

# The Simulation and Optimization of Transposition in Stator Bars of Turbo-Generator

Saeed Yousefi gaskari  
Science and Research University Semnan,  
Iran  
Kourosh Mosavi Takami  
PhD, Electric Power engineering

## ABSTRACT

In medium voltage high MVA Turbo-generators, generally Roebel bars are used in slot area. To reduce the circulating current in slot area of Turbo-generators, transposed Roebel bars are located in slots. Because of that large turbo-generators trend to offer a top power density, winding strands being as a Roebel transposition form and strands are insulated against each other. Optimized structure of the Roebel bar can remove the circulating currents which have been generated in the stator windings. The structure of the bar causes an increase in volume of copper used in strands of windings. With increasing the copper volume and length of strands, the rugged magnetic field increases in the slot area. Because of this reason, eddy current losses grow in solid winding strands. Thus there must be a balance between eddy current losses and circulating current losses in Turbo-generators. The optimal transposition way based on a finite analysis model is used to create this balance so to optimize the circulating currents desirably. To reduce circulating current, an optimized transposition should be performed in the end area too. Simulations by finite element confirm the desired effect of transpositions.

A 160 MW, 11 KV Turbo-generator has been simulated and the results verified by real data.

Keywords-Turbo-Generator; circulating current losses; eddy current losses; Roebel bars; copper losses; optimization transposition

## I. INTRODUCTION

Optimized structure of the Roebel bars has the ability to increment Turbo-generator efficiency, and therefore saving energy. The primary approach was used to optimize the Roebel bar based on the analytical method was founded [1]-[2]. Due to complexity to these methods, today, most of the methods applied to optimizing the winding losses and magnetic fields losses, utilize finite element analysis methods. Because the finite element analysis has a simple grid and the execution time is relatively short. Many technologies offered for elimination of

circulating current losses and preventing temperature rise in the Roebel bars [3]-[4]. In traditional transposition was not possible to completely eliminate circulating current. Therefore, remaining losses increases stator winding temperature. This temperature rise in stator windings was considered as an important factor in design constraints on huge Turbo-generator. In traditional technology, stator winding used widely in Turbo-generator and on winding was used for only one rotation. Which issue in addition to the circulating current losses, was increased eddy current losses. Therefore, a new technology offered for optimizing losses in

Slot area.

One of the most complex optimized transpositions which can be done in slot area is transposition with angle of  $540$  degrees. In this transposition, strands rotate one and half cycle on the tow stator core ends. This transposition has the ability to reduce circulating current in stator slot area to nearly zero. Also,  $540^\circ$  transposition can eliminate the induced voltages in the end area. While the  $360^\circ$  transposition cannot do this action. However, in the end area circulating current is being still produced. To eliminate these currents, a transposition optimization is done on the end area. Transposition on area and slot area cause increase in the volume of used copper and the length of windings compared to before. Which issue causes increases ragged magnetic field in winding. This leads to the increase of eddy current in the winding. This also makes the copper losses increase. Therefore, main objective of this paper is to compare circulating current and eddy current losses in different designs of winding, to create a balance between the losses. To obtain an optimal transposition, circulating current losses and eddy current losses are estimated as a simplified model in different transposition.

Considering copper loss in the stator winding transposition is one of the most important points that are discussed in this paper. Comparing copper and circulating losses the best transposition is chosen.

## II. STATOR WINDING CONFIGURATION

Stator winding is comprised of two sections; a slot area is located within a groove, and end area that made in the direction of the axis. Stator windings in large Turbo-generators are often double layers half windings, and each of them divided to half similar coil. As shown in fig 1.

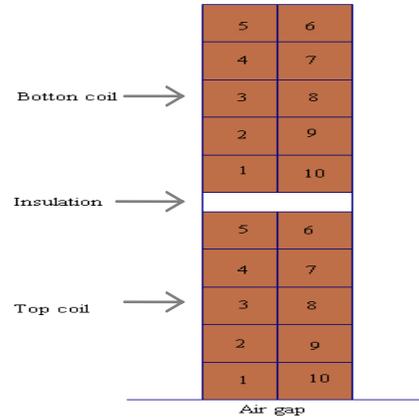


Figure 1. Copper wire order in the simulated model

Conductors used in the windings have appropriate distribution; this appropriate distribution reduces eddy current tremendously. While situation is different in extensive bar. Stator winding in turbo-generators contains number of the string that has a rectangular cross section. These strings are isolated to each other. In order to reduce eddy current losses in this strings. The main problem of such structure is circulating currents that exit however that there are appropriate distribution conductors. The simple structure of Roebel bars is shown in figure 2.

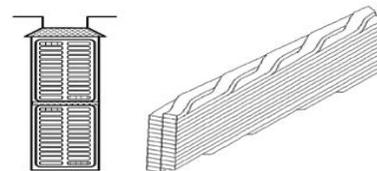


Figure 2. Easy structure of a Roebel bar [5]

## III. TRANSPOSITION IN ROEBEL BARS

Usually in traditional stator windings of turbo-generator circulating current is high in slot area. To reduce circulating currents stator windings in the slot area are transposed. For example the transposition begins from the top to the bottom of the slot and the conductors change their situations choosing available positions in the windings. Amount of circulating currents depends on transposition angle. By transposition angle of  $540$ , this current nearly goes to zero.

This transposition is the best transposition in the slot area. However because of longer core length in comparison with hydro generators the amount of copper used in slot area increase strikingly and the core becomes longer than the before transposition. This cause rugged magnetic field and eddy currents increase in slot area. Balance between increased eddy currents to circulating currents is one of the most important objectives of this paper that discussed in following sections. In windings that not transposition on the end area, leakage fluxes in the end area major factor of creating circulating currents. To eliminate these currents an optimal transposition in end area usually is used. Transposition angles might be 90 and 180 degree in the end area. 90° Transposition leads to excessive increase in volume of used copper that respect to the transposition of 540 degrees in slot area. This increment volume can be increased remarkably, and eddy currents to be inappropriate. So best transposition to end area is 180 degrees which by using lower volumes of copper, both minimize circulating currents losses and does not increase eddy current losses too much.

According to the above subject, suitable composition for transposition in slot area and end area divided into 4 designs. Which results of simulation by finite element analysis indicates that the most appropriate type of transposition is 180/540/180 transposition. 540° Transposition in slot area as shown in figure 1-2. For example transposition in strand number three is highlighted.

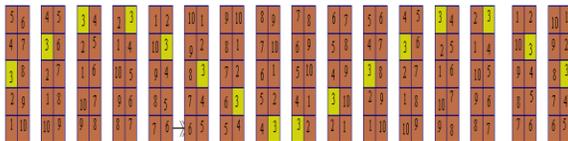


Figure3. 540 degree Transposition in slot area

Circulating current losses and Copper losses are two major factors in the rise temperature in Roebel bars so these two factors should be considered in the optimization transposition.

#### IV. ASSESSMENT OF LOSSES IN STATOR BARS

##### A) Leakage fluxes

Flux difference between the two ends of the wire wrapping is called leakage flux. There is not voltage difference between the fields in this area by 540° transposition in the slot area. Thus there are not flux differences in the slot area. There are leakage fluxes in 360° and 180° transposition, which are the fluxes as follows:

- a) Inner coil end leakage flux (figure 4.a)
- b) Outer coil end leakage flux (figure 4.b)
- c) Slot leakage flux (figure 4.c)

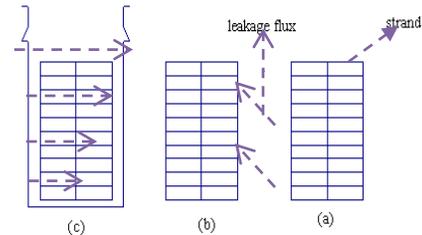


Figure 4. The leakage fluxes that lead to the circulating current.

According to entity leakage flux best for eliminate circulating currents this is that in each strand, currents that generated by leakage flux go toward uniformity. Magnetic reluctance of the leakage flux is very small and its direction is in order transverse flux. This flux has the ability to produce high amounts of circulating currents, especially on strands that are located near the air gap.

##### (B) Circulating Current losses

Circulating current losses occur by flowing circulating current in strands. Circulating current is different from strand to strand also the total to zero over the cross-section of all strands in one bar.

##### B-1) Analysis current of strands in slot area at 540°transposition

Strands current calculated as (1):

$$[Z]\{I\}=\{V\} \quad (1)$$

Where,  $[Z]$  is impedance matrix, including resistance and inductance, and  $\{I\}$  is the strand current vector and  $\{V\}$  is the voltage difference vector.

Assuming, number of strands layers in  $540^\circ$  transposition, is of  $N/2$  degree if the strands have two configurations, Roebel transposition become  $3n/2$ . Dlc is long strands within a distance transposition based on one changing situations. The following equations is used calculate the Z and V in  $540^\circ$  transposition.

$$[Z] = \frac{dl_c}{2}[Zl^0] + dl_c[Zl^1] \dots + \frac{dl_c}{2}[Zl^{3n/2}] \quad (2)$$

$$\{V\} = \frac{dl_c}{2}\{Vl^0\} + dl_c\{Vl^1\} \dots + \frac{dl_c}{2}\{Vl^{3n/2}\}$$

Where,  $Zl^\circ$  and  $vl^\circ$  are per-unit of Z and V. Superscript indicates the number of transposition.

### B-2) strand current

We assume that the number of winding layers of strings is  $N/2$ , due to the configuration of two rows, the final number of strands is N.

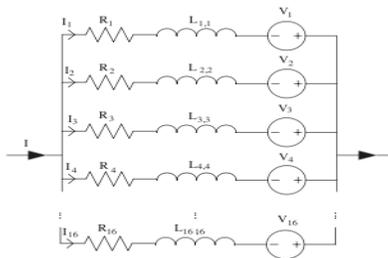


Figure 5. Strand current

Resistance R usually is equal at all strings.  $L_{lk}$  Is the abbreviation of mutual inductance between l and k.  $\Phi_{exk}$  is generated magnetic flux in k strand, that produced by rotor currents or other windings. The generated magnetic flux by the current in all strands is as considered internal magnetic flux.

### B-3) Current equations

Two types of current equation can consider:

- 1) Unknown strand current
- 2) Unknown the circulating current

In this paper, we use of second relationship. A simultaneous equation with unknown circulating current is calculated from the following equation:

$$Ri_n + j\omega \sum_{k=1}^n L_{n,k}i_k - V = -j\omega(\Phi_{exn} + \Phi_{inn}) - R\frac{I}{n} \quad (3)$$

The matrix form of (3) for n equation that has been used in MATLAB in order to compute circulating current is calculated from (4):

$$\begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_{10} \\ V \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \dots & Z_{110} & -1 \\ Z_{21} & Z_{22} & \dots & Z_{210} & -1 \\ \vdots & \vdots & \dots & \vdots & \vdots \\ Z_{101} & Z_{102} & \vdots & Z_{1010} & -1 \\ 1 & 1 & \dots & 1 & 0 \end{bmatrix}^{-1} \begin{bmatrix} -j\omega\lambda_1 - U \\ -j\omega\lambda_2 - U \\ \vdots \\ -j\omega\lambda_{10} - U \end{bmatrix} \quad (4)$$

According to the above equation circulating current losses in the winding will be calculated through the following equation:

$$P_c = \sum_{k=1}^N I_k^2 \quad (5)$$

In eq. 2,  $I_k$  is circulating current in each strand and R is equivalent Resistance.

### C) Copper losses

Copper losses are varying in different transposition. Copper losses are calculated by following equation:

$$Q_{cu} = 2.4j_a^2 \quad (6)$$

Where,  $j_a$  is current density, and  $G_{cu}$  is weigh of copper.

Weigh of copper in Roebel bar is determined by the cross sectional area and length of the string. Cross section is identical in all transposition, thus length of the string plays the main role in copper losses. In figure3 shown a single string in 180/540/180 transposition.

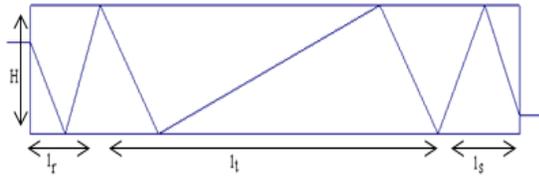


Figure 6. Calculation model of a single model

Based on figure3, length of strands is calculated from the following equation:

$$2\sqrt{L_s^2 + H^2} + 2\sqrt{L_t^2 + 4H^2} + 7L_c \quad (7)$$

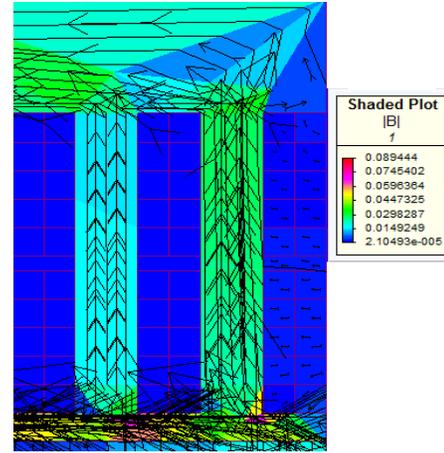
According to the above equation, length of strands in case of 180/180/180 and 180/360/180 transposition can be obtained from the following relations:

$$\sqrt{L_s^2 + H^2} + \sqrt{L_t^2 + 4H^2} + 3L_c \quad (8)$$

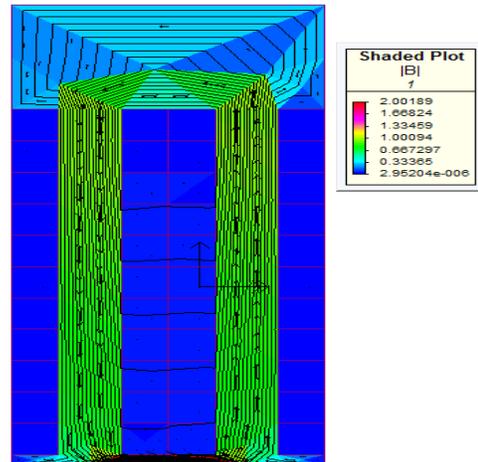
$$2\sqrt{L_s^2 + H^2} + \sqrt{L_t^2 + 4H^2} + 5L_c \quad (9)$$

## V. RESULT AND DISCUSSION

Magnet software is used to calculate circulating currents in slot and end area. Figure 7 shows the distribution of flux in slot area before the transposition.



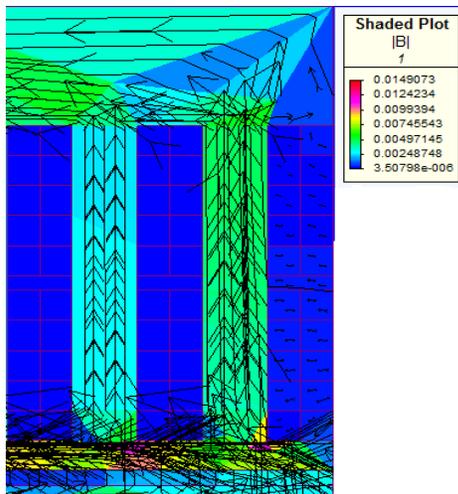
(a)



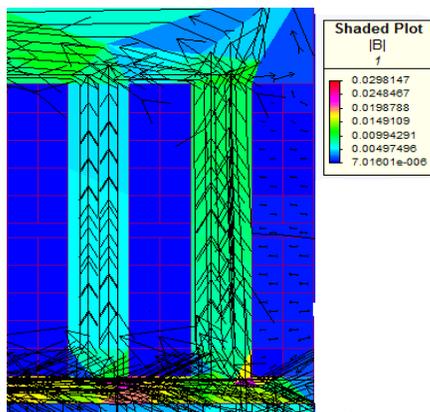
(b)

Figure7. Distribution of flux in slot area before the transposition. (a) External flux (b) internal flux

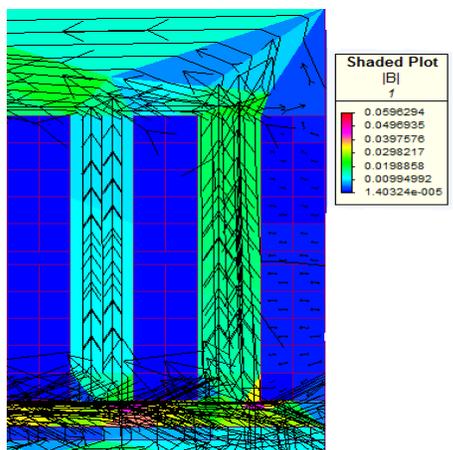
According to the figure1, the flux distribution is very high in slot area, this fluxes causes increase circulating currents in slot area, high distribution in slot area causes an increase in circulating currents in the way that existence of transposition in slot area will be essential. In figure 8 shown internal flux distribution in different transpositions.



(a)



(b)

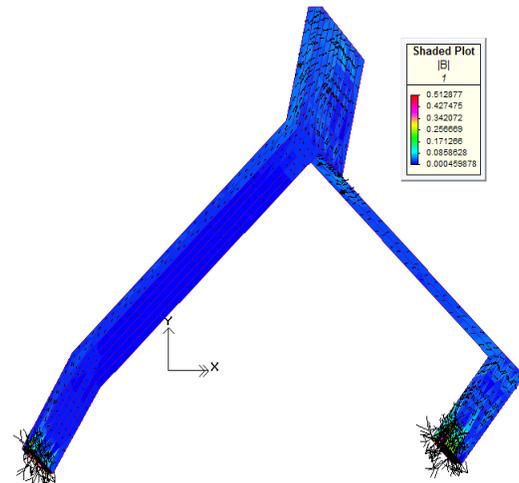


(c)

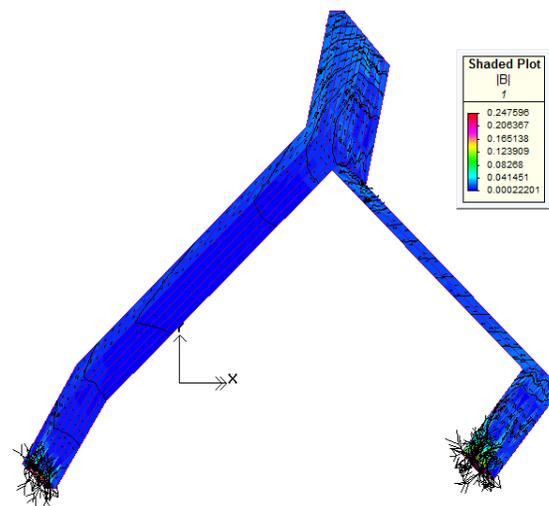
figure8. Internal flux distribution in different transpositions. (a)540° (b) 360° (c)180°

As clarified in figures, in 540 distribution of internal flux is noticeably reduced this lead to reduce circulating currents. We can calculate circulating currents and circulating currents losses in slot area, by results of the simulations and formulas mentioned in the previous section,

In figure 9 internal and external flux distributions in end area are shown before the transposition.



(a)



(b)

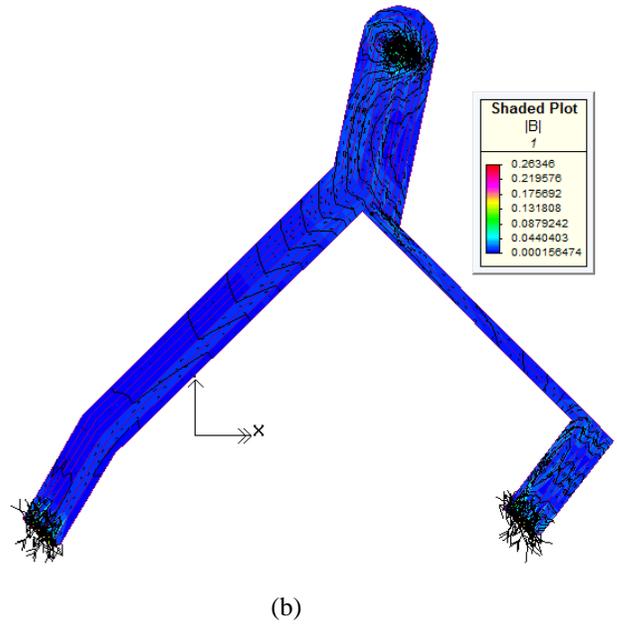
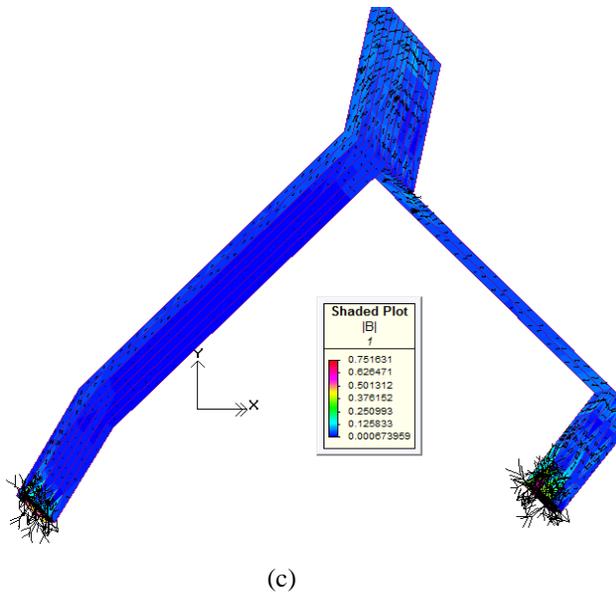


Figure 9. Flux distributions in end area before of transposition. (a) Circumferential external flux (b) internal flux (c) external and external flux

Clarified of the figures and simulation results, flux distribution which leads to an increase in circulating currents is very high. In order to reduce circulating current 180 transpositions is applied at the end area. Simulation results are shown in figure 10.

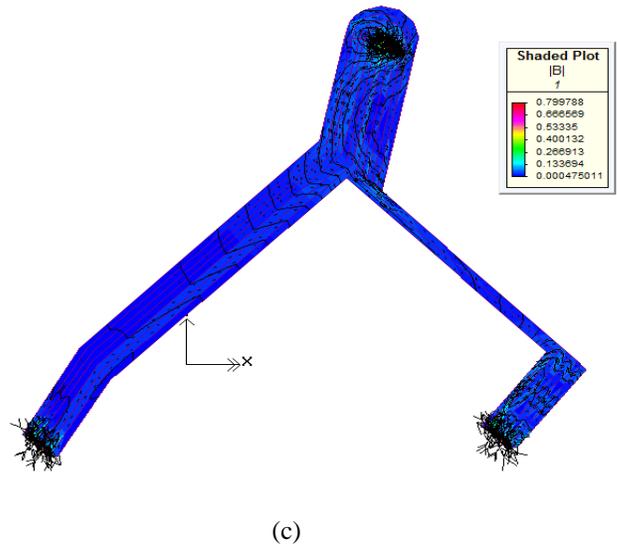
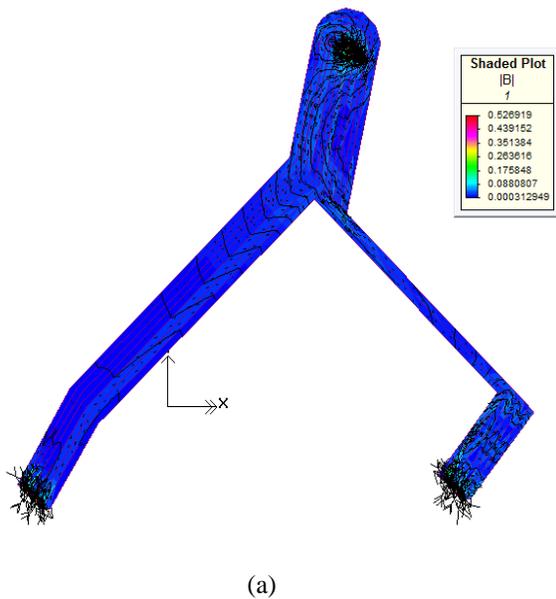
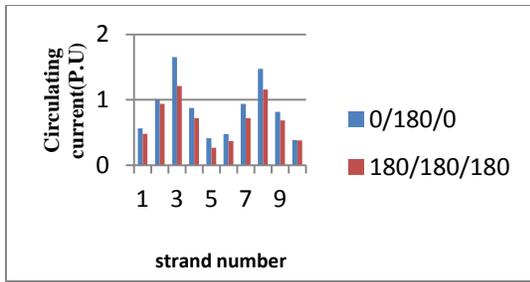
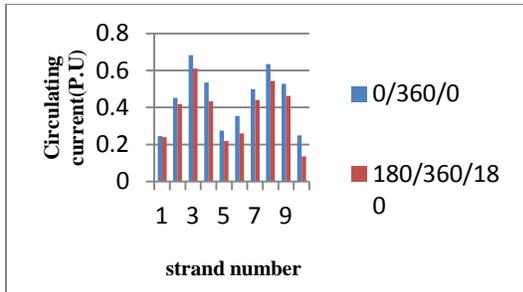


Figure 10. Flux distributions in end area with transposition. (a) Circumferential external flux (b) internal flux (c) external and external flux

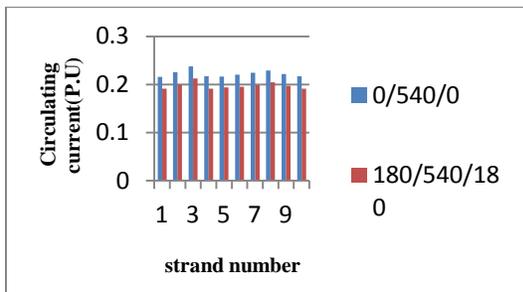
Optimal transposition angle depends on slot width, the length of the end winding, the number of strands in Roebel bar, the length of strands in bars, and the leakage flux in the slot and end area. Also circulating current greatly depends on the mentioned circumstances. In figure 11, distribution of circulating current in different transposition in upper coil is shown.



(a)



(b)



(c)

Figure 11. Calculating currents distribution in top Bar  
 a) 0/180/0,180/180/180 b) 0/360/0, 180/360/180 c)  
 0/540/0,180/540/180

In this paper, a 200MW turbo-generator has been selected for review. The table1 shows the main characteristics of this turbo- generator.

Capacity	200 MW
Number of poles	2
Speed	3000 RPM
Stator winding	Y*3
Number of stator slots	60
Kind of transposition	0/180/0
Total losses	595 W

Table1. Main characteristic of turbo- generator

In the previous section calculation methods of circulating currents and copper losses have been presented. Calculation results of circulating current in the upper and lower coil of 0/540/0 transposition is approved by [7]. 0/180/0 transposition has the maximum circulating current losses that owns the value of 140.32W. With knowing that the circulating current in the stator bars can lead to excessive temperature, the 180/540/180 transposition is the best case which reduces circulating current losses with the value of 0.79W. Though the copper losses in this type of transposition is more than mentioned types. On the other hand total losses as lower than previous transposition. Circulating current, copper and total losses in different transpositions are shown in table2.

Transposition	Circulating current losses	Copper losses	Total losses
0/180/0	140.32	449.34	589.66
180/180/180	103.54	458.29	561.83
0/360/0	57.24	465.47	522.71
180/360/180	24.87	479.25	504.12
0/540/0	18.57	485.36	503.93
180/540/180	0.79	498.25	499.04

Table2. Theoretical losses in the top Bar (in watts)

## VI. CONCLUSION

There are high circulating current losses and eddy current losses, in stator winding of huge Turbo-generator. These losses decrease machine efficiency, due to the heat generated. By optimizing the transposition of stator winding, the losses are reduced drastically. Based on the tests that performed, best transposition in stator winding is 180/540/180.

Since, end area is long, transposition with more angles become possible, e.g. 180° transposition. This transposition increases the volume of coppers which is used in windings. Simultaneously, eddy current losses increase. However, this increment in eddy current losses are more less than the reduction in circulating current losses. Hence, the total losses are reduced by using this transposition.

## REFERENCES

- [1] J.Hadermann. "Transposition in stator bars of large turbo generator" IEEE Transaction on Energy conversion, vol.19, 2004, pp.553-560
- [2] Toma Dordea, Valentin Muller, Leana Jorac, Ghroge Madescue, Martian Mot, Lucian Ocolisian. "Analytical method for the optimization of Roebel bars compose of full elementary conductors" Romanian Academy, 300223 Timisoara, bd, viteazul nv24,2006.
- [3] M.fujita, Y.Kabata, T.Tokumasu, M.Kakiuchi, H.shiomi, S.Nagano. "Air cooled large turbine generator with multiple pitched ventilation ducts" IEEE International conference, 9054152, 2005, pp.910-917.
- [4] Chen Shu-xin; Fan Ming-Qing. "Optimization of hydrogen cooled turbo-generator rotor wedge cooling method" IEEE Conference Publications" vol.12242752, 2011, pp.497-500
- [5] Jibin Zou; Bo Zao; Yongxiang Xu; Jing Shang; Weiyan Liang. "A New End Windings Transposition to Reduce Windings Eddy Loss for 2 MW Direct Drive Multi-Unit PMSM" IEEE Journals & Magazines, vol13056910, 2012, pp.3323-3326
- [6] K. Takahashi, M. Takahashi, M. Sato, "Calculation method for strand current distributions in armature windings of a turbine generator", Electrical Engineering in Japan, Vol. 143, pp. 50–58, 2003
- [7] Sheng Xia, Yingying Yao, "Optimization of Transposition in Stator Bars of Hydro-generators" School of Electrical Engineering Zhejiang University Hangzhou, China, IEEE Conference Publications, vol. 13034920,2012,pp.1-4