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A Comprehensive Review on Distributed Feeder Protection Problems in the Gaza Strip 22/0.4 kV Overhead Power Distribution System – A Case Study

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Abstract: This paper provides a perspective on protective system at 22kV overhead feeders in Gaza distribution network using symmetrical components method and ETAP software. Electrical disturbances from high rate of outage feeders at the 22 kV overhead power lines frequently cause disruptions on the generating plant and customer loads. One sub-transmission feeder from a parallel set of ten 22 KV feeders (140 MW) in the Gaza west substation is selected as a case study in this research. Because the protection system lacks a data fault recorder (DFR), the paper calculates the fault currents at both the nearest substation bus and the last bus in the distributed feeder using the symmetrical components method and verifies the results by using ETAP software simulation. The results from calculating the minimum fault at the last bus indicated that the current protective parameters are reasonable and satisfied for detecting and interrupting the occurring faults. This author paper proposes increasing the fault clearing time at farthest feeder bus to make protective functions less sensitive by adjusting TMS to 0.08 for time overcurrent and earth fault and setting pickup level to 3.8 for instantaneously overcurrent. The design model is run on the selected feeder, and simulation results guarantee the proposed model's accurate performance for both overcurrent and earth faults after changing the fault clearing time. There will be no miscoordination of protective devices or operational risks while running the design model for the selected feeder with new settings. Gaza's distribution feeder network requires structural improvements to become more reliable and to reduce the high rate of feeder trip, and practical recommendations to improve current installation distribution grid are included in this paper.

Keywords: Protection System, Electrical Faults, Short-Circuit Analysis, Clearing Fault Time, Sequences Components, Power Distribution System, Overhead Power Lines, ETAP

1. Introduction

The electrical power distribution network in the Gaza Strip is three-phase three wires, a single-point grounded system without a neutral conductor and consists of overhead electricity wires spread in a radial topology with 22- kV medium voltage, using for the industrial, commercial and residential sectors. In general, the Gaza 22 kV-distribution electrical network suffers from operation and maintenance issues, absent strategies and plans load conservations and management, and a lack of installed important devices such as modern smart breakers on both sides of DT 22/0.4 kV, fault passage indicators (FPI), and auto recloser circuit breakers (ACR) [1]. Most faults in overhead lines are either a symmetrical or unsymmetrical fault, the symmetrical fault occurs when either: three phases of the system are short-circuited to each other; or three phases of the system are short-circuited to ground, and the unsymmetrical faults might manifest themselves as single line-to-ground faults, line-to-line faults, or double line-to-ground faults [2, 3, 5]. For these unbalanced short-circuit problems, the concept of symmetrical components is used for solution [4, 6]. Because the western Gaza substation's protective system lacks a data fault recorder (DFR) to record instantaneous fault levels for time periods on the order of a second, this paper estimate fault levels at both the nearest substation bus and the farthest bus feeder using the symmetrical components method and ETAP software. The symmetrical components theory calculates the fault levels by the transformation of three unbalanced power system phases into a three set of balanced phasors (positive, negative, zero sequences components) [2, 7]. Substation protective IED device detects symmetrical and unsymmetrical faults on 22 kV feeder lines. At the 22 kV feeder line, time and instantaneous overcurrent O/C and earth fault E/F protective functions are used to detect and clear faults within the standard fault-clearing time. Variable tripping time is used for coordination with laterals protective devices without the need for additional current measurement and data transmission [8]. The term instantaneous is defined to indicate that no (time) delay is purposely introduced in the action of the device (IEEE 100). In practice, the terms instantaneous and high-speed are used interchangeably to describe protective relays that operate in 50 msec or less [9]. For breakers rated above 1000 V, the clearing time is the sum of the minimum relay time (usually 1/2 cycle), plus contact parting time and the arcing time. Sometimes referred to as total clearing time or interrupting time [10]. The paper proposes to reduce the sensitivity of time overcurrent and earth faults by assuming the fault clearance time or operate time to 350ms in the normal inverse time-current curve during fault at last bus.

The 66kV and 22 kV grid designing and modelling in ETAP software was successfully simulated to ensure that there was no mis-coordination or operation risk between the 22kV main feeder breaker and both of the upstream power transformer's 22kV and 66kV breakers.

The motivation stems from the desire to find out what is causing the high rate of annual feeder outages and study the protective system in 22 kV radial distribution network. The most important contributions made by this paper are an investigation into the accuracy of the existing protective settings for the 22 kV feeders in the western Gaza Substation; a simulation of the power model design for a distributed feeder; and, finally, the formulation of a recommendation that can be put into practice to lower the rate of annual outages suffered by Gaza's power feeders. The rest of this paper is organized as follows, Section 2, includes a review of distribution feeder line to collect the technical data for feeder elements. Then, Section 3, 4 includes an explanation of the problem and calculation for faults levels to deal with protective settings. After that, in Sections 5 the proposed methodology is presented for the detection and isolation fault schemes. In Section 6, the results are presented and the discussion about obtained results, and finally, the conclusion and recommendations.

2. Distribution Feeder Description

The dominating Gaza Generation Power Plant (GPGC), the Israeli Electricity Company (IEC), and the Egyptian Channel Company (ECC) all supply power to Gaza (ECC). All power substations reduced the 66 KV to 22 KV using step-down 66 to 22 KV transformers, and lastly to 385 KV using distribution power transformer 22/0.4 kV as shown in Figure 1. The electrical power transfers from Gaza west substation to electrical power distribution network through parallel ten 22 kV feeders and each feeder has capacity 14 MW [11].

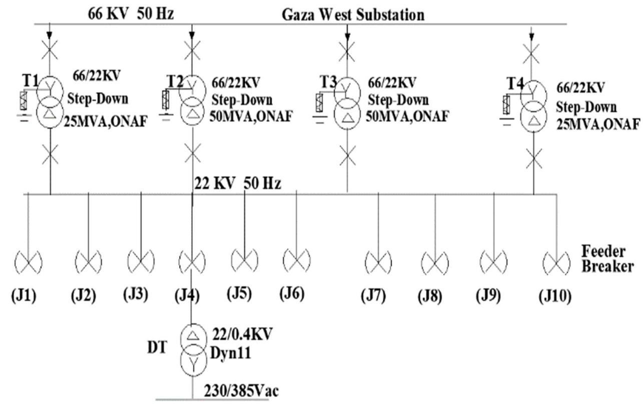

Figure 1. *Overall single line diagram for 66 and 22 kV power Grid.*

2.1. 22 kV Overhead Feeder Components

The 22 kV subtransmission feeder has the following components (see Figure 2):

a) Aluminum ASCR wiring cable and earthing wire cable.
b) Three-phase 22 kV/0.4 kV distribution transformer.
c) A glass fuse rated 22 kV is installed on the primary DT.
d) 36kV switch disconnector with an arc interrupter.
e) Surge arrestor at the primary a 22/0.4 kV transformer.
f) Polymer and tempered glass Insulator.
g) HRC overcurrent protection at 0.4 kV of DT.

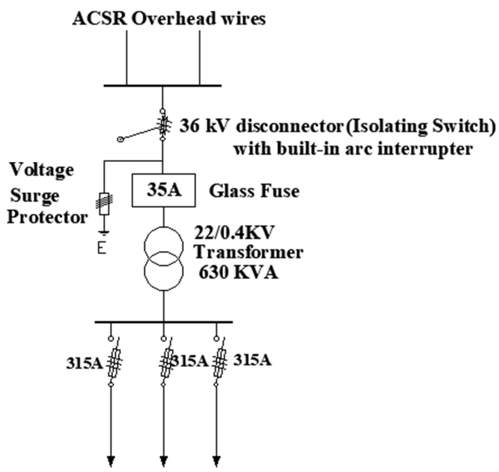

Figure 2. *Overhead Power Lines Components for Selected DT 22/0.4 kV.*

Table 1 shows the collected data for Power Transformer 66/22 kV Ratings, Table 2 shows the calculated power transformer 66/22 kV in per unit, and Table 3 shows the overhead impedance cable data from Ref [12].

Table 1. *11 kV-66 kV, 50 Hz HV power transformer ratings.*

Capacity	**MVA**	**25**
HV Voltage	kV	66
LV Voltage	kV	22
Positive Impedance	%,	9.65
Zero Impedance	%	10
Vector Group	Dyn11	
Grounding Resistor R_G	Ohm	20

Table 2. *Per unit calculation substation power transformer 66/22 kV.*

Base MVA	**Sbase**	**MVA**	**100**
Base V	Vbase	kV	22
Ibase A	Sbase / √3 x Vbase	A	2624
Zbase	kV²/Sbase	Ω	4.84
Z_T^1	$\frac{Sbase(new)}{Sbase(old)} * Zp.u(old)$	p.u	0.386
Z_T^0	$\frac{Sbase(new)}{Sbase(old)} * Zp.u(old)$	p.u	0.4

Where,
Z_T^1 Positive sequence impedance of 66/22 kV transformer.
Z_T^2 Negative sequence impedance of 66/22 kV transformer.
Z_T^0 Zero sequence impedance of 66/22 kV transformer.
$Zp.u$ Impedance, per-unit.
Zbase Base Impedance.
Vbase Base voltage, 22 kV.
Sbase Power base, 100 MVA.

Table 3. *Total Base and p.u impedances at 22 kV for 22kV power cables.*

Cable size		**ACSR 150/25**	**ACSR 95/15**	**ACSR 50/8**
Length	Km	3.5	4	4
Positive Impedance	Ohm/km	0.49	0.5	0.7
Negative Impedance	Ohm/km	0.49	0.5	0.7
Zero impedance	Ohm/km	1.7	1.7	1.8
Total Impedance	Ohm	6.5	6.5	20.3
Total Impedance	p.u	1.34	1.34	4.3

2.2. Tripping Time or Time Clearing fault Time

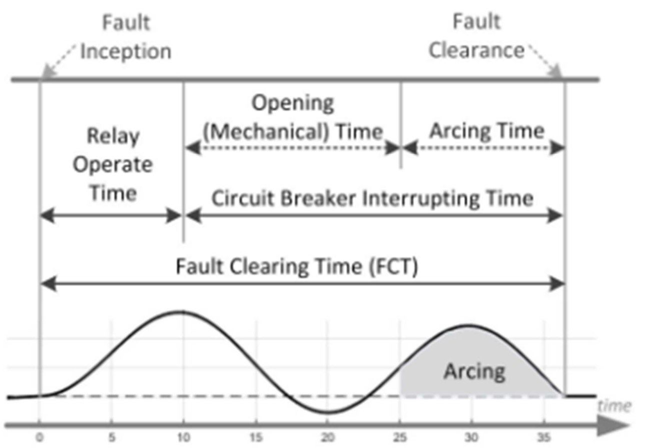

Figure 3. *Definition of Fault Clearing Time (FCT), relay operate time and circuit breaker interrupting time [17].*

The total Fault Clearing Time (FCT in Figure 3) is the time between the fault inception and the moment when fault current is interrupted and is measured in cycles or milliseconds. It consists of the relay operate time and the circuit breaker interrupting time (if CB operates correctly, otherwise it prolongs until a breaker failure scheme opens adjacent CBs). The relay operate time is the time between the fault inception and the moment when the relay operates signal triggers the CB to interrupt the current. The circuit breaker interrupting time is the interval of time between the beginning of the opening time and the end of the arcing time. The opening time is the time between the moment when relay signal appears to the CB trip coil until the moment when the arcing CB contacts physically start to separate [13-17].

3. Problem Description

The aim of this paper is to investigate the protection functions in Intelligent Electronic Device (IED) to measure the accurate protective functions at feeder breaker and going to search the main reasons for high rate of feeders' trip. Figure 4 depicts the type of upcoming faults in 2018 [14].

A 22-kV overhead grid failure activates the protective systems at the sub-transmission main breaker, and isolating all power outages from all other un-faulted pole mounted distribution transformers 22/0.4 kV on the same feeder. The study utilized one of the Gaza West substation's power flow feeders, J4, which has a maximum power rate of 14MW and consists of over thirteen 22/0.4 kV distribution transformers with varying capacities, as shown in Figure 5 [12].

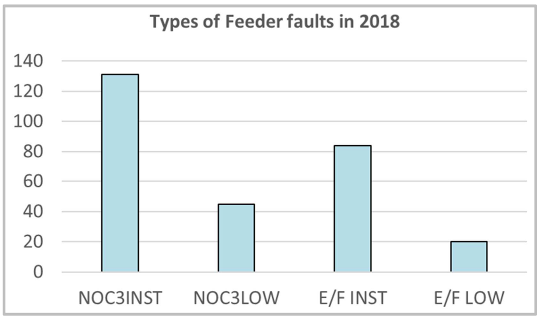

Figure 4. *Number of Feeder fault types pear year 2018.*

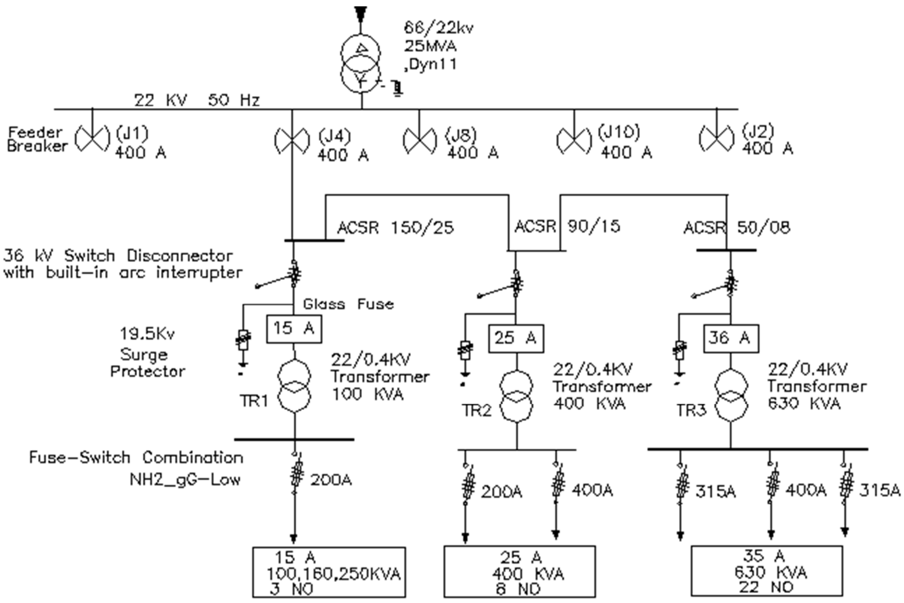

Figure 5. *Schematic diagram for 22 kV feeder partial distribution line.*

4. Designing Protective System

The symmetrical component proposed by Fortescue's was used to calculate the fault level; the theory allows the transformation of three unbalanced power system phases into three sets of balanced phasors (positive, negative, and zero sequence components) [2, 7].

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

$$I_a = \mathrm{Ia0} + \mathrm{Ia1} + \mathrm{Ia2} \tag{1}$$

$$I_b = \mathrm{Ia0} + a^2\mathrm{Ia1} + a\mathrm{Ia2}$$

$$I_c = \mathrm{Ia0} + a\mathrm{Ia1} + a^2\mathrm{Ia2}$$

Ia, Ib, and Ic are the vector phase currents for three phase line a, b, c, respectively.

Ia0, Ia1, Ia2 are vector zero, positive and negative sequence currents for phase a, respectively.

The "a" operator has a unity value at 120 degrees a= 1∠120.

4.1. Step 1: Determine Fault Current Levels

4.1.1. Three Phases Overcurrent Fault Level

During three phases short circuit at bus near to 22 kV feeder breaker, only the positive sequence components exist. The fault phase current can calculate as in equation 2 [10].

$$I_{3\emptyset} = I_{a1} = \frac{V_f}{(Z_T^{+1})} \tag{2}$$

V_f is pre-fault voltage.

Z_T^{+1} is the total positive sequence impedance from source to the fault bus.

Ia1 fault phase currents for phase a.

4.1.2. Line to Ground Fault Level (E/F)

During line to ground fault at bus near to 22 kV feeder breaker, the three sequence currents exist and are equal at faulted bus, while currents at other buses is zero. The fault currents can be computed using equations 3 or 4 [10].

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_{fa} \\ 0 \\ 0 \end{bmatrix}$$

$$I_{a0} = I_{a1} = I_{a2} = \frac{I_{fa}}{3} = \frac{V_f}{Z_1+Z_2+Z_n} \quad (3)$$

$$Z_n = Z_0 + 3R_G$$

$$I_{fa} = \frac{V_f(L-G)}{3R_G+Z_T^0+Z_T^1+Z_T^2} = \frac{3\times V_{base}}{\sqrt{3}\times Z_{Total}} \quad (4)$$

Z_n The neutral impedance.

R_G Neutral grounding resistor.

Z_0 Zero sequence impedance.

4.2. STEP2: Calculate Protective Parameters

4.2.1. TMS Parameter for Time Overcurrent and Earth Fault

The operating tripping time or clearing fault time can calculate from equation 5 according to The IEC 60255-151 and BS 142 standards [18-20].

$$t(s) = \frac{k*\beta}{(\frac{I}{Is})^{\alpha}-1} \quad (5)$$

α=0.02 and β=0.14 for selected standard Normal Inverse.

K: Time Multiplier Setting "TMS".

I = Measured phase current.

Is = adjustable start current.

t(s) = operating tripping time in seconds.

Thus, increasing the operating tripping time will increase the time multiplier setting value. However, a disaster or deteriorated insulation will occur if this is selected by un-planning. This paper assumes the clearing fault time 350 ms at the farthest bus, then, the new TMS for time overcurrent fault and earth fault is.

$$TMS = k = \frac{t(s)\left(\left(\frac{I_{s.c}}{Is}\right)^{\alpha}-1\right)}{\beta} \quad (6)$$

4.2.2. Instantaneous Pickup Overcurrent and Earth Fault

Pickup level is the minimum value of the current that can start the relay to close its contact. Equation 7 [21] can be used to calculate the pickup or tap level for instantaneous overcurrent and earth fault that represents the times factor of nominal current.

$$\text{Instantaneous Pickup} = \frac{\text{Pickup current}}{\text{Current Transformer ratio}} \quad (7)$$

The pickup current here is the fault current at the last bus of the end feeder and can get from equations 2 and 3, the current transformer ratio is 400/1 A at 22 kV feeder.

5. Numerical Analysis of the Case Study

5.1. Results from Calculating Overcurrent Fault

5.1.1. Overcurrent Fault Before 22 kV Feeder

When a three-phase overcurrent fault condition exists before the 22-kV feeder breaker as shown in Figure 6, only the positive sequence components exist and are represented by a balanced single-phase circuit, as shown in Figure 7.

Apply equation 2 to determine the fault current at first bus:

$$I_{3\emptyset} = I_{a1} = \frac{V_f}{(Z_T^{+1})} = \frac{1}{0.386} = 2.56$$

$$I_{rms,3\emptyset} = I_{a1} \times I_{a,base} = 6799\ A$$

Where:

$I_{3\emptyset}$ is the per unit three phase short circuit.

$I_{rms,3\emptyset}$ is the root mean square value for three phase short circuit.

I_{a1} is the positive sequence current for phase a.

$I_{a,base}$ is the base current and get from Table 2.

Z_T^{+1} is the positive sequence impedance for 66/22 kV substation transformer (25MVA).

V_f pre-fault voltage.

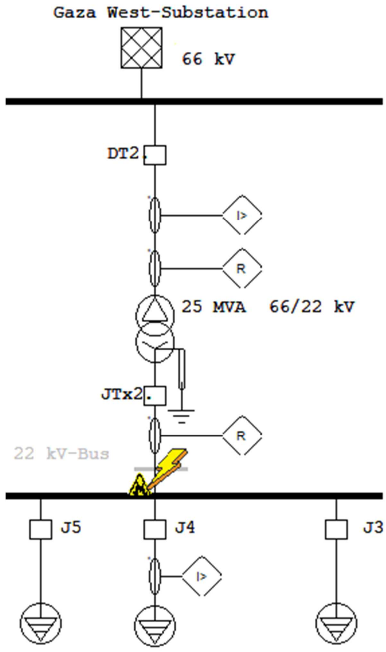

Figure 6. Symmetrical three phase fault at LV side of substation transformer.

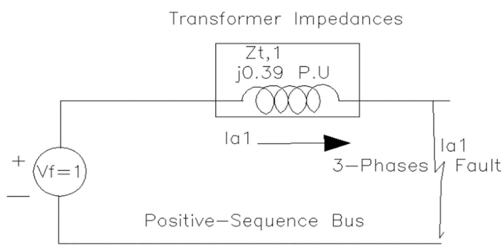

Figure 7. Symmetrical three phase fault at LV side of substation transformer.

5.1.2. Overcurrent at Last Bus in 22 kV Feeder

When there is a three-phase overcurrent fault condition at the last bus in the 22 kV feeder, the total impedance in Figure 8 includes both the overhead power lines and the substation power transformer 66/22 kV. The per unit three phase fault $I_{3\emptyset}$ at last bus is calculated by the pre-fault supply voltage and the total positive impedance $Z_{eq,T}^{+1}$. The total positive impedance includes the values of $Z_{p.u,trans}^{+1}$ and $Z_{p.u,cable}^{+1}$ from Tables 2, 3 and equals 1.726 p.u. To calculate the three-phase overcurrent fault, apply equation 2:

$$I_{3\emptyset,p.u}(\text{min. fault}) = \frac{1}{1.726} = 0.579$$

$$I_{rms,3\emptyset} = \text{Ibase} * Ip.u = 1520$$

$$minimum\ fault\ current = 1520\ A$$

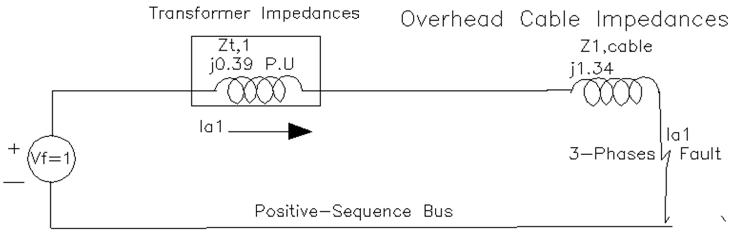

Figure 8. *Symmetrical three phase fault at farthest bus of J4 feeder.*

5.1.3. Calculate the Protective Parameter TMS

After calculating the fault current at last bus (1520A) and keep the start current 100% from nominal base current (400 A) as the existing setting. The protective parameter TMS for time overcurrent fault can be determined according to equation 6 with assuming a clearing fault time 350ms:

$$\text{TMS} = \frac{0.350\left(\left(\frac{1520}{400}\right)^{0.02} - 1\right)}{0.14} = 0.078$$

While the clearing fault time at 0.078 TMS is 180 ms at fault near to 22 kV feeder breaker.

5.1.4. Calculate the Protective Parameter Pickup Level

The pickup protective parameter can be determined from equation 5 based on the fault current value at the farthest bus feeder (1520A) and current transformer ratio 400/1 A at the 22 kV feeder breaker for instantaneous overcurrent faults.

$$\text{Pickup level} = \frac{1520}{400} = 3.8$$

5.2. Results from Calculating Earth Fault

5.2.1. Line to Ground Fault Before 22 kV Feeder

When a Line-to-ground fault situation exists prior to the 22-kV feeder breaker, all-sequence components present and the line-to-ground phase current at a faulty bus I_{fa} in per unit can be calculated by using Equations 3 or 4.

$$I_{fa} = 3\left[\frac{\frac{22\ KV}{\sqrt{3}}}{3*20 + 1.86 + 1.86 + .1.93}\right] = 580\ \text{A}$$

5.2.2. Line to Ground Fault at Las Bus in 22 kV Line

When a line-to-ground fault occurs at the last bus in the 22 kV feeder (see Figure 9), the total impedance in Figure 10 includes the grounding resistor as well as positive, negative, and zero sequence impedances for both the overhead power lines and the substation power transformer 66/22 kV.

Equation 4 can be used to calculate the per unit minimum fault current I_{fa}during line to ground fault on phase a at last bus of end overhead line:

$$I_{fa} = \frac{3*22000\ Volt}{\sqrt{3}\times(6.45+6.45+19.846+3x20)ohm}$$

$$= 410A$$

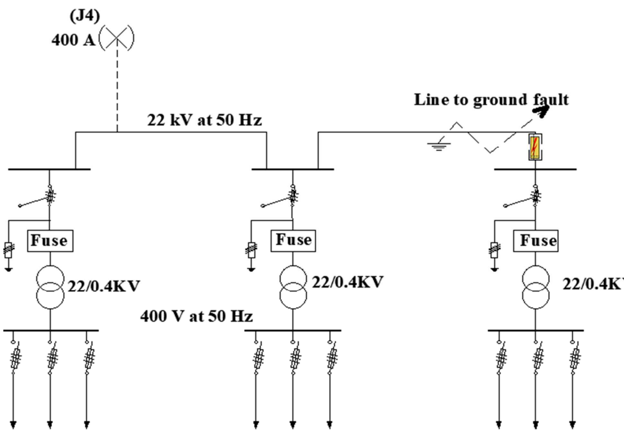

Figure 9. *Line To ground fault at the far bus of 22 kV feeders.*

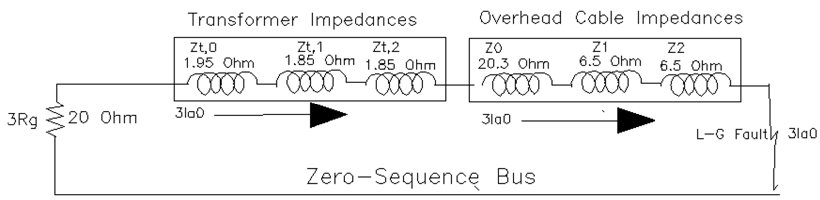

Figure 10. *Line to ground fault at end feeder.*

5.2.3. Calculate the Protective Parameter TMS

After calculating the fault current at last bus (410A), the protective parameter TMS for time earth fault can be determined from equation 6 with assuming clearing fault time 350ms and the same setting for start current 25%:

$$TMS = \frac{0.350\left(\left(\frac{410}{100}\right)^{0.02} - 1\right)}{0.14} = 0.075$$

5.2.4. Calculate the Protective Parameter Pickup Level

Calculate the pickup protective parameter from equation 5 based on the fault current value at the farthest bus feeder (410A) and current transformer ratio 400/1 A at the 22 kV feeder breaker for instantaneous overcurrent faults.

$$Pickup\ level = \frac{410}{400} = 1.025$$

Table 4 represents the protective parameters for the proposed and current settings for the overcurrent and earth fault protection functions.

Table 4. *The recommended settings for E/F and O/C at J4 feeder line.*

Function	Parameter	Current setting	Recommended setting
51 (O/C)	TMS	0.05	0.08
51G (E/F)	TMS	0.05	0.08
50 (O/C)	Pickup Level	3.75	3.8
50 (E/F)	Pickup Level	1.75	1.75

6. Verification and Simulation

The electrical transient analyzer program ETAP [22], an interactive power system analysis and design tool, is used to model and analyze the protective schemes after inserting the recommended settings in Table 4.

6.1. Overcurrent Fault Protection

Figure 11 shows the current protective relay settings in both the 66-kV transformer breaker and the 22-kV feeder breaker. The 66-kV upstream breaker overcurrent functions remain unchanged and only the time curve setting (TMS) for time overcurrent changed to 0.08 at 22 kV feeder breaker. Figure 12 shows the normalized TCC coordination devices from symmetrical three phase faults at the last bus of the overhead line. The instantaneous O/C 50 relay in 22kV feeder breaker detects the O/C fault before protective overcurrent relays in 66kV upstream breaker (successful coordination devices) without operation risks at lines or power components. The results show that the current faults are close to the calculated values when using symmetrical components, and the coordination devices between the 22kV feeder breaker and the 66kV upstream transformer breaker were successfully tested.

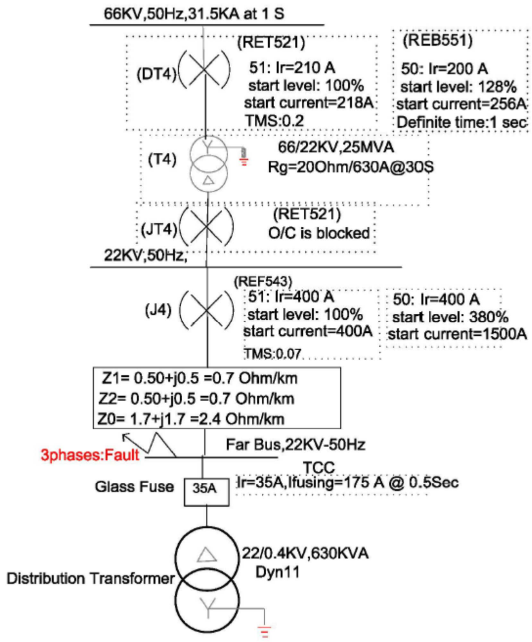

Figure 11. *The current settings for Protective overcurrent function.*

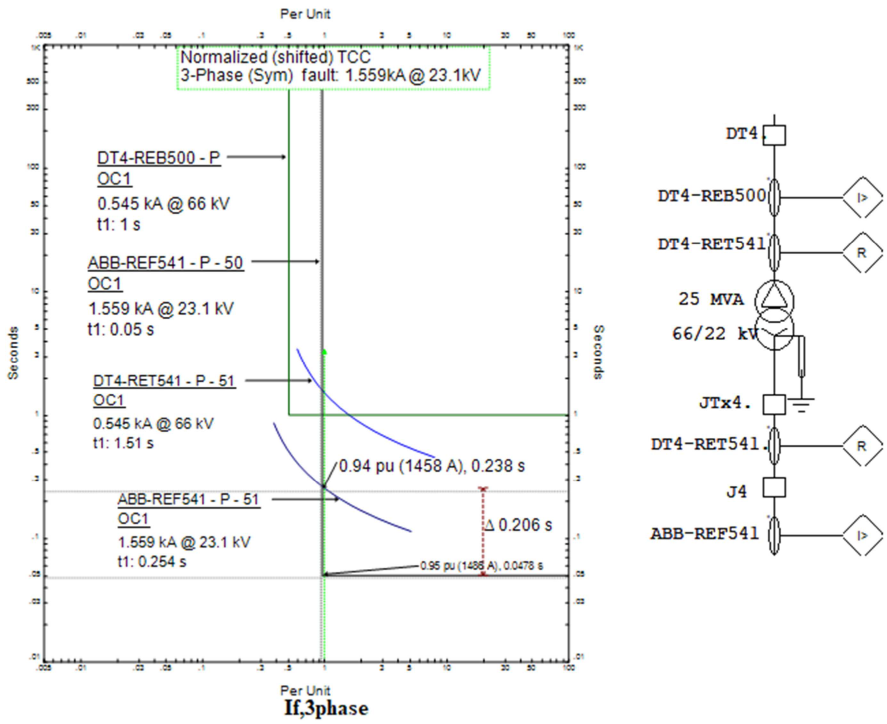

Figure 12. *Normalized TCC coordination devices from three phase faults.*

6.2. Line to Ground Fault Protection

Figure 12 shows that the earth fault function is blocked at the primary side of the step-down transformer 66/22 kV and that the earth fault function is activated at the secondary side of the step-down transformer breaker, which should be left alone. The only change at 22kV feeder breaker is the time curve setting (TMS) for time earth fault to be 0.08 rather than 0.05.

There are no miscoordination devices or overlapping in thermal curves after applying a line to ground fault at the farthest bus. Figure 14 shows the normalized TCC coordination devices from earth faults at the last bus, and the instantaneously E/F 50 relay in the 22kV feeder breaker detects and interrupts the E/F fault before interrupting the 22kV transformer breaker (successful coordination devices). The results show that the current faults are close to the calculated values when using symmetrical components, and the coordination devices between the 22kV feeder breaker and the 66kV upstream transformer breaker were successfully tested.

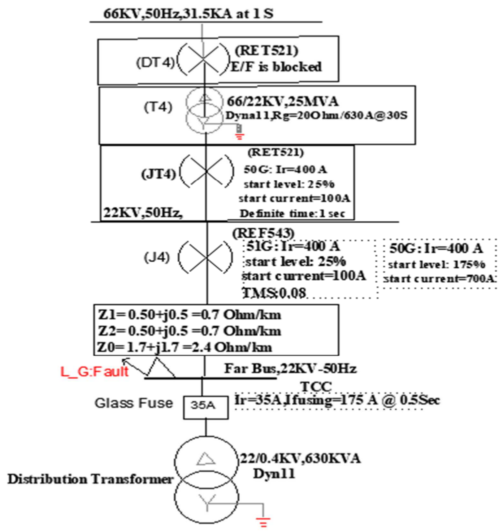

Figure 13. *The current settings for Protective earth fault function.*

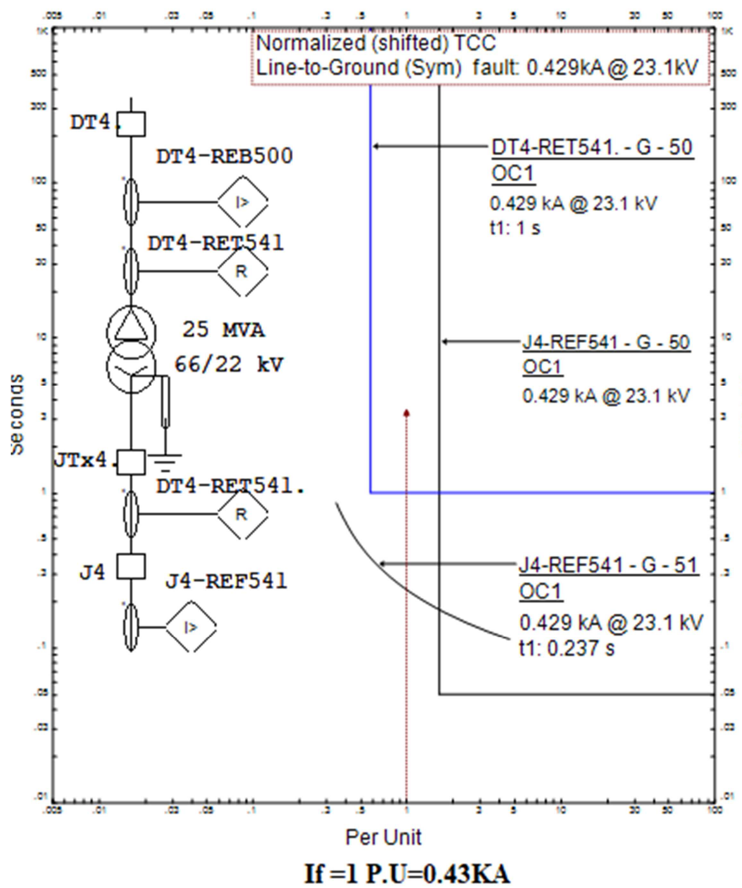

Figure 14. *Symmetrical line to ground at the far bus of 22 kV feeders.*

7. Conclusion & Recommendation

Most faults in overhead lines are either a symmetrical or unsymmetrical fault, and for these unbalanced short-circuit problems, the concept of symmetrical components is used for solution and guarantee by modelling the proposed design using the electrical transient analyzer program ETAP. The sequence components are used to determine the fault level at the end feeder and to calculate the protective settings for time overcurrent and earth fault functions using IEC 60255-151 and BS 142 standards. Fault clearance time for the feeders is as adopted by the distribution department and have flexibility in increasing this value up to certain extend but normally up to 350msec is fair enough. The study discovered that the current relay settings are satisfied for detecting and isolating electrical faults, and that the high rate of feeder trips is not caused by the current relay settings. The author believes that the high rate of feeder trips is primarily due to network topology and a lack of network upgrading. It is recommended slightly lowering the protection sensitivity by increasing TMS to 0.08 rather than 0.05 for time overcurrent and earth fault at a 22-kV feeder breaker and highly recommended to perform the following works:

1) Install automatic recloser circuit breaker at specific location without adding differential or distance relay, and the number of ACRs and the location of them varies from feeder to feeder. So, case to case analysis is done on ETAP to assess the correct location and coordination curve etc.
2) Install smart circuit breakers at both sides of DT 22/0.4 kV.
3) Install smart fault passage indicator FPI.
4) It is recommended to use ring topology rather than radial in long term plans.
5) Feeder load management is highly recommended.

Future work will conduct the same method over other 22 kV feeders and determine the optimal location for installing automatic recloser circuit breaker in the GAZA distribution network by modeling and simulating the feeder power lines.

Nomenclature

DFR: Data Fault Recorder
IED: Intelligent Electronic Device
DT: Distribution Transformer
FPI: Fault passage indicators
ECC: Egyptian Channel Company
IEC: Israeli Electricity Company
ACSR: Aluminum Conductor-Steel Reinforced
HRC: High Rupturing Capacity fuse
TMS: Time Multiplier Setting
O/C: Overcurrent
E/F: Earth fault
ETAP: Electrical Transient and Analysis Program
GPGC: Gaza Power Generating Company
NOC3inst: Instantaneously Non directional overcurrent
NOC3LOW: Non directional time overcurrent
NEF3inst: Instantaneously Non directional Earth fault
NEF3Low: Non directional time earth fault
ACR: Automatic Recloser Circuit Breaker

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