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A COMPREHENSIVE ELECTRICAL MODEL FOR THE ELECTROSTATIC DESALTING PROCESS OF CRUDE OIL

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Abstract

An electrical model is presented consisting of two interconnected parts of the power unit and the electrical load within the electrostatic AC/DC desalter of crude oil. This model can be used to design the power unit and the internal electric field of electrostatic desalters. Also, the effects of parameters such as vessel dimensions, the geometry of electrode plates, oil conductivity, and relative permittivity of oil can be investigated on the electrical performance of the desalting process. The effect of the oil conductivity and simultaneous use of two parallel power units on the desalting plant have been studied. The simulation results show that the positive and negative plates in the electrostatic desalter act as a resistance-capacitance electrical load for a high-voltage electric power source that charged and discharged in each cycle. On the one hand, an increase in conductivity of the crude oil causes a faster discharge of the plates, resulting in a voltage drop in the electric field between the plates and thus reducing the efficiency of the water separation process. On the other hand, it will increase the power consumption of the desalting unit, significantly. Also, the results of the model show that the simultaneous use of two parallel power units with different phase angles can increase the effective voltage between the plates, which will result in a significant increase in the efficiency of the water separation process from oil.

***Keywords**: Electrostatic Desalter; Electrical Model; Dual Polarity; Oil Conductivity.*

1. Introduction

The process of separating water droplets from crude oil under the effect of an electric field is referred to as the term electrostatic desalting. Crude oil is initially in the form of an emulsion of saline droplets in oil so that the water phase is saturated with various salts. The removal of water from crude oil is important for various reasons in the oil industry, such as the presence of various water-soluble salts causing corrosion and sedimentation in oil installations. Also, water separation before transportation reduces transportation costs. The simultaneous removal of some other impurities such as fine particles, clay, iron oxide, and iron sulfide is another advantage of the desalting process of crude oil [1].

Considering the importance of the desalting process, several types of research have been carried out modeling this process. Shahi *et al.* introduced a model for water droplet stability using double variable population equilibrium equations [2]. Ariyafard et al. proposed a mathematical model to predict the efficiency of water and salt removal [3]. Otabaye *et al.* introduced a model using neural network method to investigate the effect of process parameters such as the concentration of demulsifiers, temperature, wash water, mixing time and residence time on the efficiency of the desalting process [4]. Pronda et al. proposed an econo-mathematical model to obtain the optimum temperature for the desalting process [5]. However, no research has ever been carried out to model the electrical performance of the desalting process. This model needs to consider important parameters such as electrical characteristics of the high voltage power unit, conductivity and relative permittivity of crude oil, dimensions, and spacing of the plates.

In this research, a comprehensive electrical model has been introduced for a dual polarity (AC/DC) desalter of crude oil. In this type of desalters, first, crude oil passes through a weak AC field where a large portion of water is removed from the oil. Then, in order to remove the droplets of residual water, it passes through a strong DC field between the electrode plates (Fig. 1). Since the DC field exists only between the plates where the amount of salty water is very low, electrical corrosion will be reduced, significantly [1].

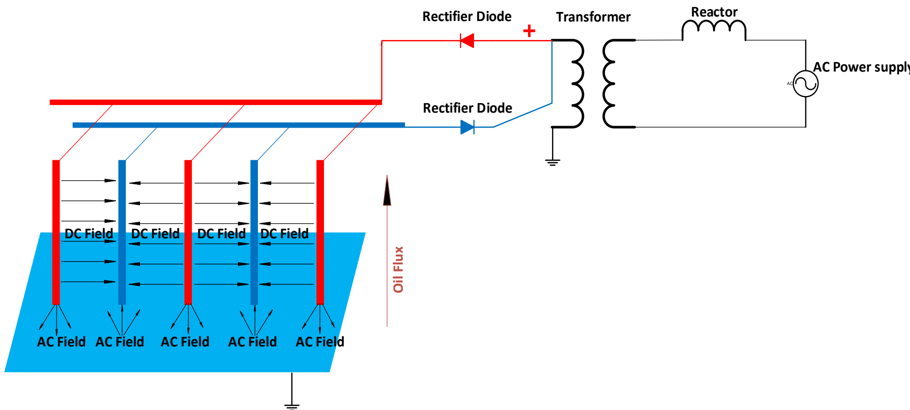

Fig. 1. Schematic AC/DC desalter

Fig. 1 displays the structure of the AC/DC desalter. As can be seen, the electrical supply section includes a reactor, transformer, and rectifier diodes. The role of the primary reactor in a transformer is described in section (2.1). The electrical load part consists of a desalter vessel and built in parallel plates which are connected one among to positive and negative bus bars.

Later on, the electrical model of the process will be described along with the method of calculating its parameters. First, the power unit model and the use of the series reactor will be described to achieve 100% reactance, and then the electrical load model and its parameters will be expressed. This two-part model is implemented for a desalter to study the effect of the oil conductivity and the effect of simultaneous using of two parallel power units.

2. Electrical model

A two-part model for the power unit and electrical load (desalter vessel) is introduced, and the method of calculating the relevant parameters is described. The elements of this electrical model include a resistor, capacitor, inductor, and ideal transformer. Also, the method of calculating reactance for a series reactor with a transformer, with a target of 100% reactance, is considered as one of the most important factors in the design of this special power unit.

2.1. Electrical power unit model

Fig. 2 displays the equivalent circuit of the power unit, and Table 1 introduces the elements of the circuit. The parameters of the model based on the design methodology are presented by the transformer manufacturers [6-8] and can also be specified through electrical tests [9].

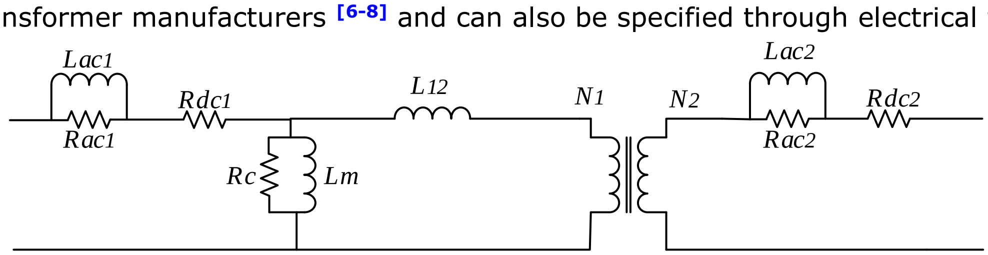

Fig. 2. The equivalent electrical circuit of the electrostatic field in desalter vessel

Table 1. Parameters of the power unit model

Parameter	Description
Rac_1 and Lac_1	Primary winding AC resistance modeling
Rac_2 and Lac_2	Secondary winding AC resistance modeling
Rdc_1 DC	Primary winding resistor
Rdc_2 DC	Secondary winding resistor
R_c	Core losses modeling
L_m	Magnetization inductance
N_1	Number of primary winding wires
N_2	Number of secondary winding wires
L_{12}	Mutual inductance

With respect to the possibility of changing the water-oil emulsion based on the type of crude oil, the temperature and the water content in the crude oil and the possibility of rising the level of accumulated water at the bottom of the vessel, the electrical power source of desalter must be designed in such way that in the case of secondary short-circuit (excessive increase in charge conductivity), the transformer current to be limited to the nominal current. For this purpose, by adding a series inductor (reactor) to the transformer, the design of the power source is achieved with a 100% reactance. By disregarding the transformer inductance, the inductance of the series inductor is calculated through Equation (1) and Equation (2) [9]:

$$X_R = Z_{BL} = \frac{(V_{BL})^2}{S} \quad (1)$$

$$L_R = \frac{X_R}{2\pi f} \quad (2)$$

where V_{BL} is the nominal voltage of the low voltage side; S is the nominal transformer power; Z_{BL} is the transformer impedance; X_R is the series inductor impedance; L_R is the inductance of the series inductor, and f is the voltage frequency.

Electrical power consumption of transformer is one of the important factors in the design of a desalting unit that depends on the conductivity of crude oil, dimensions of the vessel, distance between the electrode plates and the number of the plates. The electrical power of the transformer, P, can be calculated by Equation (3), where V_{rms} and I_{rms} are effective voltage and current, respectively.

$$P = V_{rms} \times I_{rms} \quad (3)$$

2.2. Electrical load model

In this section, based on the geometry of the vessel, the dimensions and distances of the electrodes (plates) inside the vessel and the electrical properties of the fluids (w/o emulsions) in different parts of the vessel, an electrical model is developed for the consumer (internal electric field). The important parameters in calculating the electrical model are the dimensions of the vessel, the dimensions and the distance between the plates, as well as the electrical properties such as crude oil conductivity and the relative permittivity in different parts of the vessel.

The electrodes are connected as a plate to the positive and negative bus bars inside the vessel. There are capacitance and electrical current between the opposite plates that are modeled using a capacitor and electrical resistor. Regarding the water phase accumulated at the bottom of the desalter vessel, due to the high water conductivity, it is possible to consider the water layer and the body of the reservoir as an integrated part. Between all plates and reservoir surface and water, electrical conductivity and capacitance are modeled using resistors and capacitors.

Table 2 presents the dimensions of the vessel and the internal plates. Fig. 3 shows the cross section of the vessel, together with the fluid distribution profile in different regions. At the lowest level of the vessel, the water layer is located at the highest conductivity (4 S/m) and at the top of the water layer there is a water-filled emulsion with a conductivity of 500 nS/m. At the bottom of the plates, because of the reduction of water due to droplet sedimentation, the crude oil conductivity decreases to 100 nS/m. The highest layers, related to the dehydrated crude oil between the plates and the top of the plates near the outlet, have a minimum conductivity of about 10 nS/m [9]. The relative permittivity of the crude oil is $\varepsilon_r = 2.5$.

Table 2. The geometry of the desalter vessel and internal electrodes

Vessel length	21 m
Vessel diameter	4.2 m
Number of electrode plates	140
Height of electrode plates	15 cm
Length of electrode plates	3.2 m
Distance between electrode plates	15 cm

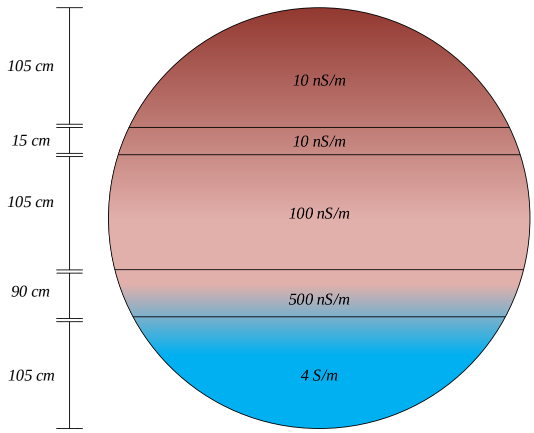

Fig. 3. Fluid conductivity profile in different areas within the vessel

In order to calculate the capacitive property between the electrode plates and to reduce the computational time, only a part of the vessel containing 8 electrode plates is considered. The layout of the desired plates and the geometry of the problem are depicted in Fig. 4. The capacitance of the plates (P_1 to P_8) with the vessel body (V_0) in terms of picofarad is as the following matrix. The first line of the matrix is related to the capacitance between the vessel and the plates, and the next lines of the matrix are related to the capacitance between the plates with each other. As you can see, the capacitance between a plate and its adjacent plates is much larger than the capacitive property between that plate and its non-adjacent plates. For example, the capacitance between plates 3 and 4 is 75.236pf, while the capacitance between plates 3 and 5 is 9.16pf. Therefore, the capacitance between the non-adjacent plates can be ignored.

\	V_0	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
V_0	341.12	−68.41	−37.276	−33.333	−32.075	−32.12	−36.876	−36.876	−36.876
P_1	−68.41	170.73	−81.503	−11.596	−4.4988	−2.1954	−1.1926	−0.7071	−0.6233
P_2	−37.276	−81.503	210.15	−75.53	−9.267	−3.865	−1.5951	−0.8692	−0.7199
P_3	−33.333	−11.596	−75.53	210.99	−75.236	−9.1601	−3.3237	−1.5957	−1.2143
P_4	−32.075	−4.4988	−9.267	−75.236	211.03	−75.222	−9.1264	−3.3765	−2.2264
P_5	−32.12	−2.1954	−3.865	−9.1601	−75.222	211.23	−75.298	−9.2761	−4.5733
P_6	−33.206	−1.1926	−1.5951	−3.3237	−9.1264	−75.298	210.91	−75.434	−11.739
P_7	−36.876	−0.7071	−0.8692	−1.5957	−3.3765	−9.2761	−75.434	209.95	−81.817
P_8	−67.82	−0.6233	−0.7199	−1.2143	−2.2264	−4.5733	−11.739	−81.817	170.73

The finite element method is used to calculate the current flow between the plates and vessel and water surfaces. Fig. 5 displays a plate with the part of the vessel. The length of the vessel is along the Z axis. Color layers are characterized by water, high water emulsion, low water emulsion, and dry crude oil, each of which has different conductivity according to Fig. 3. The electrode plate is placed inside a yellow rectangular cube. Using the finite element method, the surface density of the current is calculated, and then, by integrating the surface density of the current on the yellow packet surface, the amount of electric current is calculated. By dividing the voltage assigned to the plate into the output current of the electrode plate, the resistance between the electrode plate and the vessel can be calculated.

With respect to the fact that the distance between the plates relative to their area is small, the resistance between the plates can be calculated with a good approximation of the Equation (4):

$$R = \frac{\rho l}{A} \tag{4}$$

where ρ is the resistivity of the crude oil between the electrode plates; l is the distance between the plates and A is the area of the plate.

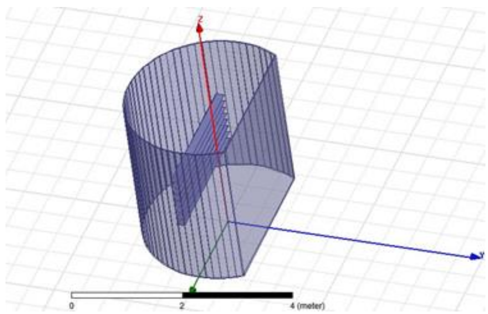

Fig. 4. The electrode plates and vessel body used to calculate the capacitive property (The surface of the water and the vessel's body are considered unified due to the equal voltage of earth connection)

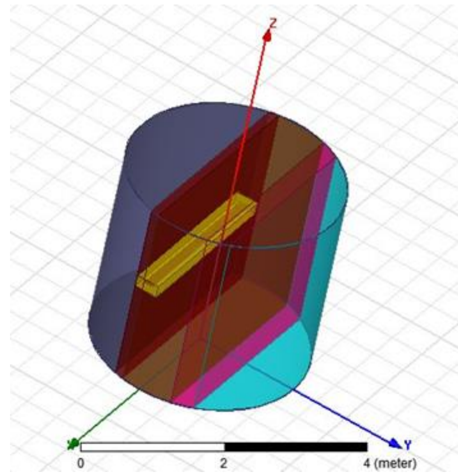

Fig. 5. The geometry used to calculate the output current from one electrode plate according to the fluid conductivity profile

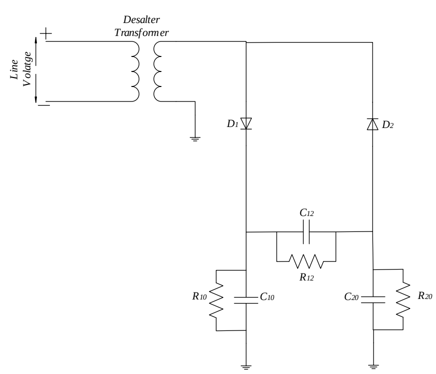

Fig. 6. The equivalent electrical circuit of the vessel

Since the resistors and capacitors between the electrode plates, the resistors and capacitors between the positive plates and the vessel's surface, and the resistors and capacitors between the negative plates and the vessel's surface are parallel; the equivalent electrical circuit of the vessel can be shown as Fig. 6.

In Fig.6, R_{12} and C_{12} are the resistor and capacitor between the plates, R_{10} and C_{10} are the equivalent resistor and capacitor between the positive plates and the vessel, R_{20}, and C_{20}, are the equivalent resistor and capacitor between the negative plates and the vessel. D_1 and D_2 are rectifier diodes at the transformer's output voltage.

3. Implementation of the electrical model for a desalting system

In section (2), an electrical model of the equivalent circuit of the power source and an electrical model of electrical load (inside the vessel) are introduced. The method of calculating the parameters of the two parts of the model are described separately. In this section, the model derived from the previous section, including the power unit and the desalter's vessel (electrical load), is implemented to simulate the electrical components of the process.

The electric power is considered to be 15 KVA, the primary/secondary voltage is 380V/22KV, and the frequency is 50 Hz. Other information regarding this power unit is provided in Table 3.

The values for the source electrical model according to Fig. 2 are as follows:
L_{ac1}=365.2 uH, L_{ac2}=1.75 H ;R_{ac1}=105.6 mΩ, R_{ac2}=257.2 Ω ; R_{dc1}=56.72 mΩ, R_{dc2}= 210.6 Ω; R_C=1.219 KΩ; L_m=1.64 H; L_{12}=1.105 mH; N_1=109, N_2= 6311; $L_R = \frac{X_R}{2\pi\times 50} = 30.6$ mH

Fig. 7 shows the variation of the secondary voltage with the voltage of the positive plates. As can be seen, due to the capacitance between the plates, the voltage of the plates is reduced at a lower speed than the transformer secondary voltage. This phenomenon maintains a DC voltage difference between the positive and negative plates (the electrodes inside the vessel). Therefore, a DC electric field generates between the positive and the negative plates.

Table 3. Information on the section on increasing transformation

Core manufacture	THOM & SKIN
The geometric structure of the core	1.125 × 5 (3) MH
Core type	EI Lamination 18.5 mil
The core weight	105 kg
Total core weight + winding	321.5 Kg
Iron losses	118.4 W
Copper losses	187.2 W
Increased transformer temperature	39.14 °C
Number of primary winding wire	109
Number of secondary winding wire	6311
The size of the primary wire	AWG 20
The size of the secondary wire	AWG 11

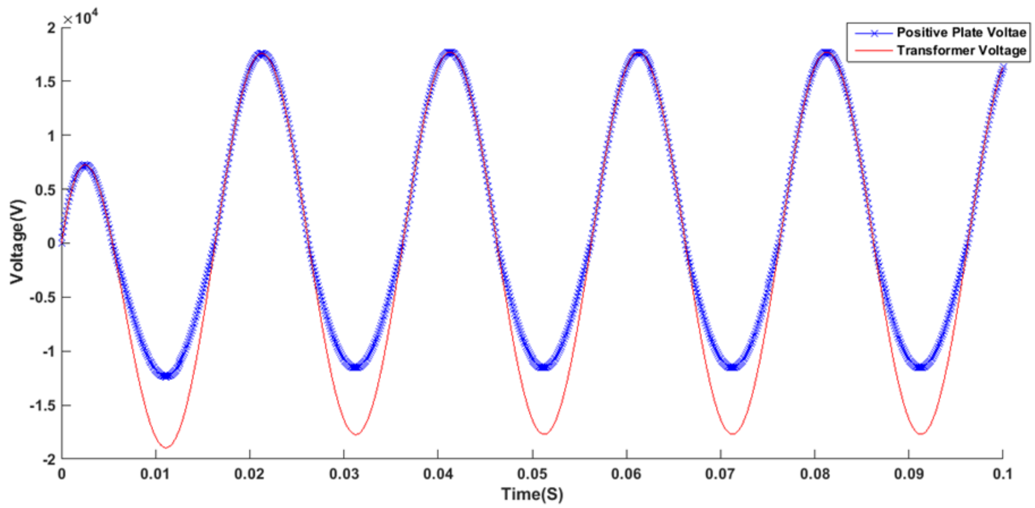

Fig. 7. Transformer secondary voltage with positive plates voltage

Fig. 8 displays the DC voltage difference between the vessel plates, which is the result of the difference between the negative and positive plates voltage. Fig. 9 shows the average DC voltage between the plates, which determines the electric field between the plates. The intensity of the electric field is one of the important factors in the efficiency of the process of desalting of crude oil.

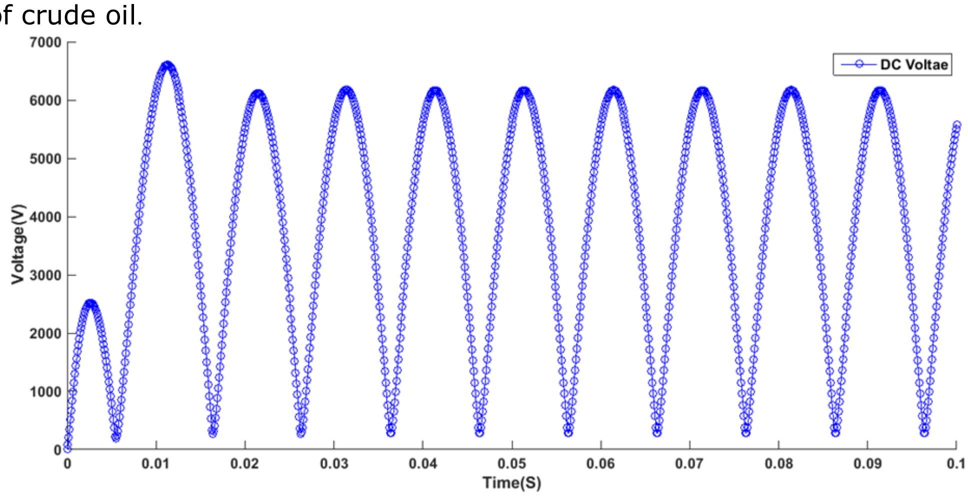

Fig. 8. DC voltage between the plates

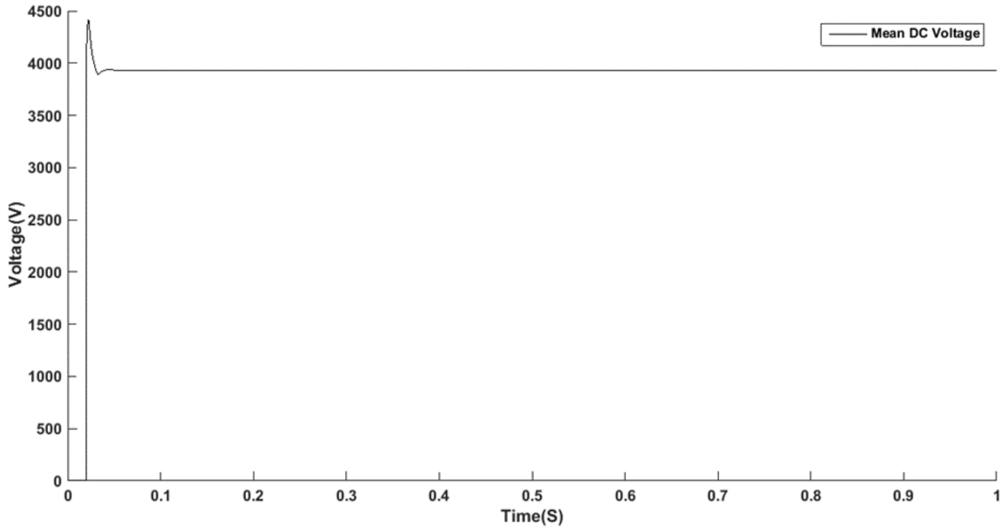

Fig. 9. The average DC voltage between the plates

In the case where the amount of crude oil conductivity in all the layers inside the vessel is affected by the type of crude oil, the increase in water percent and operating temperature, becomes 10 times of the stated values in Fig. 3, the simulation is repeated, and the result for the DC voltage between the plates is shown in Fig. 10. As can be seen, this change will reduce DC voltage to 1/8 of the previous value, and as a result, the efficiency of the desalting process will be reduced, significantly. This confirms the problems of processing high-conductivity crude oils.

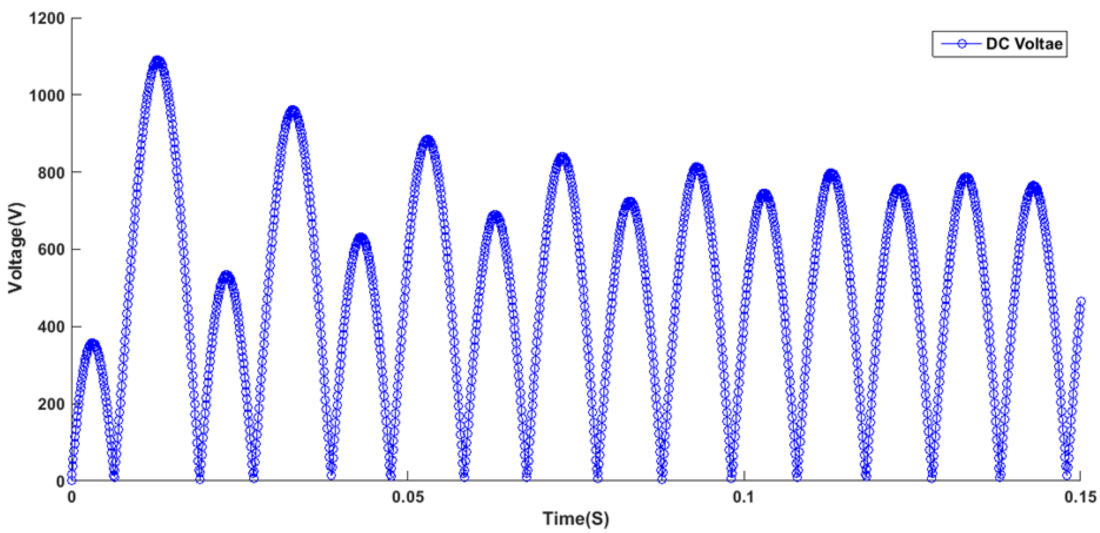

Fig. 10. The DC voltage between the plates in the case of conductivity 10 times the values of Fig. 3

One of the most commonly used methods in industrial desalting plants is applying of two or three power units connected to isolated industrial power phases on a desalting vessel. Fig. 11 shows the positive and negative plate voltages for the case of two parallel transformers with different power supplies (phase difference of 120°). It should be noted that in this case, the transformers outputs after passing the rectifier diodes are connected in parallel. Due to the 120 degrees phase difference of secondary voltage of the transformers, the positive and negative plate voltages have less time for discharging, and this increases the electrical field between the plates and as a result, improves the desalting process of crude oil.

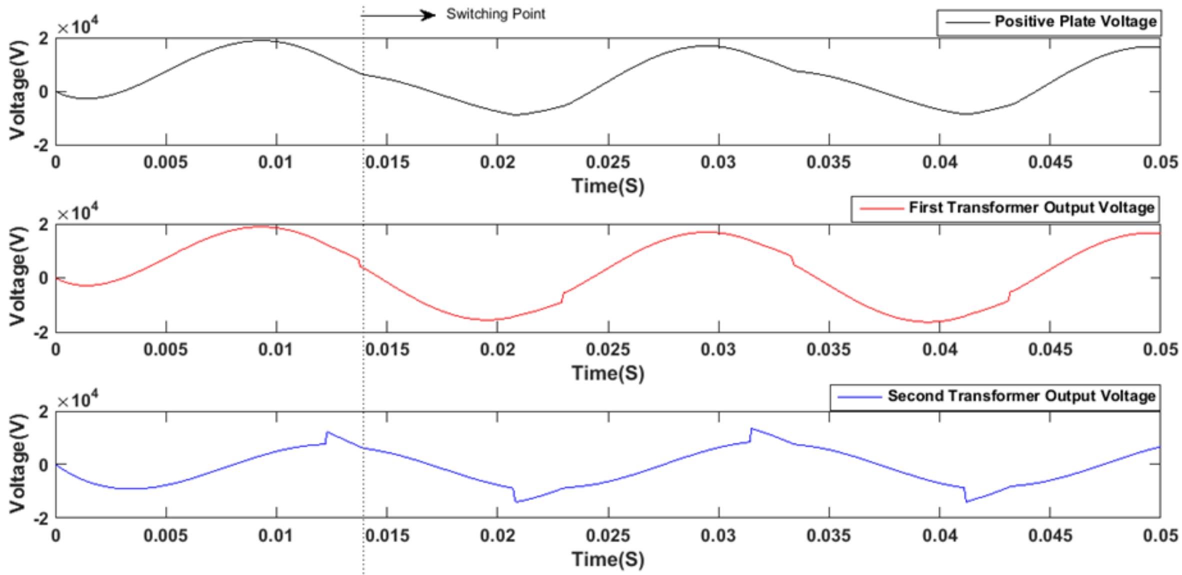

Fig. 11. Positive voltages with the secondary voltage of each transformer

In Fig. 12, and Fig. 13, the DC voltage between the plates and the average voltage difference between the plates are shown in the case of two parallel transformers. As can be seen, the difference between the effective DC voltages is more than twice that of a single source (compared to Fig. 8). This result shows that the use of two power units simultaneously will have a significant effect on the improvement of the desalting process.

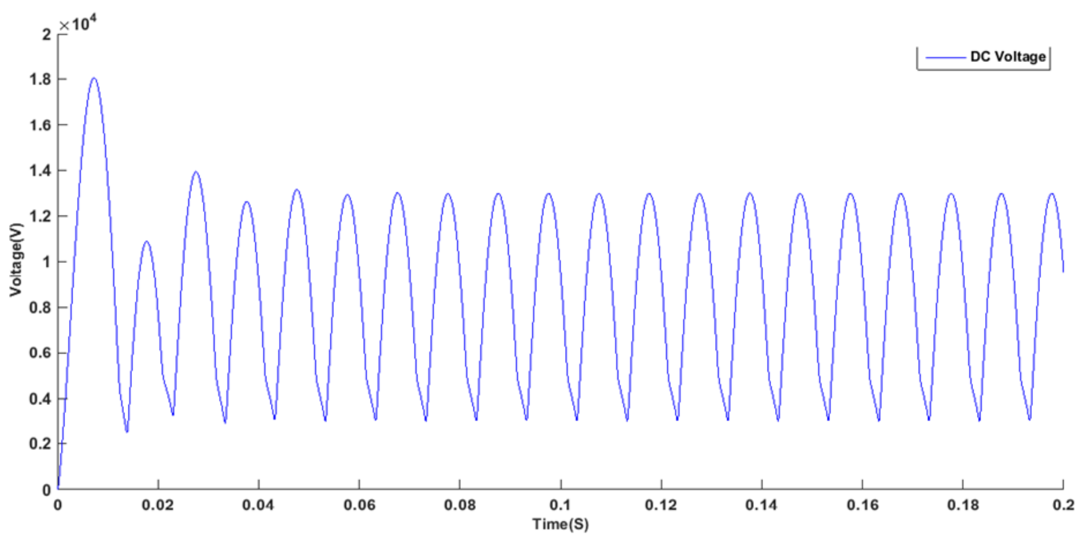

Fig. 12. DC voltage between the electrode plates in the case of two parallel transformers

4. Discussion

As shown in section (3), the electrode plates in the desalter vessel act as an RC load for a high voltage electric power unit. Due to the capacitive property, in positive half-cycle of sinusoidal voltage, positive plates are charged, and negative plates are discharged, and this is done in the negative half-cycle vice versa. We know that the time constant for capacitor discharge is defined as follows:

$$\tau = RC \tag{5}$$

where R is the resistance, and C is the capacitance of the load.

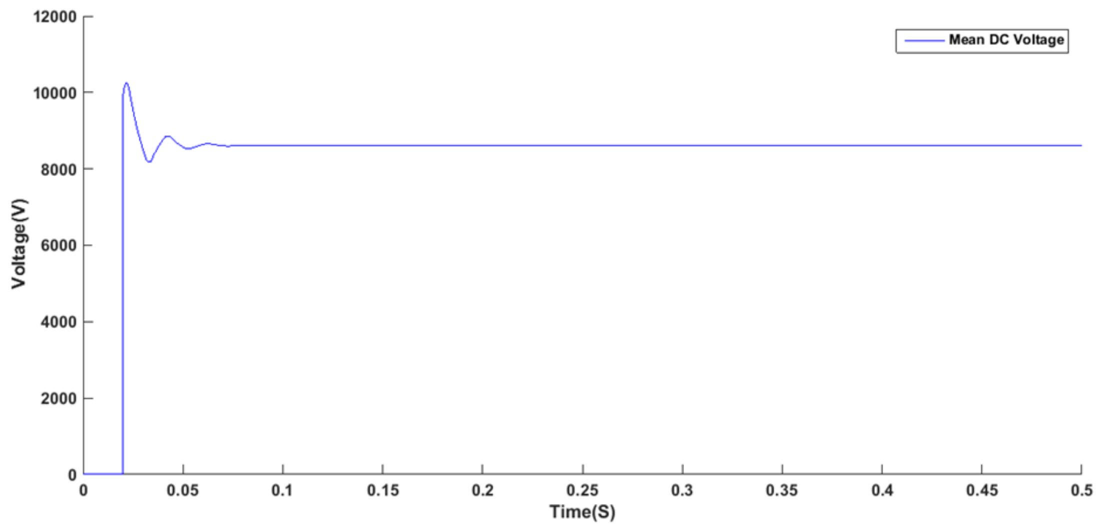

Fig. 13. The average DC voltage between the plates in the case of two parallel transformers

With regards to the above relationship, increasing the conductivity of the crude oil causes a decrease in time constant and, as a result, a faster discharge of the plates. This is considered undesirable in the process of desalting because with the discharge of the plates, the effective voltage difference between them and the intensity of the electric field will decrease, which will lead to a reduction in the efficiency of the separation process in the desalter. However, in accordance with this relationship, an increase in relative permittivity increases the time constant and resulting in an increase in discharge time of the plates, but the relative permittivity for different types of crude oil is almost the same and does not change significantly.

Fig. 14 displays the DC voltage between the plates in terms of the conductivity of the crude oil for both cases using one 15 KVA transformer and two parallel 15 KVA transformers. As expected, the increase in conductivity has a significant effect on the effective voltage between the plates and, consequently, the performance of separation in the desalting process. Important factors in determining the conductivity of water-in-oil emulsion are the type of components of crude oil, process temperature, and water content [10]. With respect to Fig. 14, this interval of variations in the conductivity of the crude oil has a great influence on the DC effective voltage between internal electrodes of the vessel. Another important point in this figure is the DC voltage difference for two cases of using a single transformer and double parallel transformers, which is large in small conductivity and reduces with increasing conductivity. For example, for the conductivity of 10 ns/m, the voltage is in the case of a single transformer is 6720 V and in a two parallel transformer case is of 35000 V, and for the conductivity of 2000 nS/m, the DC voltage between the plates is 248 V and 496 V respectively.

An important feature in the design of a desalting unit is electrical power consumption. Fig. 15 shows the power consumption in terms of the conductivity of the crude oil using Equation (3) for two different cases: 1st for the base case of Table (2); and 2nd for the case of twice diameter vessel and halved number of plates. As can be seen, the increase in the conductivity of crude oil has a significant effect on the increase of power consumption of the unit and consequently, an increase in unit costs. For example, in the base case (1st), an increase in the conductivity of the crude oil from the normal values of about 50 nS/m to relatively high values such as 1000 nS/m, rises the power consumption to more than twice.

The increase in the conductivity of crude oil reduces the R_{10}, R_{20}, and R_{12} resistances shown in Fig. 6. On the other hand, reducing the vessel size, reducing the distance between the plates and increasing number of plates are other factors that reduce these resistances. Regarding Fig. 15, inappropriate selection the above geometries can lead to excessive consumption of power, even in low levels of crude oil conductivity.

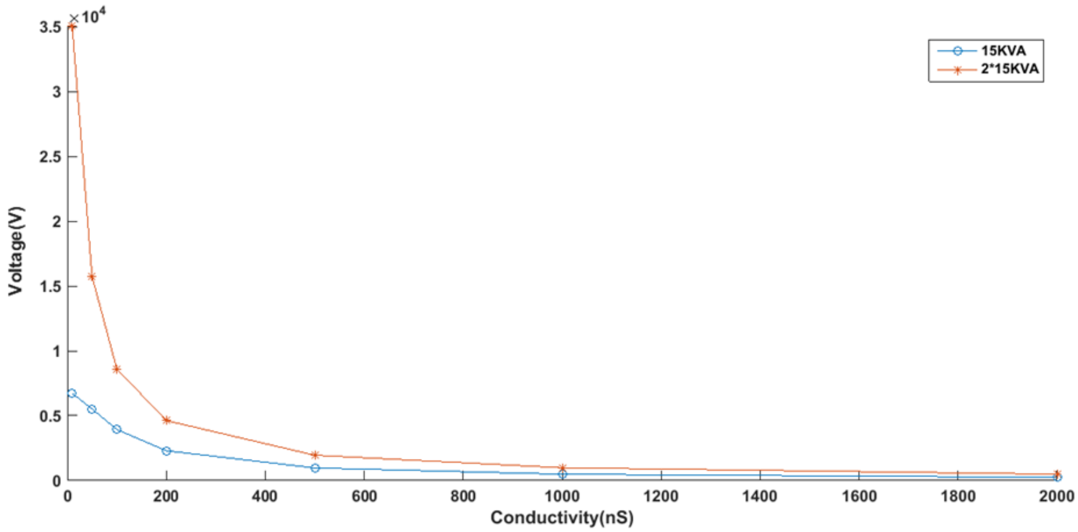

Fig. 14. The Effect of crude oil conductivity on the effective DC voltage between the plates for single and double power unit application

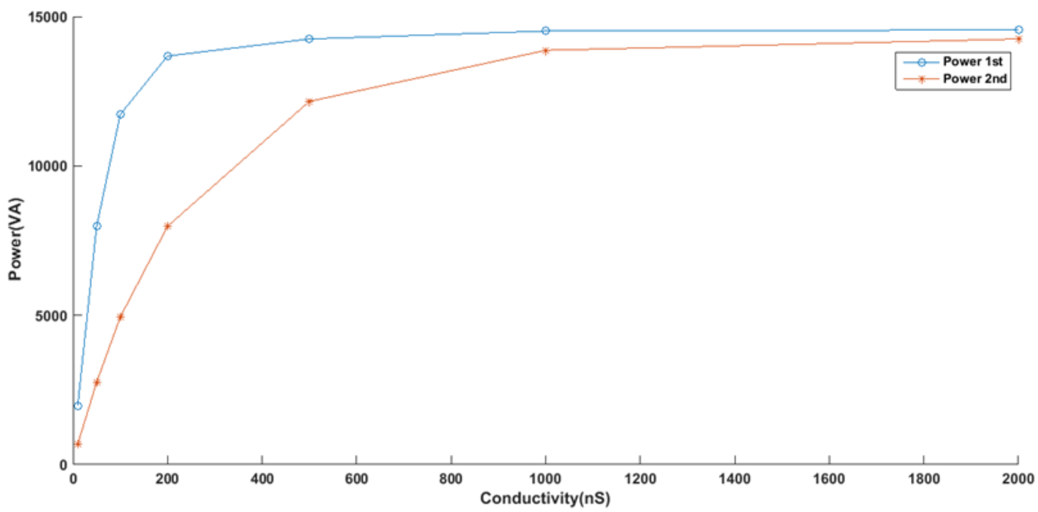

Fig. 15. The effect of crude oil conductivity on electric power consumption for 1st: the base case of Table (2); and 2nd: the case of doubled diameter vessel and halved number of plates

The 2nd diagram of Fig. 15 relates to a case state in which the diameter of the vessel is doubled, and the number of plates is halved. As can be seen, in this case, power consumption is less for the usual values of conductivity than the 1st case. For example, in the conductivity of 100 nS/m, the power consumption in the 1st case is 11.7 KVA, and in the 2nd case, it is 5 KVA. Thus, the conductivity of the crude oil, the dimensions of the vessel, the distance between the plates and the number of plates are the key factors in the process of electrostatic desalting that affect both the quality of the desalting process and the electrical power consumption of the unit.

Conclusions

An electrical model was presented for the dual polarity (AC/DC) desalting unit. The model consisted of two parts: the high-voltage power unit and desalter vessel (electrical load). This model can be used to design an external power unit and an internal electric field. Also, using this model, the effects of different geometric parameters such as vessel dimensions, electrode plates, and electrical properties such as crude oil conductivity on the performance of the desalting process were investigated.

Using the model, the effect of crude oil conductivity on the desalting process was studied. It was found that the increase in conductivity could reduce the electric field between the plates and, as a result, reduce the performance of separation in the desalting process. For example, the DC voltage between the plates in the case of the crude oil conductivity of 100 nS/m was equal to 4 KV, but at a conductivity of 1000 nS/m, this value was reduced to 500 V. Furthermore, the effect of the oil conductivity, desalter vessel dimension, and plates geometry on the power consumption of the process was investigated. It was determined that increasing crude oil conductivity and inappropriate selection of geometric parameters could increase the electrical power consumption, noticeably.

Also, the effect of simultaneous use of two parallel electrical sources on a desalter vessel was investigated through simulations. It was determined that the use of two parallel transformers could increase the DC voltage between the plates, which is more effective in low levels of crude oil conductivity. For an oil conductivity of 10 nS/m, in the state of using one transformer the DC voltage between the plates is 6720 V and in the case of using two parallel transformers is 35000 V; and in oil conductivity of 1000 nS/m, the DC voltage is 493 V for single source and 990 V for double source.

In addition to the items examined in this study, the proposed model can be used to explore, develop, and design equipment used in newer technologies for crude oil desalting, such as dual frequency technology.

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