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# Salient Pole Synchronous Generator Optimization by Combined Application of Slot Skew and Damper Winding Pitch Methods

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**Abstract**—Slot skew is applied as a method to increase the armature winding voltage waveform quality of synchronous hydro generators. Skew that matches the region of one slot pitch can effectively damp stator slot harmonics. However, achieving this condition can be difficult in some manufacturing cases, especially for the machines with greater axial length. That is why other methods are commonly used to increase the voltage waveform quality of large hydro generators. One such method is based on the damper winding slot pitch choice which ensures reduction of stator slot harmonics from the main magnetic field. Appropriate placement of damper bars over the pole shoe does not represent a significant technological problem and is much simpler to manufacture in compare with the slot skew or the fractional armature winding methods. The downside of damper slot pitch adjustment method is the damper bar currents incensement in steady state condition of the generator, which increases damper winding losses and also the rotor temperature. In order to decrease damper winding current for long term operation and enable the generator pole shoe design with smaller cross section damper bars, a combination of damper slot pitch and partial slot skew can be utilized. This paper gives insight on consequences that can occur for voltage waveform if slot skew does not not fully match the stator slot pitch and the advantages of above mentioned combined method for the design optimization of salient pole synchronous generator.

## 1. INTRODUCTION

Modern electrical generators need to satisfy different requirements among which the most prominent ones are voltage waveform quality, noise and vibration levels which are defined in tenders and measured on generator commissioning. All these requirements need to be met, while maintaining generator efficiency level. When designing a new generator such tasks are formidable and even harder to achieve in cases of generator refurbishment, where for further exploitation, parts of the old machine are kept in place [1–4].

Few methods can be used to achieve better voltage waveform, while maintaining noise and vibrations at satisfactory levels. Stator slots number, winding arrangement, slot skew and damper bar pitch can all affect the voltage waveform quality, but each has its own limitations and downsides [5–7].

The number of stator slots choices is limited due to the winding arrangement, dimensional restrictions and mechanical stiffness requirements of stator. Winding with fractional number of conductors per pole and phase has significant number of winding couplings and is more complicated to assemble [8–10].

Electromagnetically and mechanically, slot skew is one of the most effective methods to reduce the level of voltage waveform higher harmonics, noise and vibrations [1–18]. However in cases of large generators, slot skew is usually considered as a last resort method, due to technological problems such as additional stacking procedures and precision bending of the stator winding bars.

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The main purpose of the damper winding is to protect the machine components in non-regular situations such as asymmetric load or short circuit condition. If the damper winding is only used for this purpose, the slot pitch is usually chosen to be the same as the stator slot pitch. This ensures that the slot magnetic field harmonics do not induce currents in damper winding (criteria of the smallest damper bar losses in steady state operation) [4, 14, 19].

Damper winding with the same pitch as the stator slots can be used to improve the voltage waveform if the generator has a whole number of stator slots per pole and phase. A positive effect can be achieved by shifting the damper bars over the pole shoe circumference [20, 21]. However, using this method solely does not always lead to a satisfactory quality of voltage waveform and is not practically applicable when dealing with stator which has fractional number of slots per pole and phase.

If the pitch of stator and damper slots are equal, improvement of voltage waveform can be achieved by slot skew method. To fully damp the slot harmonics, skew needs to be of the same pitch as the stator and damper winding slot pitch. Such a skew can be significant in angle size and therefore causes the above mentioned manufacturing problems [15, 16, 18].

Damper bar slot pitch can be reduced in such a way that damper bar currents actively suppress slot harmonics and improve voltage waveform. This comes at the cost of increased losses and temperature of the rotor. In such situations slot skew is not required to improve voltage waveform, but can significantly reduce currents and ohmic losses of the damper bars [9, 19, 22]. As skew angle in this case does not need to match stator slot pitch, it can be significantly shorter which leads to simpler manufacturing of stator.

To investigate how the level of stator slot skew affects the damper bar currents and how damper bar pitch affects the line voltage waveform, a finite element method (FEM) analysis was performed on a 83.5 MVA, 44 pole generator. Description of the performed analysis and related findings are presented in next sections.

## 2. NUMERICAL METHODS TO CALCULATE EFFECTS OF THE SLOT SKEW

Three finite element method modelling approaches can be used to determine the effects of the slot skew on the voltage waveform and damper bar currents. Direct approach requires creating and using a 3D FEM model as can be observed in Fig. 1(a) [23]. Such simulations are computationally very demanding, long lasting and applicable mainly when analysing segment of one or two poles of the machine. That is why they are generally used for qualitative research.

In semi-direct approach a multi-slice 2D or so called 2.5D model is used [5, 13, 17, 22, 23]. In such a modelling a machine is axially divided into equal length segments as can be observed in Fig. 1(b). Each segment is magnetically represented with a 2D model, and has a geometry that is shifted in angle with relation to other segments.

Angle shift of each segment is determined based on the slot skew value. All of the segments conductors are electrically interconnected, so a link between 2D model segments is achieved as can be

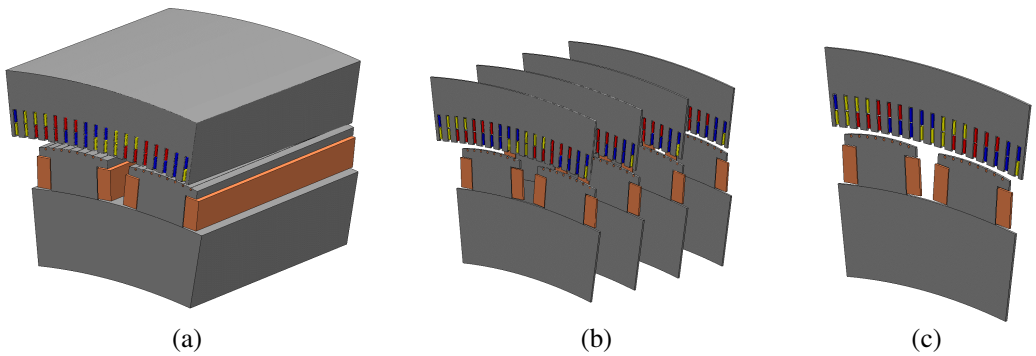



**Figure 1.** Types of FEM models that can be used for skew effect calculations: (a) 3D Model; (b) 2.5D Model; and (c) 2D model.

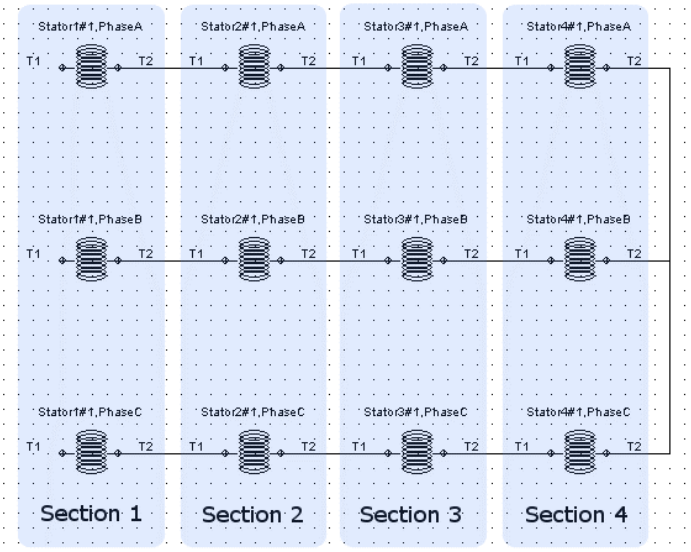



**Figure 2.** Electrical connections between cross sections of the multi-slice 2D FEM model.

observed in Fig. 2. Results precision and computational demand of such a model depend on the number of 2D slices.

In indirect approach a regular single-slice 2D model for electromagnetic calculations is used. Acquired results using a model like this is corresponding to no slot skew condition. In order to determine voltage waveforms and damper bar currents that match the situation of a slot skew, numerical results need to be processed by additional analytical calculation [1, 13, 22]. Such an indirect calculation approach is the fastest and easiest to compute, but with lower accuracy of the results than the other two FEM calculation methods.

### 2.1. Optimal Number of Cross Section Segments of the Multi-Slice 2D Model FEM Simulation

When dealing with skew effect analysis, the segments number of a multi-slice 2D model can greatly affect the results accuracy. In order to identify the required minimal number of the model axial divisions to adequately calculate damper bar currents, a number of FEM simulations was conducted. A situation of the machine with 25% pitch difference between stator and damper bar slots was chosen for this analysis, because in this situation the slot skew can greatly affect the damper bar currents. Main data of the generator used for this analysis are presented in Table 1.

Total of 7 different models are analysed, in which the number of axial slices in them varies from 1 (single-slice 2D model) to 7. Table 2 shows the main results of the damper bar calculations.

In Table 2, $NCS$ denotes the cross sections number used in the multi-slice 2D model simulation;

**Table 1.** Fundamental data of the generator.

| Data | Marking | Unit | Value |
|---|---|---|---|
| Rated power | $S_n$ | kVA | 83500 |
| Rated voltage | $U_n$ | V | 10500 |
| Number of poles | $2p$ | - | 44 |
| Diameter of stator bore | $D$ | mm | 8000 |
| Minimal air gap width | $\delta_0$ | mm | 19.5 |
| Number of stator slots | $N_2$ | - | 396 |

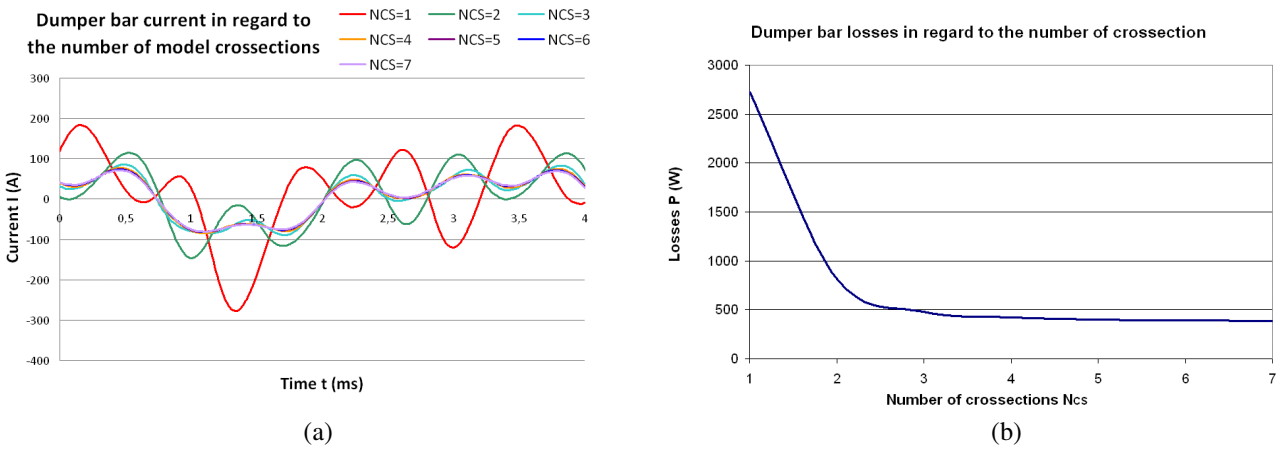
**Table 2.** Effect of the number of axial cross sections on damper bar currents and losses.

| $NCS$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | $\infty$ |
|---|---|---|---|---|---|---|---|---|
| $I_{\max}$ (A) | 343.4 | 148.1 | 122.9 | 116.7 | 114.1 | 112.8 | 112.0 | 109.8 |
| $I_{\text{mean}}$ (A) | 180.5 | 93.6 | 70.8 | 66.6 | 65.0 | 64.2 | 63.7 | 62.4 |
| $\Gamma_{\max}$ (A/mm$^2$) | 17.49 | 7.54 | 6.26 | 5.94 | 5.81 | 5.74 | 5.70 | 5.59 |
| $\Gamma_{\text{mean}}$ (A/mm$^2$) | 9.19 | 4.77 | 3.61 | 3.39 | 3.31 | 3.27 | 3.24 | 3.18 |
| $PDW$ (W) | 2733 | 812 | 477 | 423 | 403 | 393 | 387 | 372 |
| $PDW/PDW1$ (%) | 100.0 | 29.7 | 17.5 | 15.4 | 14.7 | 14.4 | 14.2 | 13.6 |

$I_{\max}$ denotes the rms current value of the most loaded damper bar of the pole; $I_{\text{mean}}$ is the mean rms current value of all the damper bars; $\Gamma_{\max}$ is the current density of the most loaded damper bar of the pole; $\Gamma_{\text{mean}}$ is the mean current density value of all the damper bars; $PDW$ denotes the total damper bar losses; $PDW/PDW1$ is the damper bar loss percentage ratio of NCS cross sectioned and a single sectioned (2D) model.

The last column of the table (where $NCS = \infty$) shows extrapolated results that correspond to infinite number of model cross sections, i.e., the smooth skew of a stator slot. The results show that values of damper bar currents are severely affected by a slot skew. With a slot skew that matches 75% of the stator slot pitch, damper bar currents value can be decreased by 3 times and ohm losses by 7 times. The accuracy of damper bar currents calculation increases drastically with the number of used cross sections of the FEM model.

The results show that for the model composed of only 2 cross sections, the damper bar currents values deviate over 30% from the continuous slot skew condition. With 3 cross sections this difference falls under 10%, and with 5 or higher number of cascading cross sections bar currents values differ in less than 4% from the continuous slot skew currents. Effect of increasing multi-slice 2D model cross section segments on the damper bar current and ohm loss calculation value can be observed in Fig. 3.




(a) (b)

**Figure 3.** Effect of increasing multi-slice 2D model cross section segments on: (a) the damper bar current, and (b) ohm loss calculation value.

## 2.2. Method to Determine Slot Skew Effect on Damper Bar Currents by Use of the 2D FEM Model

When considering generator design, usually there is a requirement to quickly evaluate a few different variants of the machine in question. Main disadvantage of 3D and multi-slice 2D FEM methods is the requirement to modify the model and repeat the time consuming numerical calculation for each stator

skew consideration. The method based on the single-slice 2D FEM model enables the determination of damper bar currents for arbitrary slot skew on the basis of the results of only one FEM calculation.

Analytical process to determine slot skew effect on the damper bar currents comprises the following steps:

(i) Waveform of each damper bar current, calculated by means of the single-slice 2D FEM model, for the non-skewed stator slot design, needs to be decomposed to harmonics, by means of the Fourier analysis.

(ii) For each harmonic $\nu$ a skew factor $\xi_{sk\nu}$ is determined which can be obtained from Eq. (1) for any desired slot skew $s$ ($s = 1$ equals slot skew of one stator slot pitch). In this expression $\tau_p$ and $\tau_s$ represent pole pitch and generator stator slot pitch, respectively.

$$\xi_{sk\nu} = \frac{\sin\left(\nu.s.\frac{\tau_s}{\tau_p}\frac{\pi}{2}\right)}{\nu.s.\frac{\tau_s}{\tau_p}\frac{\pi}{2}} \tag{1}$$

(iii) The current harmonics amplitudes for the generator with slot skew $I_{sk\nu}$ are calculated based on current harmonic amplitudes of a non-skewed waveform $I_\nu$ and a skew factor $\xi_{sk\nu}$ which can be obtained from Eq. (2):

$$I_{sk\nu} = \xi_{sk\nu} \times I_\nu \text{ (A)} \tag{2}$$

(iv) Waveform of each damper bar current is reconstructed by summation of electrical current harmonics with the amplitudes $I_{sk\nu}$ which match the slot skew state.

Effect of the described procedure on one of the damper bar currents is visually presented in Fig. 4. Depicted current matches the skew of 75% stator slot pitch ($s = 0.75$).

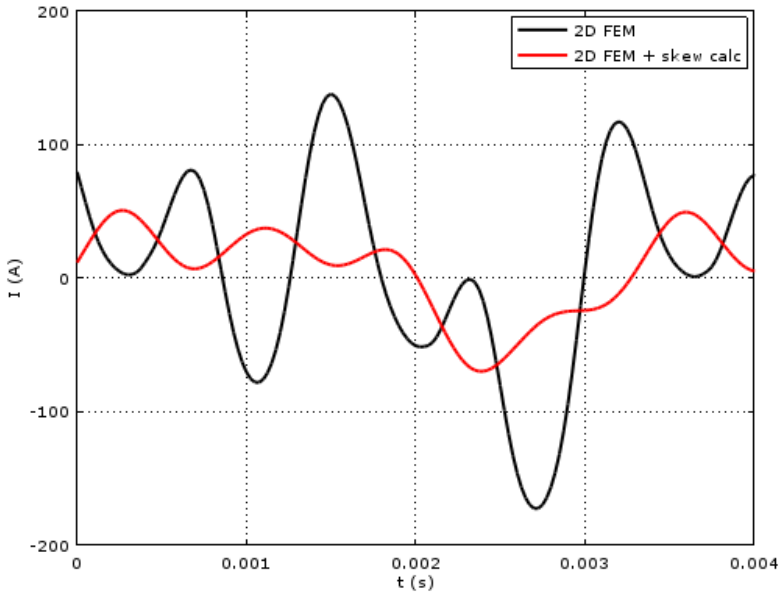



**Figure 4.** Waveform of damper bar current determined on the basis of the single-slice 2D FEM model: Current before (black) and after (red) the skew effect calculation.

### 2.3. Comparison of Results Obtained by Multi-Slice and Single Slice 2D FEM Model

Electromagnetic coupling that exists between damper winding and stator winding of the machine changes with the slot skew. That is why damper bar currents and voltage waveforms determined on the basis of a single-slice 2D model will always partially differ from the results of a multi-slice 2D model. To investigate this difference a comparison between calculated damper bar currents of a single-slice and a multi-slice 2D model with four cross sections of the machine was performed.

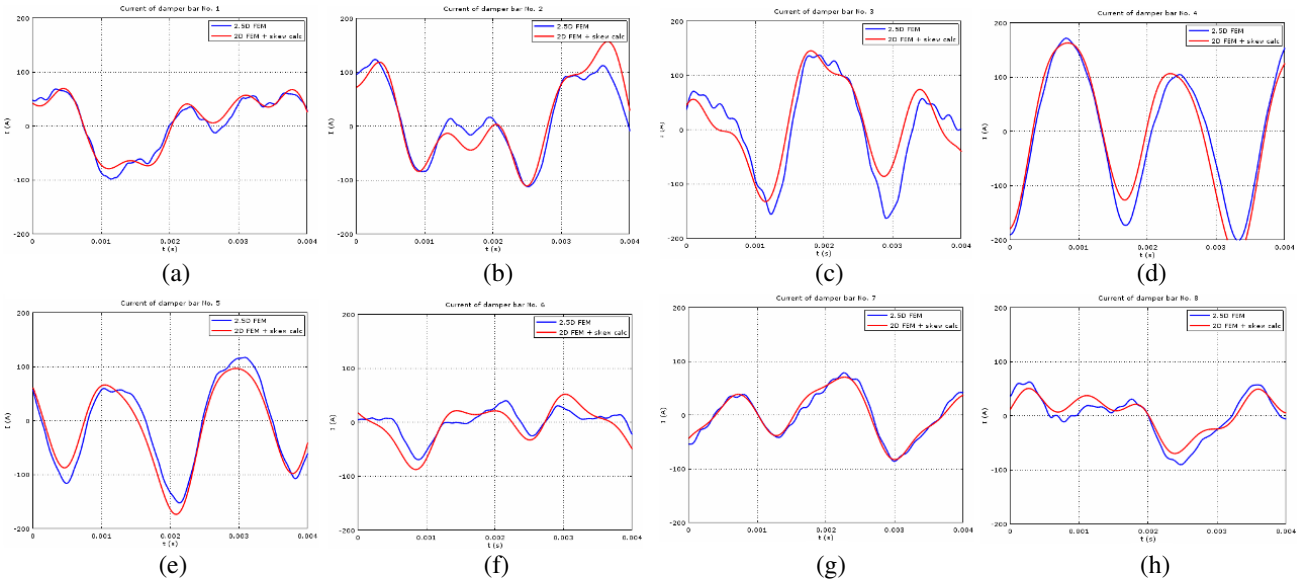



**Figure 5.** Comparison of damper bar current waveforms calculated by means of multi-slice 2D (blue) and single-slice 2D (red) modelling method for one pole of the generator for different number of damper bar: (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, (g) 7, (h) 8.

Visual comparison of the damper bar current waveforms is presented in Fig. 5, while numeric rms values of currents and damper winding losses are given in Table 3. It can be observed that the calculated damper bar currents with multi-slice 2D and single-slice 2D have similar waveforms and current distributions across the damper bars of one pole. Mean difference in rms values of these currents is 5%, and final difference in losses is about 12%.

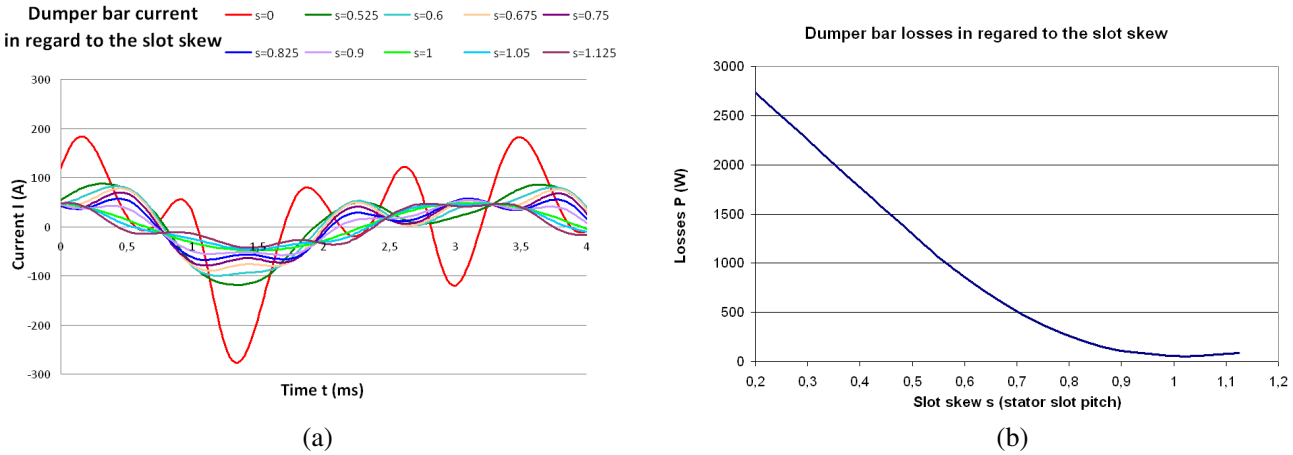
**Table 3.** Difference in damper bar currents obtained by single-slice and multi-slice 2D FEM method.

| Damper bar | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | $PDW$ (W) |
|---|---|---|---|---|---|---|---|---|---|
| $I_{2,5D}$ (A) | 51.5 | 70.4 | 93.5 | 114.8 | 80.8 | 26.0 | 47.2 | 39.7 | 417 |
| $I_{2D}$ (A) | 51.7 | 66.7 | 82.7 | 109.8 | 77.8 | 33.4 | 43.9 | 33.4 | 372 |
| $\Delta_{2,5D-2D}$ (%) | −0.4 | 5.5 | 13.1 | 4.6 | 3.9 | −22.2 | 7.5 | 18.9 | 12.1 |

## 3. EFFECT OF THE SLOT SKEW ON DAMPER BAR CURRENTS

Analyses of multi-slice 2D and single-slice 2D FEM calculations showed that the slot skew which matches full stator slot pitch significantly reduces damper bar currents. In order to determine how different values of the skew impact the damper bar currents, analysis was performed for a number of different slot skews for which the results can be observed in Table 4 and Fig. 6. Calculations were conducted based on single-slice 2D FEM simulation results, with the analytic method described in Section 2.2.

Results show nonlinear dependency between slot skew and damper bar losses. While slot skew of 50% stator slot pitch results in a 50% decrease in losses, additional 10% increase of slot skew leads to 70% decrease in the losses. If slot skew differs less than 20% from the full stator slot pitch, damper bar losses are within 10% of the losses that occur in non-skewed situation.




(a) (b)

**Figure 6.** Effect of increasing the stator slot skew on: (a) the damper bar current, and (b) ohm losses.

**Table 4.** Effect of the stator slot skew on damper bar currents and losses.

| $S$ | 0 | 0.525 | 0.6 | 0.675 | 0.75 | 0.825 | 0.9 | 1 | 1.05 | 1.125 |
|---|---|---|---|---|---|---|---|---|---|---|
| $I_{\max}$ (A) | 343.4 | 214.0 | 179.6 | 144.6 | 109.8 | 76.4 | 46.2 | 37.6 | 36.8 | 43.6 |
| $I_{\text{mean}}$ (A) | 180.5 | 106.1 | 91.6 | 77.1 | 62.4 | 47.9 | 34.9 | 24.9 | 25.7 | 30.5 |
| $\Gamma_{\max}$ (A/mm$^2$) | 17.49 | 10.90 | 9.15 | 7.35 | 5.59 | 3.89 | 2.35 | 1.91 | 1.88 | 1.95 |
| $\Gamma_{\text{mean}}$ (A/mm$^2$) | 9.19 | 5.41 | 4.67 | 3.93 | 3.18 | 2.44 | 1.78 | 1.27 | 1.31 | 1.5 |
| $PDW$ (W) | 2733 | 1174 | 856 | 588 | 372 | 211 | 108 | 57 | 59 | 84 |
| $PDW/PDW1$ (%) | 100.0 | 42.9 | 31.3 | 21.5 | 13.6 | 7.7 | 3.9 | 2.1 | 2.2 | 3.1 |

## 4. EFFECT OF THE SLOT SKEW ON VOLTAGE WAVEFORM

Both slot skew and configuration of damper bars can enhance the quality of generator line voltage waveform. To show how these methods affect line voltage when being applied independently and simultaneously, different calculations were performed. Voltage waveform was determined for a number of different slot skews and with respect to the following damper bar arrangements:

(i) damper bars placed symmetrically in regard to the pole central line, with pitch equal to the stator slots pitch,

(ii) damper bars placed with a shift in regard to the pole central line, and a pitch that is equal to the stator slots pitch,

(iii) damper bars placed symmetrically in regard to the pole central line, with a shorter pitch than the stator slots pitch.

In order to evaluate the quality of voltage waveform, the total harmonic distortion (THD) was calculated for each analysed situation. Table 5 contains numerical data, while graphical representation can be observed in Fig. 7.

For all of the analysed situations the total harmonic distortion of generator is smaller than 5% which is in compliance with the requirements of IEC 60034-1 standard. By only implementing the slot skew, THD value of line voltage can be reduced to the level of less than 1%. However, to accomplish such line voltage quality, skew value needs to be higher than 80% of the stator slot pitch.

If damper bars are actively used to reduce higher harmonics of voltage waveform, THD value of less than 1% can be achieved without the skew, although slot skew does further perfect voltage waveform.

**Table 5.** Effect of the stator slot skew on the line voltage total harmonic distortion (THD).

| $S$ | 0 | 0.525 | 0.6 | 0.675 | 0.75 | 0.825 | 0.9 | 1 | 1.05 | 1.125 |
|---|---|---|---|---|---|---|---|---|---|---|
| $THD$ (%) standard damper bar placement | 4.58 | 2.62 | 2.14 | 1.66 | 1.19 | 0.75 | 0.38 | 0.32 | 0.47 | 0.69 |
| $THD$ (%) damper bars with a shift | 0.89 | 0.56 | 0.50 | 0.44 | 0.38 | 0.32 | 0.27 | 0.22 | 0.21 | 0.20 |
| $THD$ (%) damper bars with shorter pitch | 0.48 | 0.37 | 0.34 | 0.31 | 0.29 | 0.26 | 0.24 | 0.22 | 0.21 | 0.20 |

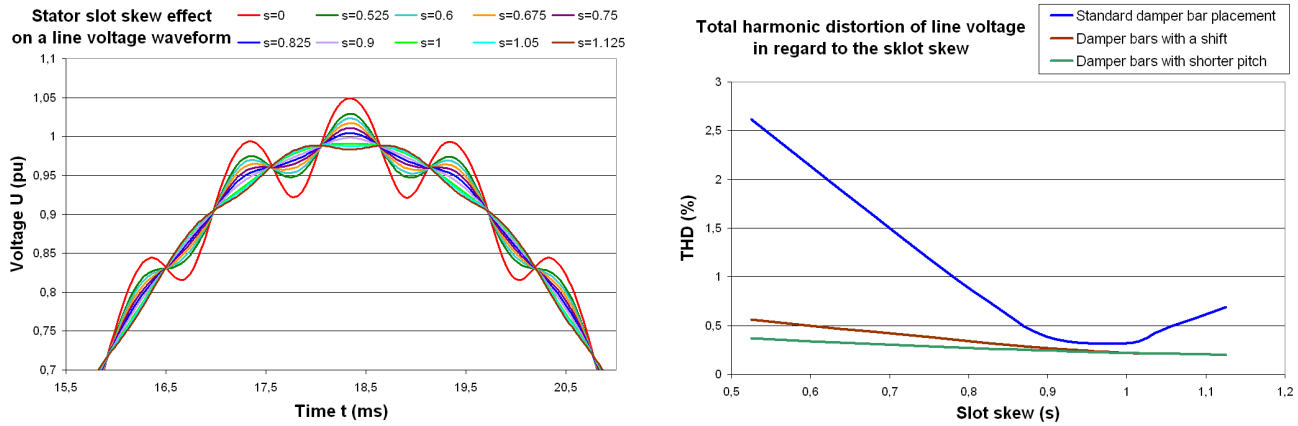



**Figure 7.** Effect of increasing the stator slot skew on: (a) the line voltage waveform, and (b) total harmonic distortion.

## 5. CONCLUSION

The numerical calculation results of slot skew impact on the voltage waveform and damper bar currents of a 44 pole 83.5 MVA, 10.5 kV synchronous vertical hydro generator have been analysed. Details of the single-slice 2D finite element method based calculation to determine slot skew effect on the generator damper bar currents and losses have been described, and the results have been compared to the multi-slice 2D finite element method calculations.

By applying a slot skew, damper bar currents can be reduced by approximately 2.6 times and damper bar losses by approximately 7 times. Total harmonic distortion of line voltage can be reduced to less than 1% with either the slot skew or the damper bar arrangement. Combination of both methods leads to even higher quality of voltage waveform, and the reduction of damper winding losses.

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