

Leakage, d Axis and q Axis Reactances Estimation of a Sample High Voltage Generator Using Finite Element Method

Mehdi Taherzadeh

Manuscript Received: 25, Sep., 2014
Revised: 23, Oct., 2014
Accepted: 15, Nov., 2014
Published: 15, May., 2015

Keywords
High Voltage Generators , Reactance, FEM, Maxwell 2D,

Abstract— high voltage synchronous generators known as powerformers, by changing stator configuration and their winding compared to conventional generator could generate fit voltage for connecting to transmission lines directly. Because of the innovation in their configuration and complication, fields and consequently reactances calculations would be so difficult by analytical formulas. In this article, numerical method based on finite element method has been used to calculate leakage, d axis and q axis reactances of a sample high voltage generator. Finally a comparison has been made between the results calculated by numerical analysis as well as analytical formulas.

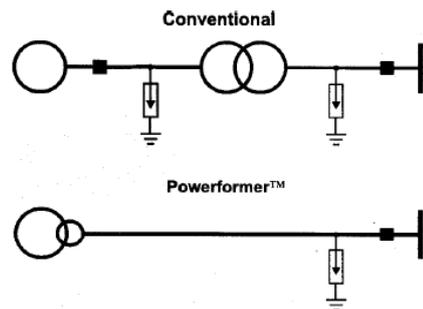


Fig1. Single line diagrams, conventional (top) and Powerformer power-plants

Compared to conventional generators, these generators create innovations that cause fundamental changes in their stator.

In one hand, because the cables cross section is circular, teeth should be designed in a way that surrounds the cables; On the other hand, Due to the increase in a number of turns in each slot, powerformer slot is designed much deeper than conventional generator slot. So, the slots of powerformer are designed so differently (Fig. 2) [4].

1. Introduction

The three phase synchronous generators are used in all power-plants to generate electrical power. Their armature winding is coils with rectangular cross section put in slots of stator. Mica tapes are taped around the coils as insulation. For high voltage generators, the electric field of the four angels of coil would be very large and may damage the insulation. So, the output voltage of them is usually limited to 25kV. Therefore, for connecting this voltage to transmission line voltage, step up transformers are necessary.

By changing conventional generators construction leijon at [1]-[2] introduces a generator known as powerformer which could generate high voltage upper than the mentioned one. So, in power-plants with these generators, the step up transformer as well as the environmental and technical problems related to it are omitted. Fig. 1 shows single line diagram of the powerformer and conventional power-plants.

By replacing XLPE cables instead of rectangular coils in slots of stator as armature winding powerformers could solve insulation limitations of synchronous generators used in power-plants. Fig. 2 shows the differences between winding of powerformer and conventional generators [3].

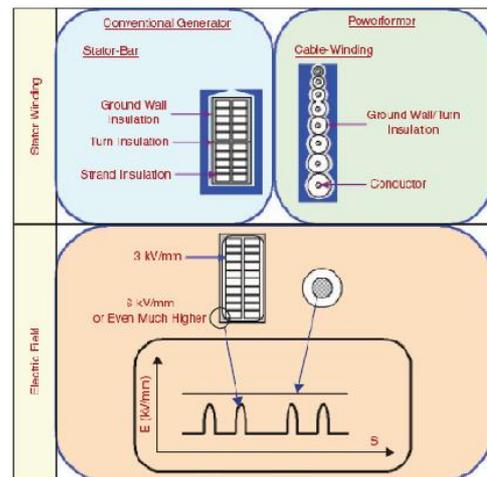


Fig. 2 Differences between slots of conventional and the new generator

Changing in slot, teeth, conductor, and also the increasing of turn numbers of the phase of this generator, cause complication of the new machine. So, solving the fields in this case would be more difficult.

Because of the complication of the powerformer,

Maxwell 2D software based on finite element method (FEM) is used to solve fields in this paper. The output results of the analysis are used to calculate reactances of a sample powerformer. Also a comparison between the results obtained by FEM as well as analytical formulas has been made.

2. A sample Powerformer

In these parts, the designed results of a sample high voltage hydro-generator have been presented (Table 1) [5]. Reactances stated in Table 2 have been calculated by given analytical formulas in [6]. Because of the mentioned complication, reactances calculated by analytical formulas are not expected to be accurate.

TABLE 1. DESIGNED PARAMETERS OF 63kV AND 25MVA POWERFORMER

Generator parameter	Designed quantities
Output Power(MW)	25×0.9
Nominal Voltage(kV)	63
Number of pole	32
Frequency(Hz)	50
Stator Inner Diameter(m)	7.22
Stator outer Diameter(m)	6.04
Length of core(m)	1.185
Cable per slot	12
Number of Slots per pole per phase	2.25
Diameter of conductor(mm)	12
Diameter of 63kV cable(mm)	42
Diameter of 33kV cable(mm)	33
Diameter of 11kV cable(mm)	23
Deep of slot(m)	0.47
Pitch fraction angle	20°
Leakage Reactance(p.u)	0.108
Longitudinal Reactance(p.u)	1.21
Transverse Reactance(p.u)	0.88

As shown in Table 1, three different XLPE cables are used in slots of this machine which include six 63kV cables, four 33kV cables and two 11 kV cables and so there are 12 cables in each slot altogether. Each pair of the adjacent cables are wired as shown in Fig. 3 [7].

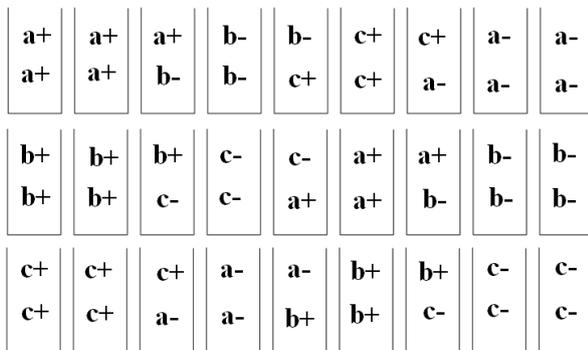


Fig. 3 Wiring of the machine for each pair of cables

According to designed parameter shown in Table 1, model of this machine is defined as similar to Fig. 4.

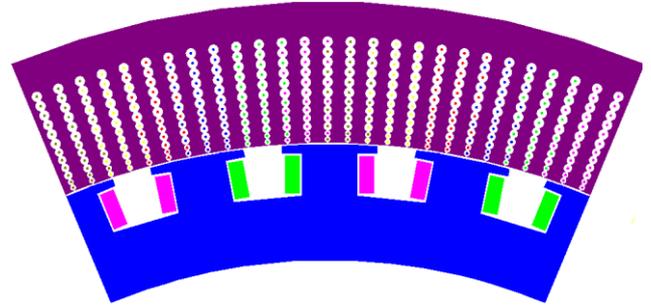


Fig. 4. model of desined powerformer

Components of the model shown in Fig. 4 are:

- Stator yoke
- Rotor poles
- Cables in slots as armature winding
- Rotor winding (field winding)

Armature and field winding made from copper and rotor and stator use a B_H curve shown in Fig. 5.

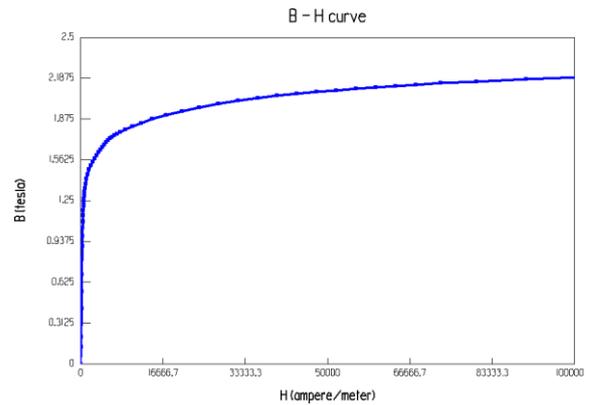


Fig. 5 B-H curve of steel uses in machine

3. Reactance Calculation

In this part, reactances of the powerformer would be calculated by numerical method.

A. Leakage Reactance (X_l)

High percentage of leakage flux in synchronous generators is slot leakage flux. So, it can be said that slot leakage reactance approximately is equal to leakage reactance of machine. In powerformers, because of deep slot and more turns in each slot, it is be more important.

For calculating slot leakage reactance in this case, first specific permeance of each slot should be calculated by FEM. Then put it in following equation:[8]-[9]

$$X_l = 2\pi \cdot f \cdot p \cdot q \cdot \lambda_s \cdot \mu_0 \cdot Z_s \cdot L_{fe} \quad (\text{Equ. 1})$$

Where L_{fe} is equal to the length of the stator core since there are no radial air cooling ducts in the stator core of Powerformer, p is number of poles, Z_s is cable per slot, f is

power frequency, and q is number of slots per pole per phase. The quantity μ_0 is the permeability of free space.

After computing fields according to FEM, slot specific permeance of the powerformer is calculated equal to $7.48\mu\text{H/m}$. Therefore, according to equation 1 leakage reactance of the machine would be equal to 28.9 ohm (0.182 p. u.). Flux lines resulted from fields solving process shown in Fig. 6.

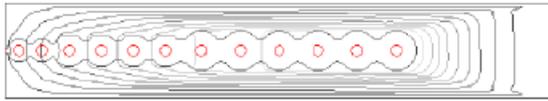


Fig. 6 Magnetic flux lines, when determining leakage reactance

B. Longitudinal Reactance (X_d)

In order to calculate the longitudinal reactance, first the relevant inductance should be calculated. When calculating the Longitudinal (L_d) inductance, the following conditions were considered in simulation:

- Excitation current was equal to zero.
- Stator winding were fed in a way that the magnetic motive force distribution is in the maximum magnitude according to d axis. This occurs when the rotor poles axis coincides with phase axis a ($\omega t=0$, Fig. 7).

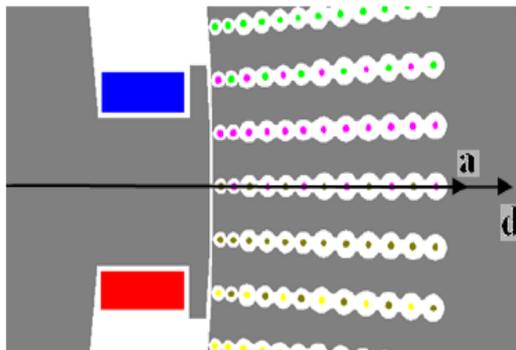


Fig. 7 model position when calculating X_d

Also, we assume that the current angle is zero. ($\cos(\varphi)=1$). So:

$$I_a = I_m \cos(\omega t) \rightarrow I_a = I_m$$

$$I_b = I_m \cos(\omega t - 120) \rightarrow I_b = -I_m/2$$

$$I_c = I_m \cos(\omega t - 240) \rightarrow I_c = -I_m/2$$

I_a , I_b and I_c are currents of stator three phases, in which I_m is the maximum value. Conditions have been set in a way that the flux lines are tangent on polar axis (d) and perpendicular to interpolar axis (q).

Considering the fact that the purpose of calculation is inductance, the current magnitude does not have any effect on it, therefore, we select one ampere for I_m . It should be noted that in this part, phase (a) axis has been set according to axis d. Longitudinal inductance is calculated according to relation (2).[10]

$$L_d = \psi_d / I_a \tag{Equ. 2}$$

I_a is the current of phase (a) and ψ_d is the flux obtained

from phase (a) in direction of d axis which is calculated based on fields solution by finite element method. The above inductance has been calculated to be to 0.57H for the sample powerformer based on equation (2). Therefore the inductance in d axis is equal to 179 ohm (1.13 p. u.).

Figure 8 shows the flux path in model after the above solution.

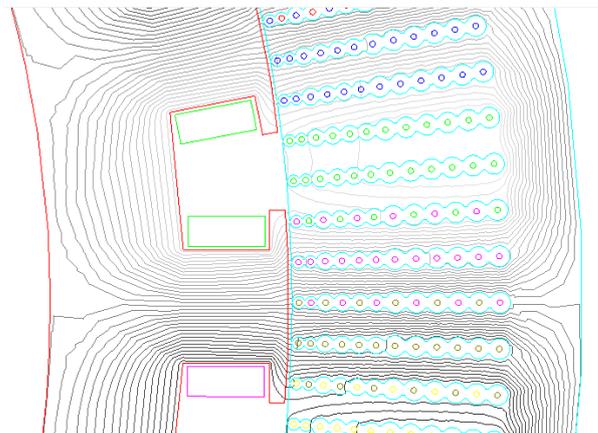


Fig. 8 Magnetic flux lines, when determining d axis reactance

C. Transverse Reactance (X_q)

Transverse reactances is calculated in the same method as direct axis reactances with the difference that phase currents must be fed in a way that magnetism motive force distribution has the maximum magnitude on axis q. For the same purpose, while maintaining stator currents, rotor could be rotated to 90° electrical degree ($\omega t=90^\circ$, (Fig. 9).

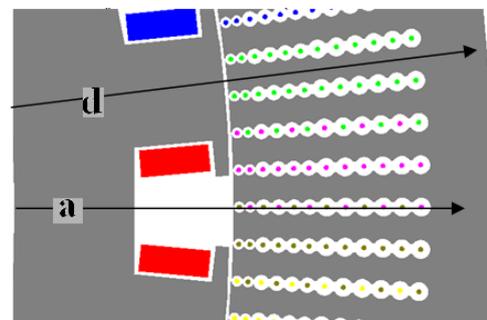


Fig. 9 model position when calculating X_q

Besides, conditions are set in a way that the flux lines are tangent on polar axis (q) and perpendicular to interpolar axis (d).

Given the points mentioned in this part, phase (a) axis has been set on q axis; q axis inductance calculated by equation 3.

$$L_q = \psi_q / I_a \tag{Equ. 3}$$

ψ_q is the flux obtained from phase (a) in line with orthogonal axis. In this part, also after fields' solution, the transverse inductance obtained from the finite element analysis is calculated to be 0.414 H. Therefore; q axis reactances would be equal to 130 ohm (0.822 p. u.)

Figure 10 shows the flux path in the model after the above solution.

In order to demonstrate the accuracy and the usefulness of finite element method in reactance calculations, the comparison between reactance values obtained from this sample powerformer have been indicated in Table 2 using analytical relations and also calculation by numerical methods presented in this article.

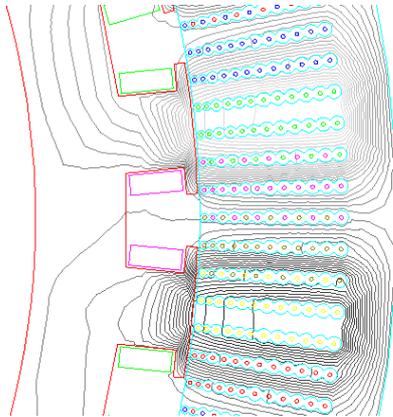


Fig. 10 Magnetic flux lines, when determining q axis reactance

TABLE 2.
COMPARISON OBTAINED REACTANCES OF THE POWERFORMER BY TWO
METHODS: ANALYTICAL FORMULA & FEM

Calculated Reactance	Analytical Formula	FEM	% ϵ
$X_d(p.u)$	1.21	1.13	7.07
$X_q(p.u)$	0.88	0.822	7.05
$X_l(p.u)$	0.108	0.182	40.6

In Table 2 parameter ϵ represents a calculation error by analytical formulas as compared with the fields solution in numerical method. The high value of the obtained error shows that the analytical formula for high-voltage machines is not appropriate due to the changes in winding and stator structure. Because, most changes in powerformer are in slots, therefore, as shown in Table 2, the percentage of the obtained error for the leakage reactance which is approximately related to slot shape is very high. It should be mentioned that slot leakage reactance calculated by analytical formulas has been considered for rectangular slots.

4. Conclusion

In this article, by using numerical analysis based on finite element method, fields are computed for a complicated sample high voltage generator. Method of computing the reactances of machine through numerical analysis was explained and also leakage, longitudinal, and transverse reactances of the sample machine were calculated by FEM.

Finally, the obtained results were compared with those obtained by analytical equations. Because of the complications created in the new machine, it can be said that calculation based on numerical analysis is more accurate.

References

- [1] M. Leijon, L. Getmer, H. Frank, J. Martinsson, T. Karlsson, B. Johansson, K. Isaksson & U. Wollstrom, "Breaking Conventions in Electrical Power Plants," (1998) *Report 11/37-3, Proc CIGRE Session*, France.
- [2] M. Leijon, S.G. Johansson, F. Owman, S. Alfredsson, T. Karlsson, S. Lindahl, C. Parkegren & S. Thoren, "Powerformer™ Experiences from the Application of Extruded Solid Dielectric Cables in the Stator Windings of Rotating Machines," (2000) *IEEE Pwr Eng Soc WM 2000*, Singapore.
- [3] M. Leijon, "Novel concept in high voltage generation: Powerformer/sup TM," (1999) *Int. Symp. High Voltage Eng. (Conf. Publ. 467)*, UK, 11.
- [4] I.A. Metwally, R.M. Radwan & A.M. Abou-Elyazied, "Powerformers: A breakthrough of high-voltage power generators," (2008) *IEEE potentials*, pp. 37-44.
- [5] M.Taherzadeh, "Design of a sample Powerformer," (2009) M.S. thesis, K.N.T.U., Tehran, Iran.
- [6] A.K. Sawhney & A. Chakrabarti, *A Course in Electrical Machine Design*, 6th Edition, D.R. Publication, 2010.
- [7] M.Taherzadeh & A. Akbari, "An investigation on Windings in New Generation of Synchronous Generators Based on XLPE Cable Known as Powerformers," (2011) *SASTech*, Iran, 5.
- [8] M. Klocke, "Slot Leakage Inductance and Eddy Current Losses in Multi-Turn Stator Windings for Very High Voltage Synchronous Generators," (2001) *ISTET conference*, Austria.
- [9] M.Taherzadeh, A. Akbari, M. Ardebili, "An Investigation on Slot Configuration in New Generation of Synchronous Generators Based on XLPE Cables," (2009) *International Conference (ELECO)*, Turkey.
- [10] O. Chiver, C.Opera, M. Horgos, L. Nemat & C. Braz, "the computation of reaction and homopolar inductances of a synchronous machine with 2D numerical analysis software," (2007) *International Conference on electromechanical and power systems*, Moldava, 6, pp. 134-137.



Mehdi Taherzadeh received his MSc degree in Electrical Engineering from K.N.T University, Iran, Tehran in 2009. He is currently a Ph.D. student in Chamran University, Ahwaz, Iran. His main subject being synchronous generators.