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Testing of High Current Transformer by Non-uniform Equivalent Magnetomotive Force Method

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Abstract- In the testing of high current transformer performance under interference from external current, it is very difficult to reproduce the high current in adjacent bus-bar or eccentric primary bus-bar. To overcome the testing difficulty, this manuscript presents an effective and simple method named as Non-uniform Equivalent Magnetomotive Force (NEMMF) Method, which uses a single non-uniformly distributed testing winding to reproduce the magnetic field from adjacent and concentric primary bus-bars simultaneously. The principle of the NEMMF method is demonstrated and proved by magnetic circuit method, and some key formulas determining the parameters of testing winding have been derived. The NEMMF method is then verified by numerical simulation using Finite Element Method (FEM).

I. Introduction

In high current transformer (HCT), the primary current can be thousands of Amperes. And HCT is usually mounted on one of several bus-bars which are close to each other, as shown in Figure 1. Taking for example the HCT mounted on the bus-bar at outlet of 1,000MW generator, the primary current can be up to 30kA, and currents of 50kA will surely not be the upper limit in the future [1]. In Figure 1, there are three HCTs mounted on each bus-bar. Consequently, each HCT is seriously interfered by magnetic fields from the other five bus-bars [2]. To eliminate or reduce the interference, shielding coils are widely used on HCT [2, 3]. However, it is very difficult to assess the shielding effect of shielding coils or the performance of HCT under interference, since the primary current is too high to achieve in testing.

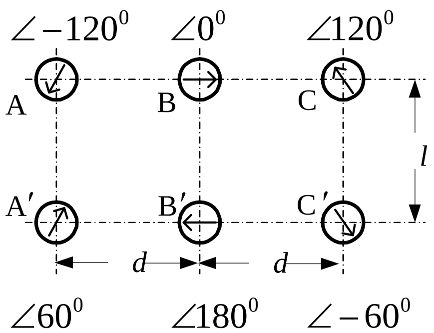


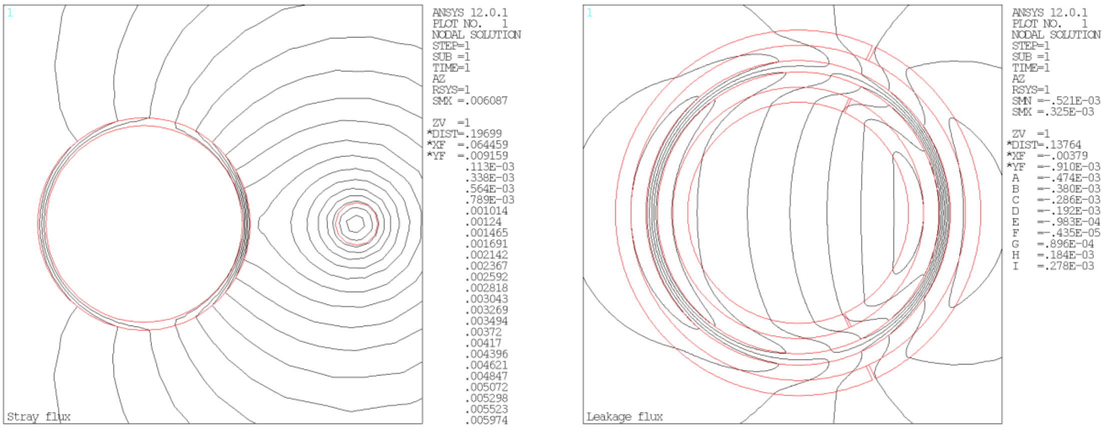
Figure 1. Disposition of terminal bushings on a large generator

For the HCT without interference from external current or eccentric primary current, the magnetic field from concentric primary current is widely reproduced by a uniformly distributed testing winding which has the same total Ampere-turns as the primary current. The method is called the Equivalent Magnetomotive Force (EMMF) Method [4, 5], and has been widely used. However, for the time being, there is still no effective and easy-to-use method to test the HCT performance under interference from adjacent bus-bars or eccentric primary bus-bar in either type testing or field testing, since it is very difficult to provide multiple bus-bars carrying 30kA current. Reference [6] presents an easy-to-use method called eccentric bus-bar testing method, but its capability is limited, the external current that can be reproduced is limited to a certain value. Therefore, it can only be used to test the HCT performance under normal working conditions, but not suitable to fault conditions, in which the adjacent short current is always more than 6 times of the primary current. Reference [7] provides a general method suitable for both normal working conditions and fault conditions, but it is too complicated to use in practical application. The lack of effective testing method of HCT performance under interference, introduces great risks to HCT and consequently to power system. Some power system failures due to the failure of HCT performance under interference have been reported [8].

In order to address the testing difficulty, also as succession of and suggested by reference [6], this manuscript presents a general, effective and simple method named as Non-uniform Equivalent Magnetomotive Force Method (NEMMF).

II. Principle of NEMMF method

Considering the multiple external bus-bars, they can be simplified to a single adjacent bus-bar by space transformation [2, 9]. The model after transformation consists of a normal HCT (including ring-type iron core and secondary winding), a concentric primary bus-bar, and a single adjacent bus-bar, as demonstrated in Figure 2-(a). The magnetic flux in iron core which comes from external current is named as stray flux, which is one type of interfering flux of HCT. For normal HCT, its working flux due to the balance of primary and secondary current is very small compared to stray flux. The other type of interfering flux is the well-known leakage flux, which comes from eccentric primary bus-bar or non-uniformly distributed secondary winding. Leakage flux from non-uniformly distributed secondary winding is demonstrated in Figure 2-(b). Comparing Figure 2-(a) with Figure 2-(b), the flux lines in cores are very similar and both are non-uniformly distributed. So it is natural to come up with the idea of using leakage flux to equivalently reproduce stray flux, which is the basic idea of NEMMF method.



(a) Stray flux lines (b) Leakage flux lines

Figure 2. Illustration of stray flux lines and leakage flux lines.

Magnetic circuit method are applied in this manuscript, to determine the key parameters of testing winding which produce leakage flux that is the same as stray flux from adjacent bus-bar. For an effective equivalent testing method, it must be able to exactly reproduce the stray flux in iron core from the adjacent bus-bar, both in magnitude and in distribution. Based on this principle, if the adjacent bus-bar, equivalent testing winding and HCT are put together, as illustrated in Figure 3, making the leakage flux in opposite direction to stray flux, the testing winding must be able to counteract all of the stray flux from adjacent bus-bar, when excited by proper current.

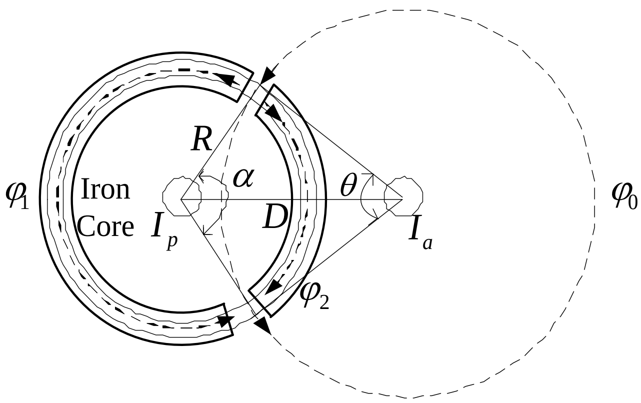


Figure 3. Magnetic circuit model in hypothetical equivalently homogeneous medium

In Figure 3, from the view point of the adjacent bus-bar, it works like in homogeneous air, since its stray flux in the iron core is totally counteracted by the leakage flux from testing winding. The flux lines of the adjacent bus-bar are approximately a group of concentric circles just like that from a bus-bar alone in the air. Therefore, the model in Figure 3 is approximately homogenous. In the homogenous model, there must be a special circular flux line called φ_0, which enters and leaves the iron core vertically. Flux lines with larger radius than that of φ_0 will flow into the left part of the iron core, while the rest flow into the right part. The corresponding central angle, of which the iron core shortens the air path of flux line φ_0, is θ. Geometrically,

$$\theta = 2\text{asin}\frac{R}{D} \tag{1}$$

R is the average radius of the iron core, and D denotes the distance between the core centre and the adjacent bus-bar centre.

Consequently, the MMF of adjacent bus-bar dropping on the iron core is

$$F_0 = \frac{\theta}{2\pi} I_a \tag{2}$$

I_a is the adjacent current. F_0 is equal on both the left and right parts of the iron core.

At this stage, it is natural to think about putting a testing winding on the iron core, with the left part uniformly distributed within angle $360-\alpha$ and the right part uniformly distributed within angle α. MMF from the two parts of the testing winding, F_L, F_R, can be the same or different. But together with the secondary winding, F_L and F_R of the two parts must satisfy that

$$F_t = F_R + F_L = I_s N_s = I_p \tag{3}$$

$$F_R - \frac{\alpha}{2\pi} I_s N_s = \frac{2\pi-\alpha}{2\pi} I_s N_s - F_L = F_0 = \frac{\theta}{2\pi} I_a \tag{4}$$

F_t is the total Ampere-turns of the testing winding. N_s is the number of turns of the secondary winding. I_s is the rated secondary current of HCT.

Because the model is homogenous, there comes

$$\alpha = 2\text{acos}\frac{R}{D} \tag{5}$$

From (1) to (5), it can be solved out,

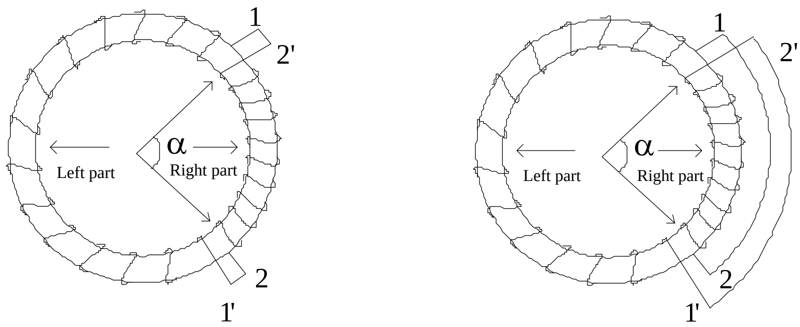
$$\begin{aligned} N_{tr} &= (\text{acos}\frac{R}{D} I_s N_s + \text{asin}\frac{R}{D} I_a)/(I_t \pi) \\ N_{tl} &= ((\pi - \text{acos}\frac{R}{D}) I_s N_s - \text{asin}\frac{R}{D} I_a)/(I_t \pi) \end{aligned} \tag{6}$$

N_{tr}, N_{tl} denotes the number of turns of right and left part of testing winding, respectively. I_t is testing current.

In (6), N_{tr} is always positive, while N_{tl} can be positive or negative. If N_{tl} is positive, the two parts of testing winding are connected in series, as illustrated in Figure 4-(a); if N_{tl} is negative, the two parts are connected oppositely in series, as demonstrated in Figure 4-(b). The connection manner can be determined by the polarity factor, k, which is defined as

$$k = \frac{I_a}{I_p} = \frac{\pi - \text{acos}\frac{R}{D}}{\text{asin}\frac{R}{D}} \tag{7}$$

In (7), k is also equal to the ratio that the magnitude of adjacent current to primary current. For the HCT mounted on the bus-bar at outlet of generator, the distance between bus-bars are usually almost the same as the HCT diameter, ie., $R \approx 0.5D$. Therefore, from (7), $k \approx 4$. In this situation, if k equals to 4, there will be no left-part winding, all the testing windings are wound on the right part. Then, the NEMMF method degenerates to the normal concentrated testing winding method, which winds the testing winding only in a limited part of the iron core.



(a) the two parts of testing winding are connected in series; (b) the two parts are connected oppositely in series.

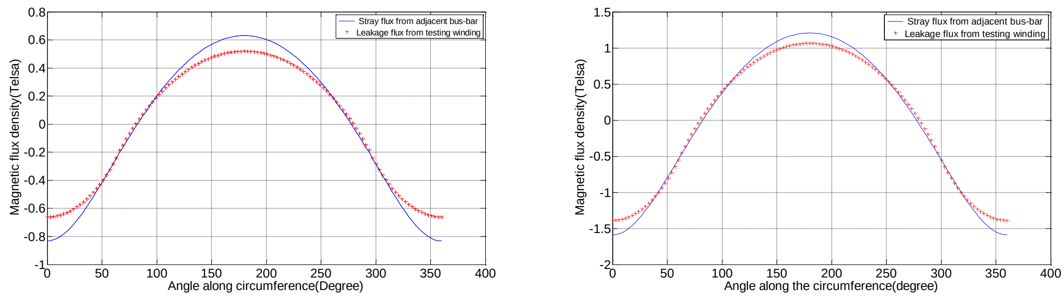
Figure 4. Connection manner of testing winding

III. Verification by FEM

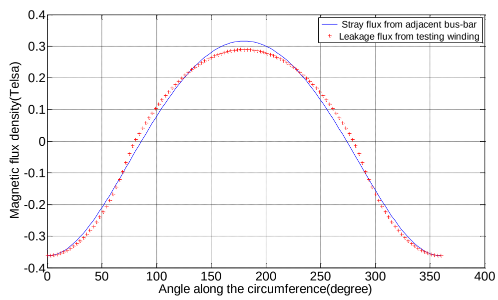
To verify the NEMMF method and formulas derived, numerical simulation by finite element method (FEM) is implemented on a HCT used for 600MW generator, using commercial software ANSYS/EMAG. Model parameters: HCT rated ratio, 25kA/5A; inner diameter, outer diameter and height of the iron core are 740 mm, 840 mm and 50 mm, respectively; relative permeability of iron core is $\mu_r = 10,000$. Three cases are studied. Case 1, $D = 1\text{m}, I_a = I_p = 25\text{kA}$; Case 2, $D = 1\text{m}, I_a = 2I_p = 50\text{kA}$; Case 3, $D = 2\text{m}, I_a = I_p = 25\text{kA}$. From (5) and (6), for case 1, $N_{tl} = 12,500$, $N_{tr} = 12,500$, $\alpha = 130$; for case 2, $N_{tl} = 9,041$, $N_{tr} = 15,959$, $\alpha = 130$; for case 3, $N_{tl} = 12,500$, $N_{tr} = 12,500$, $\alpha = 155$.

The finite element model has iron core, adjacent bus-bar, secondary winding, testing winding, and air enclosure. The number of elements of air enclosure is 126,784, 126,784, and 309,294 for the three cases, respectively; while the number of elements of the model left are 43,200 for all of the three cases.

The FEM results of stray flux from adjacent bus-bar and leakage flux from testing winding are presented in Figure 5 . The results are magnetic flux on the average radius of Iron core.



(a) Case 1, $D = 1\text{m}, I_a = I_p = 25\text{kA}$ (b) Case 2, $D = 1\text{m}, I_a = 2I_p$



(c) Case 3, $D = 2\text{m}, I_a = I_p = 25\text{kA}$

Figure 5. Comparison between stray flux and leakage flux

In each case in Figure 5, the curve shapes of stray flux and leakage flux are the same. However, there are about 10.48%, 10.14%, 7.36% relative errors at the peak of the curves, respectively; and 16.82%, 18.87%, 0.41% relative errors at the trough of the curves, respectively. It is suspected that the error may be due to the assumption of homogenous medium. In the interface between iron core and air, there may be still some convergence and divergence phenomenon of magnetic flux, i.e., the stray flux cannot be totally counteracted, nor is the medium perfectly homogenous.

IV. Conclusion

This manuscript provides a novel testing method of HCT under interference from external current, which is named as NEMMF method. With a single testing winding, the method is easy to be carried out both in type testing and in field testing. The manuscript presents the equivalence between external bus-bar and the non-uniform testing winding; and the equivalent formula between them is also derived. Due to the approximation of magnetic circuit method, there are some equivalent errors in the testing of HCT. Although the equivalent error is still acceptable in practical testing, it is suggested that the electromagnetic analytical method can be used to solve out the parameters of testing winding accurately.

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