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Earth Fault Protection Failure in the Distribution Transformer 11/0.4 kV Supply

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Abstract-*This research studies a miss-coordination problem in the protection of 11 kV distribution network in Iraq. The problem arises when an underground cable is exposed to an earth fault at a location between the High Rupturing Capacity (HRC) fuses and the high voltage windings of the distribution transformer. In this case, the protective relay of the main circuit breaker of the feeder operates at a time faster than the HRC fuses of the faulty transformer. The distribution network considered in this work is an underground 11kV distribution network at Al-Rusafa General Directorate geographical region in Baghdad city. The problem was studied using mathematical analysis and software analysis. The mathematical results and the analysis of the simulated network using CYME 7.1 program show that the relay will operate before the HRC fuses as a response to an earth fault occurrence on that part of the network. To solve this problem several solutions are proposed and discussed in this research.*

Keywords- *Earth fault, protection, distribution network, CYMDIST software.*

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1. Introduction

Due to the high need for reliable operation of the underground distribution networks, it is important to secure and protect these networks against faults. Statistics available in the Ministry of Electricity (MoE) indicate that more than 95% of the faults in the distribution networks including transformers are ground faults. The protection system of the underground distribution network in Baghdad city includes the following:

1. The over current relay that operates the main circuit breaker (CB) of the 11 kV feeder.
2. The HRC fuses which protects the transformers of the distribution substations (Kiosks) at the head of the laterals from the 11 kV feeder.

2. Problem Description

When an earth fault occurs at any section of the 11 kV feeder downstream the HRC fuses the relay will trip the feeder circuit breaker at a time less than that required by the fuses to operate. Accordingly, all the kiosks at the 11 kV feeder and a large number of consumers will be blacked out. This will cause lack of reliability, sensitivity and selectivity. A relatively long time will be required to find the fault location. The procedure starts by isolating the first transformer then energize the feeder, if the relay trip, then the first transformer reconnected and the second one is isolated. These steps will be repeated until discovering the faulty transformer. This means long time of supply interruption to consumers and reduction of energy sells which affects the revenues income for the Ministry of Electricity.

In normal cases, when the feeder is tripped by an earth fault signal, according to the instructions of the Distribution Control Center, the operator of the substation will re-energize the feeder assuming this fault is temporary. In case the fault is permanent, this will cause another trip, accordingly, each time of re-energizing the feeder with a permanent fault, a transient over voltage will occur. Repetitive transient over voltages will cause damages for the insulations of the network equipments along the fault path. This will affect the lifetime of the equipments and reduce their efficiency. This requires additional costs for maintenance and replacement. The technical specifications of the Ministry of Electricity specified the minimum number of mechanical operations for the 11 kV circuit breakers with 10,000 operations. The repetitive trips will consume a large number of these operations.

3. Aim of the Work

The main objectives of the work are:

1. Investigate the protection coordination and setting of the over current relay of an 11kV feeder with the HRC fuses located in the high voltage compartment of the 11/0.4 kV substations “kiosks” of the same feeder.

2. Highlight the effects of failure in operation and bad coordination during an earth fault between the over current relay and the HRC fuses on the network components, consumers, and revenues.
3. Represent the Time Current Characteristics (TCC) curve, to obtain the proper operating time to satisfy the best coordination between the over current protection relay and the HRC fuses.
4. Propose several solutions to overcome the miss-coordination between the protective devices of the 11 kV feeder and explain the advantages and disadvantages for each of them.

4. Mathematical Formulation

I. Calculating the resistance of medium voltage cables

1. DC resistance of conductor

The DC resistance per unit length of the conductor at its maximum operating temperature θ is given by:

$$R' = R_o[1 + \propto_{20} (\theta - 20)] \quad (1)$$

Where: R_o is the DC resistance of the conductor at 20 °C (Ω/m), $\propto_{20}$ is the constant mass temperature coefficient per kelvin at 20 °C, θ is the maximum operating temperature in degrees Celsius.

2. AC resistance of conductor

As referred to the IEC 60287 "Electric cables calculation of the current rating" [1], the AC resistance per unit length of the conductor at its maximum operating temperature is given by the following formula:

$$R = R'\left(1 + Y_s + Y_p\right) \quad (2)$$

Where: R is the current resistance of conductor at maximum operating temperature (Ω/m), R' is the DC resistance of conductor at maximum operating temperature (Ω/m), Y_s is the skin effect factor, Y_p is the proximity effect factor.

3. Skin effect factor Y_s

The skin effect factor Y_s is given by:

$$Y_s = \frac{X_s^4}{192+(0.8\times X_s^4)} \quad (3)$$

Where: $X_s^2 = \frac{8\pi f}{R'} \times 10^{-7} k_s$, f is the supply frequency in hertz. Values for k_s are given in reference [1].

The above formula is accurate providing X_s does not exceed 2.8, and therefore applies to the majority of practical cases.

4. Proximity effect factor Y_p for three-core cables

The proximity effect factor is given by:

$$Y_p = \frac{X_p^4}{192+(0.8\times X_p^4)} (\frac{d_c}{s})^2 [0.312 \left(\frac{d_c}{s}\right)^2 + \frac{1.18}{\frac{X_p^4}{192+(0.8\times X_p^4)}+0.27}] \quad (4)$$

Where: $X_p^2 = \frac{8\pi f}{R'} \times 10^{-7} k_p$, d_c is the diameter of conductor (mm), s is the distance between conductor axes (mm), Values for k_p are given in reference[1].

The above formula is accurate provided X_p does not exceed 2.8, and therefore applies to the majority of practical cases.

II. Calculating the earth fault current

An earth fault is assumed at each section of the feeder "between the HRC fuse and HV side of the transformer". The fault path consists of the following resistances:

1. For the forward path current, the cable conductor resistance.
2. For the return path current, the cable screen resistance + grounding resistance at the substation 21.1 Ω.

The value of earth fault current can be determined by dividing the phase voltage of the feeder (6350 V) by the value of the resistance of the fault path including the grounding resistance of the substation.

III. Calculating the time of operation for both IDMT relay and HRC fuses

1. For a relay with "standard inverse SI" characteristics the time of relay operation when an earth fault occurred can be calculated according to the specification "IEC 60255" by the following equation [2]:

$$t = TMS \times \frac{0.14}{I_r^{0.02}-1} \quad (5)$$

Where: I_r= I/I_s, I = Measured fault current, I_s= Relay setting current, TMS = Time Multiplier Setting

2. The operating time of the HRC fuses can be determined from the characteristic curves of the HRC fuses.

5. Case Study

As a case study, the distribution network of Al-Rusafa General Directorate geographical region in Baghdad city has been considered, as shown in Figure 1. The network considered is the 11 kV underground feeder no. (5) from Al-Muhandseen substation (33/11 kV).This feeder is an underground feeder supplying residential consumers. Table 1 shows the details of this feeder and Figure 2 shows the layout of the feeder.

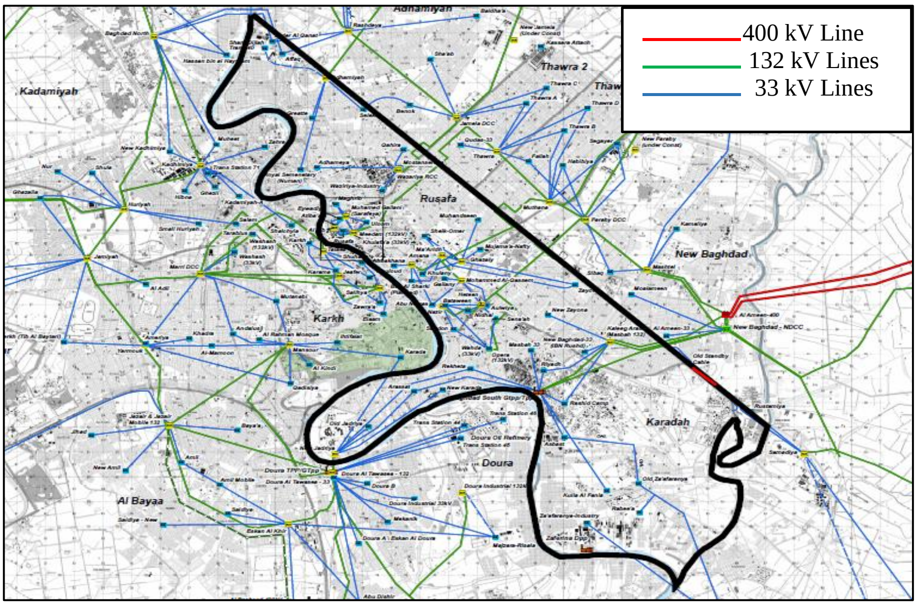

Figure 1: Electrical distribution network of Al-Rusafa General Directorate

Table 1: Data of feeder no.5 from Al-Muhandseen Substation (33/11 kV) [MoE]

Type of feeder	Underground Cable
Size of cable	3 x 150 mm^2
Type of cable insulation	XLPE
Type of cable earthing	Screen layer earthing
Resistance of conductor (at 90^0 C)	0.159 Ω/km
Resistance of conductor (at 20^0 C)	0.124 Ω/km
Resistance of screen (at 90^0 C)	0.927 Ω/km
No. of distribution transformers	8
Capacity of each transformer	630 kVA
Total capacity of transformers	5040 kVA
Maximum load of feeder	3.85 MW
Type of consumers	residential
Length of feeder	1803 m

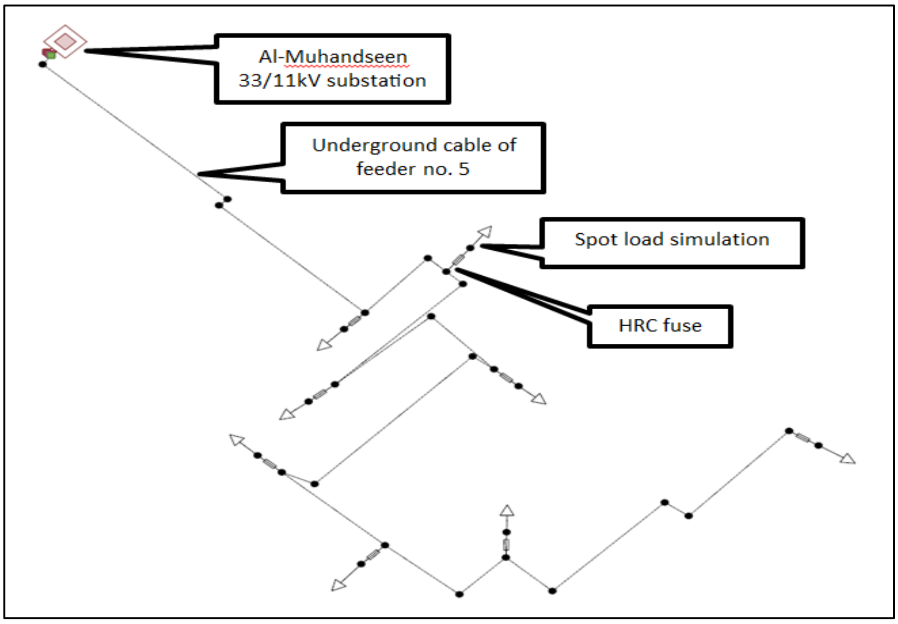

Figure 2: layout of feeder no.5 from Al-Muhandseen Substation (33/11 kV)

A protective IDMT relay is simulated and its earth fault parameters have been setted at the feeder circuit breaker according to MoE requirements. The chosen relay is a numerical protection relay of type SIEMENS 7SJ50 for radial feeders protection. It can be used as definite–time or inverse–time for overcurrent and earth–fault protection or for thermal overload protection. An HRC fuse located at the entrance point from the feeder to the distribution transformer is simulated according to MoE requirements. The circuit breaker, which control the operation of feeder (5/Al-Muhandseen), is chosen from the library of CYME 7.1, the type "Relay Controlled Circuit Breaker". According to MoE Specification (D-06 - Kiosk Type 11- 0.4 kV Substation) [3], the single line diagram of the high voltage compartment for 630 kVA transformer is as shown in Figure 3. In general, fuse links should comply with IEC60420 [4] and IEC60282-1 [5]. The fuse switch shall be triple pole with provisions for automatic tripping in case of failure of any fuse. Furthermore reclosing cannot be carried out unless the burnt fuse is replaced. The switch-fuse must be capable of switching ON/OFF the normal load current and must have a continuous current rating not less than 200 Amperes with cartridge fuse according to the capacity of the transformer.

6. Number, Length and the Calculated Resistance of Feeder Sections

According to the Geographical Information System (GIS) data taken from the General Directorate of Al-Rusafa Electricity Distribution. The feeder no.(5) is divided into sections according to the distance between the main CB to the next transformer and from each transformer to the following transformer. The resistances of the conductor for each section of the feeder are calculated using formulas (1) and (2), as given in Table 2.

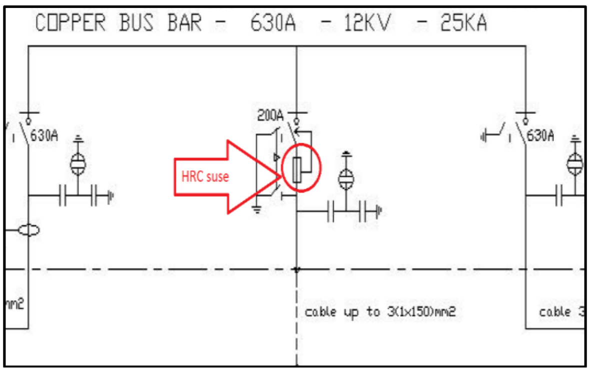

Figure 3: Single line diagram of the high voltage compartment [2]

Table 2: length and the calculated resistance of each section of the feeder.

Section of Cable	Length (km)	AC Resistance (Ω)
A	0.494	0.0787
B	0.1	0.01595
C	0.075	0.0119
D	0.241	0.0384
E	0.257	0.0409
F	0.067	0.0106
G	0.081	0.0129
H	0.488	0.0778
Total	1.803	0.2871

7. Results and Discussion

An earth fault is simulated at each section of the feeder and the corresponding time of operation of both the relay and the HRC fuses is calculated using equation (5) and using CYME 7.1 program.

8. Calculating the time of operation for both the relay and the HRC fuses

I. Calculating the resistance and earth fault current at each section of the feeder

Assume an earth fault occurs at the end of each section of the feeder. The resistance and earth fault current at each section of the cable are calculated using the formulas given in equations (1) to (4), as given in Table 3.

According to the IEC standardization, the maximum AC resistance at operating temperature 90^0 should not exceed 0.1595 Ω/km, and the maximum resistance of the screen of the cable should not exceed 0.927 Ω/km. The upper limit of cable resistance are considered because we are interested with the lowest value of earth fault current where the miss-discrimination occurs between the HRC fuse and relay operating time.

II. Time response of the HRC fuse to earth fault

Referring to the "Time – Current" characteristics curves of the HRC fuse, Figure 4, The maximum and minimum earth fault currents at the first and last section of the feeder and the corresponding time of operation of the HRC fuse can be indicated. It is found that the fastest time response of the HRC fuse is 1.5 sec. for an earth fault at the first section of the feeder where the maximum current value equals to 293.48A.

III. Time response of the relay to earth fault

The time of relay operation "standard inverse SI" in case of earth fault is determined by equation (5) where:

The Time Multiplier Setting TMS used for earth fault protection is "0.1".

The plug setting for the overcurrent relay for an earth fault is “0.25”.
The min value of earth fault current which will be sensed by the relay is:

$$relay\ setting\ current = I_s$$
$$= plug\ setting \times CT\ ratio$$
$$I_s = 0.25 \times \frac{300}{5} = 15\ A$$

The time of relay operation due to earth fault current is calculated at each section and the results are summarized in Table 4.

9. Summary of Results

The results obtained from analytical calculations when an earth fault occurs at the end of section (A) of the feeder, are given in Table 5.

10. Computing the Time of Operation for the Relay and the HRC Fuse by SYME 7.1

The value of earth fault current and the time response for both the IDMT relay and the HRC fuses can be computed using CYME 7.1. as follows:
An earth fault is assumed to occur downstream the HRC fuses at the first spot load of the feeder as shown in Figure 5.
The branch device coordination is selected at the fault location from the “TCC” list. We choose the upstream node to coordinate with. The network under coordination is shown in Figure 6.
The “time – current” characteristics of both the relay and the HRC fuse are shown in Figure 7.
Summary of the results obtained from CYME 7.1 program when an earth fault occur at the end of section (A) of the feeder is given in Table 6.

11. The Miss-coordination Problem between the Relay and the HRC Fuses

The calculations results of time of operation for both the relay and the HRC fuses, summarized in Tables 6 and 7, show a miss-coordination in the operation of the protective devices in case of an earth fault occurs in the section of the feeder between the HRC fuses and the high voltage windings of the transformer. In this case the relay of the main feeder will operate in (0.5 sec.) while the branch protection device (HRC fuses) will operates in (2.655 sec.). This miss-coordination between the two protective devices will cause a disconnection of the whole feeder instead of disconnecting only the faulted spot load.

Table 3: the resistance and the earth fault current at each section of the feeder

Sections of the feeder	Length of section (km)	Resistance of conductor per section (Ω)	Resistance of screen per section (Ω)	Fault path resistance = conductor resis. + screen resis. +21.1* (Ω)	Earth fault current at each section (A)
A	0.494	0.078793	0.457938	21.636731	293.4824
B	0.1	0.01595	0.0927	21.745381	292.016
C	0.075	0.0119625	0.069525	21.8268685	290.9258
D	0.241	0.0384395	0.223407	22.088715	287.4771
E	0.257	0.0409915	0.238239	22.3679455	283.8884
F	0.067	0.0106865	0.062109	22.440741	282.9675
G	0.081	0.0129195	0.075087	22.5287475	281.8621
H	0.488	0.077836	0.452376	23.0589595	275.381
Total	1.803	0.2875785	1.671381		

* Where (21.1 Ω) is the earthing resistance of substation at the 11 kV side.

Table 4: time of relay operation for different values of earth fault currents

Section of feeder	Earth fault current (A)	Time of relay operation (sec.)
A	293.4824	0.228461
B	292.016	0.228858
C	290.9258	0.229155
D	287.4771	0.230109
E	283.8884	0.231121
F	282.9675	0.231384
G	281.8621	0.231702
H	275.381	0.233609

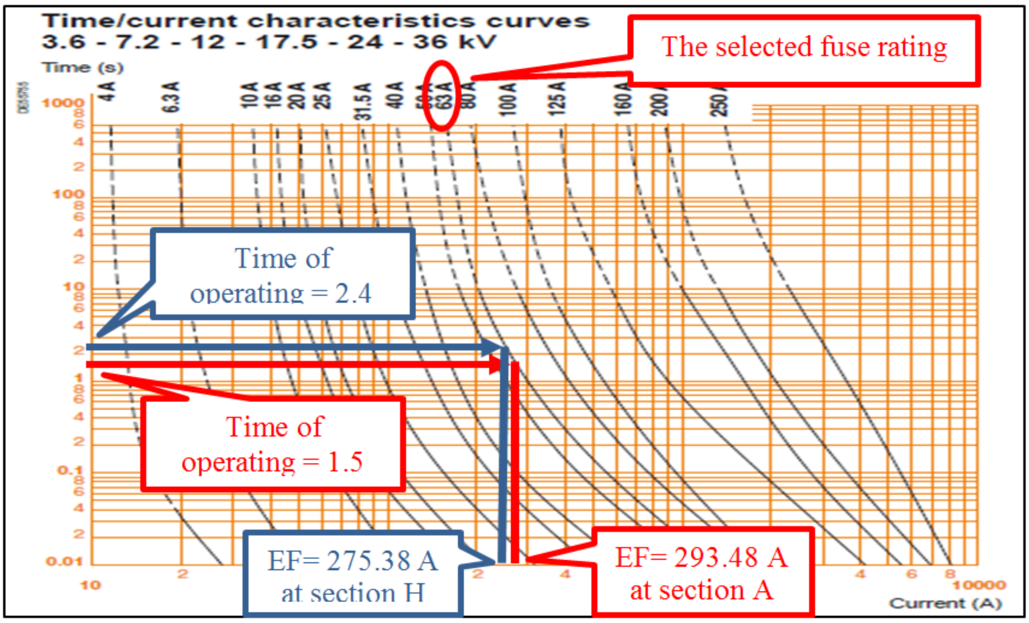

Figure 4: The maximum and minimum earth fault currents at the first and last section of the feeder and the corresponding time of operation of the HRC fuses

Table 5: summary of results obtained from analytical calculations

Protection device type	Earth fault current (A)	Operating time (sec.)
HRC fuse (370), Rating: 63A, Voltage: 11kV	293.48	1.5
Electronic Overcurrent Relay, SIEMENS 7SJ50 SI, TD: 0.1	293.48	0.228

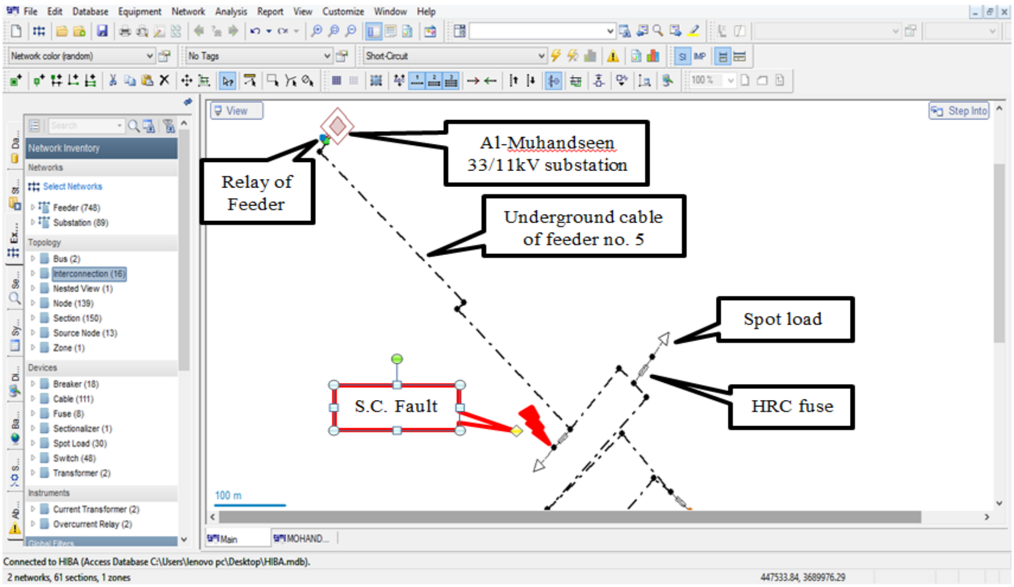

Figure 5: earth fault location downstream the first HRC fuse

Table 6: summary of results obtained from CYME program

Protection device type	Value of earth fault current (A)	Operating time (sec.)
HRC fuse (370), Rating: 63A Voltage: 11kV	294.43	2.655
Electronic Overcurrent Relay SIEMENS 7SJ50 SI, TD: 0.1	294.43	0.505

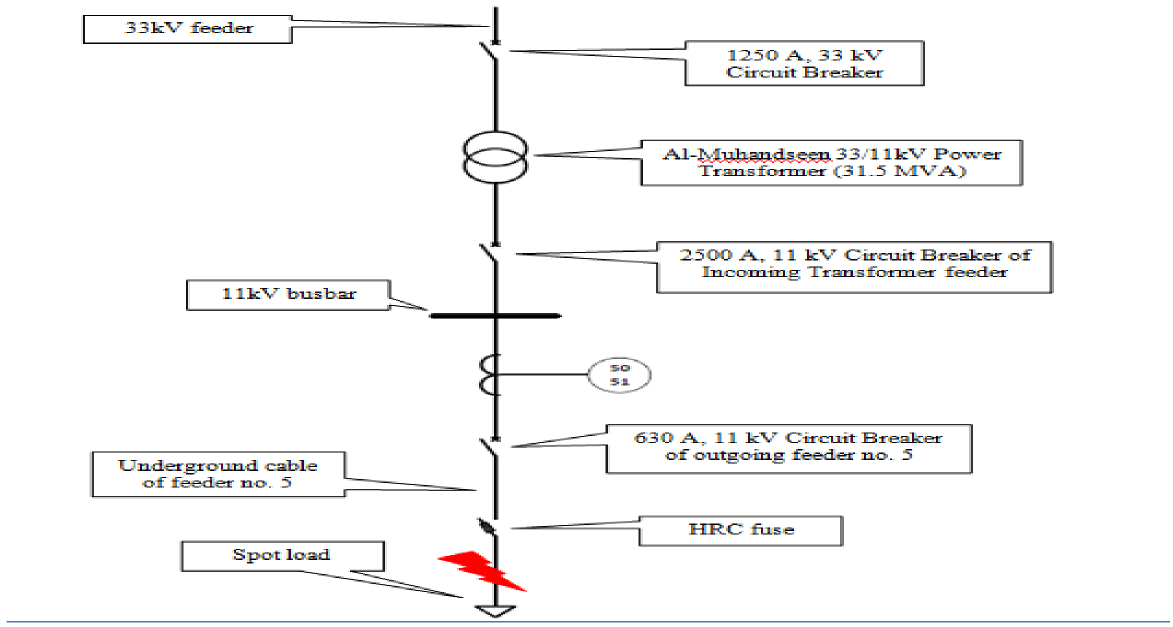

Figure 6: the network under coordination

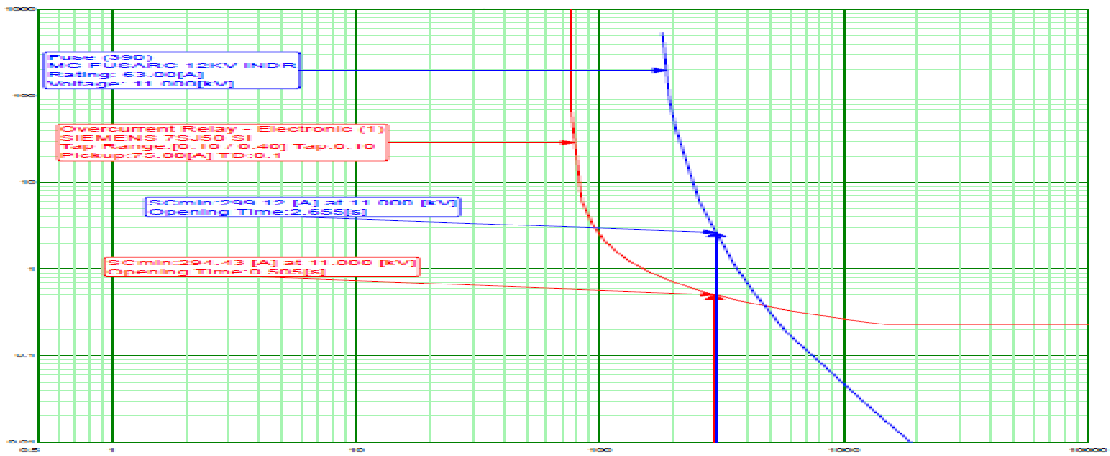

Figure 7: the "time – current" characteristics of both the relay and the HRC fuse

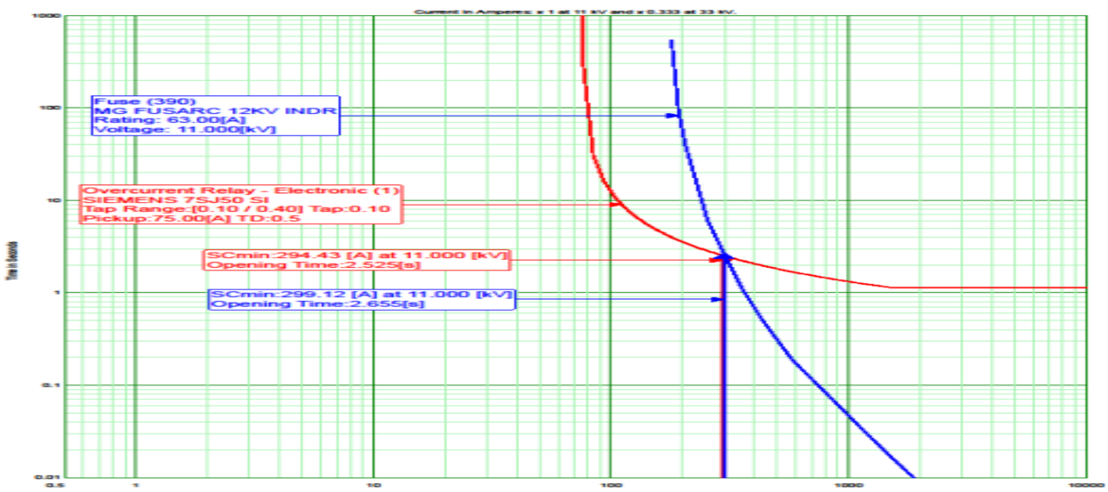

Figure 8: Branch device coordination for case (a)

12. The Proposed Methods for Solving the Problem

I. Changing the setting of the relay

The time dial setting is originally setted equal to "TD=0.1" (according to MoE requirements). This setting is changed by considering three different values of time dial and the results are described accordingly:

1. Time dial = 0.5: the branch device coordination curves will be as shown in Figure 8.

The results when applying a time dial equal to 0.5 are summarized in Table 7. It shows that the miss-coordination is still between the HRC fuse and the relay, the relay will operate before the HRC fuse.

2. Time dial = 0.55: The results when applying a time dial equal to 0.55 are summarized in Table 8. It shows a critical coordination between the HRC fuse and the relay, the time period between them is too small = 0.122 sec.
3. Time dial = 0.6: The results when applying a time dial equal to 0.6 are summarized in Table 9. It shows a good coordination between the HRC fuse and the relay and the time period between them equal to 0.375 sec.

Table 7: summary of results obtained when applying TD=0.5 for the relay

Protection device type	Value of earth fault current (A)	Operating time (sec.)
HRC fuse (370), Rating: 63A Voltage: 11kV	294.43	2.655
Electronic Overcurrent Relay SIEMENS 7SJ50 SI, TD: 0.1	294.43	2.525

Table 8: summary of results obtained when applying TD=0.55 for the relay

Protection device type	Value of earth fault current (A)	Operating time (sec.)
HRC fuse (370), Rating: 63A Voltage: 11kV	294.43	2.655
Electronic Overcurrent Relay SIEMENS 7SJ50 SI, TD: 0.1	294.43	2.777

Table 9: summary of results obtained when applying TD=0.6 for the relay

Protection device type	Value of earth fault current (A)	Operating Time (sec.)
HRC fuse (370), Rating: 63A Voltage: 11kV	294.43	2.655
Electronic Overcurrent Relay SIEMENS 7SJ50 SI, TD: 0.1	294.43	3.030

However, this procedure is not recommended due to the following:

a. Long time with fault presence until making trip for the HRC fuse "around 2.6 sec." which may cause severe damage to the network equipments before clearing the fault.

b. The relay needs to be coordinated not just with the HRC fuses but with the upstream network which requires more delay in the response of the upstream protection system. This is not possible due to the regulations of the Ministry of Electricity which fixed the time delay for operating the protection system starting from the distribution sector upstream to the transmission and generation sectors.

II. Replacing the switch-fuse of the ring main unit with a circuit breaker

In this case, the switch-fuse of the ring main unit is replaced with relay controlled circuit breaker as shown in Figure 9. This process provides coordination with the main relay of the 11kV feeder so that the circuit breaker of the transformer will trip before the main circuit breaker. This is not recommended in the current time because of:

1. The high cost which will be added to the current cost of the kiosks.
2. A relay controlled circuit breaker needs a DC source which consists of battery cells and a charger. This increases the volume of the kiosks which is already big and need large space when installed on the streets banks.

However this suggestion will be necessary when modifying the current network to smart grid in case the Ministry of Electricity adopts it in the future.

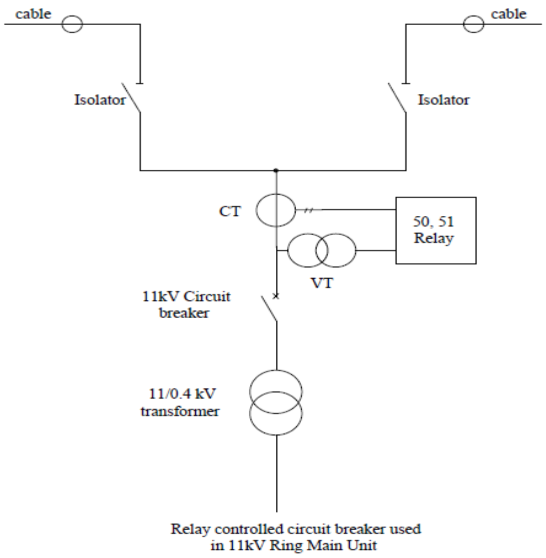

Figure 9: Ring main unit with circuit breaker instead of switch-fuse

III. Using a combination of ground current sensor transformer and capacitor trip device when an earth fault occur

1. Zero-sequence ground current sensing transformer:

It is used for sensitive ground current protection. Under normal load conditions, the vector sum of the three phase currents is near zero. When one load-side phase conductor fails to ground, the resulting vector sum of the phase currents no longer is zero. If the system is resistance grounded, the zero-sequence ground CT will see a ground current determined by the resistance of the ground resistor, plus the resistance of the load circuit.

The induced emf resulting from ground sensor current transformer is used to operate a relay coil, as shown in Figure (10).

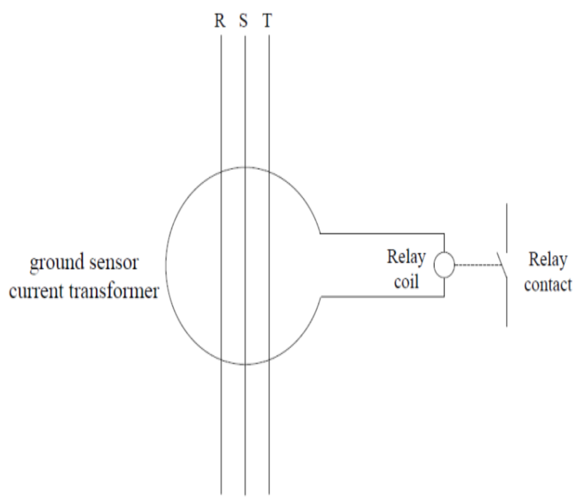

Figure 10: Relay operated by ground sensor current transformer

2. Capacitor trip device

Capacitor trip device (CTD) is an energy storage device for situations in which the normal source of control power may not be present when action is required. The principle of a basic capacitor trip device is very simple. A capacitor is connected to a half-wave rectifier or a bridge rectifier, and charged from the normal AC control power supply. The charging time of the capacitor is typically about 10 cycles. The charging current is limited by a series resistor, both to protect the capacitor from excess current, and to protect the bridge rectifier. When a protective relay contact closes, the capacitor output is connected to the trip solenoid coil circuit, and the stored capacitive energy is released to trip the switch-fuse. The capacitor unit has a blocking diode to maintain the storage capacitor charged at the peak AC voltage. In case of loss of AC the blocking diode prevents the capacitor from discharging due to upstream loads. The standard product holds sufficient charge to trip the breaker for 12 seconds after loss of AC voltage.

13. Methods of using a Combination of Ground Current Sensing Transformer and Capacitor Trip Device

Two methods are proposed, as follows:

I. ON-load tripping of the switch-fuse of the ring main unit

According to MoE specifications “D-06 / Kiosk Type 11-0.4 kV Substations” which clearly mentioned that the switch-fuse must be capable of switching ON/OFF the normal load current and must have a continuous current rating not less than 200 Amperes with cartridge fuse according to the capacity of the transformer. Accordingly, the switch-fuse cannot be tripped by using the combination of the ground sensor current transformer and capacitor trip units when an earth fault occurred (the max earth fault current “300 Amperes”) greater than the continuous current rating of the switch-fuse “200 Amperes”. To solve this problem, the current rating of the switch-fuse must be increased to be greater than the maximum earth fault current, for example 400 A. In this case, the switch-fuse will be tripped safely even under maximum fault current of the feeder 300A. Figure 11 shows the circuit diagram to control the operation of the switch-fuse.

II. Off-load tripping the switch-fuse of the ring main unit

If the continuous current rating of the switch-fuse cannot be increased (more than 200 Amperes) for economic considerations, then the feeder can be tripped by the main relay and after a time delay the switch-fuse is tripped in its OFF-load mode, during the period of power restoration (normally 5 minutes) which is specified by the control center. This circuit is almost the same as in Figure 11 with the addition of an OFF-delay timer to make the CTD capable to discharge in the solenoid coil after an earth fault occurred and the main circuit breaker of the feeder has been tripped by its own protective relay. This is shown in Figure 12.

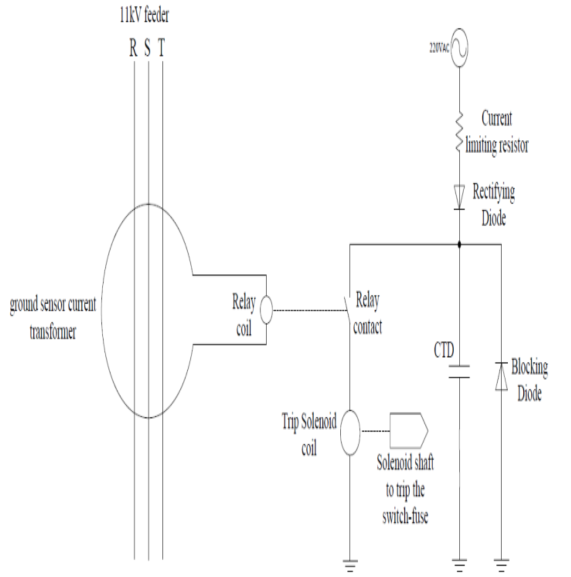

Figure 11: A diagram representing switch-fuse control circuit.

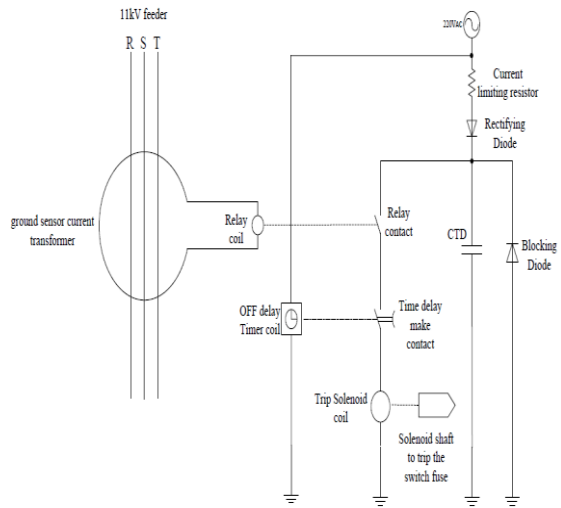

Figure 12: A diagram representing switch-fuse control circuit with time delay

14. Conclusion

No HRC fuse can sense and blow when an earth fault occur at any section of the medium voltage feeder because the feeder relay will trip the feeder circuit breaker at a time less than that required by the fuse to operate. All the kiosks at the 11 kV feeder and accordingly a large number of consumers will be blacked out even if a single earth fault occurs at any section along the feeder path. The recommended solution in the current time is to use the proposed combination of a ground sensor current transformer and capacitor trip units for earth fault protection since it is the most economic procedure, which requires only adding simple components without affecting the upstream coordination with the feeder relay.

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