2008년도 대한전기학회 EMECS학회 추계학술대회 논문집 (2008.10.23-10.25)

Dynamic Characteristics Analysis of High Speed Thomson-coil Arc Eliminator Using Equivalent Electric Circuit Method with Adaptive Segmentation of Conducting Plate

Wei Li, Jiang Lu, 정영우, 고창섭
충북대학교 전기공학과, LS 산전 전력연구소

Dynamic Characteristics Analysis of High Speed Thomson-coil Arc Eliminator Using Equivalent Electric Circuit Method with Adaptive Segmentation of Conducting Plate

Wei Li, Jiang Lu, YoungWoo Jeong, ChangSeop Koh
School of ECE, Chungbuk National University, Electrotechnology R&D center, LS Industrial Systems Co., Ltd.

Abstract - A novel solving technique has been developed to analyze the dynamic characteristics of high speed Thomson-coil arc eliminator. The electromagnetic repulsion actuator based on Thomson-coil is taken as the driving part of the arc eliminator, due to which, the opening and closing time is quite short compare to other type actuators. The electromagnetic repulsion actuator is composed of one repulsion plate and two fixed coils, corresponding to the opening coil and closing coil, respectively. The new solving technique is derived based on the equivalent electric circuit model of the system which is set up by dividing the repulsion plate into multi segments using adaptive segmentation method. This solving technique is applied to the dynamic characteristic analysis of electromagnetic repulsion actuators in high speed Thomson-coil arc eliminators. The calculation results are testified by the FEM calculation results and experiment results.

1. Introduction

In industry, the arcs caused by large fault currents are very harmful for the devices and equipments of the distribution and transmission networks. Fundamentally eliminating arcs is impossible due to its generating principle. Therefore, to minimize the arc duration becomes a more and more feasible and necessary method to protect the devices and equipments. There are several kinds of mechanism that can be taken as the driving units in high speed arc eliminators, such as the spring mechanism, permanent magnet mechanism, electromagnetic repulsion actuator and so on. Among them the electromagnetic repulsion actuator which uses the Thomson effect to generate the repulsion force takes more advantage over than other driving mechanisms in shorting the opening time and closing time. Shorter action time will directly help shorting the arc duration. Therefore, it is quite necessary to develop this kind of driving mechanism. As there is no magnetic material in the electromagnetic repulsion actuator, it is possible to analyze the property using analytic equations, which is more efficient than using FEM. Although FEM is proved accurate enough to solve this kind of problems, it is quite time consuming and difficult to combine it with optimization algorithms.

Some researches about the numerical calculation of this kind electromechanical coupled problem have been done[1][2]. In this paper, a more accurate and efficient algorithm for analyzing the dynamic characteristics of electromagnetic repulsion actuator is proposed. The whole system is transferred into an equivalent electric circuit model by considering the influence of the eddy current. The inductance parameters are calculated using an algorithm based on Bartky's transformation[3]. This novel solving technique is tested by analyzing the dynamic characteristics of a high speed Thomson-coil arc eliminator. The calculation result is also compared with the FEM result and experiment result.

2 The Equivalent Electric Circuit Model and Solving Procedure

The basic calculation procedure of the proposed method is shown as follow:

Step 1 Divide the plate into initial segments.
Step 2 Make the electromechanical coupled equations.
Step 3 Divide the whole trip to multi time steps.
Step 4 Evaluate the circuit parameters at each time step.
Step 5 Solve the ordinary differential equations.
Step 6 Get the dynamic characteristics of the system.
Step 7 according to the calculated eddy currents in each segment, divide the segments with bigger eddy current into more small segments, and go to step2, ⋯, until get an accurate result.

Fig. 1 The calculation procedure of proposed method

For the electromagnetic repulsion actuator in high speed arc eliminators, the exciting current is supplied by the capacitor storage system. Therefore, if the plate is divided into $n-1$ segments, together with the exciting current circuit, there are n circuits. The circuit equations as well as the flux equations are shown as follow

$$\frac{q}{c}+I_1R_1+\frac{d\lambda_1}{dt}=0 \qquad (1)$$
$$I_kR_k+\frac{d\lambda_k}{dt}=0 \quad k=2,\cdots\cdots n$$

$$\frac{d\lambda_1}{dt}=\frac{d}{dt}\sum_{k=1}^{n}L_{1k}I_k=\sum_{k=1}^{n}L_{1k}\frac{dI_k}{dt}+\sum_{k=2}^{n}I_k\frac{\partial L_{1k}}{\partial z}\frac{dz}{dt} \qquad (2)$$
$$\frac{d\lambda_k}{dt}=\frac{d}{dt}\sum_{j=1}^{n}L_{kj}I_j=\sum_{j=1}^{n}L_{kj}\frac{dI_j}{dt}+\sum_{j=1}^{n}I_j\frac{\partial L_{kj}}{\partial z}\frac{dz}{dt}$$

where R_1 and λ_1 are the resistance and flux linkage of the exciting circuit. I_1 is the exciting current. q and c stand for the charge and value of the capacitor. R_k and λ_k are the resistance and flux linkage of the k^{th} circuit. I_k stands for the eddy current in the k^{th}

circuit. L_{1k} is the mutual inductance between the exciting circuit and k^{th} circuit. L_{kj} is the mutual inductance between the k^{th} and j^{th} circuits. I_j ($j=2,\ldots\ldots n$) is the eddy current in each segment.

If all the inductance and eddy currents are known, the expressions of energy W and electromagnetic force F_{em} are shown as follow:

$$W=\frac{1}{2}\sum_{k=1}^{n}\sum_{j=1}^{n}L_{kj}I_kI_j \tag{3}$$

$$F_{em}=\frac{\partial W}{\partial z}=\frac{1}{2}\sum_{k=1}^{n}\sum_{j=1}^{n}\frac{\partial L_{kj}}{\partial z}I_kI_j=\sum_{i=2}^{n}I_1I_i\frac{\partial L_{1i}}{\partial z} \tag{4}$$

As the self inductance will not change with the relative position between the exciting coil and the levitation plate, so the derivative of the self inductance to the position of the plate is zero. Because all the segments move together as a whole plate, it is unnecessary to calculate the derivative of mutual inductance between two segments. Therefore, in (4) the electromagnetic repulsion force is only decided by the derivative of the mutual inductance between the exciting coil and each segment, as well as the exciting current and the eddy current in each segment.

The motional equations are shown as follow:

$$\dot{I}_{n+1}=\dot{z}=I_{n+2} \tag{5}$$

$$\dot{I}_{n+2}=\ddot{z}=(F_{em}-F_G)/m \tag{6}$$

$$\dot{I}_{n+3}=\dot{q}=I_1 \tag{7}$$

where I_{n+1},I_{n+2},I_{n+3} represent the position, speed and charge respectively. $F_{em},F_G,$ $m$are electromagnetic force, load force and mass of the plate respectively.

Combine circuit equations, energy equations and motion equations, the system matrix state equations can be obtained as follow:

$$\begin{bmatrix} L_{11} & L_{12} & \cdots & \cdots & \cdots & L_{1n} & 0 & 0 & 0 \\ L_{21} & L_{22} & \cdots & \cdots & \cdots & L_{2n} & 0 & 0 & 0 \\ \vdots & \vdots & \ddots & & & \vdots & 0 & 0 & 0 \\ \vdots & \vdots & & \ddots & & \vdots & 0 & 0 & 0 \\ \vdots & \vdots & & & \ddots & \vdots & 0 & 0 & 0 \\ L_{n1} & \cdots & \cdots & \cdots & \cdots & L_{nn} & 0 & 0 & 0 \\ 0 & \cdots & \cdots & \cdots & \cdots & 0 & 1 & 0 & 0 \\ 0 & \cdots & \cdots & \cdots & \cdots & 0 & 0 & 1 & 0 \\ 0 & \cdots & \cdots & \cdots & \cdots & 0 & 0 & 0 & 1 \end{bmatrix}\begin{Bmatrix} \dot{I}_1 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \dot{I}_n \\ \dot{I}_{n+1} \\ \dot{I}_{n+2} \\ \dot{I}_{n+3} \end{Bmatrix}=\begin{Bmatrix} -(\frac{q}{c}+I_1R_1+I_{n+2}\sum_{k=2}^{n}I_k\frac{\partial L_{1k}}{\partial z}) \\ -(I_2R_2+I_{n+2}I_1\frac{\partial L_{21}}{\partial z}) \\ \vdots \\ \vdots \\ \vdots \\ -(I_nR_n+I_{n+2}I_n\frac{\partial L_{n1}}{\partial z}) \\ I_{n+2} \\ (F_{em}-F_G)/m \\ I_1 \end{Bmatrix}$$

Where, F_{em} can be calculated as in (4).

3. Calculation Accuracy

As the numerical calculation of the proposed method is based on the multi segments model, the calculation accuracy of this solving technique mainly depends on the number of segments and the value of time step. For the time step, adaptive time step is adopted with controlling the bound of the truncation error by using Runge-Kutta-Fehlberg method. The smaller the bound of the truncation error is, the more accurate the result is, and the longer the computation time is. Therefore, a reasonable bound of the truncation error is required. For the number of segments, as the eddy current does not distribute uniformly due to the skin effect, the division of the plate should be done based on the distribution of eddy current. To get a reasonable division of the plate, adaptive division is adopted. At the beginning the plate is roughly divided uniformly, as shown in Fig.2. Then after once calculation, according to the value of eddy current in each segment, the segment with bigger eddy current value is divided into more segments. Then after several calculation loops, a reasonable division of the plate is obtained. One example is shown in Fig.3

Usually, the more segments the plate is divided into, the more accurate the result is, also the longer computation time is. Therefore, a reasonable number of segments should be selected by considering both the calculation accuracy and efficiency. Fig.4 shows the comparison of results with different number of segments. From the calculation results, it can be seen that when the plate is divided into more than 62 segments, the calculation result is almost same compare to the result with 62 segments. Therefore, the division with 62 segments is selected as the final division of the plate.

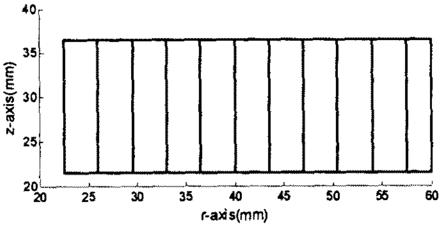

Fig. 2 The initial division of the plate with 11 segments

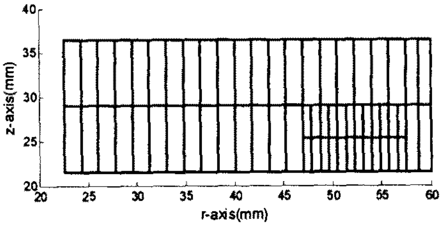

Fig. 3 The refinement of the plate with 62 segments

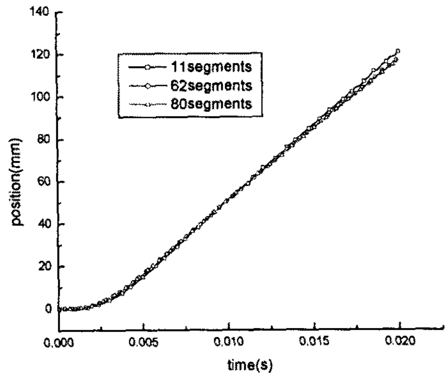

Fig. 4 Comparison of results with different number of segments

4. TestingTheExperimentModel

The calculation results from the proposed method and time-stepping FEM are compared with the experiment results, as shown from Fig.5 to Fig.8, which present the results of exciting current, force, speed and position of aluminum plate respectively.

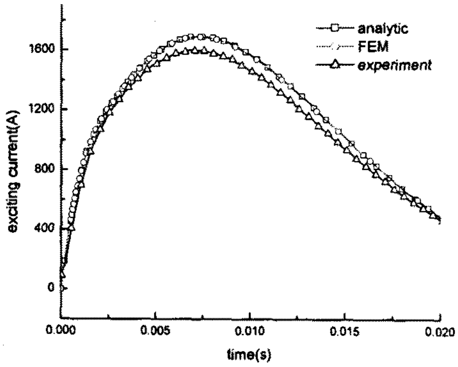

Fig. 5 Comparison of the exciting current

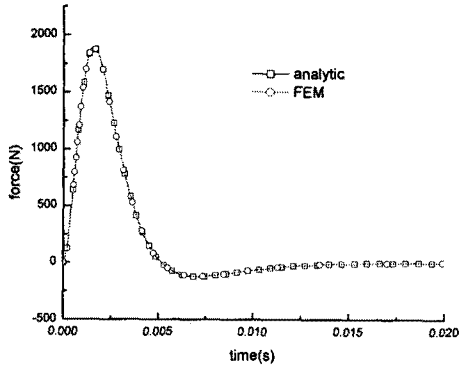

Fig. 6 Comparison of the electromagnetic force

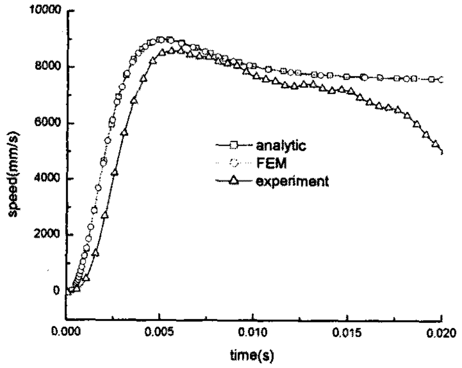

Fig. 7 Comparison of the speed

From the comparison of results, it can be seen that the results from proposed method match well with the FEM results, which proves the accuracy of the proposed method. The computation time using FEM is about ten hours, while it just takes about forty minutes by the proposed method. Therefore, it is much more convenient and efficient by using the proposed method to analyze the performance of high speed Thomson-coil arc eliminators. The experiment results have some error compare to results from FEM and proposed method. This is mainly because the friction that exists in the experiment is not considered in FEM and analytical calculation. Other reasons such as the accuracy of the parameters and the variation of temperature also contribute to the error.

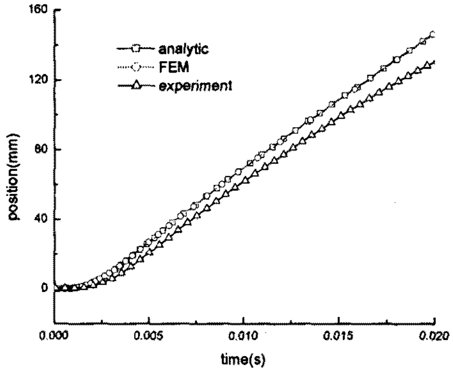

Fig. 8 Comparison of the displacement

5. Conclusion

The dynamic characteristics of a high speed Thomson-coil arc eliminator has been analyzed by using a novel solving technique which is developed based on the multi segments model. By selecting a reasonable value of time step and taking a proper division of the plate, an accurate calculation result can be obtained. Compare to the FEM, this solving technique is much more efficient to get the same accuracy, which is quite important for design and analyze electromagnetic devices. The experiment result is also compared to analysis result, and it shows the same changing trend with a tolerance error. As the proposed method is easy to be combined with the optimization algorithm, optimization of the electromagnetic repulsion actuator can be realized to improve the performance of the high speed arc eliminator in future.

[References]

[1] Toshie Takeuchi, Kenichi Koyama and Mitsuru Tsukima, "Electromagnetic Analysis Coupled with Motion for High-Speed Circuit Breakers of Eddy Current Repulsion Using the Tableau Approach," Electrical Engineering in Japan, vol. 152, no. 4, pp. 8-16, 2005.

[2] Seung-Myen Lee, Se-Hee Lee, Hong-Soon Choi and Il-Han Park, "Reduced Modeling of Eddy Current-Driven Electromechanical System Using Conductor Segmentation and Circuit Parameters Extracted by FEA," IEEE Trans. on Magn., vol. 41, no. 5, pp. 1448-1451, May 2005.

[3] Fawzi TH, Burke PE. The accurate computation of self and mutual inductances of circular coils. IEEE Trans Power Apparatus Syst., vol. 97, no. 2, pp. 464-468, March 1978.