Mitigation of Electric Fields/Induced Voltage on Oil Truck Crossing EHVAC Transmission Lines; Case Study in Saudi Arabia

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Abstract—This paper is aimed at mitigation of electric fields and induced voltages on oil trucks crossing Extra High Voltage Alternating Current (EHVAC) transmission line of 380 kV double circuits rating 900 MVA. EHVAC transmission line is crossing the way to a Petroleum Distribution Station owned by Aramco in Hail, Saudi Arabia. The method of modeling is based on the Charge Simulation Method (CSM) to determine the distribution of electric field, induced charges and the currents on an oil truck body. Experimental measurements of induced emf are taken from real oil truck loaded by gasoline crossing 380 kV Transmission lines double circuits. The calculated values of electric field and induced emf on oil truck body agreed reasonably with those measured experimentally. There are two suggested methods to mitigate the electric field and induced voltages on oil truck body due to EHVAC lines; first, by increasing the height of towers which are placed in the crossing area; second, by use shield ground wires under the stressed conductors.

Keywords—Extra high voltage transmission lines (EHVAC), charge simulation method, mitigation of electric fields, induced voltages, shielding wires, oil truck

I. INTRODUCTION

Electric field induction from AC power transmission lines was analyzed for long objects (fence wires and large vehicles) showing that objects perpendicular to the transmission line conductors have a significantly reduced induction as compared with parallel objects. The analysis was based on using an undisturbed equivalent electric field obtained by averaging the field over the length of the object. It is intuitive rather than analytical; nevertheless, it appears to agree satisfactorily with the measurements. The current flowing in transmission line conductors was disregarded. How the equivalent field was affected on the average over the surface area or over the volume object, was left unclear in the analysis [1]–[3]. Extra high voltage alternating current (EHVAC) transmission lines are widely used for transmission of electrical energy. Consequently, the possible effects of electric fields underneath these lines received an increasing interest in research studies, e.g. electric field induction and short circuit currents through conducting objects (parallel metallic fences, pipelines and large vehicles). The electric field impact on environment and interaction with human beings are also of great interest [1]–[3].

Precise calculation of the electric field underneath overhead transmission lines is a very important aspect in transmission line design. Quantitative description of the electrostatic field around EHVAC overhead transmission lines has been presented in many papers [4]–[8]. The electric field effect on transmission lines' maintenance crew is an important issue that electric utilities are most often required to respond to the potential health hazards. The effect of long term or chronic exposure to electric fields was studied in several countries [9]–[11].

In fact, most electric field effects occur close to ground level and are function of the magnitude of the unperturbed electric field at one meter above ground. For the previous reasons, electric fields must be reduced to overcome their harmful effects on the people living, work nearby the transmission lines or cars/trucks crossing the lines. One of the approaches is to use active and passive shield wires underneath the line conductors [2], [12]–[19]. Most of the previous works investigated the electric field reduction by using passive shield wires. A comparative study was done to compare between electric field mitigation using active and passive shield wires [2].

Charge Simulation Method (CSM) is very successful in most of the high voltage field problems, it is very simple and applicable to systems having more than one dielectric medium, and this method is also very suitable for 3D fields with or without symmetry. Therefore, the charge simulation method is used in this paper for calculating electric fields underneath the transmission lines with and without shield wires [20]–[25].

This paper is aimed to mitigate of electric fields and induced voltages V_{emf} on oil truck body crossing EHVAC transmission lines; case study in Saudi Arabia. If electric fields/induced voltages V_{emf} increased on oil truck body. Two methods are used to mitigate the electric field on oil truck body; first is increase height of line towers, second is using shield wires. Experimental measurements of induced emf are taken from real oil truck loaded by gasoline crossing 380 kV Transmission lines. The calculated values of electric field and induced emf on oil truck body agreed reasonably with those measured experimentally.

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II. METHODOLOGY

A. *Electric field calculation*

The idea of CSM [20]–[25] is very simple. For the calculation of electric fields, the distributed charges on the surface of a sub-conductor are replaced by N_1. There are 4 sub-conductors in the bundle, 3-phase, double-circuit, and 2-grounding lines. So the total number of fictitious charges is $(26N_1)$ placed inside the conductor at a radius r_f, Fig. 1. Oil truck which surrounded by air and loaded by gasoline is modeled by a finite line charges, its length is the length of truck with numbers of N_2 for first dielectric (air) and N_3 for second dielectric (gasoline), Fig. 1. The total numbers of fictitious charges is $n = (26N_1 + N_2 + N_3)$. In order to determine the magnitudes of the fictitious charges, some boundary points are selected on the surface of stressed conductors; shield wires and oil tuck body. The number of boundary point's $n = (26N_1 + N_2 + N_3)$ is selected equal to the number of fictitious charges. Then, it is required that at any boundary point the potential resulting from superposition of all the fictitious charges effects is equal to the known conductor potential. Let, Q_j is the jth fictitious charge and V is the known potential of the conductor. Then, according to the superposition principle,

$$V = \sum_{j=1}^{n} P_{ij} Q_j \tag{1}$$

where P_{ij} is the potential coefficient, which can be evaluated analytically for different types of fictitious charges. When Eq. (1) is applied to n boundary points selected on the phase conductors, shield wires and oil truck body, it leads to the following system of n linear equations for n unknown fictitious charges, then:

$$[P]_{n\times n}[Q]_n = [V]_n \tag{2}$$

where $[P]$ is potential coefficient matrix, $[Q]$ is column vector of known potential of contour points, $[V]$ is the applied voltage for boundary points on conductor surface and zero voltage for boundary points on shield wires and oil truck body. Eq. (2) can be solved for the unknown fictitious charges. As soon as the unknown charges are determined, the potential and the field intensity at any point, outside the line conductors, shield wires and oil truck body can be calculated. While the potential is found by Eq. (1), the electric field components are calculated by superposition of all the field vector components.

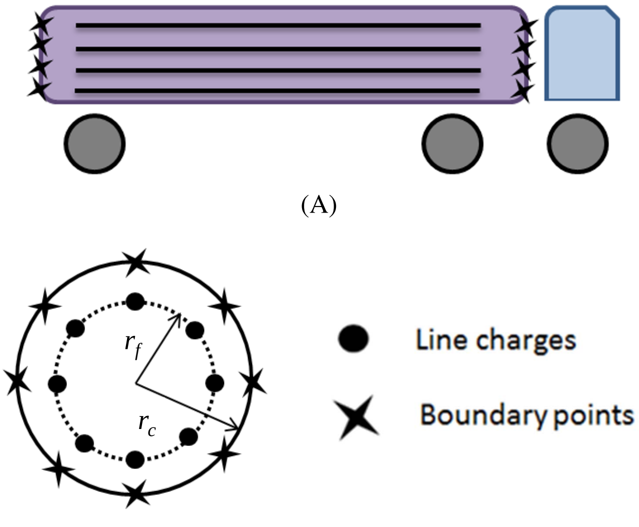
For a Cartesian coordinate system, the x, y, z coordinate E_x, E_y and E_z for a number of n charges would be given by:

$$E_x = \sum_{j=1}^{n} \frac{\partial P_{ij}}{\partial x} Q_j = \sum_{j=1}^{n} (f_x)_{ij}\, Q_j \tag{3}$$

$$E_y = \sum_{j=1}^{n} \frac{\partial P_{ij}}{\partial y} Q_j = \sum_{j=1}^{n} (f_y)_{ij}\, Q_j \tag{4}$$

$$E_z = \sum_{j=1}^{n} \frac{\partial P_{ij}}{\partial z} Q_j = \sum_{j=1}^{n} (f_z)_{ij}\, Q_j \tag{5}$$

where $(f_x)_{ij}, (f_y)_{ij}$ and $(f_z)_{ij}$ are "field intensity coefficients" in the x, y and z directions.



(A)

(B)

Fig. 1. Coordination of line charges and boundary points on: (A) Oil truck, (B) Line conductors and shield wires.

The magnitude of the electric field intensity at point p is calculated as:

$$E_p = \sqrt{E_x + E_y + E_z} \tag{6}$$

B. *Location of case study*

A Petroleum Distribution Station owned by Aramco is located in Biharah Jannayn Agricultural Area, 50 km east of Hail. The site is located in the middle between Hail and Qassim. The station is about 2 km away from highway and crossing an EHVAC transmission line of 380 kV double circuits rating 900 MVA with span of 400 m, Figs. 2 and 3. All oil trucks empty/loaded are crossing the EHVAC lines of with low speed less than 50 km/hr. Induced V_{emf} will be generated on the body of oil truck, and if there is no enough safety, may be discharge and explosion of oil truck will happen.

C. *Accuracy of charge simulation technique*

The accuracy of charge simulation technique is checked by investigating how the boundary conditions are satisfied in case of EHVAC conductors and shield wires. It is satisfactory that the maximum percentage error of the calculated surface potential of EHVAC conductors did not exceed 10^{-9} and the maximum percentage error of the calculated potential of shield wires did not exceed 3×10^{-10} (Theoretically, the potential at any point along the shield wires should be zero). It is clear from Fig. 4 that the proposed method predicts field values very close to those obtained before using boundary elements by Abdel-Salam *et al.* [1] for the same applied voltage, Fig. 4.

III. EXPERIMENTAL SETUP AND TECHNIQUE

A real oil truck filled with gasoline is used to measure experimentally the induced emf on its body near a Petroleum Distribution Station owned by Aramco in Hail, Saudi Arabia.

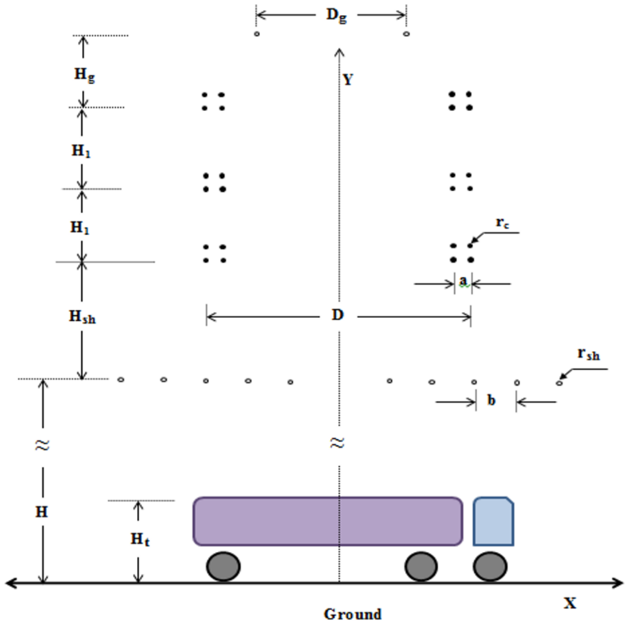


Fig. 2. Schematic diagram of microsecond pulse generation circuit. H_t: height of oil truck (= 4.5 m), H: height of shield wires from ground, H_{sh}: height between shield wires and nearest stressed phases, H_1: height between each stressed phase, H_g: height of ground wires over highest stressed phase, D_g: distance between ground wires, r_c: stressed wires radius, r_{sh}: shield wires radius, b: distance between shield wires, D: distance between the two circuits.

Fig. 3. Real oil truck crossing EHVAC transmission lines, 380 kV (Saudi Arabia).

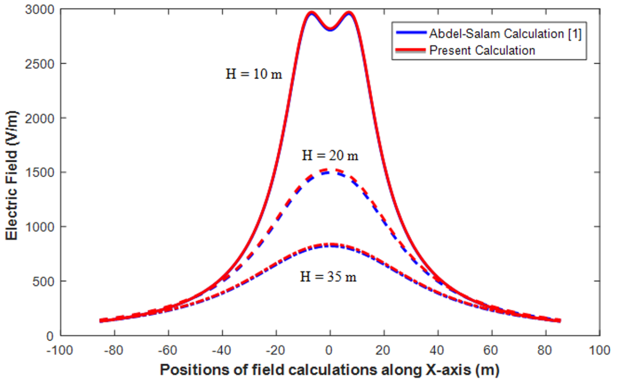


Fig. 4. Electric field distribution at 1 m height above ground surface for 220 kV transmission lines, present vs. Abdel-Salam's calculation [1].

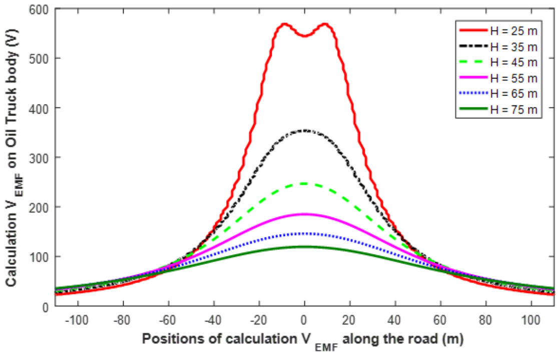


Fig. 5. Effect of increase line height on induced voltage V_{emf} on oil truck body with height of 4.5 m.

Truck has the diminutions of 23 m length, 2.6 m width and 4.5 m height. EHVAC transmission line is double circuit power rating 900 MVA, span of 325–450 m. EHVAC lines have a height of 27 m above the ground level. Measurements were made about 15 m far away from the tower with sage about 2 m, Figs. 2 and 3.

A schematic diagram of configuration of EHVAC transmission line, 380 kV, shield wires and Oil truck crossing the road is shown in Figs. 2 and 3. The configuration consists of: real oil track is crossing EHVAC lines on the high way. Digital voltmeter with high input impedance is used to measure the induced emf on the body of the truck. The voltmeter is connected between the truck body and copper rod with length of 120 cm with 50 cm immersed in soil. The truck is stopped 120 m away from the EHVAC lines and record the reading of voltmeter, induced voltage V_{emf}, then moved the truck 10 m in the direction of the EHVAC lines and record the new reading. This procedure will repeat until crossing the lines by 120 m away of the EHVAC lines. All this criteria is repeated 5 times and the mean value of readings of induced emf is obtained. All the measurements are made in Hail, Saudi Arabia of temperature 30°C, pressure 944 kPa, wind speed 14 km/hr and humidity of 15%.

IV. RESULTS AND DISCUSSION

The charge simulation method is applied to the 380 kV double circuit transmission line shown in Figs. 1 through 3. The number of sub-conductors per phase is four, the radius of a single conductor, r_c is 0.0135 m, the sub-conductor spacing, a is 0.5 m, H_1 is the vertical distance between each phase conductors. D is the distance between the two circuits. The simulation charges are arranged around a cylinder of radius R_f equal to $0.05r_c$, Fig. 1. Fig. 5 shows the induced voltage V_{emf} at the oil truck body (at level of 4.5 m above the ground) for the configuration shown in Figs. 2 and 3. The maximum induced voltage V_{emf} at 380 kV applied voltage on oil truck body is found to be about 570 V corresponding to minimum ground clearance $H = 25$ m.

Increasing the line height is the most effective parameter in line design, which reduces the maximum induced voltage V_{emf} at the oil truck body (at level of 4.5 m above the ground). Fig. 5 plots the induced voltage V_{emf} for different line heights of 25, 35, 45, 55, 65 and 75 m. The maximum induced voltage V_{emf} values corresponding to these line heights are 353.5, 250,

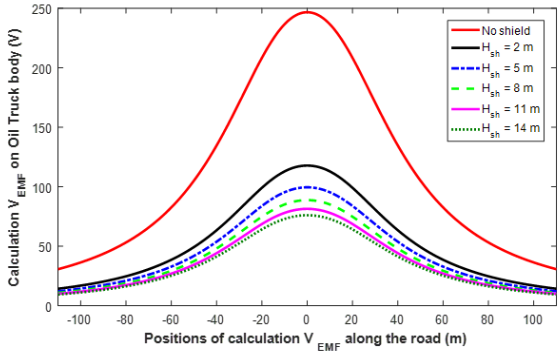


Fig. 6. Effect of increase distance between shield wires and stressed wires H_{sh} on induced voltage V_{emf} on oil truck body (height of oil truck is 4.5 m, $H = 45$ m).

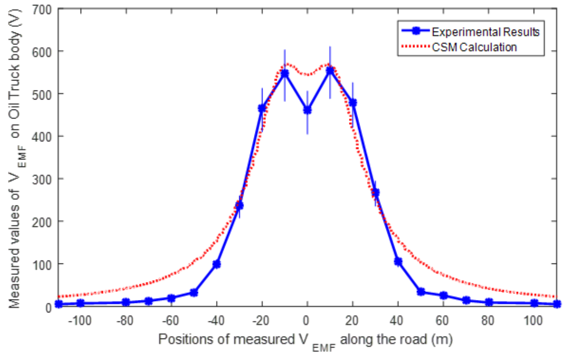


Fig. 7. CSM calculation vs. measurements results (height of oil truck is 4.5 m, $H = 25$ m).

185, 146 and 120 V respectively. It is clear that as the line height increases, the maximum induced voltage V_{emf} decreases significantly within the transmission line corridor.

From Fig. 6, it is clear that the maximum induced voltage V_{emf} on oil truck body decreases with the increase of distances between shield wires and stressed wires H_{sh}, Fig. 2. The percentage reduction of maximum induced voltage V_{emf} is 52.23%, 59.51%, 63.97%, 67% and 69.23% for five shield wires with H_{sh} of 2, 5, 8, 11 and 14 m respectively, Fig. 6.

For the 380 kV double circuit transmission lines, Fig. 2, the induced voltage V_{emf} is maximum under phases conductors, Fig. 2, and starts to decrease continuously as the oil truck position goes away from the transmission line, Figs. 2 through 7, and becomes negligible outside the transmission-line right-of-way. This trend of variation of the induced voltage conforms to the electric field profile underneath the line [3].

Measurements of the induced voltage on the oil truck body underneath the 380-kV transmission line were depicted in Fig. 7 against the calculated values based on CSM. Therefore, the measurements under the 380-kV, Fig. 2, are plotted relative to the measured values of oil truck crossing the line, Fig. 7. It is satisfying to observe a reasonable agreement between the measured and calculated values.

V. CONCLUSION

1) A theoretical model is proposed for calculating the induced voltage on oil truck body located/crossing underneath EHVAC transmission line of 380 kV, double circuit using CSM technique.
2) Experimental measurements of induced emf are taken from real oil truck loaded by gasoline crossing 380 kV Transmission lines double circuits in Hail City, Saudi Arabia. The calculated values of electric field and induced V_{emf} on oil truck body agreed reasonably with those measured experimentally.
3) Two methods for mitigation electric fields and induced voltage V_{emf} are proposed:
    a) Increasing height of towers in crossing area to decrease (mitigate) the electric fields and induced voltage V_{emf} on oil truck body.
    b) Using shield wires is an efficient method to reduce electric fields and induced voltage V_{emf} on oil truck body.

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