 and β are weights adjusted by trial and error to achieve coordination [1,5].

The objective function has two terms namely

i) Relay operating time term ($\sum_{i=1}^{N} {t_i}^2$)
The minimum of this term is achieved when relays operate in the shortest possible time.

ii)The penalty term $\{\Delta t_k - \beta(\Delta t_k - |\Delta t_k|)\}^2$
The component $(\Delta t_k - |\Delta t_k|)$ is zero if $\Delta t_k$is positive, while it equals $2\Delta t_k$ if Δt_k is negative. As a result, for positive Δt_k (meaning proper coordination), the penalty term equals $(\Delta t_k)^2$; while on the other hand, for negative values of Δt_k, the term equals $(1-2\beta)^2\,(\Delta t_k)^2$ which is a large number if $\beta \gg 1$. As a result, the optimisation

selection process will tend to favour a combination of small and positive values of Δt_k combined with low values of t_i since negative values of Δt_k add a larger term to the objective function.

To determine the suitable combination of weights α_1, α_2 and β to use in the objective function in (2), a sensitivity analysis was conducted on the IEEE8-bus grid of ref [1] to determine the combination of values that give optimal coordination defined by the extent of coordination error. Proper coordination must have positive Δt_k values for all coordinating pairs. The 8-bus grid single line diagram and grid parameters of [1] are reproduced and summarised in Fig. 4 and Tables 3 – 5 below. The grid was simulated using CAPE software for short circuit fault analysis and the current simulation results for relay coordinating pairs is summarised in Table 6. For conducting the sensitivity of the objective function to the weights α_1, α_2 and β, the genetic algorithm was set up in MATLAB with the following control parameters (Table 2) to optimise the time coordination of the relays;

TABLE 2:
GENETIC ALGORITHM CONTROL PARAMETERS

Parameter	**Setting**
Generations	2000
Population size	100
Selection	20%
Crossover fraction	90%
Mutation rate	0.57%
Stopping Criteria:	Best Fitness and average fitness value converge

To set the coordination objective function, all relays are set to have the same IEC Standard Inverse characteristic; the TMS value limits are set to vary continuously from 0.05 – 1.2 (continuous) and Pick-up current for each line segment was set to 120% of line rating (continuous). The IEC Standard Inverse characteristic for relay operation is estimated by

$$t = \left(\frac{0.14}{\left(\frac{I_f}{I_{pickup}} \right)^{0.02} - 1} \right) \times TMS \qquad (5)$$

Actual grid currents (as simulated) were used for I_f and I_{pickup} in this case.

Each of the weighs α_1, α_2 and β of the objective function in (2) is varied from 0.01 to 1000 and each time the optimal TMS values and coordination error Δt_k calculated. The variation of weights reveals that;

a) For large values of α_1 the minimum objective function selects the lowest values of TMS for the relays, but miscoordination is maximum.
b) For large values of α_2, the fitness function converges after many iterations
c) For Low values of β, the function selects the lowest values of t_i similar to case (a) above.
d) In the range of $1 < \alpha_1 < 10$; $1 < \alpha_2 < 10$; $100 < \beta < 1000$, the algorithm converged to the best coordination combination of relays and in relatively fewer iterations to meet the stopping criteria.

The observation in case (d) generally agrees with the choice of coefficients in ref [1] and [5].

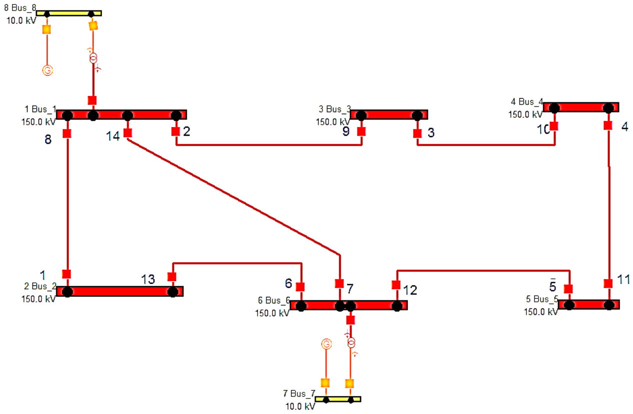

Fig 4. Single line diagram of IEEE 8-bus grid.

TABLE 3:
LINE INFORMATION

From Bus	To Bus	R(pu)	X(pu)	V(kV)	Max Load current
1	2	0.0018	0.0222	150	416
1	3	0.0018	0.0222	150	666
3	4	0.0018	0.0200	150	500
4	5	0.0022	0.0200	150	666
5	6	0.0022	0.0200	150	458
6	2	0.0018	0.0200	150	458
1	6	0.0022	0.0222	150	541

TABLE 4:
GENERATOR INFORMATION

Generators	R(pu)	X(pu)	V(kV)
	0.000001	0.1	10

TABLE 5:
TRANSFORMER INFORMATION

Transformers	R(pu)	X(pu)
	0.000001	0.026666

IV. NOVEL MODIFIED OBJECTIVE FUNCTION

The objective of modifying the objective function is to seek a more “easy to work with” objective function that can serve the same purpose as the objective function in (2) above. From (2)

i) The relay Relay operating time term ($\sum_{i=1}^{N} {t_i}^2$) is a square of small positive values, since it is always desired that the relay operates quicky to isolate close-in faults. In addition, the outcome is always a positive number. The non-squared summation would also equally give a close magnitude of outcome, yet without additional squaring operation.
ii) The penalty term $\{\Delta t_k - \beta(\Delta t_k - |\Delta t_k|)\}^2$ can be reduced to a smaller term since its contribution is only significant when Δt_k is negative. The minimum penalty equals zero when $\Delta t_k = 0$. When Δt_k is positive (i.e. $\Delta t_k \approx 0^+$) the penalty function

is affected to the same dimension by the positive magnitude of the coefficient. However, when Δt_k is negative, the term suddenly approximates $4\beta^2\,(\Delta t_k)^2$ if $\beta \gg 1$. Since Δt_k is usually small (protection scheme must operate faults in a short time), the penalty term only has a significant effect when Δt_k is negative due to the weight of β, and can, therefore, be reduced to $\{\beta(\Delta t_k - |\Delta t_k|)\}^2$ without any major consequences in the selection process. After all, the minimisation selection process favours penalty closest to zero. The purpose of squaring the term $(\Delta t_k - |\Delta t_k|)$ is to make the penalty a positive number. The similar effect can be achieved by finding the magnitude of the term i.e. $\left|\Delta t_k - |\Delta t_k|\right|$. Since $|\Delta t_k| \ll \beta$, the effect of squaring β does not make a significant change to the term $\beta^2\left|\Delta t_k - |\Delta t_k|\right|$; after all the purpose of adding the penalty is to cause the negative coefficient to be "unfit" for selection. The penalty can thus be reduced to $\beta\left|\Delta t_k - |\Delta t_k|\right|$.

TABLE 6:
POWER SYSTEM SHORT CIRCUIT SIMULATION RESULTS

Main Relay (A)	Backup Relay (A)	Main Relay Current (A)	Back-up Relay Current (A)	Main Relay Pick-up current (A)	Back-up pick-up current (A)
8	9	4,995.5	416.2	549.6	540.0
8	7	4,995.5	1,540.7	549.6	649.2
1	6	2,702.5	2,702.5	499.2	549.6
14	1	4,266.6	811.6	799.2	499.2
14	9	4,266.6	416.2	799.2	540.0
7	5	4,266.4	416.2	649.2	549.6
7	13	4,266.4	811.6	649.2	600.0
2	1	5,390.9	811.6	799.2	499.2
2	7	5,390.9	1,540.7	799.2	649.2
9	10	1,453.2	1,453.2	540.0	540.0
3	2	3,347.7	3,347.7	600.0	799.2
10	11	2,344.3	2,344.3	540.0	649.2
4	3	2,243.7	2,243.7	799.2	600.0
1	12	3,494.7	3,494.7	649.2	549.6
5	4	3,494.7	1,361.5	549.6	799.2
12	13	5,390.9	811.6	549.6	600.0
12	14	5,390.9	1,540.7	549.6	799.2
6	5	4,995.5	416.2	549.6	549.6
6	14	4,995.5	1,540.7	549.6	799.2
13	8	2,508.2	2,508.2	600.0	549.6

iii) Form the sensitivity analysis results, we can select convenient coefficient values of α_1, α_2 and β, since we know the region of best performance. If we substitute $\alpha_1 = 1$ and $\alpha_2 = 1$ in (2), these coefficients are eliminated from the expression; and we can adopt $\beta = 100$ (similar to the Miscoordination Coefficient weight trivially adopted by [13] "for ease of working") since it satisfies the best convergence region.

The foregoing would see the optimisation function reduced and modified to

$$\mathrm{OF} = \sum_{i=1}^{N} t_i + 100 \sum_{k=1}^{P} \left|(\Delta t_k - |\Delta t_k|)\right| \qquad (6)$$

Equation (6) above is the modified objective function. As can be seen, the equation has fewer terms and fewer operations than (2), and the coefficients (weights) have been replaced with definite values.

V. OBSERVATION AND DISCUSSION OF MODIFIED METHOD

When applied to the IEEE 8-bus test grid with same Genetic Algorithm initialisation settings, TMS range and pick-up current as the previous case, the outcome of the modified objective function are tabulated below (Table 7 and Table 8) and compared with results of the previous method and other methods for optimising the same IEEE8-bus grid by other authors

TABLE 7:
IEEE 8-BUS COORDINATED RELAY SETTING RESULTS I

Relay	TMS (Old Method)**	TMS (Modified Method)	TMS (Ref [13])	TMS (Ref [9])
1	0.0619	0.062	0.05	0.066
2	0.1631	0.1632	0.169	0.1833
3	0.1214	0.1214	0.126	0.146
4	0.0501	0.05	0.051	0.069
5	0.05	0.0501	0.05	0.08
6	0.1277	0.1278	0.119	0.13
7	0.1105	0.1105	0.05	0.12
8	0.1193	0.1193	0.122	0.12
9	0.05	0.0501	0.05	0.095
10	0.0929	0.0929	0.091	0.135
11	0.1368	0.1369	0.138	0.174
12	0.2314	0.2316	0.236	0.273
13	0.05	0.05	0.05	0.05
14	0.0934	0.0939	0.05	0.1

Note: **coefficient $\alpha_1 = 1$, $\alpha_2 = 1$, $\beta = 100$ in (2)

It can be seen that the Modified Objective function achieves very close results to the old objective function (old method) in equation (2) of comparable weights, in both Operating Time (for main and back-up relays) and coordination error. For a CTI of 0.3s, small negative coordination errors (as the one between relay 12 and 14 in Table 8) are insignificant and can still be considered as coordination.

It is also important that the modified function has fewer terms and the ambiguity of weights (trial and error manipulation) in the objective function of equation (2) is eliminated.

In execution of the genetic algorithm (with the same initialisation settings), the modified method also meets the stopping criteria after fewer generations than the old method of equation (2). Since the modified method has fewer operations and fewer terms, this outcome is reasonable.

TABLE 8:
IEEE 8-BUS COORDINATED RELAY SETTING RESULTS 2

Main Relay	Backup Relay	**Old Method****			**New Method**		
		Tmain (s)	Tbackup (s)	Δt_k	Tmain (s)	Tbackup (s)	Δt_k
8	9	0.370	inf	inf	0.370	inf	inf
8	7	0.370	0.887	0.217	0.370	0.887	0.217
2	7	0.587	0.887	0.001	0.587	0.887	0.000
2	1	0.587	0.887	0.000	0.587	0.889	0.002
3	2	0.486	0.786	(0.000)	0.486	0.786	0.000
4	3	0.336	0.636	(0.000)	0.336	0.636	0.000
5	4	0.186	0.655	0.169	0.186	0.653	0.167
6	5	0.396	inf	inf	0.396	inf	inf
6	14	0.396	0.990	0.293	0.396	0.995	0.298
14	1	0.384	0.887	0.203	0.386	0.889	0.203
14	9	0.384	inf	inf	0.386	inf	inf
1	6	0.252	0.552	0.000	0.253	0.553	0.000
9	10	0.350	0.650	0.000	0.351	0.650	(0.000)
10	11	0.436	0.736	(0.000)	0.436	0.737	0.000
11	12	0.559	0.860	0.000	0.560	0.860	0.001
12	14	0.693	0.990	(0.004)	0.694	0.995	0.001
12	13	0.693	1.155	0.162	0.694	1.155	0.161
13	8	0.241	0.542	0.001	0.241	0.542	0.001
7	5	0.403	inf	inf	0.403	inf	inf
7	13	0.403	1.155	0.452	0.403	1.155	0.452

Notes: (1) **coefficient $\alpha_1 = 1, \alpha_2 = 1, \beta = 100$ in (2)
(2) "Inf" means the back-up relay does not trip. This is because the back-up relay current is less than relay pick-up current setting

VI. CONCLUSION

The Modified objective function in equation (6) is superior in performance and easier to use than the generalised equation in (2). The fewer terms and unambiguous coefficients of the modified function makes it easier to use; and more beneficially, operations of the modified objective function can result in substantial time saving and less memory requirements for execution of overcurrent coordination of a bigger grid. It, therefore, offers more benefit to use the modified function.

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