

A NEW CONTRIBUTION INTO CURRENT CALCULATION METHOD FOR SALIENT POLE SYNCHRONOUS GENERATOR DAMPER BARS AT NO-LOAD CONDITION

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Abstract: The prediction of the induced current in damper windings with high accuracy are the key parameters in design process and pole shoe temperature rise estimation. This paper describes a new contribution in combined FEM -State Space method to calculate damper bar current of no load salient pole synchronous generator.

In the first stage of the method, damper bar parameters have been calculated including inductances and flux linkages with the magnetostatic FEM calculation. These parameters are calculated in some rotor positions within one stator slot pitch, considering the machine rotational periodicity. Nonlinear interpolation used between calculated parameters is the contribution of this paper to decreasing simulation time and improving the accuracy of the results.

Subsequently due to obtained inductances and flux linkages, differential equations have been driven and solved. This paper claims that simulation time reduced 50 percent in comparison to original combined method. To evaluate the effectiveness of the suggested method, it has been applied to a small 4 poles, 9 KVA salient pole generator as well as a large 32 poles, 250 MVA generator. Comparing the obtained results of described method and the results of transient FEM confirms the validity of the proposed method.

Key words: synchronous generator, damper winding current, FEM, combined method.

1. INTRODUCTION

Occurrence of phenomena such as air gap field harmonics, negative-sequence air gap field and torque oscillation in the salient pole synchronous generator are unavoidable. Adverse effects of these phenomena are reduced or eliminated with damper winding design. At steady-state conditions, parasitic voltages were induced

in the damper bars which lead to a current flow in them that improve the issues of the mentioned phenomena. This current creates additional ohmic loss in damper winding and also increases pole shoe temperature, therefore damper bar current calculation and analysis is a great subject for designers [1,2]. In the literature there are different schemes for calculating damper bar current such as, analytical, numerical, and combined methods.

In analytical methods, the structural details as well as core's material nonlinear behavior (saturation effect) and stator slots are not taken into account. Therefore, these methods cannot predict damper bar currents caused by slot pulsation. On the other hand, FEM is a calculation method which tackles the issues mentioned above. Although, considering the vast nowadays developments in hardware and software industry, FEM is a perfect and practical method for damper bar current calculation as a numerical method. But, due to the repetitive computation in conventional transient FEM simulation, this method is very time consuming. The combined numerical- analytical method have higher accuracy in compared analytical methods but lower simulation time in compared to numerical methods[3,4]. This paper suggests a contribution in combined method that reduced the number of FE computations for damper bar current calculation with the same accuracy of original combined method. This article uses different concepts such as incremental inductance and flux linkage that introduced in [3].

Synchronous generator studies show that incremental inductances can be written as combination of 5 earlier harmonics. The number of discrete data need to calculation 5 earlier harmonics is 10- samples per cycle. It means that the FEM calculations have been done in 10 rotor positions in one stator slot pitch compared previous combined FEM-State Space method that suggest 20 rotor position in one stator slot

pitch[3,4]. This technique reduced simulation time to 50 percent in compared to described method in[3,4].

An important point which should be considered is the ability to measure the current flow in damper bars using a rogowski coil around the bars[5,6]. There are a few articles in the literature which did not confine to damper winding losses or damper bar design impacts on the voltage shape improvement in synchronous generators.

In [7], an approximate equation has been suggested for calculating damper bar current and damper winding loss. In the proposed method, damping circuit flux linkage are calculated based on theoretical consideration. The effect of stator slots on air-gap permeance has been modeled as a sinusoidal function and stator slot influence on damper winding is analyzed in [8]. The effect of fractional slot of armature winding on air gap sub-harmonic MMF and damper bar current has been evaluated in [9].

In [3], Keller applied FEM for calculating damper winding current and stator voltage harmonics in unbalance air gap in salient pole synchronous generator with combined FEM-State Space method. During 2008-2010 an analytical method based on air gap permeance model was presented and damper bar current and loss in terms of the different damper slot pitches was determined[1, 10, and 11]. In addition, there are a few literature witch confirm their theoretical results with experimental measurements. In [12], a specific synchronous machine has been presented. In this machine magnetic pole is mounted on the stator and armature is wounded on the rotor and damper bar current is measured, accordingly. A new method for damper bar current measurement has been established in [13]. According to this method induced current in damper bars were measured with Hall effect current transducers. The data was transferred with wireless connection to outside of machine.

In this paper, a detailed model of machine geometry and nonlinear magnetic material are utilized to consider exact behavior of machine. In suggested method, a different concept of inductance is used to modeling of damper winding which relates damper bar's flux linkage and current in a particular way (incremental inductance). This relation obtained from slope of magnetic curve in a single operating point which is the saturation level of magnetic circuit. At this point the saturation level is constant in steady state condition. This inductances have been calculated with the FEM analysis and used to form equivalent circuit of damper

winding. Then electrical equations of damper winding are driven with circuit analysis in every rotor position. Generator has a rotational symmetry in every slot pitch, therefore circuit parameters are periodic. These parameters are calculated in some rotor position in one slot pitch and used to estimate parameters in equivalent positions of other slot pitches of stator[3,4]. A great contribution of this paper also is suggestion trigonometric interpolation between calculated parameters for each slot pitch to improve the accuracy of results. To the best knowledge of authors, sum of the 5 earlier harmonics of calculated parameters are enough to have a good estimation of continuous function of them in position. With this idea the number of rotor position in one slot pitch decrease, therefore FEM calculation and simulation time decrease. Comparing the results obtained from [3,4], the proposed method reaches the same accuracy with fewer FEM calculations and simulation time. This method used to model a 4 poles, 9 kVA generator as well as a 32 poles, 250 MVA generator. It is shown that the results obtained from the proposed method have the same accuracy as transient FEM, through simulations.

2. ELECTRICAL EQUATIONS

Fig. 1 shows equivalent circuit of synchronous machine's damper winding. In this circuit, every bar is modeled as an ohmic resistance and a voltage source. Ohmic resistance models obviously the resistance of damper bar and voltage source models the voltage induced, which is the derivative of the flux linked with the damper bar. Note that end ring resistance and leakage inductance have been considered in this model.

Working temperature generator impact on generator model parameters can be observed by thermal analysis but for simplicity parameter values are assumed constant.

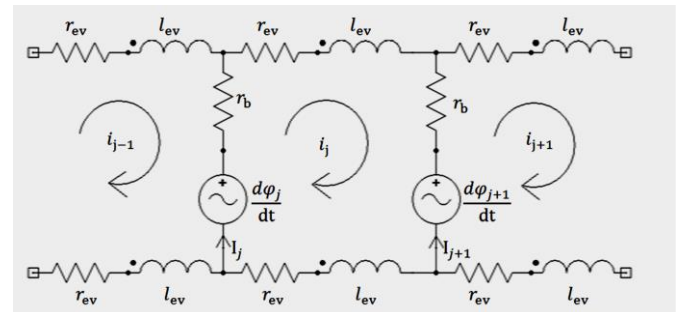


Fig. 1. Damper winding equivalent circuit

The equations governing the damper bar winding's current are derived by using mesh circuit analysis method.

$$\varphi_j = \varphi_{exc,j} + \sum_{k=1}^n (\Delta \varphi_{k,j}) = \varphi_{exc,j} + \sum_{k=1}^n (L_{diff_{k,j}} * I_k) \quad (1)$$

Where φ_j is flux linkage of j'th damper bar (see table I in appendix). On the other hand, every damper bar current in equation (1) can be written as equation (2) according Fig.1.

$$I_k = i_k - i_{k-1} \quad (2)$$

Combining (1) and (2) yields:

$$\varphi_j = \varphi_{exc,j} + \sum_{k=1}^n (\Delta \varphi_{k,j}) = \varphi_{exc,j} + \sum_{k=1}^n (L_{diff_{k,j}} * (i_k - i_{k-1})) \quad (3)$$

Utilizing KVL in mesh j results:

$$\begin{aligned} r_b * (i_j - i_{j-1}) - \frac{d\varphi_j}{dt} + \frac{d\varphi_{j+1}}{dt} + \\ r_b * (i_j - i_{j+1}) + 2 * r_{ev} i_j + 2 * l_{ev} \frac{di_j}{dt} = 0 \end{aligned} \quad (4)$$

For each damper bar, considering (3) and (4) yields (5). In this equation $L_{diff_{k,j}}$ are replaced with $L_{k,j}$.

In a generator with n damper bars and complete end rings, there are n+2 meshes, that one of them is the reference mesh. The matrix form of equation is shown in (6). where, R denotes resistance matrix and L is incremental inductance matrix.

R and L are (n+1)*(n+1) in dimension.

$\varphi_{m,exc}$ is differential flux linkage in meshes with the dimension (n+1).

$$r_b(i_j - i_{j-1}) - \frac{d\varphi_{exc,j}}{dt} + \sum_{k=1}^n L_{k,j} \frac{d(i_k - i_{k-1})}{dt} + \frac{dL_{k,j}}{dt} (i_k - i_{k-1}) + 2r_{ev} i_j + 2L_{ev} \frac{di_j}{dt} + r_b(i_j - i_{j+1}) - \frac{d\varphi_{exc,j+1}}{dt} + \sum_{k=1}^n L_{k,j+1} \frac{d(i_k - i_{k-1})}{dt} + \frac{dL_{k,j+1}}{dt} (i_k - i_{k-1}) = 0 \quad (5)$$

$$-L \frac{di}{dt} = (R + \frac{dL}{dt})i + \frac{d}{dt}(\varphi_{m,exc}) \quad (6)$$

$$L = \begin{bmatrix} L_{11} - L_{12} - L_{21} + L_{22} + 2L_{ev} & \cdots & L_{1,n-1} - L_{1,n} - L_{2,n-1} + L_{2,n} & L_{1,n} - L_{1,1} - L_{2,n} + L_{2,1} & -L_{ev} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ L_{k,1} - L_{k,2} - L_{k+1,1} + L_{k+1,2} & \cdots & L_{k,n-1} - L_{k,n} - L_{k+1,n-1} + L_{k+1,n} + 2L_{ev} & \cdots & -L_{ev} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ L_{n,1} - L_{n,2} - L_{n+1,1} + L_{n+1,2} & \cdots & L_{n,n-1} - L_{n,n} - L_{1,n-1} + L_{1,n} & L_{n,n} - L_{n,1} - L_{1,n} + L_{1,1} + 2L_{ev} & -L_{ev} \\ -L_{ev} & \cdots & -L_{ev} & -L_{ev} & -nL_{ev} \end{bmatrix} \quad (7)$$

$$R = \begin{bmatrix} 2r_b + 2r_{ev} & -r_b & 0 & \cdots & 0 & \cdots & \cdots & 0 & -r_b & -r_{ev} \\ -r_b & 2r_b + 2r_{ev} & -r_b & 0 & \cdots & 0 & \cdots & \cdots & 0 & -r_{ev} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & -r_b & 2r_b + 2r_{ev} & -r_b & 0 & \cdots & 0 & -r_{ev} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ -r_b & 0 & \cdots & \cdots & \cdots & \cdots & 0 & -r_b & 2r_b + 2r_{ev} & -r_{ev} \\ -r_{ev} & \cdots & \cdots & -r_{ev} & \cdots & \cdots & -r_{ev} & \cdots & -r_{ev} & nr_{ev} \end{bmatrix} \quad (8)$$

$$\varphi_{m,exc} = \begin{bmatrix} \varphi_{exc,2} - \varphi_{exc,1} \\ \varphi_{exc,3} - \varphi_{exc,2} \\ \vdots \\ \varphi_{exc,n} - \varphi_{exc,n-1} \\ \varphi_{exc,1} - \varphi_{exc,n} \\ 0 \end{bmatrix} \quad (9)$$

3. COMPUTER SIMULATION

In this paper, a 4 poles, 9 kVA salient pole synchronous generator of “electrical department laboratory of Tafresh University- IRAN” has been modeled. The generator’s geometrical data are shown in Table I. End ring parameters have been calculated using the practical equations presented in electrical machinery design books[14,15].

In this study, the FEM calculations have been carried out using ANSOFT MAXWELL. Fig. 2 shows magnetic model of the generator in MAXWELL software. Due to fine meshing in this model, magnetic field simulation have accurate results. Very fine meshing in the nearest edges and corners of model causes to improve accuracy in magnetic solutions.

Incremental inductances and flux linkages of damper bars have been calculated in some rotor positions. The magnitude of these parameters, depend on rotor position but due to complexity of magnetic circuit, it is not easy to explain their behavior in terms of variations in position.

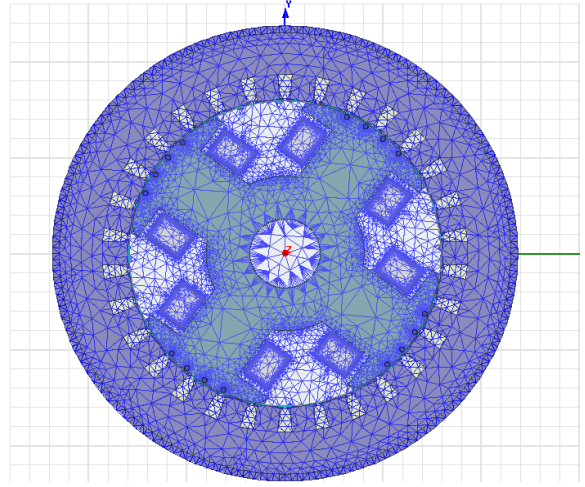


Fig. 2. magnetic model of the 4pole, 9 kVA generator in MAXWELL software

TABLE 1 Geometrical Data of 4 Poles, 9 kVA Generator

Quantity	value	unit
Outer diameter of stator	230	mm
Inner diameter of stator	160	mm
Outer diameter of rotor	159.4	mm
Inner diameter of body of rotor	72	mm
Effective length	130	mm
Pole arc	57	deg
Pole body width	36	mm
Stator slot number	30	
Damper bar number(per pole)	4	
Turn number of excitation winding	300	
Normal/ nominal excitation current	2.7/ 7.7	A
Damper bar resistance	576	$\mu\Omega$
End ring leakage inductance	5 / 25	μ H for in pole bar segments/ intra pole bar segments
End ring resistance	30 /150	$\mu\Omega$ for in pole bar segments/ for intra pole bar segments

Considering machine symmetrical rotation, it can be seen that after rotation of the rotor as much as one stator slot pitch, the machine is exactly in the same condition as at the beginning of the rotation.

Therefore, it would be enough to know the values of $\varphi_{exc,j}$ and $L_{k,j}$ just for a few rotor positions within one stator slot pitch and extend the calculated values to other slot pitches. The number of rotor positions has been practically proposed 20 point in each stator slot pitch[3]. Analysis of electromagnetic parameters of electrical machinery shows that, these parameters have harmonic nature. Thus this paper proposed that discrete parameters calculated from FEM analysis, written as continuous function of rotor position with combination of trigonometric functions. In this paper, the amplitude of trigonometric functions calculate with applying discrete fourier transform on discrete data calculated from FEM analysis. The fourier analysis of discrete parameters shows that combination of 5 earlier harmonics of the parameters are essential in parameters estimation. So, other harmonics can be eliminated. On the other hand, the number of discrete data need to calculation 5 earlier harmonics is 10- samples according to Nyquist sampling criteria. It means that the FEM calculations have been done in 10 rotor positions in one stator slot pitch. Figs. 3, 4, and 5 show comparison some of incremental inductances and flux linkages of damper bars of 4 pole generator in 20 rotor positions without interpolation and in 10 rotor positions with trigonometric interpolation in calculated data in one stator slot pitch. Fig. 3a shows damper bar number 1 self incremental inductance harmonics amplitude and Fig. 3b shows this parameter in terms of rotor position with and without interpolation. Fig. 4 shows comparison of mutual incremental inductance between damper bars 1 and 2. Fig. 5 shows flux linked to damper bar number 1. A little differences in the parameters of inductance and flux in both 20 and 10 rotor position can be seen that because of the error is inherent in the finite element method.

These Figs shown that utilization of the nature of the generator parameters cause a great improvement in performance of combined method described in[3]. The periodicity of inductance and flux linkage parameters can be seen in these Figures.

As it is obvious in Figs. 3 to 5 the incremental inductances and flux linkages are periodic. Due to damper bar flux linkages have been affected by air gap reluctance of all circumference of stator, the behavior of these parameters is not similar to air gap reluctance variation.

The continuous function of incremental inductances and flux linkages and their derivations used to form damper winding equations. The state-space equations have been solved by ODE function in MATLAB

software. This function controls the solution error coefficient with automatic adjusting of solution time step.

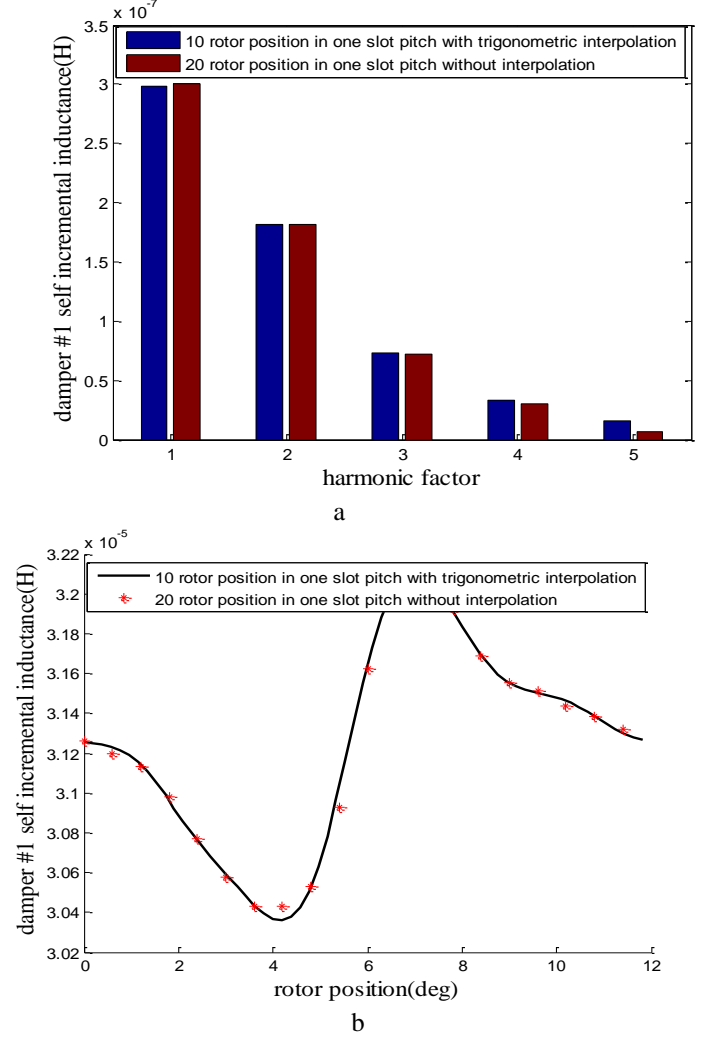
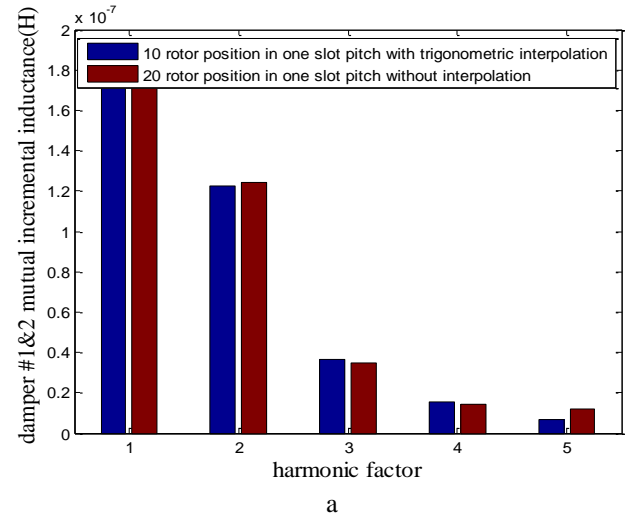


Fig. 3. self incremental inductance of damper #1(H)
a harmonics amplitude
b in function of rotor position



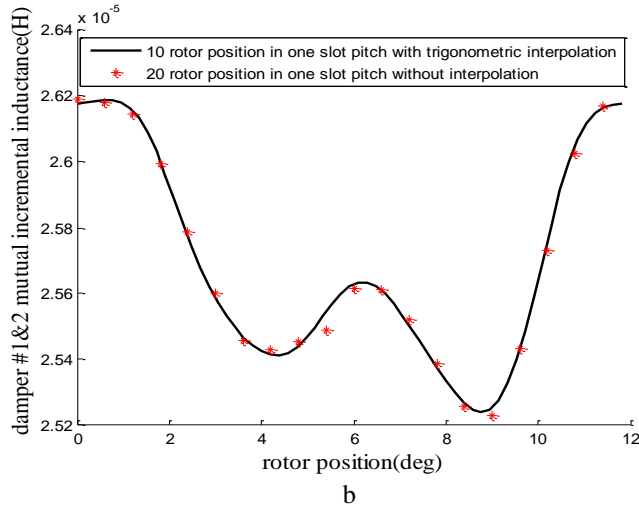


Fig. 4. mutual incremental inductance between damper #1&2 (H)
a harmonics amplitude
b in function of rotor position

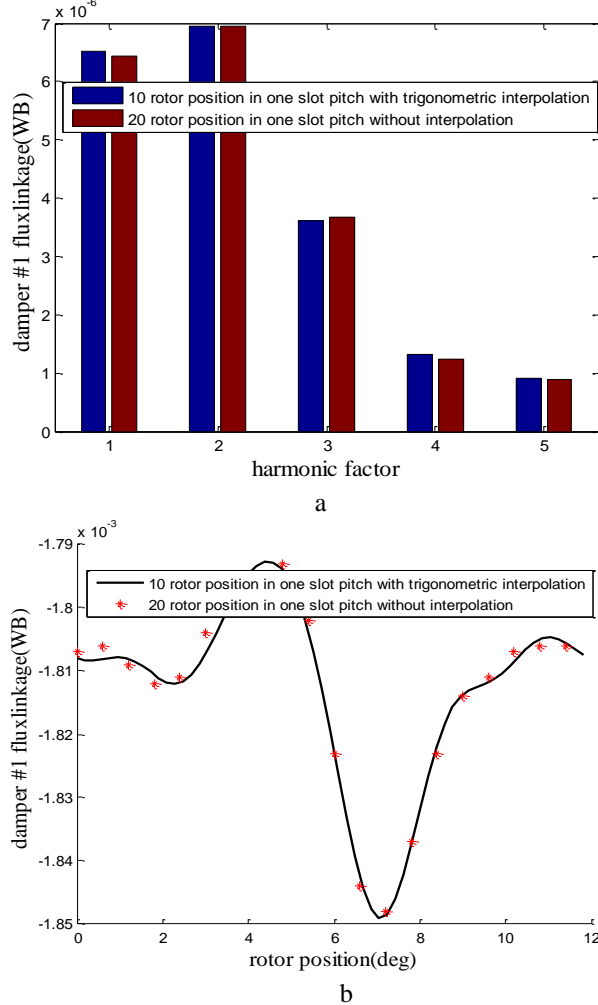


Fig. 5. fluxlinkage of damper #1(Wb)

a harmonics amplitude
b in function of rotor position

Fig. 6a shows the mesh number 1 current and Fig. 6b shows mesh number 16 current. The current of damper bar number 1 has been computed from meshes number 1 and 16 using (2).

Amplitude of the damper bar current depends on the damper winding design parameters, such as ratio of the damper bar slot pitch to stator slot pitch, symmetry of the damper cage from pole center and so on.

Due to weak initial meshing in transient solution the simulation results are not accurate. Therefore the meshing has been imported from magnetostatic simulation to the transient. This causes the transient FEM results to be accurate.

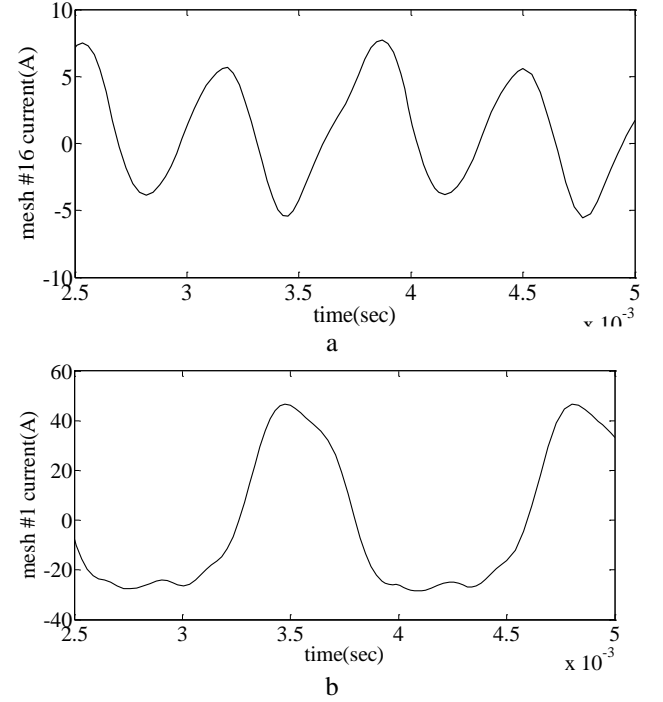


Fig. 6. mesh circuit current in damper winding equivalent circuit

a mesh number 16
b mesh number1

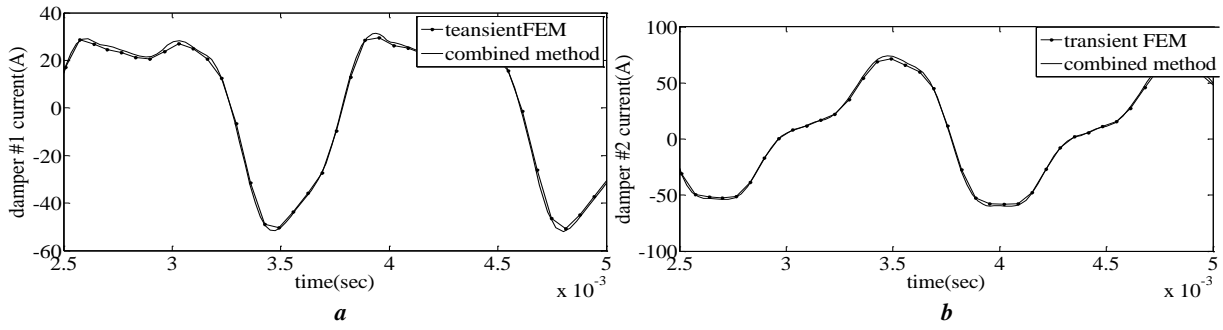


Fig. 7. damper bar currents comparison combined method with transient FEM

- a damper bar number 1
b damper bar number 2

In present study, new combined method was used to calculate damper bar current in industrial scale generator.

4.1. CASE STUDY: Upper Gotvand Hydro Power Planet Salient Pole Synchronous Generator

Upper Gotvand hydro power planet has 4 units with the capacity of 250 MVA(see table II). These generators have 6 damper bars per pole with complete end ring type. Very large dimensions and the structural details of generator cause FEM has required so much elements that cannot be analyzed with common equipment. Therefore, structural and magnetic symmetry has been applied on generator model to modeling a part of the generator [16].

In this generator, the number of the slots per pole is fractional but the number of the slots per pole pair is integer. Therefore, considering 2 poles for FEM modeling of generator cause results data have been reduced to $\frac{1}{16}$ in comparison with all geometry modeling. This cause to, large salient pole synchronous machine modeled using the common equipment. Fig. 8 shows reduced model of this generator. In this reduced magnetic model, even symmetry boundary conditions have been used, accordingly, the flux density in right and left edges is the same as the results obtained by the complete model.

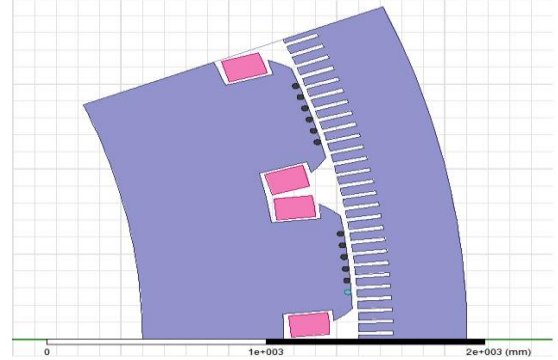


Fig. 8. magnetic model of 32 poles, 250 MVA generator

In the normal excitation conditions, differential inductances and flux linkages are calculated in 10 rotor positions in one stator slot pitch according to same reasons that are described in previous section. Figs. 9 and 10 show comparison some of incremental inductances and flux linkages of damper bars of 32 poles generator in 20 rotor positions without interpolation and in 10 rotor positions with trigonometric interpolation in calculated data in one stator slot pitch.

The generator's two poles model has 12 damper bars that create 13 independent equations. Fig. 11 shows damper bar number 1 current calculated with the proposed method has been compared with the current calculated with the transient FEM . This Figure shows high matching between the results obtained from the two methods.

Table II general data of 32 poles, 250 MW generator

Quantity	Value	unit
Nominal voltage	15.75	kV
Normal excitation current	1000	A
Nominal speed	187.5	RPM
Number of poles	32	
Number of damper(per pole)	6	
Number of Stator slot	432	
Effective length	2000	mm
Outer diameter of stator	10200	mm
Inner diameter of stator	9200	mm
Outer diameter of rotor	9146	mm
Inner diameter of rotor	7170	mm

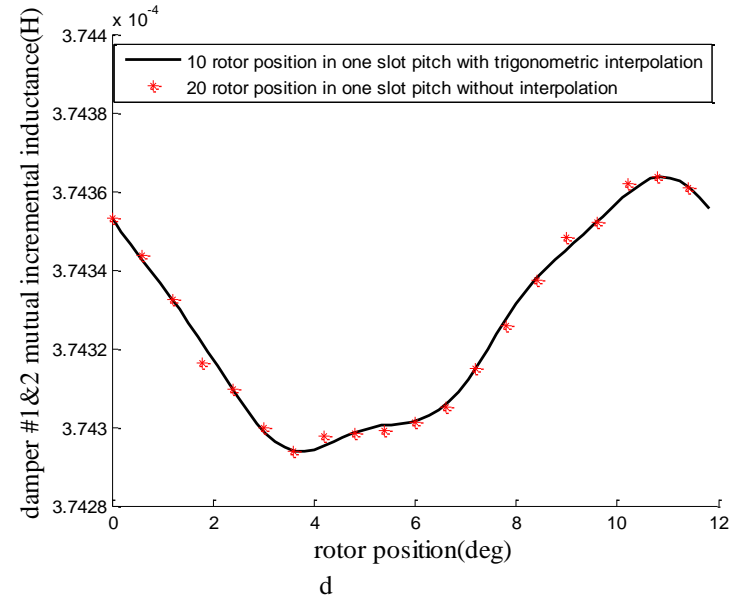
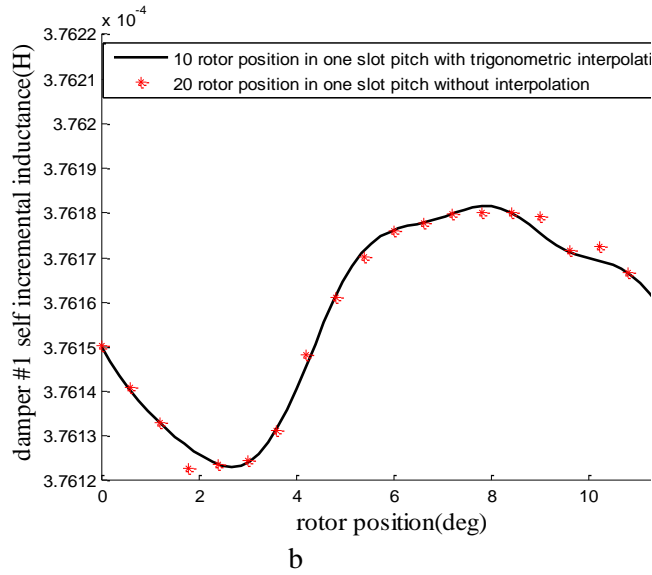
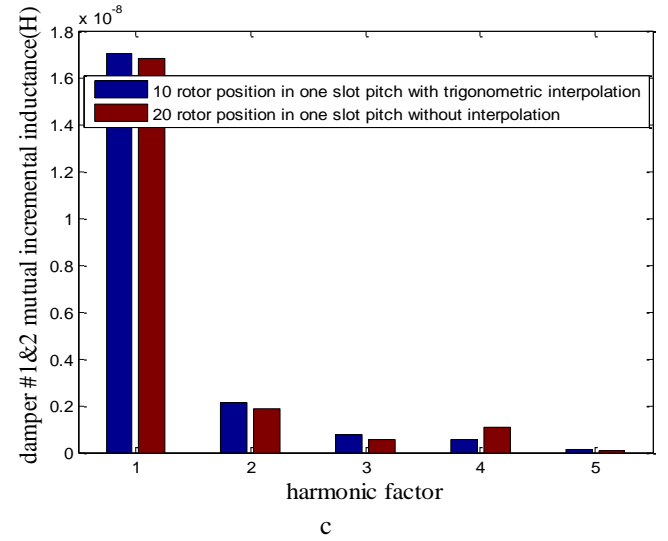
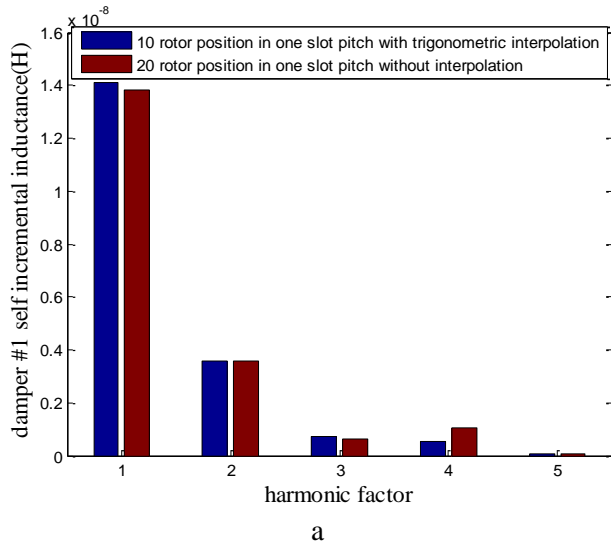


Fig. 9. incremental inductances

- a self incremental inductance of damper #1 harmonics amplitude
(H)
b self incremental inductance of damper #1 in function of rotor position(H)
c mutual incremental inductance between damper #1&2
harmonics amplitude(H)
d mutual incremental inductance between damper #1&2
in function of rotor position(H)

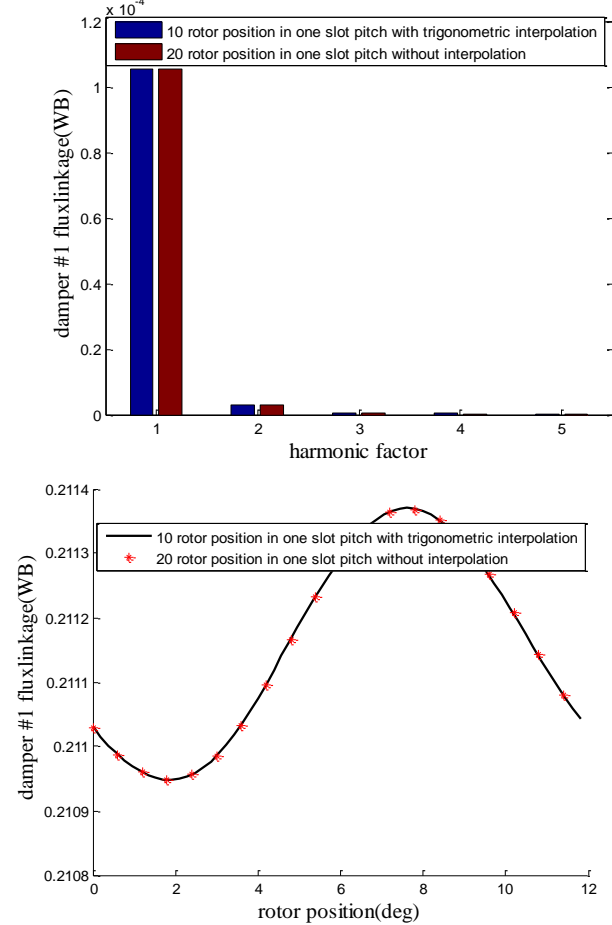


Fig. 10. fluxlinkage of damper #1(Wb)

- a harmonics amplitude
b in function of rotor position

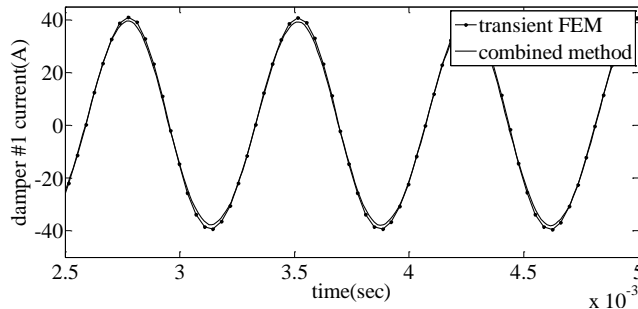


Fig. 11. damper bar number 1 current

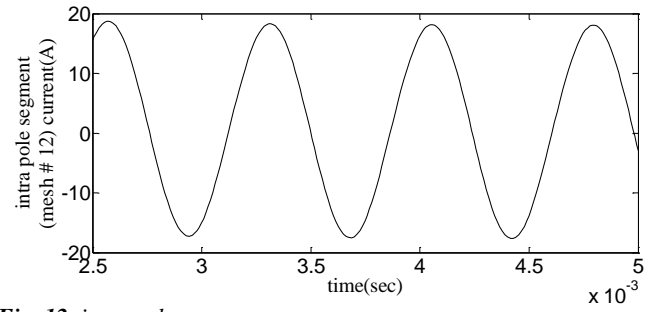


Fig. 12. intra pole segment current

Intra pole segment current has been presented in Fig. 12 that can be measured easily by a rogowski coil around it[5].The other measurement method have been introduced in [17].

Calculating damper bar current with combined method in industrial scale generator, shows that simulation results of described method have good matching with transient FEM simulation results. Comparison of the current of damper bars in generators with industrial scale show that in the no load condition of the healthy generators is about 0 to 0.02 P.U, this amplitudes are affiliated to damper cage design[17].

4. CONCLUSION

In this paper, an improved combined FEM-state space method is presented for calculating damper bar current of salient pole synchronous generators. Damper winding parameters such as incremental inductances and flux linkages are calculated with an accurate FEM analysis in 10 rotor positions in one stator slot pitch and then transferred to MATLAB software. trigonometric interpolation technique has been used between calculated data to create continuous function of inductances and flux linkages in terms of rotor position with combination of 5 earlier harmonics of them. This contribution cause simulation time and computational data reduced to 50 percent in comparison of combined method with 20 rotor positions. Then differential equation has been solved with runge-kutta method. The results of this method are compared with the results of transient FEM and show great coincidence.

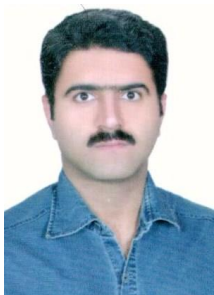
Intra pole segment current can be measured easily through the current sensor, hence the computed current and the measured one could be compared. One can clearly see that described method have good results in two different design synchronous generator(small scale and very large scale). Thus this method is a good way to replacing transient FEM analysis. This method can be used in large hydro generator to determine voltage terminal THF(Telephone Harmonic Factor) and the additional losses in pole shoes.

TABLE. A.1 LIST of SYMBOLS

Symbol	description
$L_{diffk,j}$	Mutual incremental inductance
$\varphi_{exc,k,j}$	Damper j flux linkage from excitation and damper k current
$\varphi_{exc,j}$	Damper j flux linkage from excitation
I_k	Damper k current
φ_j	Damper j flux linkage
$\varphi_{exc,n}$	Damper n flux linkage from excitation current
i_k	Mesh number k current
r_b	Damper bar resistance
r_{ev}	End ring segment resistance
l_{ev}	End ring segment leakage inductance
L	Incremental inductance matrix
R	Resistance matrix
$\varphi_{m,exc}$	Mesh differential flux linkage vector
i	Damper current vector

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