An Investigation on Slot Configuration in New Generation of Synchronous Generators Based on XLPE Cables

Mehdi Taherzadeh, Asghar Akbari, and Mohammad Ardebili

Khaje Nasir Toosi University, Tehran, Iran
meh_taherzadeh@yahoo.com, akbari@kntu.ac.ir
ardebili@kntu.ac.ir

Abstract

Regarding the change of slot in high voltage synchronous generators, and the importance of slot leakage reactance in subtransient and transient short circuit currents and in the amount of synchronous reactance, this paper studies the effect of the changing of slot and conductor shape in high voltage synchronous on the amount of slot leakage reactance, using analytical formula and numerical analysis. Considering three different slot configurations for one sample high voltage synchronous generator, rated at 63kV and 25MVA, the slot leakage reactance is calculated by applying conventional formula for rectangular conductor cross-section, and using finite element method. Then, the results are compared to each other. Finally, the effect of the new slot configuration of high voltage generator on slot leakage reactance is shown. Therefore, from electromagnetic viewpoint, it has been tried to introduce a better slot configuration of high voltage synchronous generator in this paper.

1. Introduction

In recent years, approximately all synchronous generators are designed in a way that their output voltage is limited to 25kV. Recently, it has been tried to increase of the output voltage of synchronous generators. The transformer of the power-plant can be omitted, once the output voltage of the power-plant's generator reaches the transmission line voltage.

According to [1],[2], Mat Leijon invented the first high voltage synchronous generator, called powerformer. This has the capability of being connected to the transmission line without any step-up transformer as shown in Fig. 1. The Fig. 1 shows the difference between conventional power-plants and powerformer power-plants.

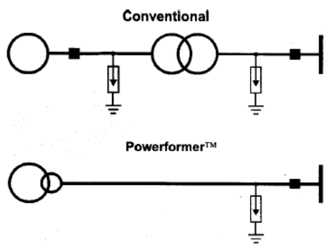

Fig. 1. Single line diagrams, conventional (top) and Powerformer power-plants

In today's large conventional generators, two layers of rectangular coils with one turn per coil are used as armature winding, while XLPE high voltage cables are used in high voltage generators [3]. These cables are then used to form multi-turn coils, which can achieve a desirably high rated stator voltage level. The replacing of rectangular coils in the conventional generators slot with high voltage cables in powerformer slots and the increasing of the turn-phase number due to the high output voltage of the powerformer compared to conventional generators cause the powerformer slot to be very different from that of conventional generators.

Powerformers, compared with conventional generators stator windings and slot, have three main differences:

1- They use circular conductors in armature winding, while the conductors that used in conventional generators are rectangular coils.

2- The number of turns per phase in each powerformer slot is more than that of the conventional generator slot.

3- Teeth in powerformer stator are differently shaped, as shown in Fig. 2, to surround cables inside slots.

Fig. 2 shows two different slot configurations and their inside conductors used in conventional generator and powerformer.

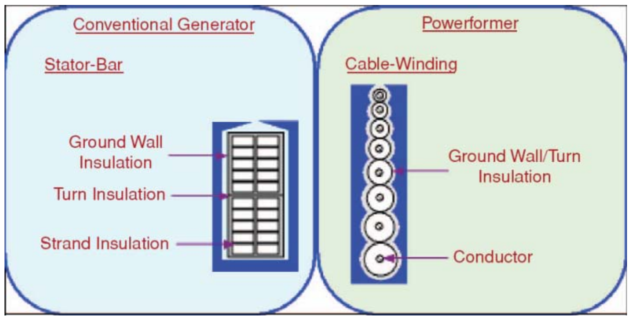

Fig. 2. Two types of slot used in conventional generators and powerformers with two different windings

Regarding the differences between powerformers and conventional synchronous generators that were mentioned above, in this paper, first the effect of circular conductor shape of high voltage generators on slot specific permeance are studied by using analytical formula and numerical analysis . Then, the study is repeated for a circular slot which is different from conventional slots. Finally, for a designed powerformer, rated at 63kV and 25 MVA, the slot leakage reactance is calculated for three different slot configurations by using finite element methods, and next the results are compared with those obtained by analytical formula; then, the effect of the changing of slots in high voltage generators compared to conventional generators on their slot leakage reactance and generator performance is investigated.

2. Analytical and numerical calculation of slot leakage specific permeance

The estimation of the leakage flux is difficult owing to the complex geometry leakage paths. It is impossible to get very accurate results as simple mathematic models can not define the complexity of leakage flux. Normally the results obtained by modeling and computation are checked against experimental data. At this paper, the results are calculated based on Finite Element Method (FEM) to get more accurate answers.

As mentioned above, two main differences between powerformers and conventional generators stator are the shape of their conductor and slot, while powerformers use circular conductor and slot compared to rectangular coil and slot used in conventional generator. So, at the following section, the effect of conductor cross-section and new slot configuration on slot specific permeance is investigated. It is stated that the specific slot permeance is a factor of the slot leakage reactance.

2.1. The effect of armature conductor cross-section on slot leakage specific permeance

Fig. 3 shows two slots with the same configuration and different conductor cross- sections. One slot has a conductor with circular cross-section similar to conductor used in powerformers, and the other slot has a conductor with square cross-section similar to conductors used in conventional generators. It has been assumed that the diameter of circular conductor equals to the width of square conductor and slot ($2r=W_s$).

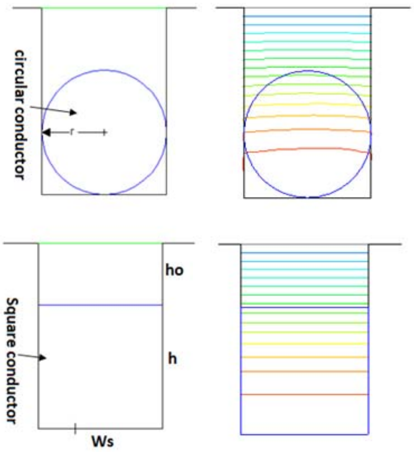

Fig. 3. Two similar slot with two different conductors inside them, and their flux leakage lines, rectangular conductor and circular conductor (top)

As an example, It is assumed that $h=2r=W_s=10$mm. by using analytical formula for rectangular conductor, the slot specific permeance (λ_s) is calculated to:[5]

$$\lambda_s = \mu_0 [\frac{h}{3 \cdot w_s} + \frac{h_o}{W_s}] \qquad (1)$$

$$\lambda_s = 4\pi \cdot 10 - 7 \cdot (\frac{10}{3 \cdot 10} + \frac{5}{10}) = 1.047 \frac{\mu H}{m}$$

The obtained results by numerical analysis (FEM) for two slots shown in Fig. 3 are presented in Table 1.

Table 1. The Results calculated by FEM and analytical formula for slots that shown in Fig. 3

Type of conductor	λ_{slot}(μH/m)(FEM)	λ_{slot}(μH/m)(analytical formula)
Rectangular conductor	1.047	1.047
Circular conductor	1.078	-

Regarding the simple configuration of the slot with the square conductor, the obtained results by numerical analysis and the results calculated by analytical formula are exactly the same. As shown in Table 1, the results for a circular and square conductor with approximately similar dimensions are nearly the same. Therefore, it can be concluded that the changing of the conductor from rectangular shape in conventional generators to a circular conductor in high voltage generators has no effect on the slot leakage reactance. It should be said that both of square and circular conductors have approximately equal cross-sections. While in practice, the cross-section of circular conductor used in high voltage generators is somewhat less than the cross-section of rectangular conductor used in conventional generator owing to the low current of powerformers. Fig. 4 shows a slot that its inside circular conductor cross-section is 25 percent of the circular conductor cross-section shown in Fig 3.

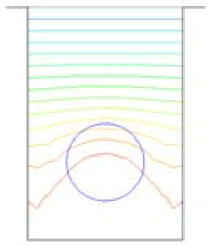

Fig. 4. Flux leakage lines for a conductor with cross-section equal to 25 % of cross-section of conductor that is in the slot shown in Fig. 3

The obtained result is that by decreasing the circular cross-section inside the slot to 25 percent of its previous amount, the slot specific permeance is raising from 1.07 μH/m to 1.2 μH/m. So, it is concluded that the decreasing of the conductor cross-section in powerformers owing to the low level of current yields to increasing of the slot leakage reactance.

2.2. The effect of the new configuration of slot in high voltage synchronous generators on slot specific permeance.

Regarding the use of high voltage cables for armature winding in high voltage synchronous generators, powerformer slots are shaped in such a way that they completely surround the cables inside them to prevent the cable vibration in slots. The changing of slot shape clearly influences the slot leakage reactance. Hence, in this section the effect of the new configuration of slot on slot specific permeance is investigated.

Two slots with the same conductor and the different shape of slot are considered in Fig. 5. Circular slot compared to square slot have less effective slot width and more steel. By applying analytical formula, the slot specific permeance for circular slots is calculated to:[4]

$$\lambda_s = \mu_0[0.66 + \frac{h_o}{W_o}] \qquad (2)$$

$$\lambda_s = 4\pi \cdot 10 - 7 \cdot (0.66 + \frac{2}{2}) = 2.08 \frac{\mu H}{m}$$

Again, the results obtained by finite element method for two slots shown in Fig. 5 are presented in Table 2.

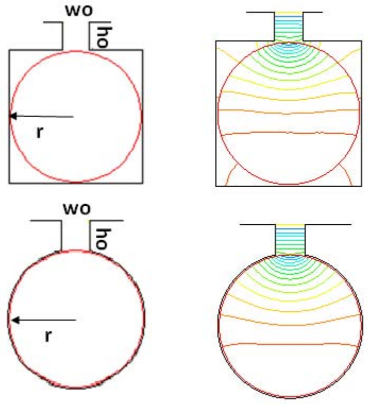

Fig. 5. Two similar slots with two different conductors inside them, and their flux leakage lines, rectangular slot (top) and circular slot

Table 2. The Results calculated by FEM and analytical formula for slots that shown in Fig. 5

Type of slot	λ_s (μH/m)(FEM)	λ_s (μH/m)(analytical formula)
Square slot	2.28	-
Circular slot	2.15	2.08

The results presented in Table 2 show that, the specific permeance of circular shape slot is more than that for square shape slot. This point indicates that the changing of the teeth as well as slots in high voltage generators for controlling cables inside slots yield to the increasing of slot leakage reactance. On the other word, it can be said that the slot using more steel or having less effective slot width have more slot leakage reactance. Fig. 6 shows the effect of the increasing of slot width on the slot specific permeance by FEM.

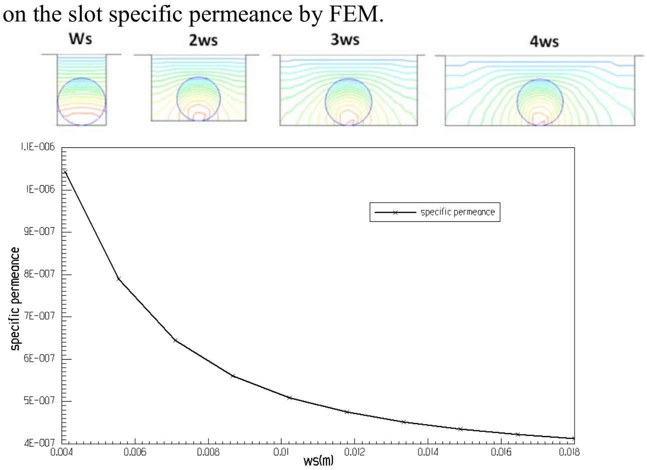

Fig. 6. Flux leakage lines for four slots with different width and similar conductor, and Slot specific permeance – slot width curve

In Fig. 5 it is clear that by increasing the slot width, the slot specific permeance, and consequently the slot leakage reactance is decreased non-linearly. The results for four different slot widths with the same conductor diameter are shown in Table 3.

Table 3. The Results calculated by FEM for four slots shown in Fig. 6

Width's slot	λ_s (μH/m)(FEM)
4mm	1.04
8mm	0.56
12mm	0.47
16mm	0.42

As mentioned above, for supporting cables inside slots, teeth in the powerformers stator are shaped in such a way that they surround cables. For this purpose, the amount of steel that used in circular slots for high voltage generators is increaseed compared to conventional rectangular slots. As shown in Fig. 6 and Table 3, the mentioned point causes the increasing of the slot leakage reactance.

3. Calculation of slot leakage reactance for a designed powerformer by considering three different slot configurations

In this section, the slot leakage reactance is calculated for a sample high voltage synchronous generator with three different slot configurations.

A 63kV, 25MVA high voltage synchronous generator is considered. For this powerformer, as shown in Fig. 7, there are twelve cables within each slot in way that the first two cables near rotor surface are 11kV cables, the next four cables are 33kV cables, and the last six cables are 63kV cables.

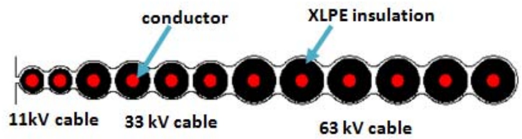

Fig. 7. Slot of a 63kV powerformer with twelve cables inside it

Because the two-layer windings are used for the armature winding of this powerformer, the six upper cables in slots are chosen as one layer and the six lower cables are chosen as another layer. First, the slot leakage reactance of powerformer is calculated by applying analytical formulas.

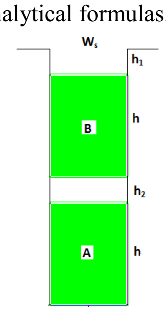

Fig. 8. Rectangular slot of conventional synchronous generators with two-layer winding inside it

Fig. 8 shows a conventional slot with two-layer windings that have coil A and coil B in it. The slot specific permeance is calculated to:[4]

$$\lambda_A = \mu_0\left[\frac{h}{3 \cdot w_s} + \frac{h_1 + h + h_2}{w_s}\right] \quad (3)$$

$$\lambda_B = \mu_0\left[\frac{h}{3 \cdot w_s} + \frac{h_1}{w_s}\right] \quad (4)$$

$$\lambda_{AB} = \mu_0\left[\frac{h}{2 \cdot w_s} + \frac{h_1}{w_s}\right] \quad (5)$$

$$\lambda_s = \frac{\lambda_A + \lambda_B + 2 \cdot \lambda_{AB} \cdot cos\alpha}{4} \quad (6)$$

Where h, h_1, h_2, and W_s are defined in Fig. 5, λ_A, λ_B, and λ_{AB} are coil A, coil B and mutual permeance respectively, λ_s is slot specific permeance, and α is pitch fraction angle. The corresponding slot leakage reactance ($X_{l(slot)}$) is given by:[4]

$$X_{l(slot)} = 2\pi \cdot f \cdot p \cdot q \cdot \lambda_s \cdot Z_s^2 \cdot L_{fe}. \quad (7)$$

Where L_{fe} is the length of the stator core since there are no radial air cooling ducts in the stator core of Powerformer, Z_s is cable per slot, p is number of poles, f is power frequency, and q is number of slots per pole per phase. The quantity μ_0 is the permeability of free space.

The designed parameters of the powerformer are presented in Table 4.[5]

Table 4. Designed parameters of 63kV and 25MVA powerformer

q = 2.25	Number of Slots per pole per phase
p = 32	Number of pole
Z_s = 12	Cable per slot
L_{fe} = 1.185m	Length of core
d_{cond} = 12mm	Diameter of conductor
$D_{(63kV\ cable)}$ = 42mm	Diameter of 63kV cable
$D_{(33kV\ cable)}$ = 33mm	Diameter of 33kV cable
$D_{(11kV\ cable)}$ = 23mm	Diameter of 11kV cable
h_s= 0.47m	Deep of slot
α = 20˚	Pitch fraction angle
$W_{s(max)}$=45mm	Maximum slot width
$W_{s(min)}$=26mm	Minimum slot width

Regarding the fact that each layer in the powerformer slot has six cables, powerformer slot parameters for their using in analytical formula are as follows:

h = 6 · 12 = 72 mm, h_1 = 9mm, h_2 = 470 - 2·72 – 9 = 317mm, $W_{s(eff)}$= 38 mm

Where $W_{s(eff)}$ is slot effective width.

So, slot specific permeance and slot leakage reactance are calculated to:

$$\lambda_A = 4\pi \cdot 10^{-7}\left[\frac{72}{3 \cdot 38} + \frac{9 + 72 + 317}{38}\right] = 13.955\ \mu H/m$$

$$\lambda_B = 4\pi \cdot 10^{-7}\left[\frac{72}{3 \cdot 38} + \frac{9}{38}\right] = 1.091\ \mu H/m$$

$$\lambda_{AB} = 4\pi \cdot 10^{-7}\left[\frac{72}{2 \cdot 38} + \frac{9}{38}\right] = 1.488\ \mu H/m$$

$$\lambda_s = \frac{13.955 + 1.091 + 2 \cdot 1.488 \cdot 0.94}{4} = 4.46\ \mu H/m$$

$$X_{l(slot)} = 2\pi \cdot f \cdot p \cdot q \cdot \lambda_s \cdot Z_s^2 \cdot L_{fe} =$$

$$2\pi \cdot 50 \cdot 32 \cdot 2.25 \cdot 4.46 \cdot 10^{-6} \cdot 12^2 \cdot 1.185\ \Omega/phase$$

$$= 17.2\ \Omega/phase = 0.108\ p.u$$

Now, to study the effect of the changing of slot configuration on the slot leakage reactance, the slot leakage reactance is calculated by using the finite element method for three different slot configurations that have been shown in Fig. 9.

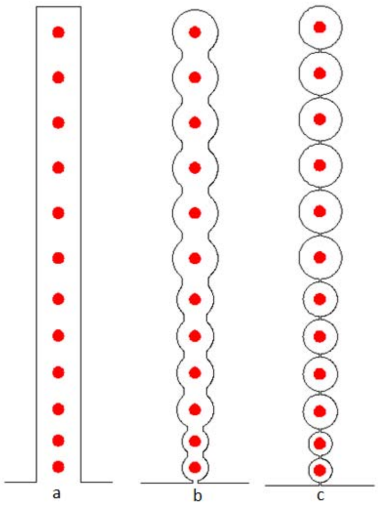

Fig. 9. Three different slot configuration of a 63kV and 25MVA powerformer

As shown in Fig. 9, slot a is similar to conventional slots. manufacturers of high voltage generators Usually make slots similar to slot b, to control cables inside them. And finally, slot c is one slot that completely surround its inside cables. It is clear that the effective width of slot from slot a to slot c is decreased, on the other word, the iron used in slots from slot a to slot c is increased. Therefore, it is predicted that the slot leakage reactance from slot a to slot c will increase. In Fig. 10 and Table 5, flux leakage lines and the slot leakage reactance obtained by finite element method are presented. The result obtained for slot a by using numerical analysis is approximately the same of the obtained result by applying analytical formula presented for conventional slot.

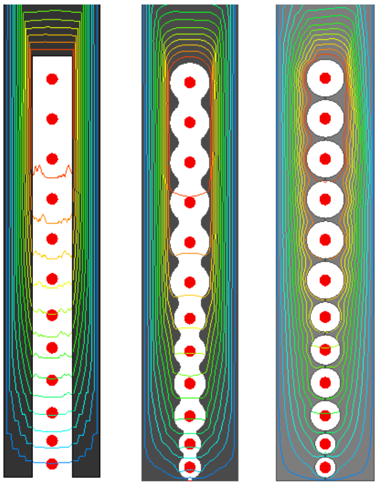

Fig. 10. Flux lines calculated by FEM for Three different slot configuration of a 63kV and 25MVA powerformer

Table 5. The results calculated by analytical formula and FEM for three slots shown in Fig. 9

slot	λ_s (μH/m)(analytical formula)	λ_s (μH/m)(FEM)	$X_{l(slot)}$(p.u)
Slot a	4.46	3.7	0.09
Slot b	-	7.48	0.182
Slot c	-	32.3	0.78

It is concluded from the results shown in Table 5 that the more the slot surrounds the cables, the more slot leakage reactance is resulted and this increasing rate is nonlinear.

The increasing of the slot leakage reactance yield to the increasing of the synchronous reactance and the high amount of the synchronous reactance decreases the short circuit level but makes difficult the voltage regulation. So, considering the compromise among voltage regulation, short circuit level, and the cable vibration inside slot, slot b is recommended among the three slot configurations shown in Fig 9.

4. Conclusions

The effect of the changing of the armature conductor and the slot configuration of high voltage generators compared with conventional generators on slot leakage reactance has been studied by applying existent analytical formula for rectangular conventional slots and by using numerical finite element calculations. The obtained results have been shown that the decreasing of conductor cross-section in high voltage generators owing to their low current yields to the increasing of the slot leakage reactance.

Again, it has been concluded that the more the slot encompasses its inside cables, the more the slot will have the slot leakage reactance, and this raising will be nonlinear.

Therefore, the present paper suggests that from electromagnetic view point, the best slot of high voltage generators is a slot that somewhat encompasses its inside cable for controlling the cable vibration, but this encompassing shouldn’t be too much that the slot leakage reactance is increased from its usual level.

5. References

[1] Leijon,M., "Powerformer – A radically new rotating machine," ABB Review, No.2, pp. 21-26, 1998.

[2] Leijon,M.,Owman,F., and Karlsson,T., "New electric generator takes a giant step back to basics," Modern Power Systems, pp. 19-24, May. 1998.

[3] Ibrahim A. Metwally, R.M. Radwan, AND A.M. Abou-Elyazied, " Powerformers:A breakthrough of high-voltage power generators," IEEE Potential Magazine, pp. 37-41,2008

[4] A. K. sawny, "Electrical Machines Design", fourth chapter, magnetic circuits, pp. 118-172

[5] M. T. Taherzadeh, " electromagnetic design and simulation of a high voltage synchronous generator, rated at 63kV and 25 MVA" , M.S. thesis, Khaje Nasir Toosi university, Tehran, 2009

[6] Ansoft Corporation, " A 2D Magnetostatic Problem" Maxwell 2D software Guide, Version 10, February, 2002.