Project Title: Feasibility study and developing technological design know-how, construction and operational knowledge of executing smoothing reactors in HVDC substations

Department:	Transmission line and substation equipment	***Employer:***	NRI
Project/Program Manager:	Ali Kadivar	***Executor:***	Arman Safaei
Project Financial Code:	126013	***Project Quality Code:***	PPTPN06-4
Type of Project/Program:	Related to agreement	***Assistant:***	Deputy of Research

Project Staff: Arvin Pourebrahim shishvani

Keywords: Air-core smoothing reactor; Thermal behavior; Winding layer; HVDC systems: fault limiter: Multiphysics; COMSOL; Magneto-hydro-dynamics

Project Necessity:

DC smoothing reactors play an inevitable role in the reliability and stability of HVDC systems by reducing current harmonics, transient over-currents, and other fluctuations that may occur in the system due to switching and load changes [1-3]. Two types of smoothing reactors are used in DC networks, iron-core reactor, and air-core reactor. The structure of the iron-core reactor resembles a power transformer. They have an iron-core and an oilpaper insulating system. The main structure of an air-core reactor is a hollow multi-layer winding that is typically placed on an insulating stand. Nowadays utilizing dry-type air-core smoothing reactors in DC transmission systems is on the rise due to their simple structure, easy transport, simple installation, and low operation and maintenance costs [4-6].
Given that the load current flows through the reactor (nominal DC current plus harmonics), high resistive losses occur in the reactor winding which leads to its temperature rise. Therefore, proper cooling must be considered carefully during the reactor winding design. If not, overheating or local heating in the winding can occur, which can cause permanent failure or reduce the lifetime of the winding [1, 7].

Project Goals:

In the light of the rapid development of numerical methods and the performance of computers, many researchers have utilized finite element methods to study air-core smoothing reactors from different viewpoints [5]. For instance, [3] has used Ansys® software to evaluate the magnetic field distribution around an air-core smoothing reactor. In [2] and [5] the electric field distribution around the reactor as well as on its insulator surface has been assessed using three dimensional (3D) models. given the importance of reasonable cooling in air-core reactors, many researchers have been dedicated to studying their thermal characteristics. In this regard [8] has studied the effect of the surrounding acoustic barrier around the air-core reactor winding on its steady-state temperature distribution. This research has optimized the dimensions of the acoustic barrier to reduce the sound pressure around the winding while maintaining its temperature as low as possible. In a similar approach in [1, 7, 9] the effect of the acoustic barrier and the rain cap on the winding temperature distribution of air-core smoothing reactor is investigated.

In this paper thermal behavior of an air-core smoothing reactor winding designed based on the requirements for the future network in Iran is investigated and its basic design stage is studied by analyzing temperature distribution in winding with and without rain cap and acoustic enclosure. The obtained results can be very useful in selecting proper insulation for the winding conductors and a general understanding of the thermal behavior of the designed winding.

To increase the accuracy of the analysis and obtained results, the issue is resolved in COMSOL® Multiphysics by involving electromagnetic fields, heat transfer in solids and fluids, laminar fluid flow, and electric current distribution all at the same time. This way, the steady-state condition of the winding is determined considering the interaction of winding temperature distribution, the magnetic field around the coil, ventilation of the winding by air, and current distribution in the winding.

Abstract: Air-core smoothing reactors are widely used in DC transmission systems to reduce the rate of rise of the fault current, harmonics and are much favorable due to their low maintenance and operation cost beside the higher saturation points compared with the iron-core ones. The proper design of air-core reactors can play a crucial role in increasing their reliability and lifetime. One of the most important aspects of air-core reactor design which has a sever effect on its lifetime is the winding ventilation and its steady-state temperature. In this paper design of an 80mH air-core smoothing reactor is investigated through finite element method modeling of its winding temperature in its steady-state operation condition. The results show that the temperature distribution in different winding layers is highly dependent on the airflow velocity between the layers. Moreover, mounting acoustic enclosure and the rain cap at the winding top can disturb the airflow through the reactor, hence its ventilation. However, with proper design, their negative effect on winding ventilation can be decreased.

Steps and Methodologies:

To increase the accuracy of the analysis and obtained results, the issue is resolved in COMSOL® Multiphysics by involving electromagnetic fields, heat transfer in solids and fluids, laminar fluid flow, and electric current distribution all at the same time. This way, the steady-state condition of the winding is determined considering the interaction of winding temperature distribution, the magnetic field around the coil, ventilation of the winding by air, and current distribution in the winding. The interplay of the abovementioned cases is illustrated in Fig. 1.

In the following sections, first, the winding structure of an air-core smoothing reactor is reviewed, and the specifications of the modeled winding are presented. Then the governing equations of the simulations are explained and eventually the obtained results are analyzed.

The air core smoothing reactor winding is mainly composed of several layers of coaxial coils, which are connected in parallel and each individual layer is made of one or more insulated conductors. As mentioned, layers are connected in parallel by welding their ends to the metal beam structures on the top and bottom of the winding, known as spider arms. In addition to enhancing the mechanical strength of the winding, spider arms also act as current terminals to the reactor. Also, the individual concentric layers are radially separated from each other by fiberglass sticks which form the air ducts that are necessary for the cooling of the winding [8, 10, 11]. A simplified demonstration of smoothing reactor winding is shown in Fig. 2.

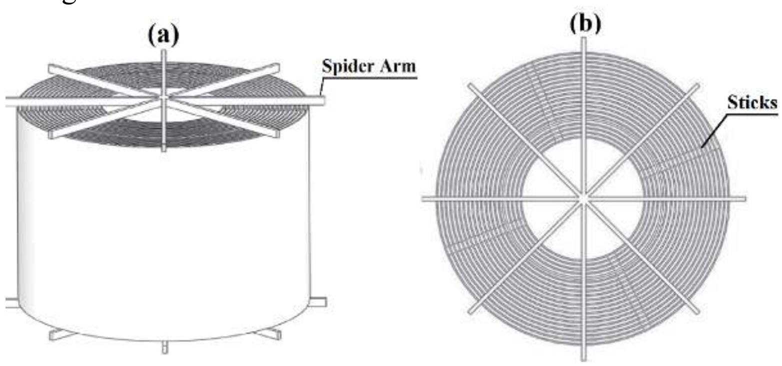

Fig. 2. Structure of an air-core smoothing reactor winding, (a) side view, (b) top view.

It was considered based on the available data from HVDC research center that the requirements will be a smoothing reactor at 280 kV DC (full wave DC at 400 kV AC) and about 1500 A. Generally, air-core smoothing reactors' inductance is between 75mH and 100mH [6]. With that in mind, the winding parameters were considered in a way that its inductance be in that range. It was also considered that each layer of winding is consisting of an aluminum conductor with a cross-section of $70mm^2$. Moreover, considering that the fiber sticks and spider arms have a negligible effect on the airflow through winding layers and its ventilation, they were omitted in modeling. An scaled section of the modeled winding is shown in Fig. 3 and its parameters are listed in Table I.

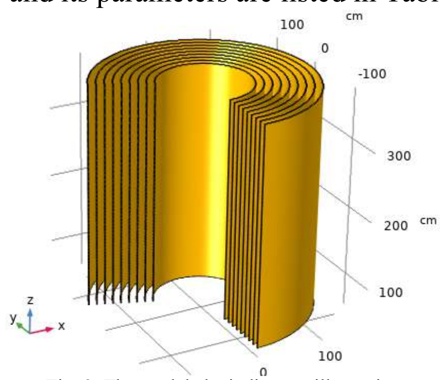

Fig. 3. The modeled winding cut illustration.

TABLE I. MODELED WINDING PARAMETERS

Characteristics of the winding	*Value*
Reactor height	320cm
Number of layers	9
Inner layer diameter	66cm
Outer layer diameter	154cm
Space between layers	10cm
Rated DC current	1500A
Number of turns in each layer	320
Inductance	80mH

Main Results (technical outputs, patents, papers, books, reports, etc.):

The main objective of this study is to analyze the thermal behavior of an air-core smoothing reactor with and without an acoustic barrier and rain cap. In this regard, the winding model with and without outer accessories was implemented in COMSOL® Multiphysics. Due to the axial symmetry of the modeled structures and to reduce the required calculations for modeling, the simulations were conducted in a two dimensional (2D) axisymmetric domain. An illustration of modeled windings is given in Fig. 4 and the final revolved geometry of the windings is displayed in Fig. 5. It was assumed that the rated DC current passes through the winding and the ambient temperature is 293K then its behavior was analyzed.

Each

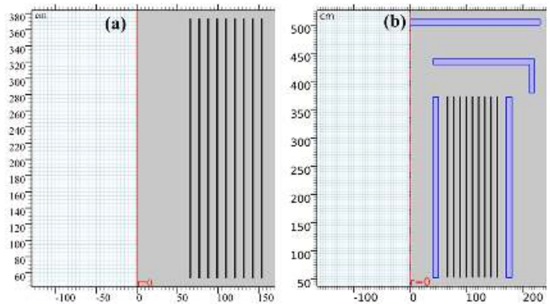

Fig. 4. 2D axisymmetric modeled windings, (a) without acoustic barrier and rain cap, (b) with acoustic barrier and rain cap.

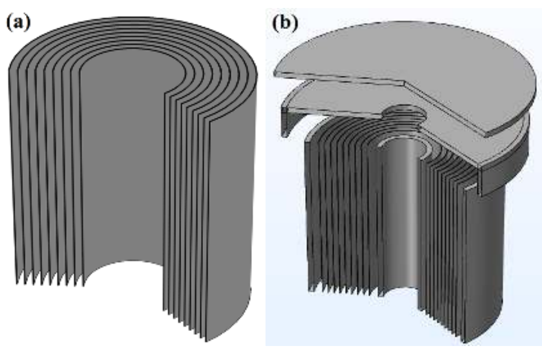

Fig. 5. Revolved model of studied windings, (a) without acoustic barrier and rain cap, (b) with acoustic barrier and rain cap.

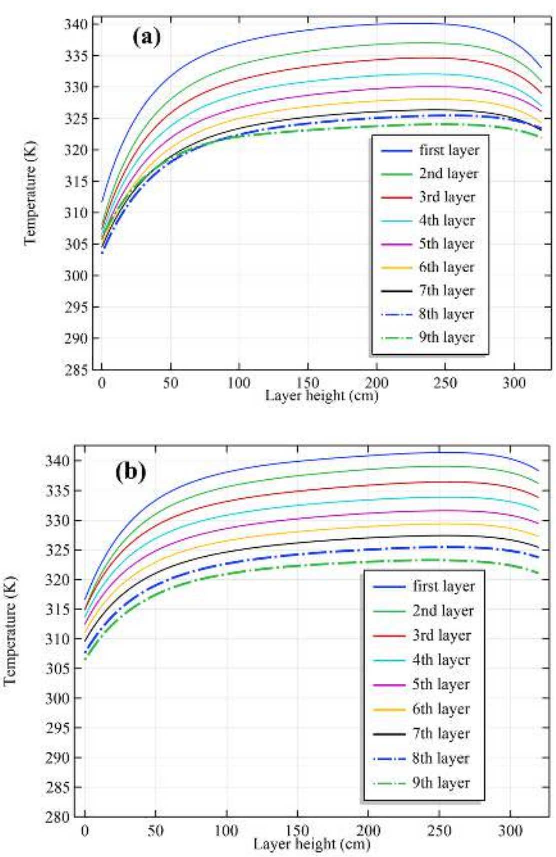

Fig. 6. Winding layers temperature, (a) without acoustic barrier and rain cap, (b) with acoustic barrier and rain cap.

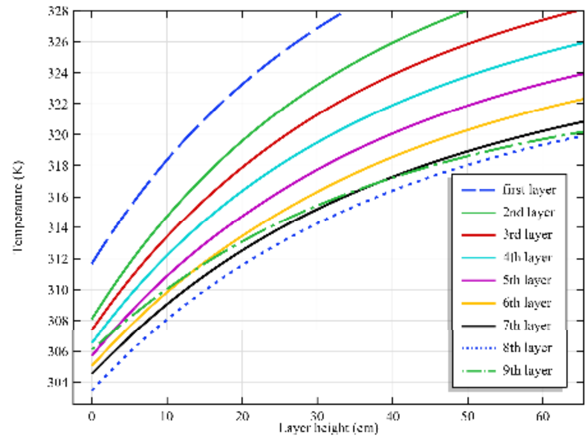

Fig. 7. Temperature distribution of layers in the lower quarter of winding with no acoustic enclosure and rain cap.

winding layer's temperature from its bottom to the top is measured and displayed in Fig. 6 for both case studies i.e., with and without acoustic barrier and rain cap. The winding layers are numbered from the inward to the outward layer, respectively. Layer one is the interior layer of the winding and layer 9 is the most exterior one.

According to Fig. 6, the following can be observed:

- In both cases, the layers display a similar temperature distribution pattern, however, the winding temperature while it is surrounded by acoustic enclosure and rain cap is slightly higher.
- The inner layers in both cases are a bit warmer than the outer layers and the most inner layer has the highest temperature. Moreover, the hottest point of the reactor winding is in the innermost layer and its upper third.
- Moving upward from the bottom of the winding to its top, in the lower quarter, a significant temperature increase is observed. In the middle of the coil, the temperature difference between the parts of each layer is somewhat smaller and in the upper quarter of the layers, the temperature has started to decrease.
- There is a slight anomaly in the temperature distribution of layers in the lower quarter of winding with no acoustic enclosure and rain cap. The temperature of the 9th layer is higher than the adjacent interior layers in the lower quarter, which contradicts the expected behavior of the coil. temperature distribution in the lower quarter of winding with no rain cap and acoustic enclosure is displayed in Fig. 7.

References:

[1] J. Cao, T. Chen, Z. Jiang, X. Wen, and M. Zhang, "Coupling calculation of temperature field for dry-type smoothing reactor," in *2014 17th International Conference on Electrical Machines and Systems (ICEMS)*, 2014: IEEE, pp. 3259-3263.

[2] T. Chen, J. Cao, G. Zhou, J. Zhipeng, Y. Wang, and X. Wen, "Electric field research of±800kV dry-type smoothing reactor," in *2014 17th International Conference on Electrical Machines and Systems (ICEMS)*, 2014: IEEE, pp. 1484-1487.

[3] S. Gong, T. Li, C. Gao, J. Zhou, and Z. Chen, "Harmonic Magnetic Field Analysis based on UHVDC Smoothing Reactor," in *2019 IEEE 2nd International Conference on Automation, Electronics and Electrical Engineering (AUTEEE)*, 2019: IEEE, pp. 627-634.

[4] R. Shulga, Y. A. Ivanova, N. Lozinova, and M. Mazurov, "Choice of line reactors for HVDC lines and back-to-back links," *Russian Electrical Engineering,* vol. 82, no. 9, pp. 469-474, 2011.

[5] P. Wang, Y. Zhao, F. Lv, K. Li, and Y. Ding, "Distribution of electric field and structure optimisation on the surface of a±1100 kV smoothing reactor," *IET Science, Measurement & Technology,* vol. 13, no. 3, pp. 441-446, 2019.

[6] M. Dong *et al.*, "Influence of smoothing reacteor arrangement on transients of converter station for±500kV double-circuit HVDC system," in *IEEE PES General Meeting*, 2010: IEEE, pp. 1-8.

[7] Y. Wang *et al.*, "Theoretical and experimental evaluation of the temperature distribution in a dry type air core smoothing reactor of HVDC station," *Energies,* vol. 10, no. 5, p. 623, 2017.

[8] F. Yuan *et al.*, "The Optimization Design of Sound Arrester for the Dry Type Air Core Smoothing Reactor Based on the Multi□Physical Field Coupling Method," *IEEJ Transactions on Electrical and Electronic Engineering,* vol. 16, no. 5, pp. 704-714, 2021.

[9] F. T. Yuan, Z. Yuan, J. X. Liu, Y. Wang, W. X. Mo, and J. J. He, "Research on temperature field simulation of dry type air core reactor," in *2017 20th International Conference on Electrical Machines and Systems (ICEMS)*, 2017: IEEE, pp. 1-5.

[10] D. Caverly, K. Pointner, R. Presta, P. Griebler, H. Reisinger, and O. Haslehner, "Air Core Reactors: Magnetic Clearances Electrical Connection and Grounding of their Supports," in *Minnesota power systems conference*, 2017.

[11] T. A. Fiorentin, L. F. Lopes, O. M. Da Silva, and A. Lenzi, "Vibroacoustic models of air-core reactors," *The International Journal of Acoustics and Vibration,* vol. 21, no. 4, pp. 453-461, 2016.