Analysis of a Practical Study for Under-Ground Cable Faults Causes

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***Abstract*—The underground cables are widely used for the transmission and distribution of the electrical energy over a wide range of voltages due to their merits. On the other hand, there are limitations for using the underground cables because the fault location is very difficult and consuming long time to be detected. In order to achieve a reliable operation of the electrical network and minimize the rate of the cable faults, accurate and effective fault causes analysis has to be carried out as we aim to prevent faults from happening rather than to restore the system after fault occurrence. This paper discussed the different underground cable faults and their causes through the analysis of a practical statistical study carried out for Dokky underground cable distribution networks in the Egyptian ministry of electricity to show the rate of occurrence of the different cable fault types during the previous twelve years, a practical study results were statistically analyzed and correlated to the cable faults causes analysis. It is noted that the underground cable faults are mainly due to cable insulation failure or joint insulation failure as a direct result of different partial discharge forms inside the cable or the joint.**

***Keywords*— Cables faults, cable fault causes**

I. Introduction

Since the first cable installations by Thomas Edison's in the 1870s in New York city[1], the underground cables become the best choice for the electrical energy transmission, distribution and utilization, due to rugged construction, greater service reliability, increased safety, better appearance, it is not affected by the climatic conditions (storm, ice, tree or lightning), it require lesser right of-way, it is also more suitable for areas where it is impractical to use overhead lines (transmission lines through sea – air field crossing). Therefor the underground cables increasingly replaced the overhead lines especially inside towns and near densely populated areas up to 500 kV [2]. On the other hand, the cost of installation of underground cable is nearly about from 10 to 15 times that cost of overhead transmission line for the same voltage, moreover the cable fault location and repairing is very difficult and has a long time-consuming process; where it takes 3–5 times longer than that time required for an overhead line [3]. All these factors represent limitations for the use of the underground cables and require great effort from researchers to overcome these limitations. In this paper, firstly a practical statistical study is conducted to Dokky underground cable distribution networks in the Egyptian ministry of electricity to conclude a real indication of the rate of occurrence of each cable fault type over the year for ten years from 2009 to 2020 with practical analysis of the causes and mechanism of each fault, accordingly the most suitable and the right precaution is introduced to avoid fault repeating in the future and to prevent faults from happening rather than to restore the system after fault occurrence.

A practical study of the underground cables different fault location techniques is carried out on practical feeders on Dokky underground cable distribution networks in the Egyptian ministry of electricity to conclude the suitable technique for each fault case to facilitate the fault location process and save the time. The aim of all these efforts is to create a reliable and stable power system capable of delivering a high-quality service to the consumer with minimum electricity cut off times and have economic benefits for the power utility companies.

II. Classification of Underground Cables Faults and Their Causes for Case Study

The experience in the operation of electrical networks has shown that the underground cable faults may have several forms; accordingly, it can be classified into

A. Cable Faults due to Cable Insulation Failure

This type is a commonly occurred and it is due to the insulation breakdown between phases to earth or between phase to phase, this breakdown may be due to different causes which summarized into:

- Insulation defects during cable manufacturing: The defects may be due to existence of air voids or impurities inside the insulating material, unsymmetrical insulation layer thickness or unsymmetrical semi-conducting material layer thickness. This resulting in a non-uniform electric field distribution inside or at the insulation surface, creating high stressed points leading to partial discharge (PD) activity, creating channels of carbonization with branch-like structure resembling a tree. Once an electrical tree grows big enough and bridges the electrodes of the cable system, the cable insulation will break [4] as shown in (Fig.1).
- Conductor defects during cable manufacturing: The cable conductor may have a bad welding during its manufacturing process which leading to a bad contact resulting arcing and raising the temperature at the

connection point resulting in insulation thermal aging leading to a total breakdown [5].

Fig.1: The cable insulation breakdown by the treeing process due to existence of air voids or impurities inside the insulating material.

- Insulation deterioration due to cable bad storing: The direct exposure to the sun rays for long periods causes cable insulation deterioration and destroys the outer jacket of the cable which allows the penetrating of the water and acids from the soil into the cable insulation after bedding. The existence of electrical stresses inside the cable forms water, trees, which can help to initiate an electrical tree, causing the insulation deterioration leading to insulation breakdown [6-9].
- Insulation failure due to mechanical stress: Cable insulation may suffer from mechanical deformation as a result of high mechanical stress during the cable loading, transportation, bedding with unsuitable instruments or bedding at a small depth with insufficient sand layers under and above the cable and without any mechanical protection above it.
- Insulation deterioration due to its exposure to high concentrations of acids or alkalis of the soil as it is passing beside petrochemicals factory... etc. Also, it may deteriorate due to thermal breakdown as a result of exposure to very high temperatures from external source (oven... etc.) [5].
- Insulation deterioration due to cable aging: The underground cable's lifetime is estimated to be from 40 to 70 years [10] and as most of oil impregnated paper insulated cables in DOKKY medium voltage underground cable distribution networks in the Egyptian ministry of electricity are installed since more than 40 years, they are suffering from natural aging phenomena which take the form of cracks in the outer lead sheath of the cable leading to facilitate the penetration of soil contents and moisture to the internal components of the cable, creating water, trees causing insulation deterioration which will lead to breakdown [11]. The cable aging will also cause the cable's outer mechanical protection erosion so the cable will easily be damaged by any digging process beside it leads to insulation failure as shown in (Fig.2).

B. *Cable Faults due to its Joint or Termination Failure*

Joints and terminations are a fundamental part of cables, which are expected to perform all functions of the cable on which they are installed; the joint and the termination faults are mainly due to bad workship which lead to partial discharge at the interface between the different layers of the joint. Practically, this PD causes a current flow in the outer sheath of cable which causes insulation deterioration inside the joint, leading to a total insulation breakdown between the cable cores or between the core and the earth [12].

On the other hand, in case of termination fault the partial discharge may be occurred on the outer surface of the solid insulation and is called surface discharges causing the well-known surface tracking [13]. The surface tracking is a result of the partial discharge activities at the irregular sharp needle-like point edges which having very strong electric field values sufficient to ionize the surrounding air and converting it to a conductive, moreover the existence of contamination and moisture may lead to a leakage path to ground and over the time, a partially conducting carbonized electrical trees will be formed which causes a greater stress on the remaining insulation, which leading to further growth of the damaged region and resistive heating along the tree [14, 15]. Finally, it will cause a complete insulation breakdown with electrical explosion. (Fig.3) shows cable termination insulation failure due to electrical surface tracking

Fig.2: Oil impregnated paper cable insulation breakdown due to aging and existence of old digging process beside it.

Fig.3: Cable termination insulation failure due to electrical surface tracking [16].

During the installation of cable joints and terminations, the bad workship may have different causes which can be summarized as follows:

- Using unsuitable joint for the cable e.g. using 18/30 kV joint for 12/20 cable and vice versa.
- Using inaccurate installation dimensions as mentioned in manufacture's recommendations.
- Using unsuitable tools for cable preparing will result in un-symmetrical and non-smooth cable insulation surface with sharp edges, causing high stressed points inside the joint or the termination and leading to the appearance of the partial discharge activities causing total breakdown after a short time. (Fig.4) shows Knife cut into the insulation surface caused using an unguarded knife to remove the outer semiconductor layer.
- Mal setting and/or misuse of screen removal tool will result in removing a thick layer of the insulation during the removal of the semiconductor layer, decreasing the cable insulation at this point and creating rough insulation surface as shown in (Fig.5). Moreover, if the removal of semi conductive layer is not done accurately, a screen edge having projections or filaments will be created as shown in (Fig.6). In addition, if the removal of conductive screen material is not completed and part of it is still found as shown in (Fig.7), it will lead to the occurrence of partial discharges inside the joint, which causing joint failure. (Fig.8) shows the immediate failure due to not removing insulation screen totally during installation.

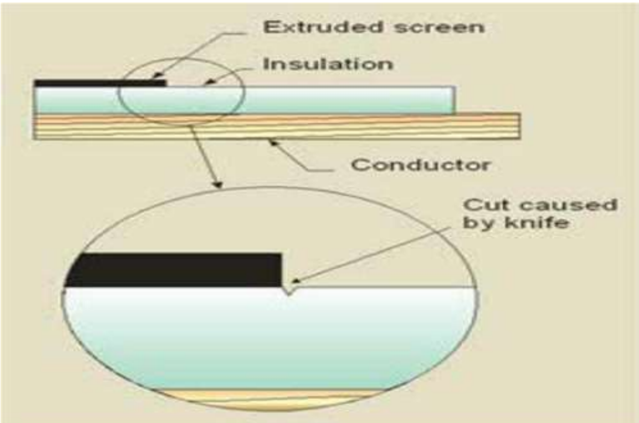

Fig.4: Knife cut into the insulation surface caused by use of an unguarded knife [16].

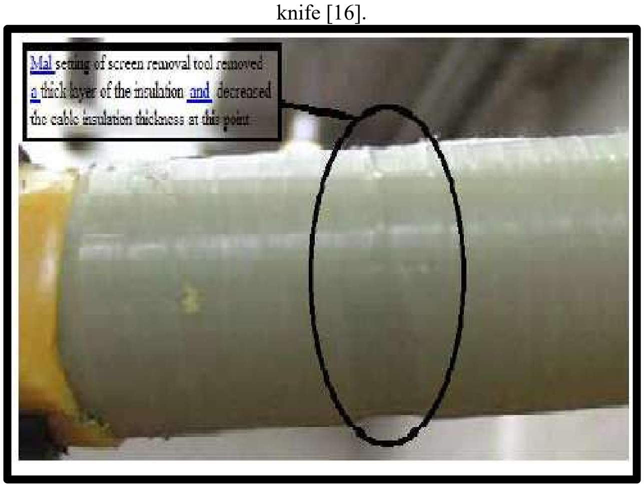

Fig.5: Extremely rough insulation surface resulting from incorrect setting and/or misuse of screen removal tool [16].

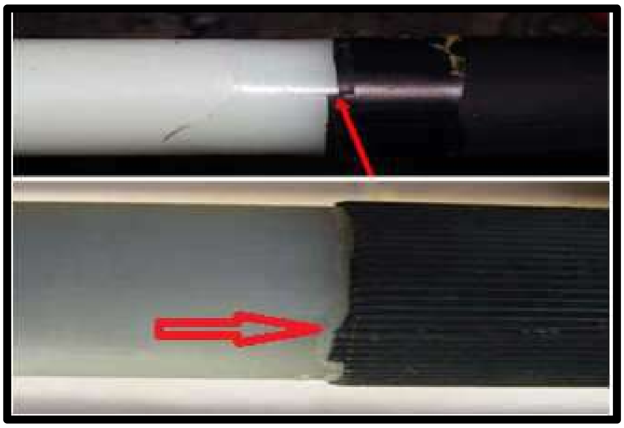

Fig.6: Screen edge having projections or filaments [16].

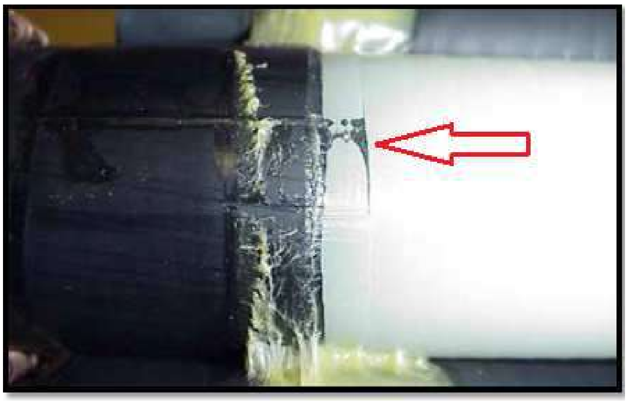

Fig.7: Incomplete removal of conductive screen material from insulation surface [16].

Fig.8: Immediate failure due to insulation screen not being removed during installation [16].

- Bad crimping of the joint splice connector or termination lugs leading to the bad conductivity of this part, which cause resistive heating of this region causing insulation failure.
- Cutting of the stress control tube leads to unsymmetrical electric field distribution inside the joint.
- Non-use of the mastic tape sealing for water protection, this will permit the water leakage into the joint.
- Bad restoring of metallic screen by welding, this leads to a bad screen shielding to electric field.
- Non-use of the joint armour in armoured cables as a result the joint insulation may suffer from mechanical deformation due to high mechanical stress.
- Joint installation on unsuitable location (garage entrance – trough the road – beside water source -....) as shown in (Fig.9).

Fig.9: The joint installation beside permanent water source [16].

- Non-use of the sheds in case of outdoor termination, this leads to surface partial discharge in case of moisture or fog conditions.
- Sometimes the panel may have moisture, which condensate on the outer surface of the termination causing surface tracking leading to insulation failure with time, in case of oil impregnated paper cable the termination is filled with oil which may absorb the moisture from the surrounding medium inside the panel causing a repeated partial discharge within the oil, as a result the oil's chemical properties will be changed and a conducting carbonized electrical tree will be formed resulting in a total breakdown with great explosion after a period of time. The explosion may also occur due to oil dryness from the cable termination. (Fig.10) shows the expulsion of oil impregnated paper, oil filled termination.

C. Cable Faults due to Mechanical Insulation Failure

The cable may be suddenly exposed to high mechanical stress by mechanical instrument which causes insulation failure. (Fig.11) shows the cable insulation failure by mechanical compressor digging instrument.

D. Cable Faults due to Destroyed Lugs

Cable lugs may totally disconnect or cut off due to short circuit between two or three phases or phase to ground, due to passage of snake on these lugs or due to using inefficient lugs to the cable conductor size, type or not correctly crimped, resulting in an open circuit fault. (Fig.12) shows the destruction of the cable termination lugs.

Fig.10: The expulsion of oil impregnated paper oil filled termination.

Fig.11: The cable mechanical fault by mechanical digging instrument.

Fig12: The destruction of the termination lugs.

Sometimes due to bad workship the edge of the insulation end point is left sharp, if the termination lug is not installed according to the dimensions (i.e. the length of the bare cable conductor > the lug length) there will be a small air filled the gap between the lug end and the insulation end point,

The electric field will be very high in this region causing P.D with arcing specially with moisture existence, increasing the temperature in this region and cause punching of the conductor in this region, finally leading to the lugs to be destroyed by explosion.

E. Cable Faults due to Disconnected Joint Fault

This fault is an open circuit fault in which one or more cores of the cable are totally disconnected from the other terminal of the same phase at the joint point causing disconnecting of electrical power. It may be due to cable disconnection by mechanical instruments, or due to splices connector thermal destruction because of excessive fault current, cable overloading, bad connector cramping or due to PD arcing inside the joint.

F. Cable Faults due to Other Causes

Moreover, cable faults may be occurred due to additional external causes resulting in the de-energization of the cable such as explosion of low voltage cable routed adjacent to the medium voltage cable or cable stealing

III. DESCRIPTION OF PRACTICAL CASE STUDY

A statistical study is conducted on DOKKI 11 kV medium voltage electrical distribution networks as it is one of the oldest electrical networks in Egypt, it has about 1253 km of underground cables representing different types of cables (oil-impregnated paper and XLPE cables) with different cross section area (3*150 mm^2, 3*240 mm^2, 3*300 mm^2, 3*400 mm^2, 3*500 mm^2 and 1*400 mm^2). These cables have been operating since 1950. The actual cable faults occurred in DOKKI 11 kV medium voltage electrical distribution networks from 2009 to 2020 are statistically analyzed to show the frequency of occurrence of each fault every year and the percentage ratio of each fault on the year and correlated these ratios to the actual causes of cable faults to explain and analysis these faults ratios.

IV. STATISTICAL STUDY RESULTS, ANALYSIS AND DISCUSSIONS

Table (1) shows the frequency of occurrence of each fault every year and the total number (NO.) of cable faults occurred per year in addition to the percentage ratio of each fault to the total faults on the year from 2009 to 2020.
The study results are statistically represented as shown in Figures below from (Fig. 13) to (Fig. 24). (Fig.13), (Fig. 14) and (Fig.15) show that in 2009, 2010 and 2011 the faults of the cable due to insulation breakdown have the highest ratio due to cable aging, as most of the cables in Dokky underground cable distribution networks in the Egyptian ministry of electricity in this period was of oil impregnated paper insulated type with a large portion of this cable system infrastructure has reached the end of its lifetime, consequently the end of its reliable service life. It is also noted that the fault due to joint insulation breakdown has a very high ratio due to two causes, one of them is the bad workship which results in very high partial discharge rate inside the joint which decrease the joint lifetime and the other is due to aging effects.
(Fig.16), (Fig.17), (Fig.18) and (Fig.19) show a decrease in the ratio of the cable faults due to insulation breakdown as the DOKKY underground cable distribution networks started a plan to replace the oil impregnated paper insulated type cables with XLPE insulated type cables , on the other hand the ratio of insulation failure due to mechanical causes increased as a direct result of digging process for the old cable replacement and due to new cable bedding process, it is also noted that the joint insulation failure ratio increased as a result of natural aging phenomena effect and due to bad workship which result in very high partial discharge rate inside the joint which will decrease the joint life time.

(Fig.20), (Fig.21) and (Fig.22) show noticeable increases in the mechanical fault causes due to digging processes with mechanical instruments for the cable route modifications required for the metro tunnels foundation, reached maximum value in 2018 with the foundation of MORAD tunnel in Giza Street as shown in (Fig. 22). On the other hand, the ratio of the cable insulation and the joint insulation failure still high because of the natural aging phenomena effect and due to joint bad workship.

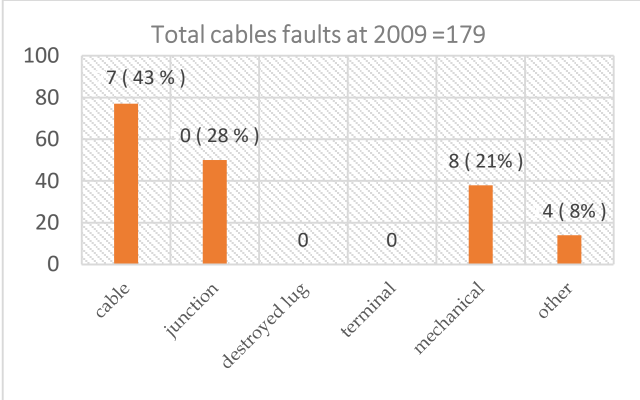

Fig.13: NO. and percentage of fault occurrence to the total fault in 2009.

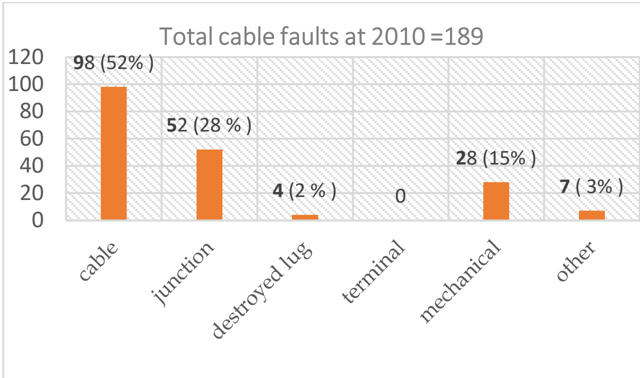

Fig.14: NO. and percentage of fault occurrence to the total fault in 2010.

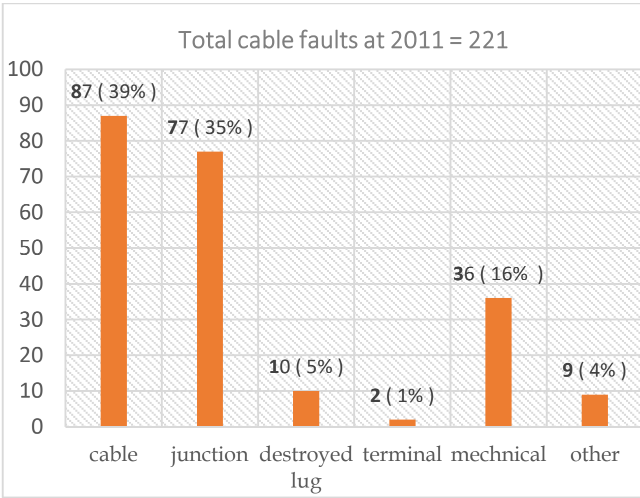

Fig.15: NO. and percentage of fault occurrence to the total fault in 2011.

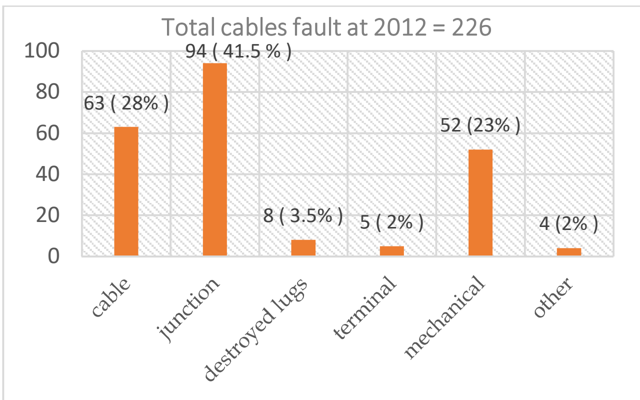

Fig.16: NO. and percentage of fault occurrence to the total fault in 2012.

TABLE 1
THE FREQUENCY OF OCCURRENCE OF EACH FAULT EVERY YEAR AND THE PERCENTAGE RATIO OF EACH FAULT TO THE TOTAL FAULTS PER YEAR FROM 2009 TO 2020.

Total Number of Cable Faults per Year per Type From 2009 to 2020 in DOKKY Electricity Distribution Network

Fault Causes	Cable insulation		joint insulation		Mechanical		Terminal		Destroyed lugs		Others		Total
Year	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.
2009	77	43 %	50	28 %	38	21 %	0	0 %	0	0 %	14	8 %	179
2010	98	52 %	52	28%	28	15%	0	0%	4	2%	7	3%	189
2011	87	39 %	77	35%	36	16%	2	1%	10	5%	9	4%	221
2012	63	28 %	94	41.5%	52	23%	5	2%	8	3.5%	4	2%	226
2013	54	26 %	78	37%	48	23%	0	0%	8	4%	22	10%	210
2014	49	26 %	64	33.5%	55	28.5%	2	1%	13	7%	8	4%	191
2015	44	23 %	60	31%	51	26.5%	13	6.5%	12	6.5%	12	6.5%	192
2016	39	17.5 %	75	34%	70	31.5%	15	7%	10	4.5%	12	5.5%	221
2017	60	29%	77	37%	43	21%	9	4.5%	1	.5%	16	8%	206
2018	82	27 %	64	21 %	99	33 %	22	7.5 %	16	5.5 %	18	6 %	301
2019	52	30.75 %	76	23.5 %	58	14.6 %	36	4.85 %	12	5.3 %	13	21 %	247
2020	45	22 %	85	44.5 %	173	10.5 %	41	3.3 %	13	8.2 %	32	11.5 %	389

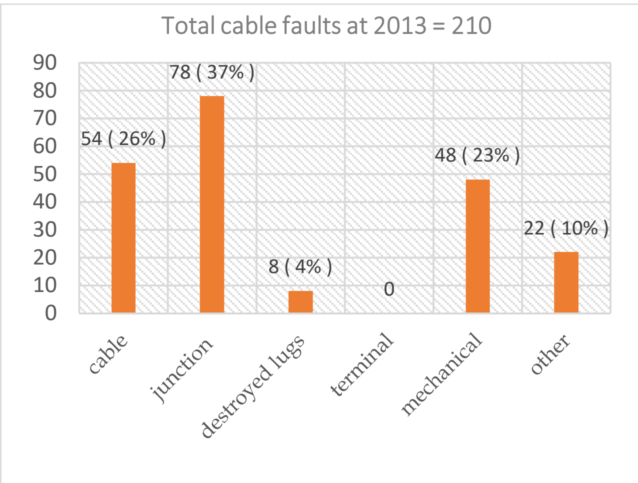

Fig.17: NO. and percentage of fault occurrence to the total fault in 2013.

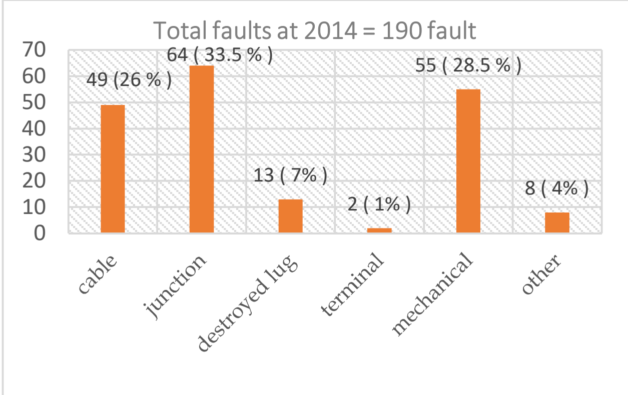

Fig.18: NO. and percentage of fault occurrence to the total fault in 2014.

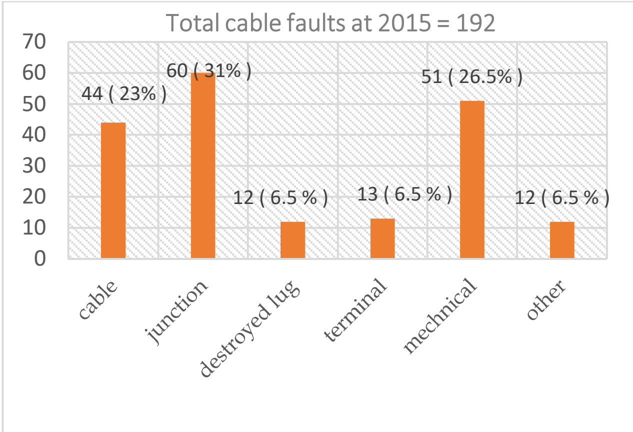

Fig.19: NO. and percentage of fault occurrence to the total fault in 2015.

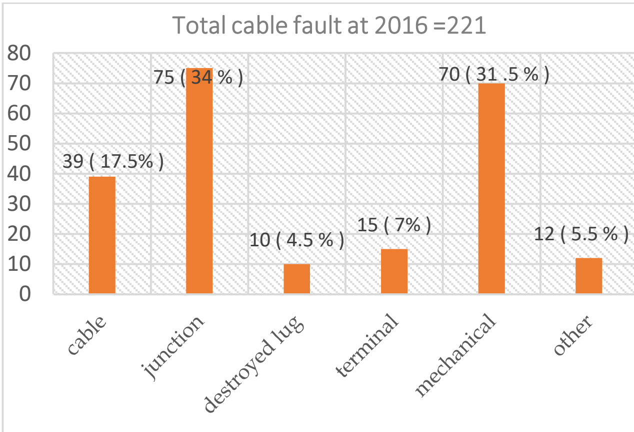

Fig.20: NO. and percentage of fault occurrence to the total fault in 2016.

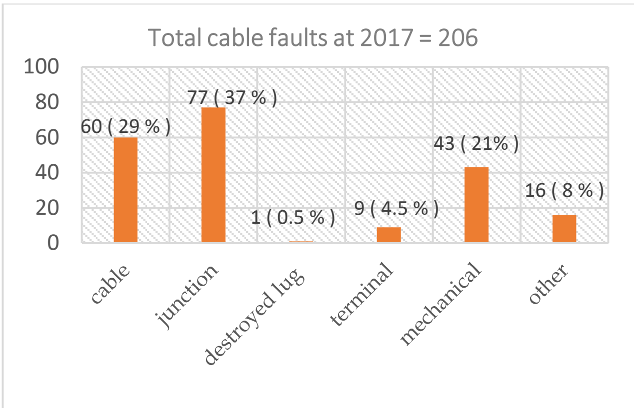

Fig.21: NO. and percentage of fault occurrence to the total fault in 2017.

(Fig.23) and (Fig.24) show a noticeable increase in cable insulation and the joint insulation failure ratio as a result of the natural aging phenomena effect and due to repairing the oil impregnated paper cables with the transition joint instead of the oil filled joint, as the manufacturing stop producing the oil impregnated paper cables and its accessories since 2016, the transition joint insulation failure occurs as a result of the oil impregnated paper dryness at the joint point. It is also noticed that the mechanical fault ratio increased as a direct result of digging with mechanical instruments for the metro tunnels foundation, reached maximum value in 2020 with the foundation of EL-ZOMAR canal axis.

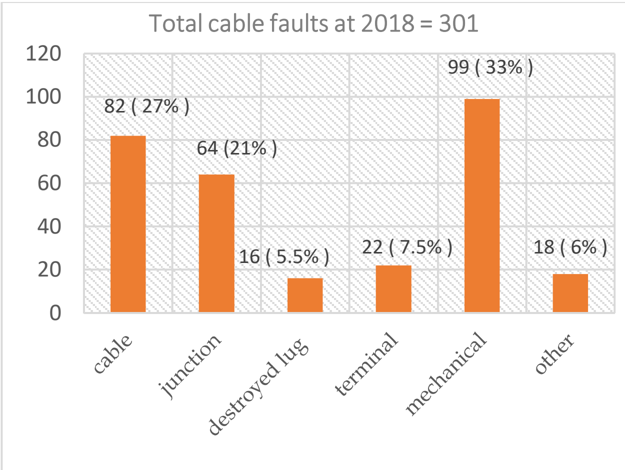

Fig.22: NO. and percentage of fault occurrence to the total fault in 2018.

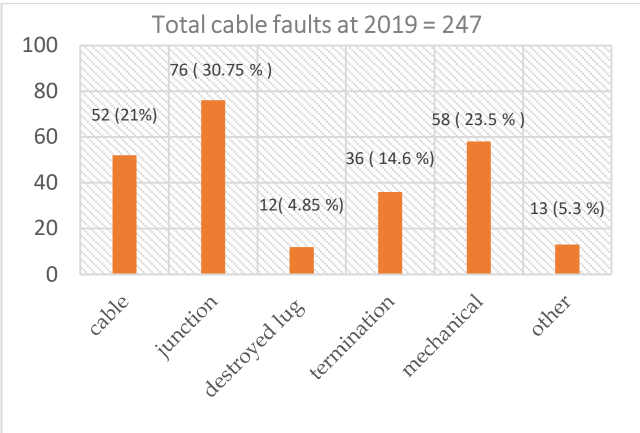

Fig.23: NO. and percentage of fault occurrence to the total fault in 2019.

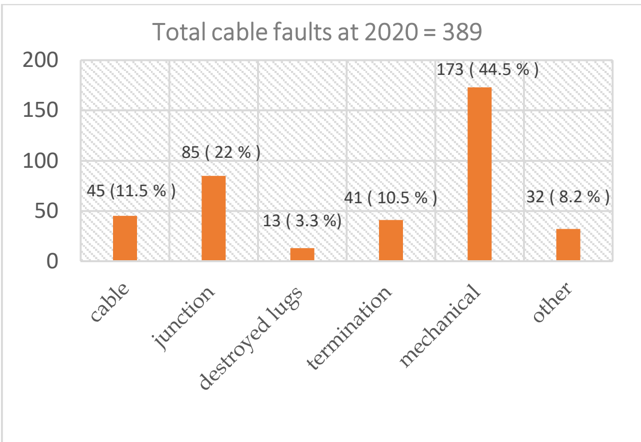

Fig.24: NO. and percentage of fault occurrence to the total fault in 2020.

V. Conclusion and Recommendations

The partial discharges are the most important causes for the underground cable faults; they are having different causes and take place in different positions along the cable and inside the different components of the network (cable, joint, terminal, etc...). From the practical statistical study conducted on DOKKI 11 kV medium voltage electrical distribution networks - as one of the oldest electrical networks in Egypt. It is concluded that:

- Underground cables faults are mainly occurred due to cable or joint insulation failure as a direct result of different partial discharge forms inside the cable or the joint.
- The joint insulation failure ratio increased as a result of natural aging phenomena effect and due to bad workship which result in very high partial discharge rate inside the joint which will decrease the joint lifetime.
- For last Years, the mechanical fault ratio increased as a direct result of digging with mechanical instruments for the metro tunnels foundation, reached maximum value in 2020 with the foundation of EL-ZOMAR canal axis.

Therefore, the underground fault causes stated in this paper should be taken into consideration when constructing or manufacturing of underground cable networks to avoid cable faults which result in un-planned electricity shutdown.

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