**Development of an Algorithm for Cleaning Transformer Oil from Various Mechanical Impurities Using an Electric Field**

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**Abstract.** The author of the article creates a mathematical model of the process of cleaning transformer oil under a constant electric field of mechanical impurities and an algorithm to organize activities. The model suggested is made up on the theory of electrostatics, fluid mechanics and theory of the electromagnetic field and enables it to calculate the degree of purification by means of the utilitarian interconnection between the consumption of oil and the voltage. In accordance with the data of graphical analysis performed in the environment of the MS Excel, the nature of the change in the concentration of mechanical impurities in dependence upon electrical voltage and time intervals was estimated. As well, a mathematical statement was constructed and critically examined on the basis of the relationship of oil consumption and value of voltages in a constant condition in order to ascertain the law of the degree of purification of the oil in the transformer. This practice enables improving the electrostatic precipitation technology and raises the reliability of transformers as well.

**Keywords:** transformer, transformer oil, rigid insulation, algorithm, mechanical impurities, electric field, electroconvection, turbulent and laminar flow

**INTRODUCTION**

The transformers can be said to rank as one of the key technological appliances in the transportation and distribution of the electrical power and their effective functionality significantly depends on the physicochemical characteristics of the transformer oil which serves as its insulating material. Insufficient capabilities of transformer oil, which makes negative impact on the electrical strength and heat exchange of transformers, is damaged during the working process under the impact of different mechanical impurities acted by external and internal factors. Thus, the most significant demands to provide reliable operation of transformers are regular cleanings of oil supplied to them and control of the technical state. Up to date filtration, centrifugal separation and thermal vacuum are the widely used forms of purification of transformer oil [1, 2, 3]. These technologies are however not efficient with regard to full separation of mechanical impurities. Thus, the electrostatic oil purification technology with the use of precipitators whose operation is based on the inert electric field is suggested as new technology. The technology is founded on the basis of relaxation of particles subjected to forces exerted on mechanical impurities by the electric field, which makes it much more accurate and profitable than regular filtration [8, 9]. A mathematical description of purification of transformer oil of mechanical impurities with the help of an electrostatic precipitator was built in this article, and the analysis was performed according to the functional expression and the algorithm of purification complexity in terms of the parameters of oil consumption and the voltage. The method enables expanding the cycle of transformer servicing, making it more reliable, and efficient in operation. It is developed based on the mathematical model of the process of cleaning transformer oil of mechanical contaminants with an electric field and gives a theoretical foundation of the optimal control of the process with regard to the technological parameters of oil cleaning systems with an electric field in increasing the efficiency of maintenance and security and ensuring energy efficiency [4, 5, 6].

**RESEARCH OBJECTIVE**

Creation of an algorithm to the process of purifying transformer oil of various mechanical impurities with the help of constant electric field.

**MATERIALS AND METHODS OF RESEARCH**

In the research process, the theories of electrical engineering and electrostatics, the law of electromagnetic induction, Stokes' law, the theory of fluid flow, and the theory of the electric field were used.

**RESULTS OBTAINED AND THEIR DISCUSSION**

The algorithm, developed dealing with the process of purifying transformer oil of the mechanical impurities under the condition of the constant electric field works by the following stages:

1-stage. Introduction of initial parameters: when the algorithm is launched, the user enters the following parameters: B - magnetic induction of the electric field, L - length of the electrode, H - effective height of the electrostatic precipitator, mobility of charged particles generated by electroconvection, characteristic size of the transformer oil, c - coefficient of proportionality for turbulent flow and for laminar flow ,   
Q - transformer oil consumption, - surface density of the electrode. mass of transformer oil, efficiency of the electrostatic precipitator, constant voltage supplied to the electrostatic precipitator [7, 10, 18].

2-stage. Determination of the oil flow regime: the oil flow regime is determined based on the entered parameters (the Reynolds number is selected by introducing the liquid flow characteristic). The conditions are reflected as per Reynolds number, in case of , it represents laminar flow and is considered to be , in case of  
, it is turbulent flow, supposed to be .

3-stage. Simple calculations of the degree of purification: in case of failure in the above condition, then the flow of transformer oil is assumed laminar and calculating the degree of purification of mechanical impurities of transformer oil under the action of a constant electric field by the following expression:

(1)

Concentration of residual mechanical impurities in the transformer oil is determined by the following expression:

(2)

4-stage. The comparison with the standard: enters the condition to compare the above-calculated concentration of residual with the values of the international regulatory document GOST 982-80:

*=min*  (3)

In the case of the low concentration ratio of the mechanical impurities, the algorithm acknowledges the situation “HA” and indicates the concentration of the impurities on the screen. Otherwise (when the level of concentration is not minimized), the algorithm accepts the condition of “NO” and the process is redirected to the initial point.

*Yes*

*No*

*=min*

*Re>2320*

*No*

*Yes*

**FIGURE 1.** Algorithm of operation based on the mathematical expression of an electrostatic precipitator that purifies mechanical impurities from transformer oil through a constant electric field

5-stage. Final stage: At the point, when the number of mechanical particles in the oil will meet the required minimum, the algorithm will assume the cleaning is accomplished and will switch to the state of Completed.

The algorithm was elaborated on the mathematical model of cleaning transformer oil of mechanical impurities in the electric field, which is operating in electrical networks in non-traction of railway transport (fig.1).

Theoretical interpretation of the calculated findings of the derived mathematical formula of determining the algorithm of the realization of the process of purification of transformer oil of various mechanical impurities by using a constant electric field: in the purification of transformer oil with the use of a constant electric field, there can be no actual possibility of complete purification, as it has been noted above. Based on the given expression  
 produced in the course of theoretical study, we find the values of the function which is the degree of oil purification against the mechanical impurities depending on the known constant voltage and used transformer oil in MS Excel program. For this, we introduce the following initial parameters (table.1).

**TABLE 1.** Values of initial calculation of the functional state of the degree of purification of transformer oil of the contaminants of a mechanical nature in a constant regime of oil consumption

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Δφ | χ | m | M | He | Q |
| 0.831033 | 0.2 | 0.115 | 1. | 1. | 5. |
| 0.848642 | 0.24 | 0.115 | 1. | 1.2 | 5. |
| 0.86382 | 0.28 | 0.115 | 1. | 1.4 | 5. |
| 0.877187 | 0.32 | 0.115 | 1. | 1.6 | 5. |
| 0.889149 | 0.36 | 0.115 | 1. | 1.8 | 5. |
| 0.894695 | 0.38 | 0.115 | 1. | 1.9 | 5. |
| 0.905052 | 0.42 | 0.115 | 1. | 2.1 | 5. |
| 0.919058 | 0.48 | 0.115 | 1. | 2.4 | 5. |
| 0.923382 | 0.5 | 0.115 | 1. | 2.5 | 5. |
| 0.931591 | 0.54 | 0.115 | 1. | 2.7 | 5. |
| 0.935495 | 0.56 | 0.115 | 1. | 2.8 | 5. |
| 0.939278 | 0.58 | 0.115 | 1. | 2.9 | 5. |
| 0.942947 | 0.6 | 0.115 | 1. | 3. | 5. |

To construct a graph of the dependence of mechanical impurities in transformer oil on the voltage supplied to the electrostatic precipitator, if the parameters Q, M - coefficient of transformer oil consumption and the mth degree of χ, i.e., m is conventionally assumed to be constant, then according to Table.1. [14, 15, 16, 17] above, the following graph of the dependence of the function was obtained (fig.2).

**FIGURE 2.** Graph of the dependence of the degree of purification on the voltage and oil consumption

The graph in fig.2. shows a total of 14 voltage values in ascending order. With increasing voltage, the degree of oil purification from mechanical impurities for a constant transformer oil consumption decreases, i.e., applying a voltage above the norm negatively affects the degree of oil purification [13, 14, 15]. Therefore, the degree of transformer oil purification was considered for a constant voltage and transformer oil consumption (table.2).

**TABLE 2.** Parameters given for the degree of transformer oil purification for DC voltage and transformer oil consumption

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| No | Δφ | χ | m | M | He | Q |
| 1. | 2,708641 | 0.6 | 0.2 | 3. | 3. | 5. |
| 2. | 2.508847 | 0.6 | 0.35 | 3. | 3. | 5. |
| 3. | 2.32379 | 0.6 | 0.5 | 3. | 3. | 5. |
| 4. | 2.152383 | 0.6 | 0.65 | 3. | 3. | 5. |
| 5. | 1,993619 | 0.6 | 0.8 | 3. | 3. | 5. |
| 6. | 1.846566 | 0.6 | 0.95 | 3. | 3. | 5. |
| 7. | 1.71036 | 0.6 | 1.1 | 3. | 3. | 5. |
| 8. | 1.584201 | 0.6 | 1.25 | 3. | 3. | 5. |
| 9. | 1,467,348 | 0.6 | 1.4 | 3. | 3. | 5. |
| 10. | 1.359113 | 0.6 | 1.55 | 3. | 3. | 5. |
| 11. | 1.258863 | 0.6 | 1.7 | 3. | 3. | 5. |
| 12. | 1,166007 | 0.6 | 1.85 | 3. | 3. | 5. |
| 13. | 1.10794 | 0.6 | 1.95 | 3. | 3. | 5. |
| 14. | 1.052765 | 0.6 | 2.05. | 3. | 3. | 5. |
| 15. | 1,000337 | 0.6 | 2.15 | 3. | 3. | 5. |
| 16. | 0.950521 | 0.6 | 2.25 | 3. | 3. | 5. |
| 17. | 0.903185 | 0.6 | 2.35 | 3. | 3. | 5. |
| 18. | 0.858207 | 0.6 | 2.45 | 3. | 3. | 5. |
| 19. | 0.815468 | 0.6 | 2.55 | 3. | 3. | 5. |
| 20. | 0.774858 | 0.6 | 2.65 | 3. | 3. | 5. |
| 21. | 0.73627 | 0.6 | 2.75 | 3. | 3. | 5. |
| 22. | 0.699604 | 0.6 | 2.85 | 3. | 3. | 5. |
| 23. | 0.664764 | 0.6 | 2.95 | 3. | 3. | 5. |
| 24. | 0.648 | 0.6 | 3. | 3. | 3. | 5. |
| 25. | 0.625238 | 0.6 | 3.07 | 3. | 3. | 5. |
| 26. | 0.612592 | 0.6 | 3.11 | 3. | 3. | 5. |
| 27. | 0.609471 | 0.6 | 3.12 | 3. | 3. | 5. |
| 28. | 0.606366 | 0.6 | 3.13 | 3. | 3. | 5. |
| 29. | 0.603276 | 0.6 | 3.14 | 3. | 3. | 5. |
| 30. | 0.600202 | 0.6 | 3.15 | 3. | 3. | 5. |
| 31. | 0.597144 | 0.6 | 3.16 | 3. | 3. | 5. |
| 32. | 0.594102 | 0.6 | 3.17 | 3. | 3. | 5. |
| 33. | 0.591075 | 0.6 | 3.18 | 3. | 3. | 5. |
| 34. | 0.588063 | 0.6 | 3.19 | 3. | 3. | 5. |
| 35. | 0.585067 | 0.6 | 3.2 | 3. | 3. | 5. |
| 36. | 0.582085 | 0.6 | 3.21 | 3. | 3. | 5. |
| 37. | 0.57912 | 0.6 | 3.22 | 3. | 3. | 5. |
| 38. | 0.576169 | 0.6 | 3.23 | 3. | 3. | 5. |
| 39. | 0.573233 | 0.6 | 3.24 | 3. | 3. | 5. |
| 40. | 0.570312 | 0.6 | 3.25 | 3. | 3. | 5. |
| 41. | 0.567407 | 0.6 | 3.26 | 3. | 3. | 5. |

Due to the repetitive purification of transformer oil with the help of high-voltage electric filter in constant electric field, it achieves the minimum of purifications. Thus, to get a graph of the dependence of the degree of purification by transformer oil of mechanical impurities on time, it is assumed that the voltage applied to the electrostatic precipitator and the consumption of oil of transformer oil is constant and the dependence is created through the degree of dependability [11, 12, 13]. Based on the conditions mentioned above, the graph of the dependence of the purification degree of the transformer oil upon time gets the following form. Figure.3. - indicates that the purification level of transformer oil in mechanical impurities follows an exponentially change with the time. Hence, the level of mechanical impurities in transformer oil does not change with time [17, 18]. Therefore, the period the concentration of the mechanical impurities in transformer oil reaches a constant is seen as the time of transformer oil purification. Due to this period, it is believed that cleaning of transformer oil on the mechanical impurities is inefficient.

**FIGURE 3.** Oil of transformer cleansing from mechanical impurities

**CONCLUSION**

1. The algorithm of the cleaning process of transformer oil by mechanical impurities with the help of an electric field has been elaborated.

2. The dependence of the consumption of oil and voltage during the separation of impurities by oil transformer was established, and, in accordance with it, an analytical formula was derived that estimates the efficiency of the electrostatic cleaning.

3. In order to achieve the purpose of defining the role of the degree of purification of transformer oil of mechanical content, it was worked out that the value of oil consumption and the value of the voltage is represented through the degree of dependence in a constant process.

4. Resting on the received mathematical model, the graphs of the dependence of the degree of cleaning on the voltage and the oil consumption, and on the time were drawn with the help of the Excel environment. Based on such graphs, it was possible to establish the best operating conditions of the electrostatic precipitation process.

5. The conclusions of the work have a profound character and contribute to the scientific substantiation of the essence of cleaning transformer oil by an electrostatic precipitator and can be used as good scientific knowledge on the practical level.

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