Mathematical Model of High Voltage Sandwich Bus Duct

Vishal Ramnani*, Mrunal Parekh[1], Vihang Dholakiya*,Gaurang Buch*
*Department of Electrical, Institute of Technology, Nirma University, Ahemdabad
[1] Technology centre, ERDA, Vadodara

***Abstract*— Bus duct technology is widely used due to its compactness and high current carrying capacity. Sandwich bus duct is energy efficient and compact technology in LT (Low Tension) systems. This paper aims the mathematical modeling of HT (High Tension) bus duct for 7.2 kV system and the comparison of voltage drop and power loss in HV (High Voltage) sandwich Bus duct and in conventional Air insulated phase bus duct (AIPBD). Maximum potential gradient and magnetic flux density is calculated using finite element method (FEM) approach, through which capacitance and inductance matrix are derived which leads to mathematical model of HV sandwich bus duct. Effect of Mutual inductance on voltage drop and power loss is shown. A commercial finite element code Maxwell 2D/3D and Ansoft Simplorer is used for prototype sandwich bus duct design.**

***Keywords* —Bus Duct system (BDS), skin effect and proximity effect, AIPBD, Mutual inductance, EM (Electro magnetic) loss.**

I. INTRODUCTION

Bus duct technology is widely used for power transfer due to its high current carrying capacity and lower impedance compared to the cable. Most of the bus duct systems are air insulated with large sizes. Recently a new compact BDS (Bus duct system), in which the space between two adjacent copper bus bars is only 1 to 2 mm, is emerging in industry [1]. The sandwich construction has much more benefits over the conventional air insulated bus duct as shown in Table – I.

Sr. No	Issue	H.T Sandwich Bus Duct	High Voltage (AIPBD)	High voltage cable
1	Voltage drop	Less compared to AIPBD	Moderate	High
2	Size	1/3 of AIBPD	Large	Large
3	Fire retardant	Excellent	Poor	Poor
4	SC (Short Circuit) withstand capacity	High	low	Low
5	Power loss	Lower	Average	High
6	Combustive energy	Less	Less	More

Table I: Comparison among different types of bus duct and cable

The current carrying capacity of these compact BDS is generally larger than conventional ones and the enclosures of these BDS are made of aluminum alloy with excellent heat transfer characteristic [1]. The analysis must include both the linear section of BDS as well as the connecting joints [1]. For BDS to be commercially viable, problems arising from induced magnetic heating and induced eddy-currents in the enclosure and bus-bars due to the heavy current flow in modern bus duct system have to be overcome. The two-dimensional (2-D) Finite-Element Method (FEM) has been used to calculate and analyze the voltage distribution and magnetic field distribution in compact BDS. Design of BDS requires a three-dimensional (3-D) study of the eddy-current field, induced magnetic heating and thermal behavior of the bus-bars [3]. In this paper 2-D eddy current field model is used to calculate the eddy current losses and eddy current induced in the enclosure and adjacent conductor and 3-D electrostatic model is solved for evaluating the voltage distribution and maximum electric field strength of the dielectric material. With help of above simulation inductance and capacitance matrices are derived which leads to the mathematical modeling of HV sandwich bus duct. A 1600 A, 7.2 kV compact bus duct system is studied and analyzed.

II. MATHAMATICAL MODEL

FEM approach is used for the mathematical modeling of the sandwich bus duct. In this paper various equation are solved for the electrostatic and electromagnetic solution.

For the electrostatic analysis, Poisson's and Laplace' equations are solved.

$$\nabla^2 V = \frac{\rho}{\varepsilon}$$

$$\nabla^2 V = 0$$

After finding potential at each point using above equation, electric field strength can be found as,

$$E = -\nabla V$$

All vector potentials are to be calculated for finding flux density and losses (EM and ohmic losses). Vector potentials are solved as shown below.

$$\nabla^2 A = 0$$

$$B = \nabla \times A$$

III. Simulation Result

The analysis of the bus duct is performed using MAXWELL and Simplorer.

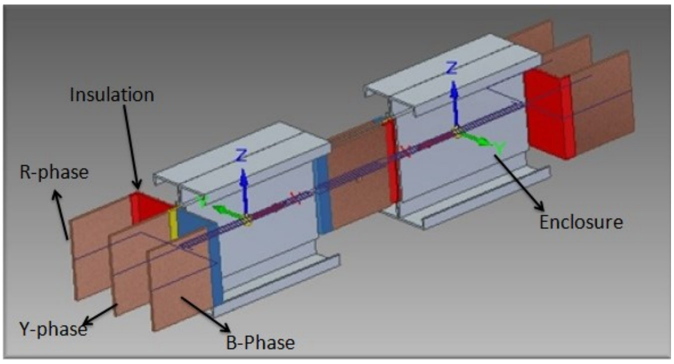


Fig.1 Sandwich bus duct model

The electrostatic analysis of sandwich bus duct is done to find the capacitance matrix and maximum potential gradient between the two phases. This analysis sets the basis for the insulation design of the system. For 7.2 kV system, the maximum power frequency withstand voltage is 20 kV and so is the applied test voltage. So the maximum electric field strength is found during 20kV and basis on this insulation material can be designed.

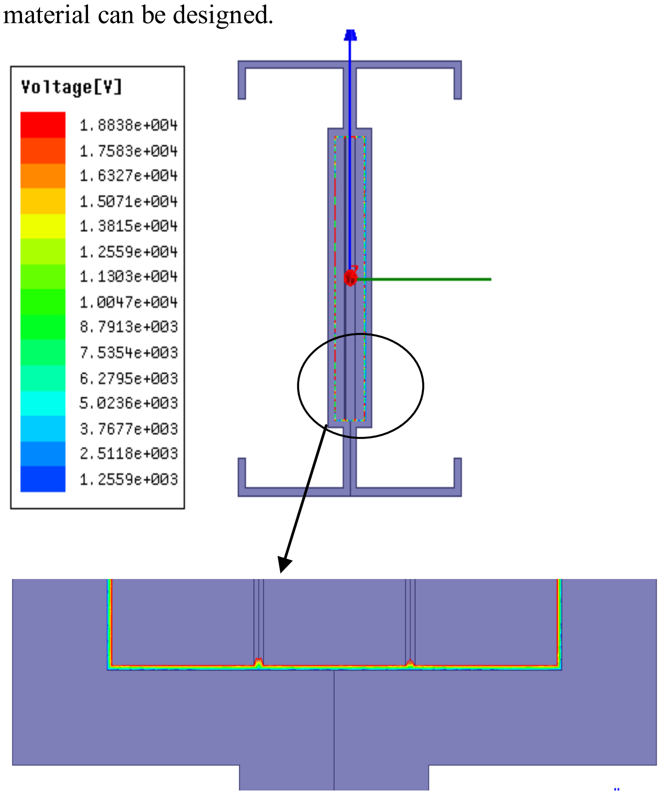


Fig.2 Voltage distribution through the bus duct

The red line shows the maximum Electric field stress and it decreases as distance increase from the phase as shown in Fig.2.The maximum electric field strength between phase to ground is 4 kV/mm and is shown in Fig.3.

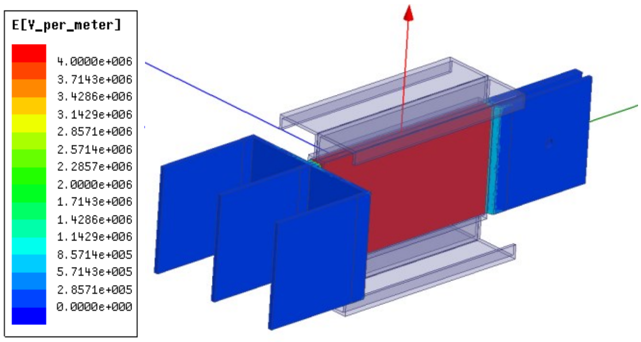


Fig.3 Electric field strength through the Sandwich bus duct

With the help of electrostatic analysis, maximum electric field strength is found from which insulation can be designed and along with this a capacitance matrix is generated which is used for mathematical modeling of the bus duct. A capacitance matrix represents charge coupling within the group of conductors (relationship between charges and voltage for a given conductors).

$$Q = CV$$

$$Q = \begin{bmatrix} C_{10}+C_{12}+C_{13} & -C_{12} & -C_{13} \\ -C_{21} & C_{20}+C_{12}+C_{23} & -C_{23} \\ -C_{31} & -C_{32} & C_{30}+C_{13}+C_{23} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

$$\text{Where } C = \begin{bmatrix} 18545 & -6145 & -3.2037 \\ -6145 & 16189 & -9044.8 \\ -3.2037 & -9044.8 & 21436 \end{bmatrix} \text{ pF}$$

Constant DC excitation is applied to the sandwich bus duct model to find the inductance matrix for voltage drop and power loss calculation. The magnetic field and magnetic flux density produced on the bus bar, enclosure and the surrounding region (induced current is avoided) is shown in the Fig.4.

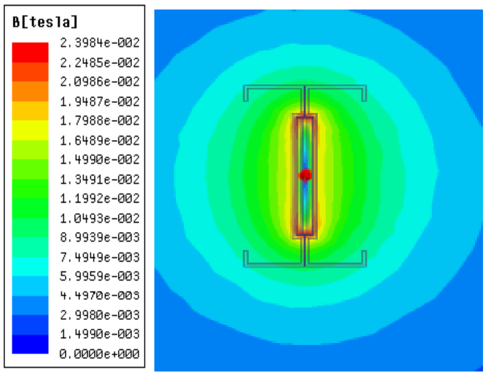


Fig.4 Flux density distribution through the bus duct

The flux density is maximum at the top and bottom edges. The maximum flux density is 0.002 T during constant excitation. As there is more clearance between two phases in AIPBD, the flux linkage and hence flux density is low compared to sandwich bus duct when same excitation is applied to the AIPBD. Lower flux linkage results in lower value of mutual inductance, which causes more voltage drop. The maximum flux density is 0.0097 T in AIPBD. Inductance matrix obtained is given below.

$$\begin{bmatrix} 6.6388E-07 & 6.4706E-07 & 6.2431E-07 \\ 6.4706E-07 & 6.6389E-07 & 6.4705E-07 \\ 6.2431E-07 & 6.4705E-07 & 6.6385E-07 \end{bmatrix} \text{H}$$

Time varying current induces eddy currents, which causes power loss due to skin effect and proximity effect. Flux density is more in the middle between two phases as shown in Fig.5.

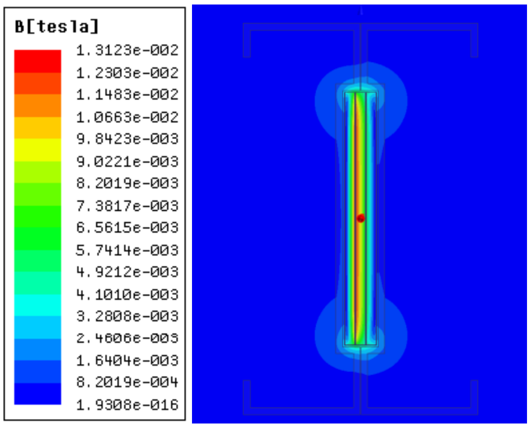


Fig.5 Flux density through the bus duct during time varying excitation

The inductance and capacitance matrix derived can be now used for the mathematical modeling of bus duct. The voltage drop is more in AIPBD compared to sandwich bus duct and can be validated by simulating the bus bar equivalent circuit. The equivalent circuit of sandwich bus duct for single phase is shown Fig.6.

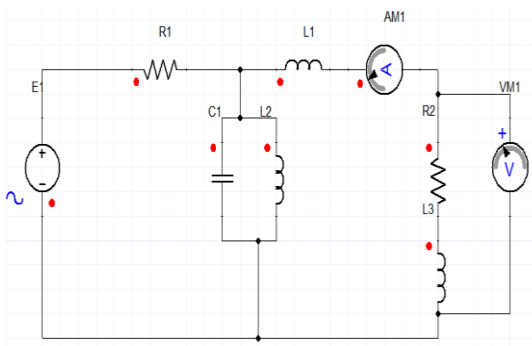


Fig.6 Equivalent circuit of HV sandwich bus duct

In the equivalent circuit of sandwich bus duct, the value of capacitance is in Pico farad. So it is not playing an important role for voltage drop. The value of mutual inductance (L2) is playing important role for voltage drop. The Fig.7 shows the waveform of input voltage and output voltage.

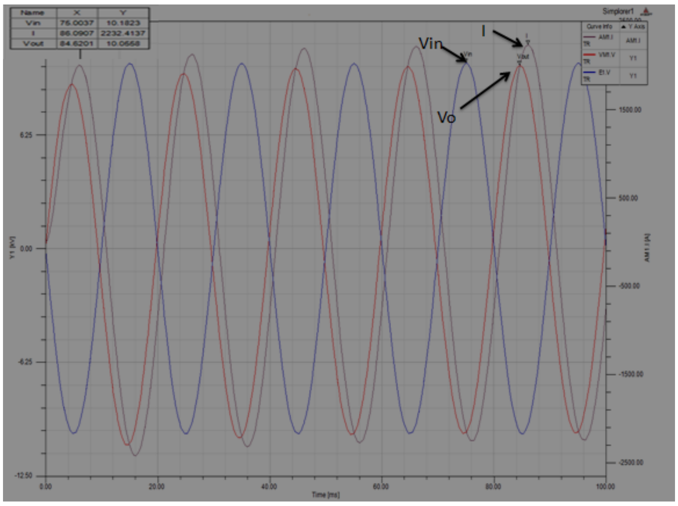


Fig.7 Output waveform for V_{in}, V_{out} & I

The input voltage is 7.2 kV (Line to Line) and output voltage is 7.110 kV. Voltage drop is about 89.66 V (Line to Line).

The Load R and L are varied in such a way that current drawn from the source is about 1600 A and power factor is maintained at 0.9 lagging. The voltage drop varies in proportion to the value of mutual inductance. The voltage drop will be more with lower value of mutual inductance (L2) and vice & versa. Figure 8 shows the voltage drop variation for different values of mutual inductances.

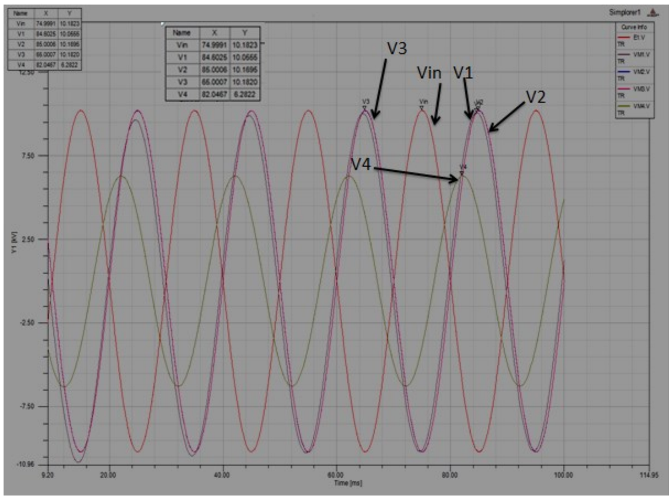
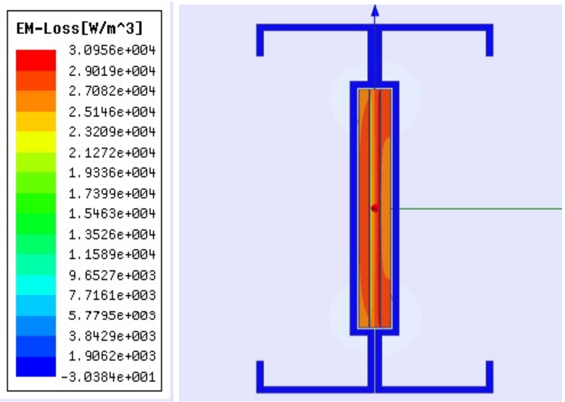
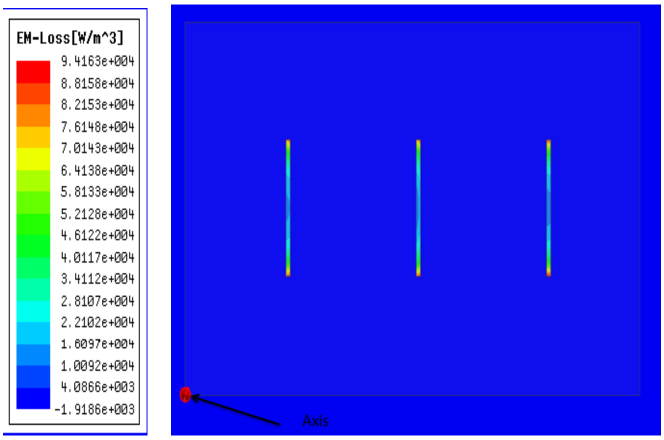


Fig.8 Variation of voltage drop by varying mutual inductance

The EM losses depend on the air gap flux density between two phases. Air gap flux density is higher in Sandwich bus duct compared to AIPBD. So higher the value of mutual inductance results in lower voltage drop and reduced losses. Electromagnetic loss are more in AIPBD compared to Sandwich bus duct.



(a) Sandwich bus duct



(b) AIPBD

Fig.9 EM LOSSES

Parameters	Sandwich bus Duct	Air Insulated Phase Bus ducts
Mutual impedance	6.243e-007H	4.8165e-007
Flux Density during constant excitation	0.02T	0.009T
EM loss(3-phase)	73.59W/m	88.134W/m
Total Losses(3-phase)	220.71W/m	235.25W/m
V out	7.110kV	7.088kV
Voltage drop	89V(Line to Line)	155Volts(Line to Line)
Voltage drop%	1.24%	1.53%

Table: II Comparison between Sandwich Bus Duct and AIPBD

IV Conclusion

The paper focuses on the mathematical modeling of sandwich bus duct for 7.2kV electrical system. For the said specification, sandwich bus duct has been designed and same designed has been analyzed for electrostatic and electromagnetic analysis by conventional mathematical approach using FEM software. By deriving inductance & capacitance matrix, an equivalent circuit of sandwich bus duct has been developed. From the equivalent circuit of the bus duct, the parameter like effect of mutual inductance between two phases serves as variable for power loss and voltage drop. It is derived using weakly coupled field approach in this paper. Along with this, power loss due to skin effect and proximity effect is analyzed and results are compared with conventional AIPBD. Developed mathematical model and equivalent circuit can be serves as the basis for developing a prototype model of sandwich bus duct and can be tested further to validate the same practically.

REFERENCES

[1] S.L. Ho, Y.Li, X.Lin,H.C Wong and K.W.E.Cheng, "A 3-D study of Eddy Current Field and Temperature Rises in a Compact Bus Duct System." IEEE TRANSACTIONS ON MAGNETICS, VOL.42, NO.4, APRIL 2006.

[2] Chang-Chou Hwang, J.J. Chang and Y.H. Jiang. "Analysis of electromagnetic and thermal field for a bus duct system". Electric Power system Research 45(1998)39-45.

[3] S.L Ho, Y.Li, X.Lin, Edward W.C.Lo, K.W.E Cheng, "CALCULATION Of Eddy Current ,Fluid, and Thermal Fields in an Air Insulated Bus Duct System", IEEE TRANSACTIONS ON MAGNETICS , VOL.43, NO.4, APRIL 2007.

[4] N.H Malik, A.A AArainy, M.I Quershi and F.R. Pazheri "Calculation of Electric Field Distribution at High Voltage Cable Termination". Journal of Energy Technologies and Policy. ISSN 2224-3232,Vol.1, No.2, 2011.

[5] Mario Chiampi, Daniela Chiarabaglio, Michele Tarta, "A General Approach for Analyzing Power Busbar under A.C condition.".IEEE TRANSACTIONS ON MAGNETICS, Vol.29, NO.6, NOVEMBER 1993.

[6] O.BOTTAUSCIO , E.CARPENETO ,M.CHIAMPI , D. CHIARABAGLIO,I. PANAITESCU, "Numerical and Ex-perimental Evaluation of Magnetic Field generated by Power Busbar System", IEEE Pro.-Gener. Transm. Distrib., Vol.143, NO.5, September 1996.

[7] R.Jafari-Shapoorabadi, "Comparison of Three Formulation for Eddy Current and Skin Effect problems" IEEE TRANSACTION ON MAGNETICS,VOL.38,NO.2 MARCH 2002.

[8] Zygmunt Piatek, Dariusz Kusiak, Tomaz Szczegielnaik, "Electrcomagnetic Field and Impedances of High Current Busduct", Modern Electric Power Systems 2010, Wroclaw, Poland.