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# Optimum Setting and Coordination of Overcurrent Relays Considering Cable Damage Curve

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*Abstract*— **Relay coordination of distribution networks is somehow similar to the transmission networks by some differences. One of the differences is the nature of distribution feeders are usually cables. Occurrence of high current faults in distribution networks may cause thermal damages to the cable insulations. The fault current should be cleared by main overcurrent relay. In the case of operation failure of the main relay, backup relays should be tripped after discrimination time.**
**Optimum coordination of overcurrent relays for both distribution and transmission networks have been developed by many authors before. The authors of this paper have developed a new method for overcurrent relay coordination using genetic algorithm (GA).**
**In this paper the objective function (OF) of the existing GA method is improved to incorporate the cable thermal damage curves. The advantages of this method are decreasing the ageing rate of the cable insulations and increasing reliability of the distribution networks. The algorithm is applied to a sample distribution network and results shows the new settings are more realistic than the results of the previous methods.**

*Index Terms*— **Cable Insulation, Overcurrent Protection, Power Cables, Power Distribution Protection, Protective Relaying.**

## I. Introduction

DIRECTIONAL overcurrent relaying is commonly used for power system protection, as a main protection in distribution and sub-transmission systems and as a backup protection in transmission systems [1]. The coordination of these relays poses serious problems in the modern complex power system networks, which are interconnected. The relay coordination problem is to determine the sequence of relay operations for each possible fault location so that the faulted section is isolated to provide sufficient coordination margins without excessive time delay [2]. The procedure consists of selecting suitable settings such that relay fundamental protective function is met under the requirements of sensitivity, selectivity, reliability and speed [3].

In the directional overcurrent relay coordination problem, two types of settings should be calculated, namely plug setting (PS) and time setting multiplier (TSM) [4]. PS for each relay is determined by two parameters: the minimum fault current and the maximum load current. However, the variables of interest in coordination problems are the Time Setting Multiplier (TSM) [5].

Many efforts have been made to determine appropriate TSM of overcurrent relays. The methods can be classified into three classes: trial and error methods [6], topological analysis methods [7], [8], and optimization methods [9], [10].

In all of overcurrent relays coordination methods, the operating time of the relays is minimized by constitution of the OF, subject to the coordination criteria in different ways [11]. However these methods have two disadvantages. First, they were based on an initial guess and may be trapped in the local minimum [1]. Second, the absence of a systematic procedure for coordination resulted in repeated iterations [11]. To solve these problems, intelligent optimization techniques such as GA have come up. In these methods the constraints are included as part of objective function [3]. In [11], [12], overcurrent relay optimal coordination problem is solved using GA.

All this techniques make reduction of operation times for all relays without any priorities to the short circuit current magnitudes. Short circuit in power cable causes heat production that should be transferred to environment via cable insulation. Cable insulator has a definite heat transferring capacity. If the generated heat in conductor is more than transferred one, it may cause starting the partial discharge (PD) of insulator. Generally the range of main relay operation times is smaller than cable insulation capacity. However if the main relay fails to operate, the increment of heat generation may cause damage to the cables. The relay failures may occur because of its hidden failure. Higher currents cause more thermal stress to the cables. Therefore this important factor should be taken into account in the coordination process.

In this paper a new objective function is proposed which incorporates the amount of thermal stress subjected to the cable insulation during the fault. This is done by adding a new term to the existing OF. The most advantages of the proposed method are summarized as:

1-Reduction of thermal stress on power cables and decrease in deterioration rate of cable insulations.

2-Prioritized protection of aged cables to make prolongation deterioration.

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## II. Review

### A. Cable Insulation Ageing

Large numbers of installed cables in distribution networks are now of advanced age. Electrical supply industries have shown a strong interest to extend those cables in service with longer period than they were designed for. The only option available to maintain the cables in good condition is to reduce ageing rate of them [13]. Insulation ageing is described as a result of the chemical and physical changes in electrical materials or electrical systems, resulting from stresses with the passage of time [14]. These stresses start partial discharge (PD) in cable insulation. PD causes to accelerate ageing of the cables. PD activity may be a symptom of thermal, mechanical and environmental stresses [15]. These ageing factors cause irreversible changes in the overall properties of materials in cable insulation [16]. One of these properties is insulator heat transferring capacity which is shown by damage curve. The damage curve shows the time in which the cable can tolerate a fault current magnitude passing through it. The cable damage curve is given for each cable by manufacturers.

Fig.1 shows the changes of the properties of a cable. In this figure curves A and B illustrate the characteristics of a new cable and deteriorated cable insulation, respectively.

As it is seen in Fig. 1, the cable insulation ageing causes decrease of its heat transferring capacity. Therefore, if the main relay fails, then occurrence of heat stress of cable insulation is more probable.

### B. GA to Relay Coordination Application

In the existing GA methods the OF is considered as sum of two terms. The first term shows sum of the relays operation time for faults in front of them. This term is appeared to represent certainty of fast clearance of fault. The second term states the deviation of time difference of the main and the backup relay operation times from discrimination time (DT). This term guarantees coordination of the main and backup relays. The OF in the latest existing method [4] is considered as follow:

$$O.F = \alpha_1 \times \sum (t_i)^2 + \alpha_2 \times \sum \left(\Delta t_{mb} - \beta_2 \times \left(\Delta t_{mb} - |\Delta t_{mb}|\right)\right)^2 \quad (1)$$

where

$t_i$ is the relay operation time for the fault in front of it.

$\alpha_1, \alpha_2$ and $\beta_2$ are weighting parameters to control the magnitude of each term.

$\Delta t_{mb}$ is time difference between operation time of main and backup relay from DT. Operation time of relays is obtained for fault in front of main relay. It is defined as follow:

$$\Delta t_{mb} = t_b - t_m - DT \quad (2)$$

It is proved in [4] using this OF, coordination results will be more realistic than other previous methods. So in this paper the

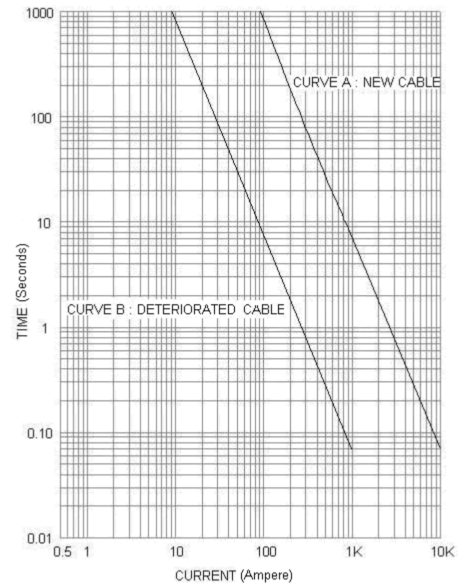


Fig. 1. Cable thermal damage curve, A: New Cable, B: Deteriorated Cable

latest existing objective function in [4] is improved by adding a new term related to cable insulation thermal stress.

## III. New Method

During fault occurrence, the main relay should interrupt short circuit current, first. The main relay and its related circuit breaker (CB) operate properly with a defined probability. This probability is dependent on hidden failure rate of the relay and CB. If even one of them fails, fault should be cleared by operation of the backup relays.

As mentioned in section II, in distribution networks there is another constraint should be considered. By the above described OF, if the main relay or its relative CB fails to operate, there is no specific limitation for cable stress reduction. In this paper another term is added to the OF to complete this requirement. Therefore protection of power system equipments which is one of the major philosophies of protection system is fulfilled, in addition to fast operation and coordination of relays. The proposed objective function is considered as follow:

$$O.F = \alpha_1 \times \sum (t_i)^2 + \alpha_2 \times \sum \left(\Delta t_{mb} - \beta_2 \times \left(\Delta t_{mb} - |\Delta t_{mb}|\right)\right)^2 + \gamma \times \sum \left(I^2 t\right) \quad (3)$$

where

$I^2 t$ represents thermal stress of power cable insulation.

$\gamma$ is the weighting parameter for magnitude control of the added term. The other parameters have been defined in (1).

If a short circuit current with defined magnitude of $I$ flows through a cable in duration of $t$, the thermal stress produced is proportional to $I^2 t$.

When a fault occurs, short circuit currents flow from sources to the fault location via various paths. Maximum of the fault current flowing in the network is in the main cable near the fault location. Of course, the fault current magnitudes in

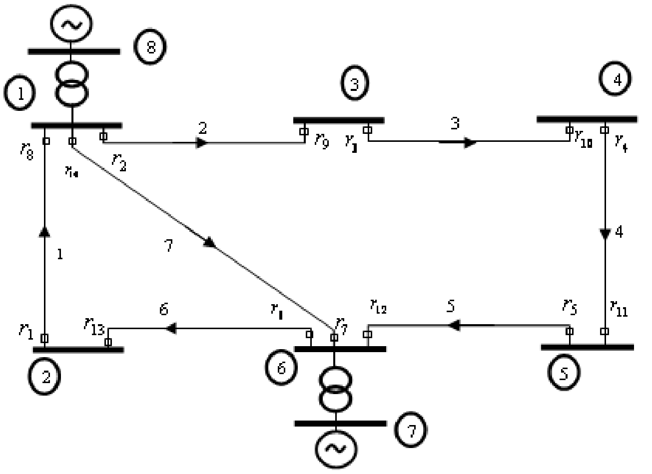


Fig. 2. Sample network

TABLE I
GENERATOR DATA

| Generator no. | Bus no. | R1 (pu) | X1 (pu) |
|---|---|---|---|
| 1 | 7 | 0.01 | 0.1 |
| 2 | 8 | 0.01 | 0.1 |

TABLE II
TRANSFORMER DATA

| Transformer no. | HV side bus no. | LV side bus no. | R1 (pu) | X1 (pu) |
|---|---|---|---|---|
| 1 | 1 | 7 | 0 | 0.2 |
| 2 | 6 | 8 | 0 | 0.2 |

backup cables are less than the main. Since thermal stress is proportional to square of fault current magnitude, thermal stress of power cable insulations which are far from fault location is smaller than those being close to the fault point. So in this paper for each fault, only thermal stress of the main and the backup power cable insulation is considered. In the other words, the relative thermal stresses are inserted as the last term of the OF.

Regarding the second part of the last term i.e. parameter *t*, if the main relay operates, the parameter is the main relay operation time. If the main relay or its relative CB doesn't operate, the parameter denotes backup relay operation time.

## IV. TEST RESULT

### A. Network and Protection Information

The method is applied to the 8-bus sample network which is shown in Fig. 2. The sample network consists of 8 lines, 8 buses and 2 generators. The generators represent equivalent sources of upstream network. The Information data of the network is given in Tables I-III.

R (pu) and X (pu) are based on 10MVA and 33kV.

It is assumed that all of the lines are protected by overcurrent relays and the overcurrent relays are normal inverse type. They are shown in Fig.2 on both sides of each cable. The relay characteristic is formulated by (4).

TABLE III
LINE AND RELAY DATA

| Line no. | Sending bus no. | Receiving bus no. | R1 (pu) | X1 (pu) | Relay no. on sending bus | Relay no. on rec. bus |
|---|---|---|---|---|---|---|
| 1 | 2 | 1 | 0.18 | 0.22 | 1 | 8 |
| 2 | 1 | 3 | 0.18 | 0.22 | 2 | 9 |
| 3 | 3 | 4 | 0.18 | 0.20 | 3 | 10 |
| 4 | 4 | 5 | 0.22 | 0.20 | 4 | 11 |
| 5 | 5 | 6 | 0.22 | 0.20 | 5 | 12 |
| 6 | 6 | 2 | 0.18 | 0.20 | 6 | 13 |
| 7 | 6 | 1 | 0.22 | 0.22 | 7 | 14 |

TABLE IV
MAIN AND BACKUP RELAY DATA

| Main relay no. | Backup Relay no. | Main relay no. | Backup Relay no. |
|---|---|---|---|
| 8 | 9 | 14 | 9 |
| 8 | 7 | 1 | 6 |
| 2 | 7 | 9 | 10 |
| 2 | 1 | 10 | 11 |
| 3 | 2 | 11 | 12 |
| 4 | 3 | 12 | 14 |
| 5 | 4 | 12 | 13 |
| 6 | 5 | 13 | 8 |
| 6 | 14 | 7 | 5 |
| 14 | 1 | 7 | 13 |

TABLE V
RELAY CORRECT OPERATION PROBABILITY

| Relay no. | Probability of proper operation | Relay no. | Probability of proper operation |
|---|---|---|---|
| 1 | 0.98 | 8 | 0.99 |
| 2 | 0.99 | 9 | 0.985 |
| 3 | 0.95 | 10 | 0.99 |
| 4 | 0.97 | 11 | 0.95 |
| 5 | 0.98 | 12 | 0.97 |
| 6 | 0.975 | 13 | 0.98 |
| 7 | 0.985 | 14 | 0.99 |

$$\frac{t}{TSM} = a_0 + \frac{a_1}{(M-1)} + \frac{a_2}{(M-1)^2} + \frac{a_3}{(M-1)^3} + \cdots \quad (4)$$

where

$M$ is the ratio of relay current to the pickup current.

$t$ is the relay operation time.

$\alpha_0, \alpha_1, \alpha_2, \alpha_3$ are scalar quantities which characterize the particular device being simulated and is given below:

$$\begin{cases} a_0 = 1.98772 \\ a_1 = 8.57922 \\ a_2 = \text{-}0.46129 \\ a_3 = 0.0364465 \end{cases} \quad (5)$$

It is also assumed that TSM's of the relays are discrete and TSM's varies from 0 to 1 in steps of 0.05.

For simple analysis of relay coordination, main and backup pairs of relays are given in Table IV.

Proper operation probability of each relay and its relative CB is given in Table V.

### B. GA Information

The control parameters of GA are listed in Table. VI. As described in the previous section, to compose the OF, determination of $\alpha_1$, $\alpha_2$, $\beta_2$, $\gamma$ is essential. For testing the effectiveness of GA for coordination overcurrent relays, several trial using different values of $\alpha_1$, $\alpha_2$, $\beta_2$, $\gamma$ are tested. The variations of $\alpha_1$, $\alpha_2$, $\beta_2$, $\gamma$ are listed in Table VI.

### C. Results and Discussion

Optimal settings of overcurrent relays are obtained using the latest existing OF and the proposed one. Then total thermal stress of power cable insulations is evaluated in each case. The results are shown in Tables VII, VIII.

TABLE VI
GA PARAMETERS

| Population | Generations | $\alpha_1$ | $\alpha_2$ | $\beta_2$ | $\gamma$ | DT |
|---|---|---|---|---|---|---|
| 100 | 1000 | 1 | 100 | 100 | $10^{-8}$ | 0.3 |

TABLE VII
TSM OF RELAYS USING TWO METHODS

| Relay no. | TSM | |
|---|---|---|
| | Existing method | Proposed method |
| 1 | 0.65 | 0.6 |
| 2 | 0.75 | 0.8 |
| 3 | 0.65 | 0.65 |
| 4 | 0.45 | 0.45 |
| 5 | 0.4 | 0.4 |
| 6 | 0.8 | 0.8 |
| 7 | 0.75 | 0.8 |
| 8 | 0.75 | 0.75 |
| 9 | 0.3 | 0.3 |
| 10 | 0.45 | 0.5 |
| 11 | 0.6 | 0.6 |
| 12 | 0.75 | 0.75 |
| 13 | 0.6 | 0.55 |
| 14 | 0.7 | 0.7 |

TABLE VIII
THERMAL STRESS FOR TWO SETTING GROUPS

| Setting group no. | Thermal Stress ($A^2s$) |
|---|---|
| 1 | 2.9438E9 |
| 2 | 1.8732E9 |

TABLE IX
OBJECTIVE FUNCTION VALUES FOR TWO SETTING GROUPS

| Setting group no. | Objective function value |
|---|---|
| 1 | 30.6492 |
| 2 | 30.7724 |

The value of the latest existing OF for the two setting groups is evaluated according to (1) and is listed in Table IX.

As it is seen in Table IX, the both setting groups result in approximately equal values. Therefore both of them have equal chance to be selected by GA in the latest existing method. In the other words, none of them have preference to the other one using the latest existing method. However, applying the proposed method a considerable reduction in cable insulation thermal stress is achieved.

So it is shown by using the proposed method extra of optimum coordination of overcurrent relays, the thermal stresses of cable insulations are reduced. The results of using the new method are reduction of probability of PD in insulators and respectively decrease ageing rate of cable insulations. The results shows without incorporating cable damage curves in relay coordination procedure in distribution networks, relay settings may cause to accelerate ageing process of power cable insulations.

## V. CONCLUSION

In this paper a new GA method has been proposed which incorporates cable thermal stresses as well as the other parameters used in exiting methods. It has been done by adding an expression related to the cable thermal stress to objective function.

By applying the existing and proposed method to a sample distribution network, the coordination results have been obtained. The results have been shown that the proposed method reduces thermal stresses of the cable insulations. It was illustrated that use of this method guarantees fast operation, coordination and reduction of cable insulation thermal stress.

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