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Optimizing the Design of a Dry-Type Single Phase Gapped-Core Shunt Reactor to Empower National Industries

Mohammad Zia Zahedi[1]; Akbar Haidari[2]
[1,2]Physics Department & Kabul Polytechnic University, Afghanistan
[1] mzzahedi@kpu.edu.af; [2] akbar.haidari@kpu.edu.af

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Abstract— The import dependency of essential components in our country's electrical power system poses a significant challenge, emphasizing the importance of focusing on the design, development, and maintenance of power system components, particularly shunt reactors, from an economic standpoint. Domestic production of these components contributes to employment opportunities and enhances self-sufficiency. This study aims to address these challenges by optimizing the design of a dry-type single phase gapped-core shunt reactor with a rating of 100 kVAr and 10 kV. The reactor operates at a frequency of 50 Hz and experiences a maximum core flux density of 1.2 T. The study thoroughly examines the fundamental aspects related to the design of gapped-core shunt reactors. An optimal design is achieved by determining the optimal ratio of the cross-sectional area to the height of each core disk, employing a MATLAB code to minimize the reactor's initial manufacturing cost (IC) or losses. In addition, the proposed design undergoes simulation and analysis using the finite element method (FEM) in the MAXWELL software. The reactor's inductance is obtained through both Maxwell three-dimensional (3D) simulation and analytical methods, demonstrating a reasonable agreement that validates the effectiveness and reliability of the proposed approach.

Keywords— Shunt reactor, Reactor design, Optimal design, Gapped-core, Finite Element Method

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I. INTRODUCTION

The import dependency of essential components in our country's electrical power system poses a significant challenge, emphasizing the importance of focusing on the design, development, and maintenance of power system components, particularly shunt reactors, from an economic standpoint. The design and domestic production of these components contribute to employment opportunities and enhance self-sufficiency.

Shunt reactors are essential in high voltage and extra-high voltage power systems as they compensate large capacitive currents from high-voltage transmission lines over long distances and limit overvoltage during load shedding or line faults [1], [2]. The voltage increase at the end of a transmission line due to no or low load is referred to as the Ferranti effect [3], [4].

A shunt reactor is constructed similarly to a no-load transformer. As depicted in Fig. 1, shunt reactors are constructed with a single winding and a core composed of laminated magnetic steel disks separated by air-gap wedges [5].

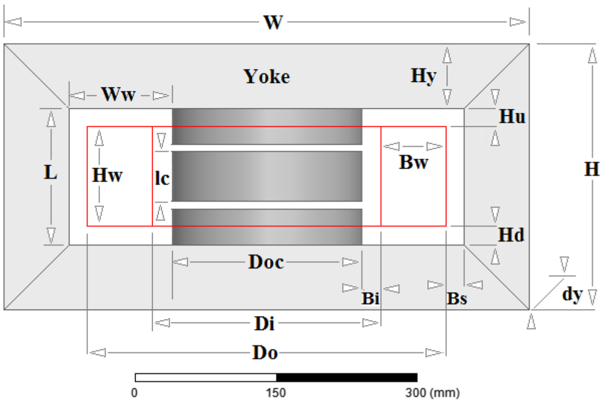

Fig. 1 Modelling of the shunt reactor

The dimensions and materials of shunt reactors are influenced by the area and length of the air gap, which require optimization to minimize iron and copper losses. The ratio of the area to the length of the air gap is a key parameter in shunt reactor design [6]. In this study, we aim to determine the appropriate value for this ratio in order to achieve an optimal design for a specific case of shunt reactor. By decreasing this ratio, the area of the air gap decreases, which requires an increase in the number of turns of the winding to maintain a constant inductance. This leads to increased copper consumption and the initial cost of the design. Conversely, increasing the ratio results in increased iron consumption and higher design costs. Hence, our study focuses on obtaining a suitable value for the ratio, aiming to decrease the initial price of the design while minimizing losses, as the design flowcharts illustrated in Fig. 2 and Fig. 3.

One of the common methods to design and analyze the shunt reactor is to use the magnetic circuit theory [6]–[9]. Using the magnetic circuit theory (analytical approach), we have successfully acquired an optimal design for the specific shunt reactor, reducing the initial manufacturing cost and decreasing losses in the core and winding components. To validate the data obtained from this optimal design, the shunt reactor model was analysed using the finite element method in the Maxwell Software. Finally, a comparison was made between the results obtained from the analytical and numerical methods.

While finite FEMs can accurately calculate magnetic flux density and inductance [8]–[11], they are time-consuming and not suitable for our optimization problem. Therefore, the magnetic circuit theory was employed as the preferred method to determine the optimal design.

It is worth mentioning that while there is limited research available, some studies have explored various aspects of shunt reactor interactions with power systems, including transient conditions, nonlinear dynamic modelling, and manufacturing aspects [12]–[15].

In cases where flux fringing effects in the air gap have a significant impact, the air gap length is distributed along the core leg to mitigate these effects [7].

II. OPTIMAL DESIGN USING ANALYTICAL METHODS

A. *Initial cost consideration*

The model of a single phase shell-type gapped-core shunt reactor is shown in Fig. 1. As a case study, we want to design a shunt reactor with specifications of 100 kVAR, 10 kV, 50 Hz, and 1.2 T. The design process utilizes equations derived from magnetic circuit theory while disregarding the reluctance of iron and copper losses [7].

The design flowcharts for minimum IC and losses illustrated in Fig. 2 and Fig. 3, respectively.

By utilizing the basic specifications of the shunt reactor, including parameters such as reactive power, voltage, frequency, and magnetic flux density, we can determine the volume of the air gap and inductance.

A reactor is an energy storage device which receives energy W_m from and returns it to the supply at a rate, double that of the frequency $\omega = 2\pi f$ supplied.

$$W_m = B_m^2/(2\mu_r\mu_0) \cdot V \tag{1}$$

where B_m and μ_r are the maximum flux density, relative permeability in the volume V respectively, μ_0 is the free space permeability $4\pi \times 10^{-7}\mathrm{H/m}$. It is apparent that, when considering energy storage, only non-magnetic materials such as air with a relative permeability μ_r of 1 are taken into account. Consequently, for a given rating, the product of $B_m^2 \cdot V$ remains constant.

There are two primary solutions to this design problem [16]:

1. Utilizing a large volume V and reducing the flux density B_m.
2. Opting for a small volume V and increasing the flux density B_m.

Examples of each solution are the air core and the gapped-core shunt reactor, respectively.

The reactive power Q is the amount of power absorbed or generated by the reactor, which helps regulate the system voltage and improve power factor. The reactive power rating Q for a gapped-core shunt reactor is given by

$$K_f \cdot Q = W_m \cdot \omega \tag{2}$$

Where K_f is the fringing effect factor. Then, by substituting W_m from Eq. (1) into Eq. (2) we obtain the gap volume V_g as following:

$$V_g = A_g \cdot l_g = K_f \cdot Q / \left(\omega \cdot B_m^2/(2\mu_o)\right) \tag{3}$$

Based on eq. (3), the volume of the air gap is determined by main parameters such as reactive power, magnetic flux density, and voltage frequency.

The size and dimensions of the air gap can be adjusted to achieve the desired level of reactor inductance and reactive power compensation [6].

The inductance of a shunt reactor L is an important parameter the amount of reactive power absorbed or generated by the reactor. It can be obtained from the equation $K_f \cdot Q = V_e^2/(\omega \cdot L)$:

$$L = V_e^2/(2\pi f \cdot K_f \cdot Q) \tag{4}$$

where V_e is the effective nominal voltage of the power system [6], [9].

Since the crucial parameters of the design depend on the ratio of the gap area (the effective surface of air gap) to the length of the air gap i.e. $x = A_g/l_g$, the optimal design algorithm involves adjusting this ratio within a specific range. By varying the ratio x, we can optimize the design for desired specifications.

Having the volume of the air gap and the mentioned ratio, the total length of the air gap can be determined as follows:

$$l_g = \sqrt{V_g/x} \tag{5}$$

So, the gap area can be acquired such as:

$$A_g = x \cdot l_g \tag{6}$$

Since the inductance is calculated based on the reactor's physical dimensions and number of turns N [6], [9]:

$$L = \mu_o \cdot N^2 \cdot \left(A_g/l_g\right) \tag{7}$$

Therefore, the number of turns in the winding can be calculated as follows:

$$N = \sqrt{L/(\mu_0 \cdot x)} \tag{8}$$

In the case of a dry and naturally cooled shunt reactor, the current density is typically assumed to be $J = 2.3\ \mathrm{A/mm^2}$. Therefore, the cross-sectional area of the winding A_w can be determined as following [6]:

$$A_w = N \cdot I_e/(K_u J) \tag{9}$$

where I_e and K_u are effective current and the winding filling factor, respectively.

By considering A_w, the width B_w of the winding can be obtained from the $H_w/B_w = 2$, because of the technical and financial point of view [7].

Considering the diameter of the air gap area and the width of the winding, the average length of each turn of the winding can be obtained such as [6]:

$$l_{\mathrm{av}} = \pi \cdot (D_i + D_o)/2 \tag{10}$$

The volume of the core V_{Fe} can be obtained by summing the volume of the yoke i.e. $l_y A_y$ and the leg i.e. $\left(L - l_g\right) A_{\mathrm{leg}}$. Hence, to calculate each of these volumes, we multiply their respective lengths by their cross-sectional areas [6].

$$V_{Fe} = l_y A_y + \left(L - l_g\right) A_{\mathrm{leg}} \tag{11}$$

Considering the densities of iron $\rho_{Fe} = 7650\ \mathrm{kg/m^3}$ and copper $\rho_{Cu} = 8960\ \mathrm{kg/m^3}$, the mass of the main components in the construction of the shunt reactor can be determined as follows:

$$M_{Fe} = \rho_{Fe} \cdot V_{Fe} \tag{12}$$

$$M_{Cu} = \rho_{Cu} \cdot (l_{\mathrm{av}} \cdot A_w) \tag{13}$$

The initial cost of manufacturing the shunt reactor, taking into account the prices of iron (M5 Steel) $A = 2.5\ \$/\mathrm{kg}$ and copper $B = 5.0\ \$/\mathrm{kg}$, can be determined as follows:

$$IC = M_{Fe} \cdot A + M_{Cu} \cdot B \tag{14}$$

According to the flowchart for determining the minimum cost of the initial manufacturing of the shunt reactor, as shown in Fig. 2, the design algorithm involves comparing the initial manufacturing cost obtained with the costs of previous designs. If the obtained cost is the minimum among the previous costs, the algorithm reaches its end. However, if the cost is not the minimum, the algorithm proceeds by adjusting the mentioned ratio x and repeating the calculations to obtain the minimum cost within the desired range. This iterative process allows for refinement and optimization of the shunt reactor design to achieve the most cost-effective solution.

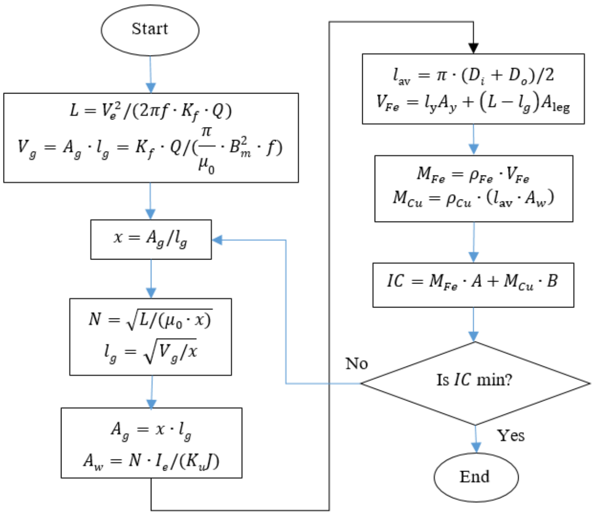

Fig. 2 Presents the flowchart outlining the algorithm for the optimal design of the IC

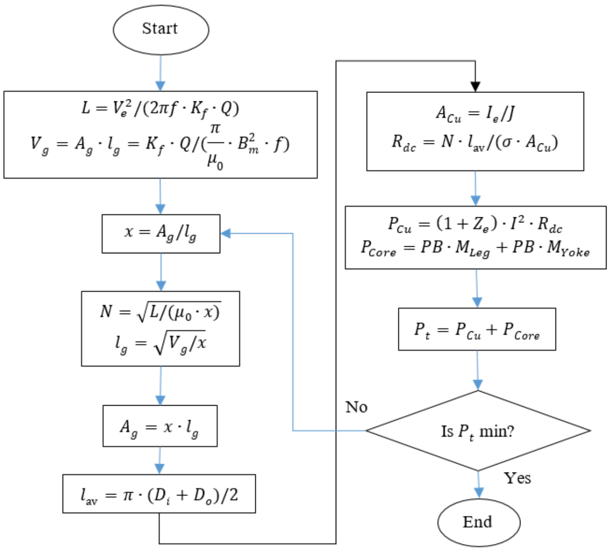

Fig. 3 Illustrates the flowchart representing the algorithm for minimum losses design

B. *Losses consideration*

To achieve the optimal design of the shunt reactor with minimum losses, it is necessary to follow the process outlined in Fig 3. As explained earlier, the inductance and air gap volume are determined using the specifications of the shunt reactor. Since the parameters affecting losses are dependent on the mentioned ratio, it is important to consider a specific value within the desired range for the ratio. Then, as in the previous calculations, the number of turns, length of the air gap, area of the air gap, and average length of each winding turns are calculated.

The effective current of the winding is obtained by using the equation

$$I_e = B_m \cdot l_g/(\sqrt{2}\mu_o \cdot N) \tag{15}$$

The cross-sectional area of each turn of the winding can be obtained from the current density as follows:

$$A_{Cu} = I_e/J \tag{16}$$

Therefore, the DC resistance of the winding is

$$R_{dc} = N \cdot l_{av}/(\sigma \cdot A_{Cu}) \tag{17}$$

where σ is the conductivity of the copper.

The total loss of the reactor, P_t, consists of the iron loss, P_{Fe}, induced in the cores, and the conduction loss, P_{Cu}, of the joule losses in the windings. Moreover, P_{Fe} can be divided into the core loss, P_{Core}, derived from the magnetic properties of the core materials, and the gap loss, P_{Gap}, due to in-plane eddy currents induced from the leakage magnetic flux around the air gaps between the core components. Therefore, P_t can be defined as

$$P_t = P_{Fe} + P_{Cu} = (P_{Core} + P_{Gap}) + P_{Cu} \tag{18}$$

P_{Cu} Calculated from the ac resistance of the coil, R_{dc} as

$$P_{Cu} = (1 + Z_e) \cdot I^2 \cdot R_{dc} \tag{19}$$

where Z_e is the eddy loss factor of the winding.

The core losses consist of two parts: leg and yoke losses. To obtain the value of losses per unit mass in each part, the losses-magnetic flux density graph provided by the manufacturer of the magnetic core is used. Considering the desired magnetic flux density in each part, the amount of losses is obtained from the following equation.

Under sinusoidal flux conditions, core loss is computed in the frequency domain as the following:

$$P_{Core} = PB(B_m) \cdot M_{Leg} + PB(B_m) \cdot M_{Yoke} \tag{20}$$

According to the flowchart for determining the minimum total losses, P_t of the shunt reactor, as shown in Fig. 3, the design algorithm involves comparing the P_t obtained with the loss of previous designs. If the obtained loss is the minimum among the previous ones, the algorithm reaches its end. However, if the P_t is not the minimum, the algorithm proceeds by adjusting the mentioned ratio x and repeating the calculations to obtain the minimum loss within the desired range. This iterative process allows for refinement and optimization of the shunt reactor design to achieve the most loss-effective solution.

C. *Design results*

Based on the plots of variations in losses and the initial price with respect to x in Fig. 4, the initial price of constructing the shunt reactor and its minimal losses are obtained for a specific value of 1.35 m. That is, from the economic point of view, not only the initial manufacturing cost but also the losses have been minimized.

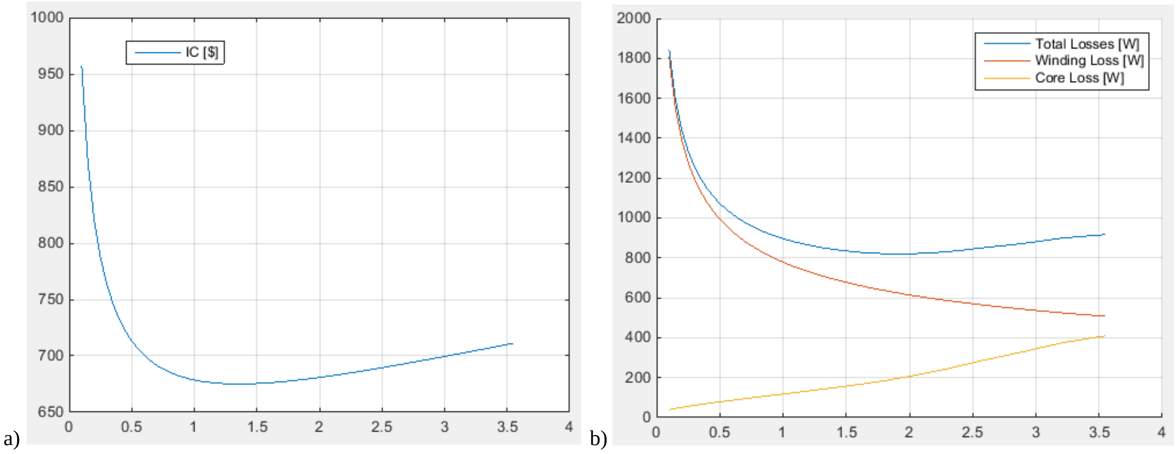

Fig. 4. a) IC and b) Total losses curves vs. $x = A_g/l_g$

The dimensions and other parameters, based on the specified shunt reactor specifications and $A_g/l_g = 1.35$ m, have been presented in Table I. Each parameter has been previously introduced.

To ensure the accuracy of these results, we will perform a simulation of the obtained design using the Maxwell software program by FEM.

TABLE I
THE RESULT OF THE PROPOSED OPTIMAL DESIGN

Parameters	Value	Parameters	Value	J	2.3 A/mm^2
A_g/l_g	1.35 m	H_u	20 mm	K_w	0.30
B_m	1.2 T	H_w	141.8 mm	K_t	0.73
Q_e	100 kVAr	B_w	70 mm	K_c	0.95
V_e	10 kV	H_y	70 mm	K_f	1
I_e	10 A	l_g	20.3 mm	K_{leg_Loss}	1
L_s	3.18 H	L	181.8 mm	Z_e	0.15
R_{dc}	6.11 Ohm	W_w	110 mm	K_u	0.6
R_{ac}	7.02 Ohm	d_y	186.7 mm	A_y/A_{leg}	0.4773
N	1370	H	321.8 mm	IC	675.13 $
B_i	20 mm	W	546.7 mm	P_t	847.47 W
B_s	20 mm	D_o	366.7 mm	P_{Cu}	702.42 W
H_d	20 mm	W_{Fe+Cu}	220.31 kg	P_{Core}	145.06 W

III. SIMULATION WITH FINITE ELEMENT METHOD

A. *Model by FEM*

To model the described reactor using 3D FEM. The past research has proven the validity and accuracy of FEM in reactor modelling [17]-[19]. Thus, a 3D model is created. Meshing the space of the problem and presuming linearity, the Poisson vector equation (Eq. (21)) is solved.

$$\nabla \times \left(\frac{1}{\mu_o \mu_r} \nabla \times \vec{A}\right) = \vec{J} \tag{21}$$

where $\vec{A}$ is the magnetic potential vector and μ_r is the relative permeability.

Once the problem has been solved and the magnetic potential vector has been obtained, other parameters such as magnetic flux density $\vec{B} = \nabla \times \vec{A}$ and the magnetic field strength $\vec{H} = \vec{B}/\mu_o\mu_r$ will be calculated. Subsequently, the equations below will provide the density of the energy in the space of the problem, and the inductance of the winding:

$$W_m = \frac{1}{2}\int \vec{H} \cdot \vec{B} dv \tag{22}$$

$$L = \frac{2W_m}{I_m^2} \tag{23}$$

where W_m, $\vec{B}$ and $\vec{H}$ represent the magnetic energy, magnetic flux density, and magnetic field strength, respectively.

In order to calculate the core loss in Maxwell, the loss curves of the core material obtained from the manufacturer have been defined in the transient solution type solution step [20].

B. *FEM results*

3D-Magnetostatic solution type in an Ansoft Maxwell 15.0 is used to simulate the single phase reactor [20]. In the following figures the 3D mesh, the distribution of the magnetic flux density and the energy density in the design have been resulted, respectively.

Inductance of the main air gap is obtained $L = 3.15$ H by using the following code in the field calculator of the program:

$$Scl: 3.15$$

$$Scl:/(*\ (Integrate(Volume(Gap).energy).2).Pow(Irms.2)) \tag{24}$$

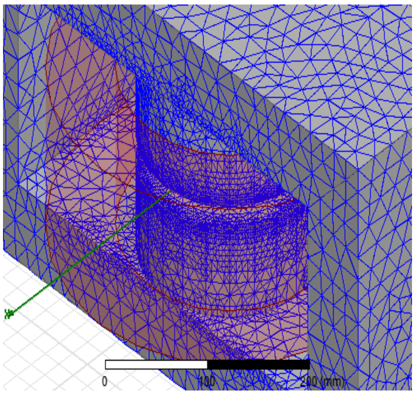

Fig. 5 Displays the used 3D mesh.

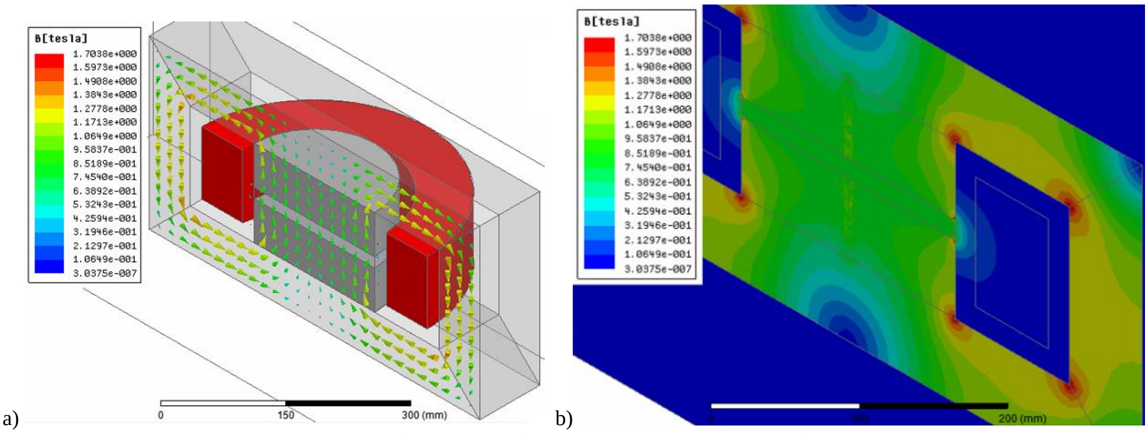

Fig. 6. Distribution of a) Magnetic flux density vector, b) Magnetic flux density value

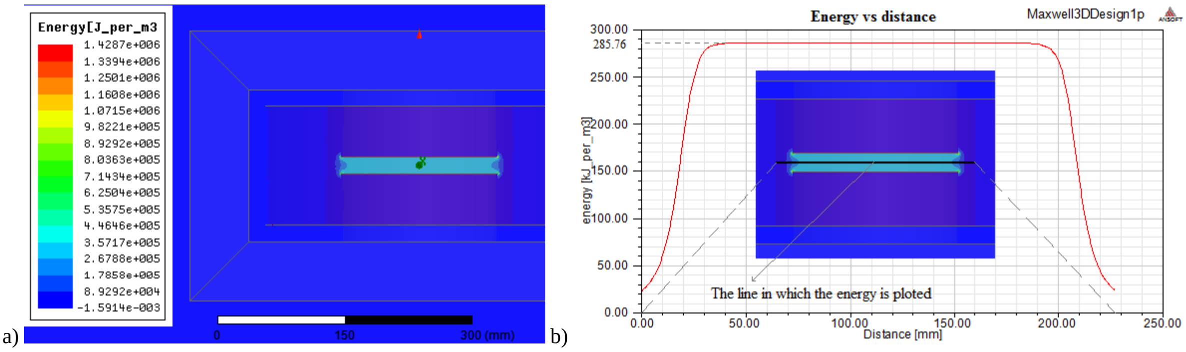

Fig. 7. a) Distribution of magnetic energy density, b) Energy variation along the line at the middle of the air gap

By comparing the obtained inductance of the mentioned shunt reactor from analytical method calculation, which is 3.18 H, with the numerical method calculation of 3.15 H, the relative error is found to be 0.95%.

IV. CONCLUSIONS

In this work firstly, the fundamental aspects in a dry type gapped-core shunt reactor design have been presented, and then an optimum design (optimum value for the A_g/l_g ratio) of a 100 kVAr, 10 kV, 50 Hz and 1.2 T in the core of the shunt reactor to minimize the IC or losses has been done using the MATLAB code.

Finally, a FEM simulation of the proposed design in the MAXWELL software has been done and analyzed. Inductance parameters have been calculated by using Maxwell 3D optimization work. Since the obtained inductance from the simulation matches well with that acquired from the analytical method, the authors hope that by using the proposed analytical method, the groundwork for simulating and manufacturing a single phase shunt reactor with the minimum IC or losses provided domestically.

Considering the credibility of the simulation results using the FEM, it is economically reasonable to suggest that each product be simulated before its manufacturing.

REFERENCES

1. Y. G. Zhang, K. X. Chang, and Y. C. Su, "Shunt reactors compensation research of UHV accessed to Jiangxi power grid," *Advanced Materials Research*, 1070, pp. 1029-1034, 2015.
2. J. C. Whitaker, *AC Power System Handbook*. San Diego, CA: Morgan Hill, 2007.
3. G. Deb, "Ferranti effect in transmission line," *International Journal of Electrical and Computer Engineering (IJECE)*, 2(4), pp. 447-451, 2012.
4. A. D. S. Sri, K. T. Devi, K. D. Raju, and B. Tanya, "Depiction and Compensation of Ferranti Effect in Transmission Line," *International Journal for Research in Applied Science and Engineering Technology*, 6(3), pp. 1522-1526, 2018.
5. Y. Ikeda, H. Naito, and M. Abe, "Technological trend in the recent development of shunt reactor," 1982.

6. A. Lotfi, and M. Faridi, "Design optimization of gapped-core shunt reactors," *IEEE transactions on magnetics*, *48*(4), pp.1673-1676, 2012.

7. A. Lotfi, and E. Rahimpour, "Optimum design of core blocks and analyzing the fringing effect in shunt reactors with distributed gapped-core," *Electric power systems research*, 101, pp.63-70, 2013.

8. H. B. Duc, T. P. Minh, T. P. Anh, and V. D. Quoc, "A Novel Approach for the Modeling of Electromagnetic Forces in Air-Gap Shunt Reactors. Engineering," *Technology & Applied Science Research*, 12(1), 8223-8227, 2022.

9. T. P. Minh, H. B. Duc, N. P. Hoai, T. T. Cong, M. B. Cong, B. D. Thanh, and V. D. Quoc, "Finite element modeling of shunt reactors used in high voltage power systems," *Engineering, Technology & Applied Science Research*, 11(4), 7411-7416, 2021.

10. S. Magdaleno-Adame, R. Escarela-Perez, J. C. Olivares-Galvan, E. Campero-Littlewood, and R. Ocon-Valdez, "Temperature reduction in the clamping bolt zone of shunt reactors: Design enhancements," *IEEE Transactions on Power Delivery*, 29(6), pp.2648-2655, 2014.

11. T. P. Minh, H. B. Duc, and V. D. Quoc, "Analysis of leakage inductances in shunt reactors: Application to high voltage transmission lines," *Engineering, Technology & Applied Science Research*, 12(3), pp. 8488-8491, 2022.

12. P. Mestas, M. C. Tavares, and A. M. Gole, "Implementation and performance evaluation of a reclosing method for shunt reactor-compensated transmission lines," *IEEE Transactions on Power Delivery*, 26(2), pp. 954-962, 2010.

13. G. W. Chang, H. M. Huang, and J. H. Lai, "Modeling SF_6 Circuit Breaker for Characterizing Shunt Reactor Switching Transients," *IEEE transactions on power delivery*, 22(3), pp. 1533-1540, 2007.

14. E. Kurt, A. Arabul, I. Senol, and F. K. Arabul, "An Investigation on Flux Density of Three Phase Distributed Air-Gap 3-5 Legged Shunt Reactor," *in Proceedings of The IRES 21st International Conference*, 2015, Amsterdam, Netherlands.

15. I. Uglešić, S. Hutter, M. Krepela, B. Filipović-Grčić, and F. Jakl, "Transients due to switching of 400 kV shunt reactor," *in International Conference on Power System Transients (IPST)*, 2001, Rio de Janeiro, Brazil.

16. M. Rhristoffel, "The design and testing of EHV shunt reactors," *IEEE Transactions on Power Apparatus and Systems*, (6), pp.684-692, 1967.

17. A. Lotfi, and M. Faridi, "Inductance calculation of shunt reactor using 3D finite element method," *in Power System Conf.(PSC)*, 2009.

18. T. Sakura, N. Takashi, and K. Fujiwara, "3D-finite element analysis of eddy current loss of three-phase shunt reactor," *JSAEM*, 1, pp. 81-88, 2003.

19. L. Yan-ping, Z. Fang, Z. Hai-ting, and A. Zhen, "Leakage inductance calculation and simulation research of extra-high voltage magnetically controlled shunt reactor," *in 2010 International Conference on Mechanic Automation and Control Engineering*, 2010, pp. 4025-4028.

20. ANSYS, F. (2012). User's Guide, ANSYS, Inc., Canonsburg, PA, USA.