Influence of Fault Locations on the Pipeline Induced Voltages Near to Power Transmission Lines

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***Abstract*— In this paper, the simulation induced voltages along the buried pipeline due to normal operating condition as well as symmetric and un-symmetric fault conditions of the power transmission lines are calculated. By using the ATP program and MATLAB software, to simulate the power line–pipeline system under all fault conditions, the simulation results of induced voltages are obtained then compared with the actual measurement values. Moreover, the influence of fault locations, either in the first quarter or in the middle place of the power line, on the pipeline induced voltages is studied. Furthermore, the variation of soil resistivity on the pipeline induced voltages under normal and fault conditions is analyzed. It is found that El-Kurimate power line is the most effective power line on the pipeline at normal operating condition. Also, it is seen that a good agreement between the experimental and simulation results of induced voltages, under normal condition, is achieved. Moreover, the simulation results show that the most serious type of abnormal conditions on the pipeline itself and its coating is the single line to ground fault when it occurs at the first quarter of the transmission line. Finally, it is concluded that soil resistivity variation has a great effect on the pipeline induced voltage under fault conditions.**

Keywords— Electromagnetic Interference, Fault location, Induced voltage, Inductive coupling, Pipelines.

I. INTRODUCTION

Nowadays, pipelines sharing the same right of way with high voltage transmission line (HVTL) produce a huge values of induced voltages along the pipelines that attract the attention of many researchers to mitigate it. Where, the HVTL passes through crowded places, HVTL forces any metallic objects, like a gas pipeline, to join the same corridors either parallel or partially parallel proximity [1]. This is because of the reduction in economic costs and the limited free space area. This sharing causes an induced voltage over the metallic pipelines by means of electromagnetic fields, which consisting of three types of couplings; capacitive, inductive and conductive coupling [2, 3]. Due to this interference, many problems can be appeared such as danger for people who may make a contact with the pipeline or any exposed part of it, such as its valve, coating…etc. In addition, the possibility of damage to the pipeline coating, insulating flanges or rectifiers is much higher and the corrosion of the metal is rapidly happen [4]. Beside that, the induced AC voltage should be near or greater than a standard limit rms value (15 V) that may cause an electric shock to this person [3]. Also, the pipeline coating can be damaged by the inductive or conductive coupling, rather than the capacitive one, because its effect can be eliminated under a certain depth. Moreover, under abnormal operating conditions, the pipelines metal and the cathodic protection systems may be damaged [5]. The capacitive coupling is due to the electrostatic field, whereas this influence can be neglected for buried pipelines. While, the inductive coupling occurs due to magnetic fields [6-8]. Whereas, the conductive coupling appears when any abnormal conditions such as; symmetric and un-symmetric faults, lightning or switching occur near the HVTL. From the previous literature on the electromagnetic interference between power lines and pipelines, the topic of fault locations effect on pipeline induced voltages is rarely discussed. Abdel-Gawad et al. simulate the different abnormal conditions include symmetric fault, un-symmetric faults, direct and indirect stroke on the HVTL using the alternative transient program (ATP) [9]. In addition, the induced voltages under the previous conditions is calculated using the nodal network analysis by the same research group, where the highest values of the pipeline induced voltage along the length of the pipeline are obtained; firstly under double phase to ground fault, then single phase to ground fault, then under phase to phase fault, and finally under three-phase to ground fault, which has the least induced voltage due to its symmetric waveform [10]. X. Wu et al. suggest an analytical approach for calculating the transient induced voltages and currents on the pipeline due to the inductive coupling, where the transient induced voltage along the pipeline can be much greater than the steady state fault values [11]. With respect to corrosion, F. Babaghayou et al. investigate an experimental and numerical model for the electrochemical reactions involved in the corrosion, also simulate the cathodic protection and the deformation happen in the steel of pipeline, thus there is a good agreement between the different methods that can mitigate the corrosion automatically [12]. Otherwise, B. Hu et al. calculate the corrosion distribution using the transient electromagnetic method that improve the accuracy of calculation, then the field test was done by the addition of a Mn-Zn ferrite core that improve the measurement results [13]. Kamar et al. determine the location of coating defects along the Jordanian gas pipeline, and also the numbering of polarization cells and its allocations to mitigate the induced voltages and currents along the pipeline [14]. Regarding to soil resistivity, Abdel-Gawad et al. concluded that the pipeline induced voltages

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under normal conditions are directly proportional to the soil resistivity of the earth layer, where the pipeline is buried in it [15]. Although many researchers dealt with pipeline induced voltage under fault conditions, a few has dealt with the effect of fault locations on the pipeline induced voltages.

In this study the effect of fault locations, either in the first quarter (at point 14 km) or in the middle place of the power line (at point 34 km), on pipeline induced voltage under single line to ground fault, double line to ground fault, double line fault, and three line to ground fault is studied on actual pipeline (El-Fayoum gas pipeline that transmit gas between El-Fayoum and Dahshour cities, Egypt) [16], then compared with the actual measurements in [10]. Furthermore, ATP software with Line/Cable Constants (LCC) module with the help of MATLAB (m. file) are used to simulate the tower configuration, pipeline location, fault locations, soil resistivity variations and to calculate the pipeline induced voltages during normal and abnormal operating conditions [17].

II. SYSTEM DESCRIPTION

In this study, El-Fayoum gas pipeline is adjacent to three HVTLs; El-Kurimate (500 kV), Samaloute (500 kV) and 6th October (220 kV) for a longitude distance about 72 km with a different separation distances from each transmission line. Full data details about the tree power lines can be found in appendix A in reference [16]. The pipeline is buried at depth of 1.5 m with soil resistivity varying from 100 to 2500 Ω.m, as shown in Figure 1.

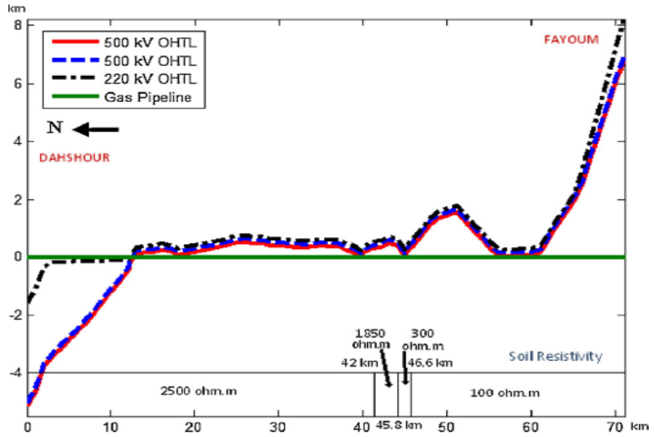

Fig. 1. Pathway and separation distances of El-Fayoum pipeline and the three HVTLs [16]

III. CALCULATION OF INDUCED VOLTAGES ON PIPELINE

The pipeline induced voltages due to capacitive, inductive and conductive couplings can be calculated as follows:

3.1 Mathematical equations

3.1.1 Capacitive coupling between HVTL and pipeline:

This form of capacitive interference operates across the capacitance between the power lines and the pipeline in series with the capacitance between the pipeline and adjacent ground [3]. During the simulation run, the factors affecting pipeline induced voltage and electric field due to capacitive coupling are taken into consideration. The typical method of calculating induced voltage due to electric field induction is applied by using potential coefficients as described in equation (1) [18]:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_p \end{bmatrix} = \begin{bmatrix} p_{aa} & p_{ab} & p_{ac} & p_{ap} \\ p_{ba} & p_{bb} & p_{bc} & p_{bp} \\ p_{ca} & p_{cb} & p_{cc} & p_{cp} \\ p_{pa} & p_{pb} & p_{pc} & p_{pp} \end{bmatrix} \begin{bmatrix} Q_a \\ Q_b \\ Q_c \\ Q_p \end{bmatrix} \quad (1)$$

Where, V_a, V_b, V_c and V_p are the phases and pipeline voltages respectively, P_{ii} is self-potential coefficient of a conductor, P_{ij} is potential coefficient between any two conductors and Q_a, Q_b, Q_c and Q_p are the charges per unit length on phases a, b, c and pipeline respectively [18]. Thus, the pipeline induced voltage due to capacitive coupling will be calculated by equation (2):

$$V_p = \left(-\frac{1}{C_{pp}}\right)\left(C_{pa}V_a + C_{pb}V_b + C_{pc}V_c\right) \quad (2)$$

From equations (1) and (2), it can be easy to calculate the capacitive induced voltages on the exposed pipeline, although it is buried beneath earth's surface such a potential will not normally induced as the capacitance between the pipeline and ground is negligible.

3.1.2 Inductive coupling between HVTL and pipeline:

When the current flow in a conductor, a time varying magnetic field around this conductor was producing, then AC voltage will be induced on any nearby metal structure. During simulation, the factors affecting magnitude of pipeline induced voltage due to inductive coupling are taken into consideration. Thus, the pipeline induced voltage due to inductive coupling can be calculated by the " Nodal network analysis " method, where the induced voltage is calculated with the help of the longitudinal driving electric field $\boldsymbol{E_Z}$, which calculated along the pipeline length as a contribution of each phase current and the currents of the ground wires as described in details in [19]:

$$E_z = I_{ph\_a}\, Z'_{ph\_pipe\_a} + I_{ph\_b}\, Z'_{ph\_pipe\_b} + I_{ph\_c}\, Z'_{ph\_pipe\_c} + \Sigma\, I.Z \quad (3)$$

Where; I_{ph} is the current of each phases a, b and c; Z'_{ph} is the mutual impedance between each phases a, b and c of the power line and the pipeline including the effect of ground wires and $\Sigma\, I.Z$ is the effect of ground wires.

The inductive induced voltage at any distance x along the pipeline length can be calculated as follows [10]:

$$V(x) = \frac{E_z}{\gamma}\left(\frac{-Z_1}{Z_1 + Z_0}\, e^{-\gamma x} + \frac{Z_2}{Z_1 + Z_0}\, e^{-\gamma(x - L_p)}\right) \quad (4)$$

3.1.3 Conductive coupling between HVTL and pipeline:

Electrical conductance occurs in case of direct contact between an energized AC conductor and a metallic pipeline or ground fault conditions. When an earth fault occurs, the current flowing through earthing system to earth will increase the potential of the earthing system and the ground potential will be very high. This potential rise will affect any metallic structures, e.g. pipelines, located in the ground potential rising zone. Pipeline coating may be damaged if it is subjected to a ground potential that exceeds its coating dielectric strength[5]. The conductive voltage at any point x along the pipeline length can be calculated as mentioned in equation (5). Hence, more details about the methodology of calculation can be found in [10].

$$v_x = v_g \frac{r_e}{x_l + r_e} \quad (5)$$

Where, v_x is the induced voltage at distance x in volts, v_g is the earth potential rise in volts, r_e is the radius of an equivalent hemispherical earth electrode in meters and x_l is the distance between edge of ground grid and pipeline.

3.2 Simulation using Alternative Transients Program (ATP)

The system under study consists of three HVTLs and the pipeline sharing the same way for the 72 km distance that simulated using ATP software. Where, the HVTL/pipeline is divided into 77 sections and the induced voltage on this pipeline is calculated at each section under normal and all fault conditions in the first quarter or in the middle place of the power line. Figure 2 shows the ATP model and LCC modules for the whole system.

IV. RESULTS AND DISCUSSION

The pipeline induced voltage is simulated at different cases of study during normal and abnormal operating conditions, and the following sub-sections contain the discussion of results.

4.1 Induced voltage during normal operating condition

The simulated pipeline induced voltages due to El-Kurimate, Samaloute and 6th October power lines are shown in Figure 3. It is noticed that, El-Kurimate induced voltages along the most points on pipeline length are below the acceptable steady state touch and step potential range, 15 Vrms value, according to NACE standards [20] except few points, where the induced voltages at these points are exceeding the acceptable limit. Thus, the maximum value is about 26.5 V at 39.7 km-point which is the nearest point to the power line that separated with 29.6 meter.

Regarding to Samaloute HVTL, it is found that the induced voltages along the length of the pipeline are below 15 V (Max. permissible value) except one point where the induced voltage at this point is 22.1 V at 12.5 km-point that separated with 116.5 meter from the power line. With respect to 6th October power line, it is obtained that the pipeline induced voltage doesn't exceed the acceptable value (15 V). So, it is concluded that the induced voltage along the pipeline due to El-Kurimate power line is higher than that of Samaloute and 6th October power lines, this is because El-Kurimate HVTL is closer to the pipeline and its rated line voltage is more effective than 6th October HVTL. Also, the summation of pipeline induced voltages due to the three HVTLs have a lot of peaks over than the permissible value, which the maximum one tends to 33.1 V at 39.7 km-point.

By making a comparison between the simulation results here and the actual measured values of total induced voltages mentioned in [10], it is summarized that there is a good agreement between the simulation and measured induced voltage values, as presented in Table I, and the error percentage tends to be 2 ~ 5%.

4.2 Induced voltage during abnormal conditions

From Table I, it is noted that El-Kurimate power line is the most effective power line on the pipeline at normal operating condition. Therefore, the study of the total induced

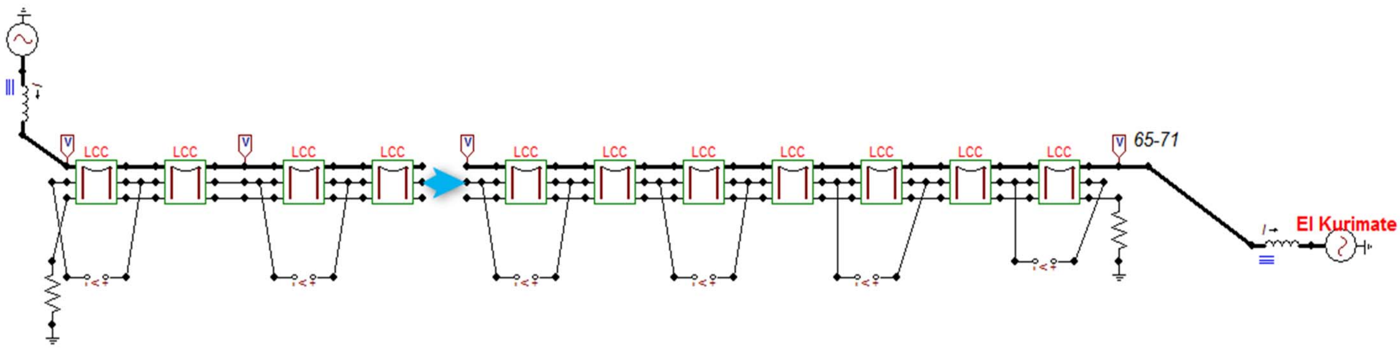

Fig. 2. ATP model for whole system

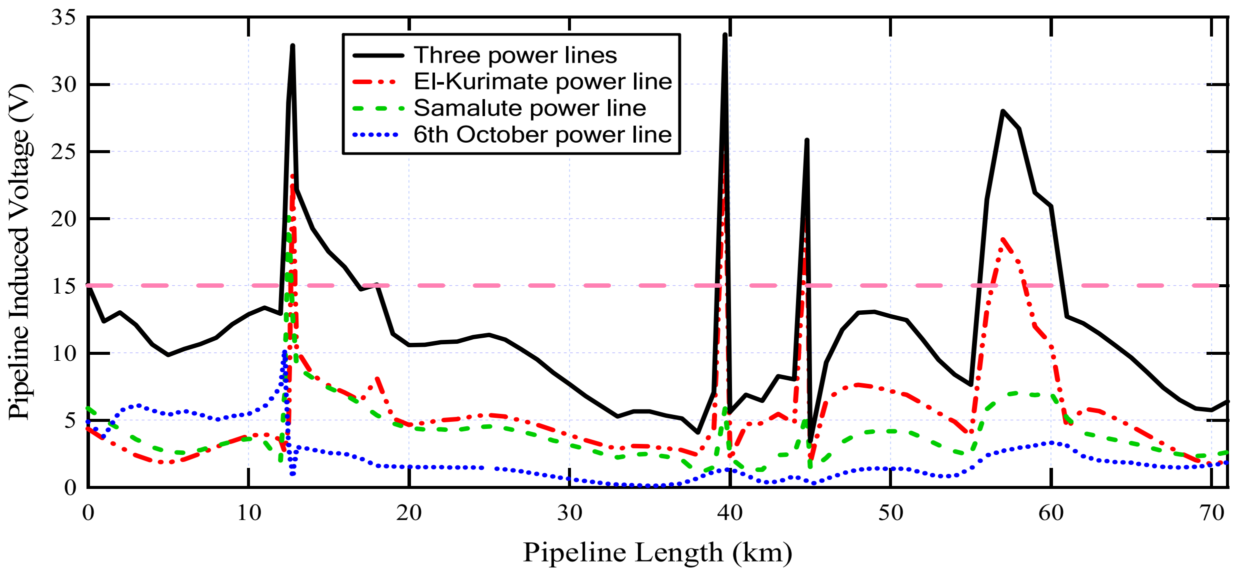

Fig. 3. Pipeline induced voltages due to El-Kurimate, Samalute, 6th October HVTLs and its summation under normal operating condition

voltages along the pipeline under different abnormal conditions will be applied for El-Kurimate HVTL only, then these values compared with the permissible limits of the pipeline coating voltages, which equal 3 to 5 kV for fusion-bonded epoxy (FBE) and polyethylene that will take here 4 kV as an average value [21].

TABLE I. MEASURED AND SIMULATED PIPELINE INDUCED VOLTAGES AT DIFFERENT POINTS DUE TO THE THREE HVTLS

Kilo-Point \ Data	Measured induced voltage (V) [10]	Simulated induced voltage (V)
12.5	32	31
39.7	32.2	33.1
44.8	26.7	25.86
55	8	7.6
64	11.2	10.6

4.2.1 Single line to ground fault (SLG):

Figures 4, 5 and 6 illustrate the pipeline induced voltages during a single line to ground fault occurs on phases A, B and C respectively, and the fault locations are happen in the first quarter of the power line (kilo-point 14) and also in the middle of the power line (kilo-point 34). In addition, the maximum and average values of induced voltages in different cases of SLG fault can be summarized as in Table II.

It is concluded that the maximum value of induced voltage occurs directly under fault location area. Moreover, the maximum and average values of the pipeline induced voltages, when the fault occurred at the first quarter length of the power line (kilo-point 14), are higher than these values when the fault happened at the middle length of the power line (kilo-point 34). This is because the fault location is near to the generation station that can supply the fault with a larger current, as shown in Fig. 6. Also, the transmission line fault impedance, when the fault occur at kilo-point (14), is smaller than its value when the fault happen at kilo-point (34). It is also noticed that the average and maximum values of the pipeline induced voltages, when the fault occurred on phase (A) as in Fig. 4, are different than that values when the fault occurred at phase (B or C) as in Figs. 5 and 6. . This is because the instantaneous values of the voltage and current of the three phases are not the same at that instant of the fault, and also due to the unbalancing of loading.

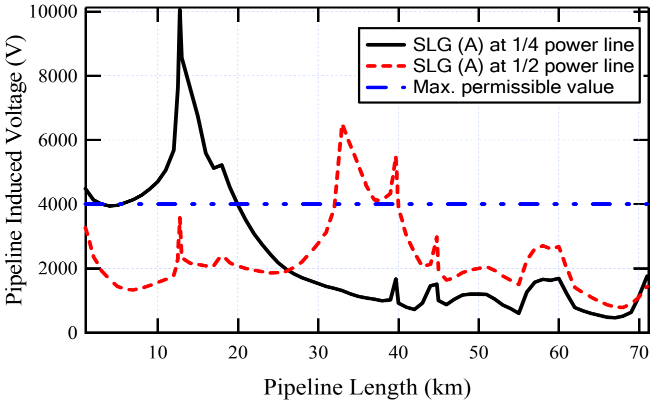

Fig. 4. Induced voltage along the pipeline under SLG fault on phase (A) at kilo-points (14) and (34)

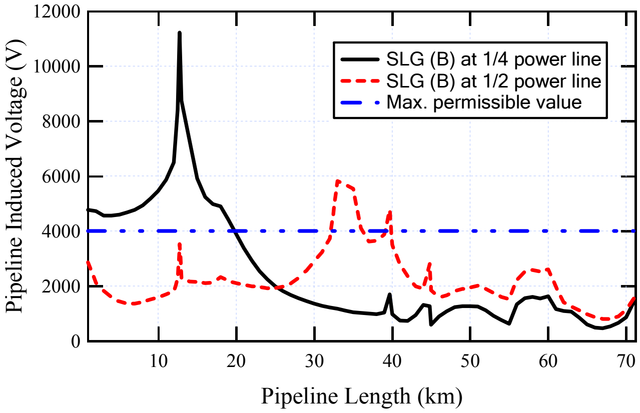

Fig. 5. Induced voltage along the pipeline under SLG fault on phase (B) at kilo-points (14) and (34)

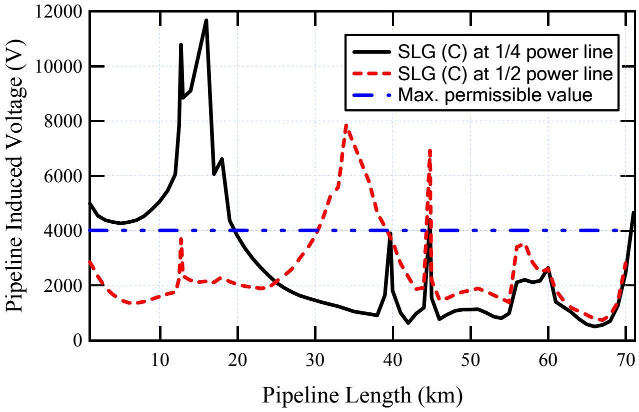

Fig. 6. Induced voltage along the pipeline under SLG fault on phase (C) at kilo-points (14) and (34)

TABLE II. MAXIMUM AND AVERAGE PIPELINE INDUCED VOLTAGES WHEN SLG FAULT OCCURS ON DIFFERENT PHASES AT KILO-POINTS (14) AND (34) OF THE POWER LINE

Kilo-Point \ Data		Simulated induced voltage for SLG (A) in volts	Simulated induced voltage for SLG (B) in volts	Simulated induced voltage for SLG (C) in volts
34	Max. value	6489	5813	7858
	Avg. value	2276	2211	2443
14	Max. value	10042	11225	11671
	Avg. value	2472	2518	2977

Furthermore, the position of pipeline is nearest to the phase C rather than other phases. Which the maximum and average values of simulated induced voltages for SLG fault occurs on phase C are the highest values compared with the other phases that tends to 11671 V, and 2977 V (at kilo-point 14) and equal 7858 V, and 2443 V (at kilo-point 34), respectively.

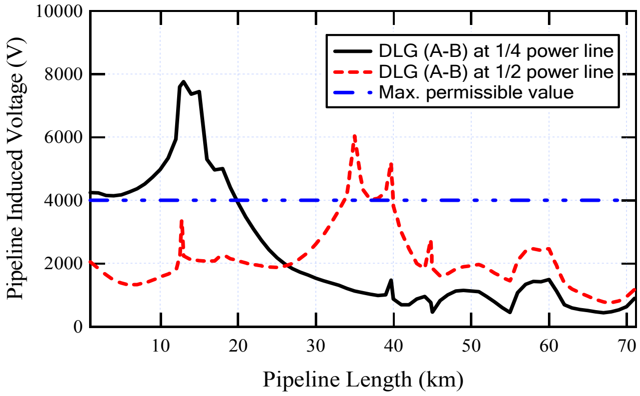

Fig. 7. Induced voltage along the pipeline under DLG fault on phases (AB) at kilo-points (14) and (34)

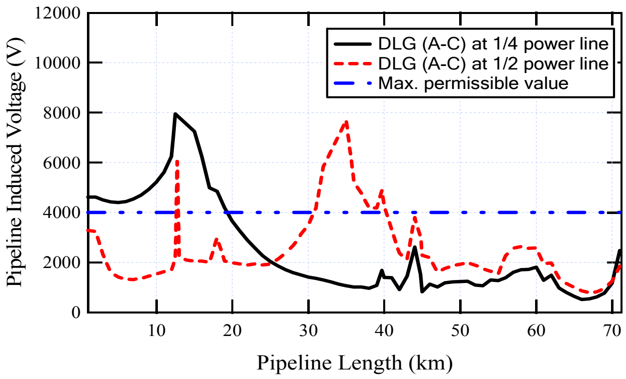

Fig. 8. Induced voltage along the pipeline under DLG fault on phases (AC) at kilo-points (14) and (34)

TABLE III. MAXIMUM AND AVERAGE PIPELINE INDUCED VOLTAGES WHEN DLG FAULT OCCURS ON DIFFERENT PHASES AT KILO-POINTS (14) AND (34) OF THE POWER LINE

Kilo-Point \ Data		Simulated induced voltage for DLG (A-B) in volts	Simulated induced voltage for DLG (A-C) in volts
34	Max.	6027	7698
	Avg.	2170	2415
14	Max.	7753	7948
	Avg.	2399	2417

4.2.2 Double line to ground fault (DLG):

Figures 7 and 8 show the pipeline induced voltages when a double line to ground fault occurs at kilo-points (34) and (14) on two phases (A-B) and (A-C), respectively. Besides that, the maximum and average values of induced voltages in different cases of DLG fault can be tabulated in Table III.

It is obtained that, when the DLG fault happen between phases (A and B) or phases (B and C), the maximum and average values of pipeline induced voltages are similar and have the same waveforms. Moreover, the maximum and average values of pipeline induced voltages, when the DLG fault occurs between phases (A and C), have the highest values compared with the other values when the fault happen between phases (A and B) or phases (B and C). This is because the phase displacement between phases (A and C) is 240°, while the phase shift between phases (A and B) or phases (B and C) is 120°, therefore pipeline induced voltages caused by DLG fault occurs between phases (A and C) have the highest value.

4.2.3 Double line fault (LL):

Figures 9, 10 and 11 describe the pipeline induced voltages when a double line fault occurs between phases (A and B), phases (A and C) and phases (B and C) at kilo-points (34) and (14), respectively. In addition, the maximum and average values of induced voltages in different cases of double line fault can be presented in Table IV.

It is concluded that, when the LL fault happen between phases (A and B) or phases (B and C), the maximum and average values of pipeline induced voltages are lower than that value when LL fault occurs between phases (A and C), as mentioned in Table 4. Also, the maximum value of the pipeline induced voltages when LL fault happen between phases (A and C) at kilo-point (14) is equal 1724 V, as shown in Fig. 10, which is the lowest value compared with any value of pipeline induced voltages caused by SLG fault or DLG fault. This is because in double line fault the field in two interrupted phases cancels each other that the same fault current passes through this two phases. So, the total equivalent current passes through neutral is the healthy phase current that considered the most effective one in the generation of induced voltage along the pipeline which have minimum value.

4.2.4 Three lines to ground fault (LLLG);

Because of balanced nature of LLLG fault**,** the symmetrical fault rarely occurs in practice, but it is necessary to study its effect on pipeline. Hence, Fig. 12 describes the pipeline induced voltages when a three lines to ground fault occurs at kilo-points (34) and (14).

It is shown that, when LLLG fault occurs at kilo-point (34), the maximum and average induced voltages on pipeline are 2240 V and 486 V, while they are equal 2393 V and 488 V when LLLG fault happen at kilo-point (14), respectively. By comparing the results from previous two sub-sections that analyze the pipeline induced voltages under the effect of LL and LLLG faults. It is concluded that the maximum induced voltages for both cases are below the maximum permissible value (4 kV) and the pipeline induced voltages caused by LL fault become the least value with respect to the other faults. Hence, from the previous researches, the LLLG fault caused the least pipeline induced voltages because of its symmetric waveform. But here, the induced voltages, in case of LLLG fault, record a little bit high value compared to LL fault. This is because the consideration of DC-component with the transient period of fault current that increase the total equivalent current in LLLG fault, resulting in high value of pipeline induced voltages.

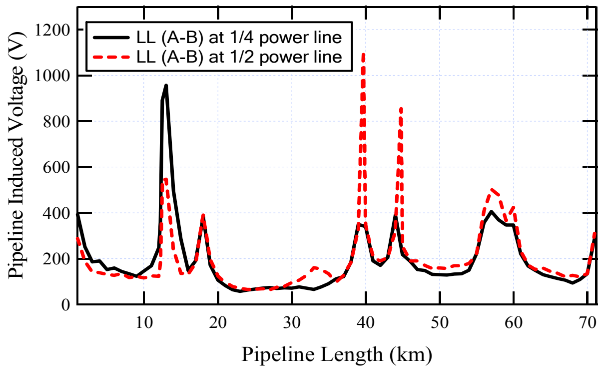

Fig. 9. Induced voltage along the pipeline under double line fault on phases (AB) at kilo-points (14) and (34)

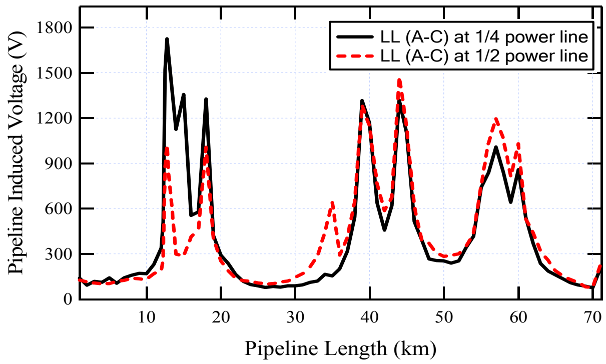

Fig. 10. Induced voltage along the pipeline under double line fault on phases (AC) at kilo-points (14) and (34)

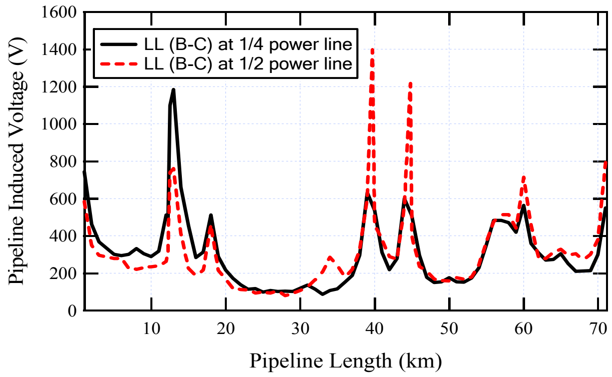

Fig. 11. Induced voltage along the pipeline under double line fault on phases (BC) at kilo-points (14) and (34)

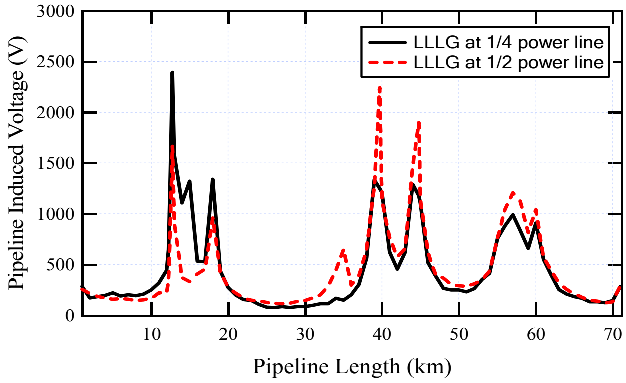

Fig. 12. Induced voltage along the pipeline under LLLG fault on all phases at kilo-points (14) and (34)

TABLE IV. MAXIMUM AND AVERAGE PIPELINE INDUCED VOLTAGES WHEN DOUBLE LINE FAULT OCCURS ON DIFFERENT PHASES AT KILO-POINTS (14) AND (34) OF THE POWER LINE.

Kilo-Point \ **Data**		Simulated induced voltage for double line fault (A-B) in volts	Simulated induced voltage for double line fault (A-C) in volts	Simulated induced voltage for double line fault (B-C) in volts
34	Max. value	1104	1417	1396
	Avg. value	216	415	326
14	Max. value	956	1724	1184
	Avg. value	199	436	318

4.3 Effect of soil resistivity change on pipeline induced voltage

In this section, the induced voltage due to the variation of soil resistivity along a section of the pipeline, from kilo-point (44) to (61), due to El-Kurimate power line only is studied.

4.3.1 Under normal operating condition:

Figure 13 demonstrates pipeline induced voltage due to soil resistivity variation from 100 to 2500 Ω.m under normal operating condition. It is seen that the induced voltage along the length of the pipeline section is almost the same, just a little bit variation. Hence, at kilo-point (55), the induced voltage increased from 3.87 V to 5.11 V due to the variation of soil resistivity from 100 to 2500 Ω.m. Therefore, the effect of soil resistivity variation on induced voltage under normal operating condition can be neglected.

4.3.2 Under abnormal operating conditions:

Here, the pipeline induced voltage due to the variation of soil resistivity under SLG fault occurs on phase (A) at kilo-point (34) is presented, as shown in Fig. 14. From this sub-section, it is concluded that as the soil resistivity increased under abnormal operating conditions the pipeline induced voltage also increased.

Hence, at kilo-point (55), the induced voltage increased from 1495 V to 1890 V due to the variation of soil resistivity from 100 to 2500 Ω.m. So, the soil resistivity is an effective factor in the calculation of conductive coupling, especially in case of abnormal conditions that agree the results in [22].

V. CONCLUSIONS

A study of electromagnetic interference between a three HVTLs (EL Kurimate – Samalute – 6th October) and an underground pipeline (El-Fayoum Gas pipeline) is made.

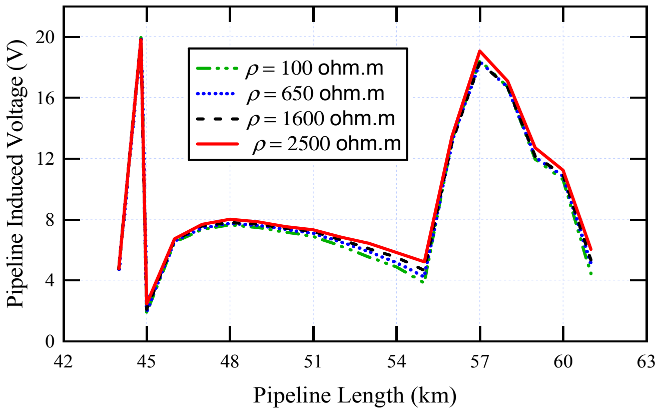

Fig. 13. Induced voltage along a pipeline section due to soil resistivity variation under normal operating condition

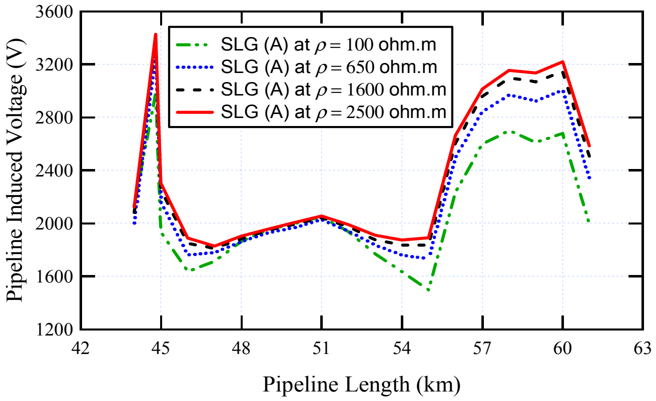

Fig. 14. Induced voltage along a pipeline section due to soil resistivity variation under SLG fault

By using ATP software with the help of MATLAB, the total pipeline simulated induced voltages during normal operation are calculated then compared with the actual measurements. The results show that there is a high matching between them and the error percentage tends to be (2 ~ 5%). The investigation of pipeline induced voltages under abnormal condition of the HVTL is carried out. It is shown that the highest values of induced voltages are caused by SLG fault then DLG fault followed by the double phase and LLLG faults. Also, it is found that the nearest the fault to the generating unit, the more serious of its bad effect on the pipeline itself and pipeline coating as well, where the transmission line fault impedance has a small value compared with farthest fault location. After that, the pipeline induced voltage under soil resistivity variation is calculated during normal and abnormal conditions, which show that the soil resistivity variation has no effect on the pipeline induced voltage under normal operating condition, however it has a great effect on the pipeline induced voltage under SLG fault. Whereas the soil resistivity increased, the induced voltage on the pipeline is increased as well.

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