Study on Application of Two Different Magnetic Materials in Rotor of Cylindrical Synchronous Generator to Produce Reluctance Torque

H. Yaghobi*(C.A.) and H. Kafash Haghparast*

Abstract: This paper presents a study on the new design of cylindrical solid rotor synchronous generator. In this new design, rotor of the machine is designed in such a way that the required inductance values are reached to produce reluctance torque, besides electromagnetic torque due to field excitation. In this contribution, a combination of two different ferromagnetic materials is considered in the design of the rotor. In this theory, the tight connection between the different materials is very important from a mechanical point of view. In other words, this new idea and production principal has potential in some areas after some further research and engineering. But this paper is focused on magnetic flux-carrying materials and presents a study of the new design of cylindrical solid rotor synchronous generator (NCG). Then a comparative analysis was made between this new (NCG) and conventional cylindrical solid rotor synchronous generator (CCG) and the effectiveness of the new cylindrical solid rotor from a magnetic point of view is demonstrated. In this paper, mechanical and thermal aspects of design such as vibration did not analyze.

Keywords: Cylindrical Rotor, Electromagnetic Torque, Reluctance Torque, Salient Pole Rotor, Synchronous Generator, Two Different Magnetic Materials.

1 Introduction

Synchronous generators are basic and significant elements of power systems and the two main types of generator are salient pole and cylindrical rotor generators. In these machines, there is usually a three-phase winding in the stator, whereas the rotor is equipped with a single-phase excitation winding supplied with adequate DC voltage and current. Both these types are synchronous machines in which the rotor turns in exact synchronism with the rotating magnetic field in the stator [1-5]. Synchronous generators remained the universal machines of choice for the generation of electric power. With the increasing of load in power networks, more and more interest is focused on the large synchronous generator. These machines have continuously grown in size over the years. The justification is based on simple economies of scale: the output rating of the machine per unit of weight increases as the size of the unit increases. Thus, it is not uncommon to see machines with ratings reaching up to 1500 MVA, with the largest normally used in nuclear power stations. The largest generators used in main power stations are usually cylindrical rotor generators. More commonly used in smaller and medium power ranges is the salient-pole generator [6-9].

Therefore, increasing output power of synchronous generator without any increase in total machine size and decrease in efficiency is a significant task. Hence, in recent years, some researchers have tried to increase the output power of synchronous generators by inserting additional permanent magnets and different problems in this field have investigated by these scholars [10-15]. It is important to know permanent magnets on the adjacent rotor-pole shoes may be demagnetized under short circuit conditions. However, the flux of the permanent magnet is fixed and the air gap flux weakening is generally achieved by applying a large demagnetizing current. Also, it's worth mentioning that excitation winding repairs can be done with difficulty by the existence of permanent magnets on the adjacent rotor-pole shoes.

On the other hand, ref [16] reports on outcomes of study on the impact of two different magnetic materials in a core structure of a current transformer. This construction is shown in Fig. 1. In fact, two magnetic cores were utilized, one made from transformer steel and the second made from nanocrystalline material.

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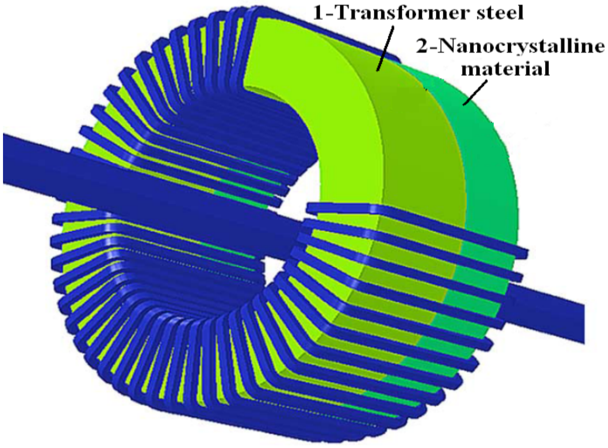


Fig. 1 The 3-D model of the new measuring current transformer, proposed in [16].

The results of this reference [16] illustrates that, this construction (combine two different ferromagnetic materials) improves of current transformers measurement properties without changing the size and any increase in the dimensions of the current transformer.

Even though the content of this research refers to a current transformer, which is a static industrial device, this theory (combination of two different ferromagnetic materials) may also be considered in the design of electrical machines. It's worth mentioning that, design of electrical machines is the most important activity and the designer of electrical machines should have perfect information about properties of good electrical materials, magnetic materials, insulating materials, mechanical and metallurgical properties of all types of steel. Materials used in design are categorized into three types: conducting; insulating and magnetic and the design of electrical machines depend mostly on the quality of these materials [17]. The design of synchronous generator must therefore integrate electrical conducting materials, magnetic materials, insulating materials, structural members, and cooling media, all working together under the operating conditions of a synchronous generator.

As stated earlier, a combination of two different ferromagnetic materials may also be considered in the design of electrical machines. In this theory, the tight connection between the different materials is very important from a mechanical point of view. In other words, in mechanical respect and manufacturing process, this procedure might not be the easiest, but it has an advantage when it comes to combining different materials [18]. In fact, this new idea and production principal has potential in some areas after some further research and engineering. But this paper is focused on magnetic flux-carrying materials and presents a study of the new design of cylindrical solid rotor synchronous generator (NCG). In fact, in this paper, mechanical and thermal aspects of design such as vibration did not analyze and the effectiveness of the new cylindrical solid rotor from a magnetic point of view is demonstrated. In this study, a synchronous machine is designed in such a way that the required inductance values are reached to produce reluctance torque, besides electromagnetic torque due to field excitation. The simulation studies show that the output power of this generator is increased without any increase in total machine size and decrease in efficiency.

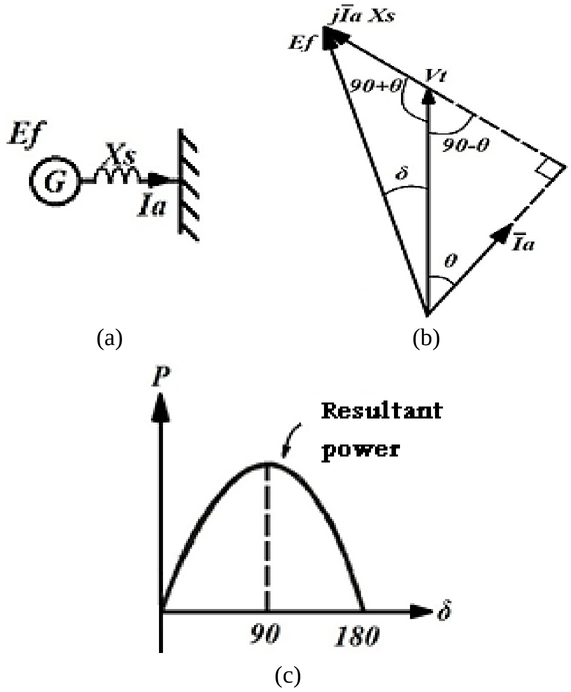


Fig. 2 Cylindrical rotor synchronous machine [8], (a) connected to an infinite bus system, (b) phasor diagram, (c) load angle characteristic.

2 Operation Principle of Salient Pole Synchronous Generators

Consider the simple circuit of Fig. 2(a), consisting of a cylindrical rotor synchronous machine connected to an infinite bus system. The phasor diagram is shown in Fig. 2(b).

The maximum power a cylindrical rotor synchronous generator can deliver to the infinite bus can be expressed as follows [8]:

$$p = \frac{E_f V_t}{X_s} \sin \delta \tag{1}$$

where, E_f is excitation voltage, V_t is the infinite bus voltage and X_s is the series impedance. Equation (1) is commonly referred to as the load angle characteristic (power-angle characteristic), and the angle δ is known as the power angle. The general form of this load-angle characteristic is illustrated in Fig. 2(c). On the other hand; consider a salient pole synchronous generator connected to an infinite bus system (Fig. 3(a)). The

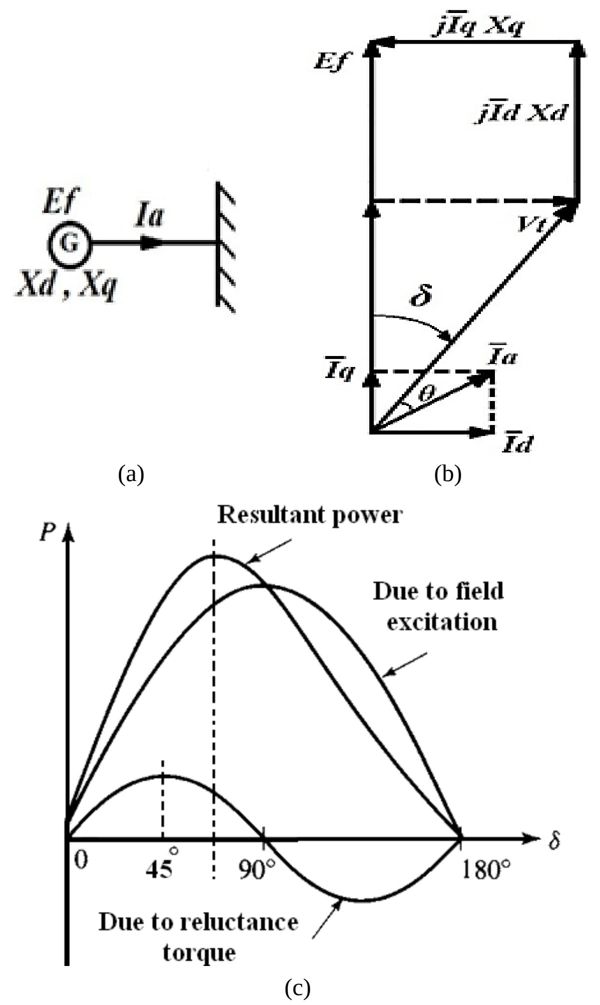


Fig. 3 Salient pole synchronous generator [8], (a) connected to an infinite bus system, (b) phasor diagram, (c) load angle characteristic.

phasor diagram of this generator is shown in Fig. 3(b). The maximum power a salient pole synchronous generator can deliver to the infinite bus can be expressed as follows [8]:

$$p = \frac{E_f V_t}{X_s}\sin\delta + \frac{V_t^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta \qquad (2)$$

where, the reactances X_d and X_q are, respectively, the direct-and quadrature-axis synchronous reactances. The general form of this load-angle characteristic is illustrated in Fig. 3(c).

Comparing Eq. (1) with Eq. (2), the first term is the same as the expression achieved for a cylindrical rotor synchronous generator. In fact, the load angle curve of a cylindrical rotor synchronous machine comprises a single sine term only while in salient pole synchronous generators, power-angle characteristic has two terms. The first term is the fundamental component due to field excitation and the second term includes the effect of salient pole. This term is the second harmonic component due to reluctance torque and it represents the fact that the air-gap flux linkage produces torque, tending to align the field poles in the position of minimum [6-9]. The reluctance torque is independent of field excitation and in a cylindrical rotor machine the reluctance torque is zero. Therefore, in synchronous machine, the dimensioning of the magnetic circuit has a notable effect on the operation of the machine.

It is worth highlighting that, another important issue should be considered in the power-angle characteristic is the static stability limit of the machine. In fact, the static stability limit of the machine due to the presence of reluctance torque occurs at $\delta = 45^{\circ}$ and the static stability limit of the machine due to the field excitation torque occurs at $\delta = 90^{\circ}$. Finally, the static stability limit of the machine due to the presence of both reluctance torque and field excitation torque occurs at δ between 45-90. Because of the reluctance torque, a salient-pole machine is "stiffer" than one with a cylindrical rotor; i.e., a salient-pole machine develops a given torque at a smaller value of δ , and the maximum torque which can be developed is greater. In other words, due to the reluctance torque, the salient-pole generator has a higher maximum power than an equivalent non-salint pole generator at a smaller value of δ.

3 Design Criteria and Key Points

Design of electrical machines is a time-consuming task and the aim of design is to determine the sizes of each part of the machine, the material specification, prepare the drawings and equip to manufacturing units. Design is the most significant activity and like all machine types, synchronous generators are designed through some steps. These steps are listed as follows [6]:

1) Compute output coefficient, main dimensions of stator core D, L and flux/pole, turns/phase, the number of slots, checking the peripheral speed and slot loading.

2) Compute the size of the slot, conductor size, checking current density, slot balance. Compute tooth flux density, depth of core, weight of copper, copper losses and leakage reactance.

3) Compute air gap length, rotor diameter, dimensions of poles and excitation coils.

4) Compute carter coefficient and ampere-turns for air gap, stator tooth, core, poles, rotor core and total no-load AT.

5) Computation and planning of open circuit characteristic.

6) Computation of excitation ampere-turns at rated load and power factor.

7) Compute copper size, number of turns in excitation winding. Computation of iron loss and total losses and efficiency.

8) Calculation of temp-rises, total weight and KG/KVA.

4 Design Procedures of Synchronous Generators

The theoretical design procedure for a synchronous machine is explained in detail in [6, 7, 19, 20] and is used to design the synchronous generators. On the other hand, it is not the primary purpose of this paper to discuss the theoretical design procedure for synchronous machine; however, a general review of the main steps and criteria is presented in this section. Real machine design starts with the choice of the main dimensions of the machine, i.e. L which is the machine's axial length and D which is stator inside diameter or air gap diameter. These two parameters are the most critical and earlier dimensions in machine design which other dimensions and parameters are extremely depending on them. The identity of the machine is somehow specified by choosing these two dimensions. The relationship between apparent input power and main dimensions of the machine can be expressed as follows [6, 19, 20]:

$$Q = C_0 D^2 L n_s = \frac{P_{out}}{\eta \cos\varphi} \tag{3}$$

where, Q is in KVA and n_s is speed (rps) and C_0 is output coefficient and is calculated as follows:

$$C_0 = 1.11 \times \pi^2 .ac.B_{av}.K_w \times 10^{-3} \tag{4}$$

As stated earlier, in design of electrical machine, D^2L is a significant parameter. From these main dimensions, the remainder of the synchronous machine dimensions can be calculated. On the other hand, in design of electrical machines, determine of slot dimensions is very important because it significantly affects the magnetic flux distribution and saturation inside the machine.

A schematic illustration of stator core of the low power of a synchronous generator is shown in Figs. 4(a) and 4(b) while stator lamination of a larger synchronous generator is illustrated in Fig. 4(c). Also, parameters and dimensions are shown in these figures. According to Fig. 4(c), it's worth mentioning that stator slots of larger synchronous generator are rectangular and teeth are trapezoidal. Consequently, manufacturing and maintenance procedure is easy and less time consuming [21].

The equation governing the stator tooth (B_t) and core (B_{bi}) flux density-specific magnetic loading (B_{av}) relationship of the machine can be expressed as follows [19, 20]:

$$B_t = \frac{\pi.D}{w_t.z.\psi} B_{av}\, , \; B_{bi} = \frac{\pi D}{2P.h_{bi}} B_{av} \tag{5}$$

where w_t is the minimum stator tooth width and h_{bi} is the minimum height of stator yoke. ψ is the ratio of pole arc to pole pitch, D is the inner diameter of the stator. h_{bi} is the minimum height of stator yoke and P is the number of poles. Also, one of the inherent limitations in the design of electrical machines is the saturation flux density of magnetic materials. Hence,

$$B_t \le B_{Sat} \; , \; B_{bi} \le B_{Sat} \tag{6}$$

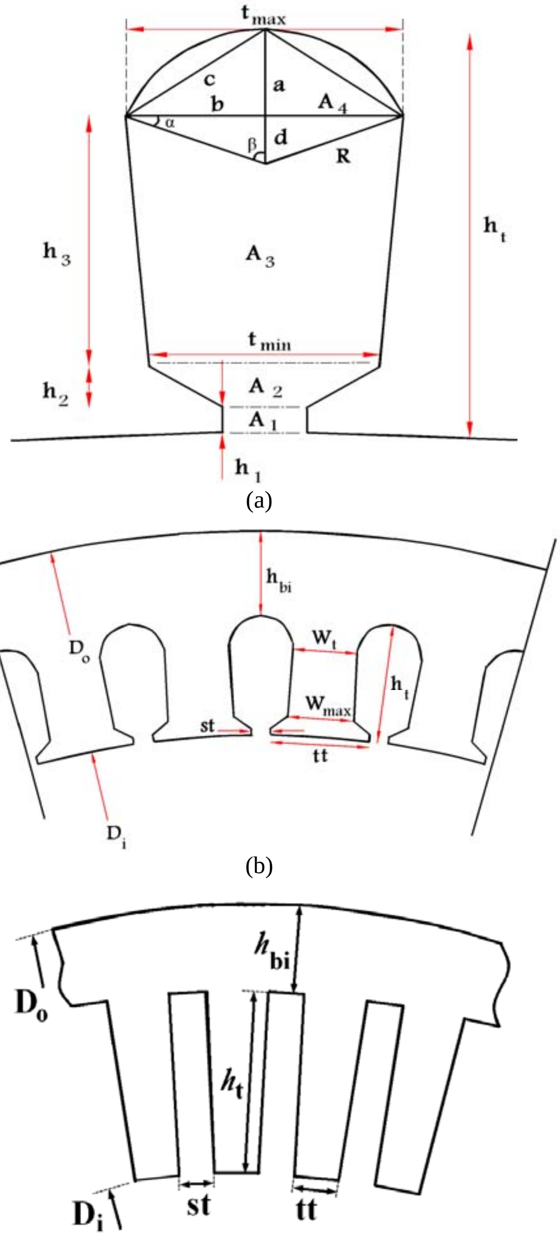


Fig. 4 Dimensions and parameters. (a) Stator slot. (b) Stator core of low power of synchronous machine. (c) Stator lamination of large synchronous machine [21].

Therefore:

$$w_t \ge \frac{\pi.D}{z.\psi}.\frac{B_{av}}{B_{Sat}}\, , \; h_{bi} \ge \frac{\pi D}{2P}.\frac{B_{av}}{B_{Sat}} \tag{7}$$

Maximum tooth width (tt) is given by the following:

$$tt = \frac{\pi D_i}{z} - st \tag{8}$$

where st is the minimum stator slot width, D_i is the inner diameter of the stator and Z is the number of slots in the stator. Also, according to Fig. 4 other important equations can be expressed as follows [20]:

$$\frac{D_o}{2} = h_t + h_{bi} + \frac{D_i}{2} \tag{9}$$

$$h_t = h_1 + h_2 + h_3 + a \tag{10}$$

$$(\frac{D_i}{2} + h_1 + h_2 + h_3)2\pi = Z(2b + w_t) \tag{11}$$

$$(\frac{D_i}{2} + h_1 + h_2)2\pi = Z(t_{\min} + w_{\max}) \tag{12}$$

$$A_{Slot} = A_3 + A_4 \tag{13}$$

It must be noted that the electromagnetic performance of the synchronous machines depends on many design parameters. Only the influence of key design parameters was summarized in this section.

5 Results of the Design

In this section, results from the design of two new and conventional cylindrical solid rotor synchronous generators are presented (see Fig. 5). Then a comparative analysis was made between these generators. In fact, two synchronous generators with the same main dimensions are designed. Table 1 presents the main properties and dimensions of the two designed synchronous generators. Fig. 5(b) shows new design of cylindrical solid rotor synchronous generator. The rotor of this new generator is built of two different materials in such a way that the required inductance values are reached to produce reluctance torque, besides electromagnetic torque due to field excitation.

It must be noted the reluctance torque is independent of field excitation. While in conventional cylindrical solid rotor synchronous generator, the direct axis reactance (X_d) and quadrature axis reactance (X_q) are equal and there is no preferential direction of magnetization. Therefore, in this generator, the reluctance torque is zero and (2) reduces to the power-angle equation (1). It's worth mentioning that, the simulations in this research have been done in transient mode by using Maxwell software that uses finite element analysis (FEA) to solve transient problems.

Also, in this research external circuits are used to drive the windings of the transient finite element model. It is defined transient sources using the Maxwell circuit editor. This allows designers to define an external circuit which can be connected to the 2D model to work as a source in the time domain. The driving circuit for the winding in this research is three-phase circuit and it is illustrated in Fig. 6.

A different operation conditions were simulated on each machine. The effect of magnetic saturation was included in the FEM software by using B-H curves of the materials. On the other hand, as shown in Fig. 5(b), the rotor of the new cylindrical solid rotor synchronous generator is composed of two materials. B-H curves of these two materials of the rotor are presented in Tables 2 and 3.

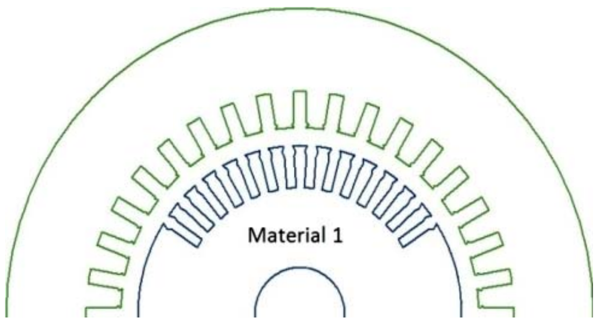
Also, the 2D meshing grid of the analysis models is illustrated in Fig. 7.

Table 1 Characteristics of two designed synchronous generators.

Dimension/Parameter	Value
Rated capacity	75000 kVA
Rated voltage	15.7 kV
Phases/pole	3 phases/ 2poles
Synchronous speed	3000 rpm
Diameter of the stator	1175 mm
Diameter of the rotor	650 mm
Stator slot	36
Rotor slot	28

Table 2 BH curve of material 1.

B [T]	H [A/m]	B [T]	H [A/m]
0.0	0	1.1	228
0.1	84.5	1.2	254
0.2	107	1.3	304
0.3	121	1.4	402
0.4	133	1.5	660
0.5	145	1.6	1480
0.6	156	1.7	3710
0.7	168	1.8	7300
0.8	180	1.9	15000
0.9	194	2	30000
1	209	2.1	100000



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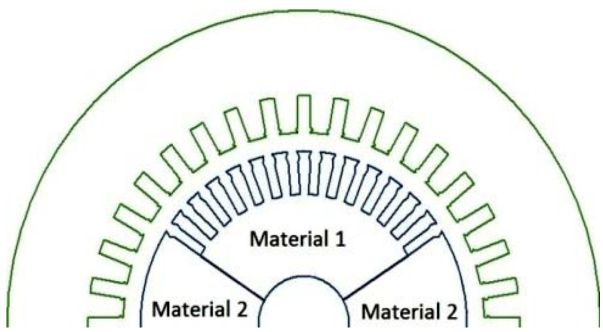
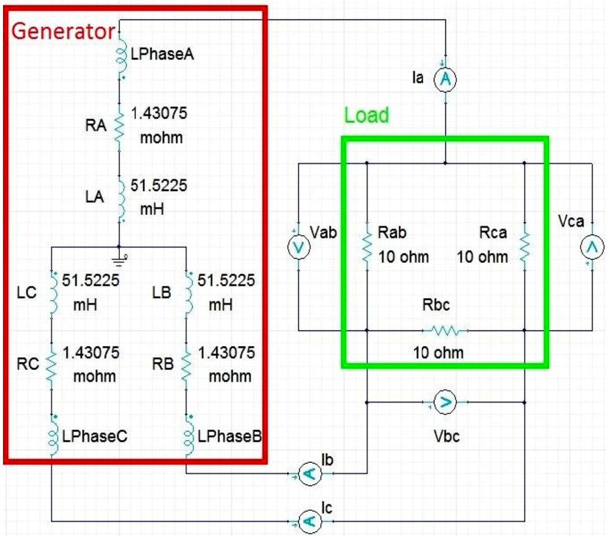


(b)

Fig. 5 Two designed cylindrical solid rotor synchronous generators. (a) Conventional design. (b) New design.



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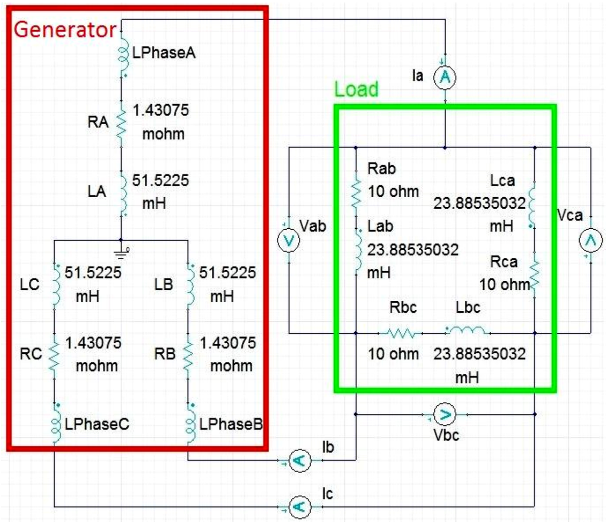

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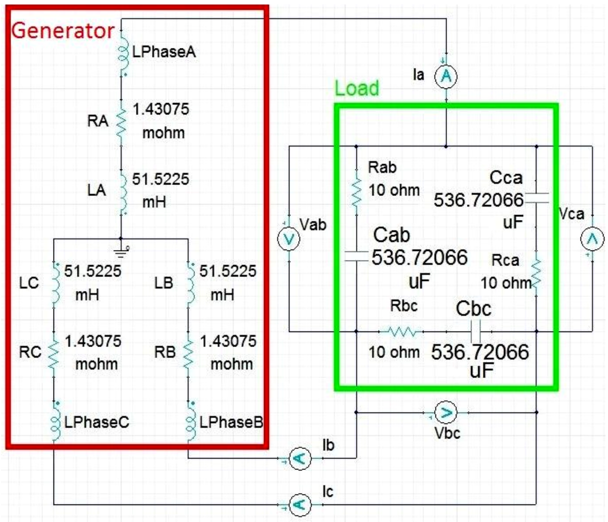
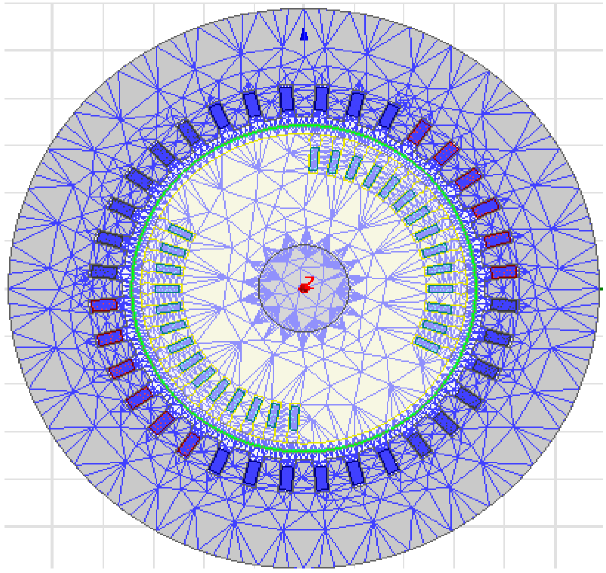


(c)

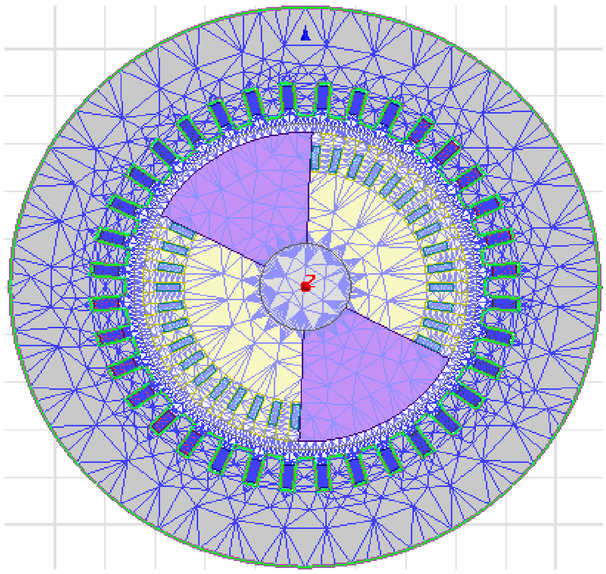
Fig. 6 Different loading conditions (different PF) for two designed synchronous generators. (a) PF=1. (b) PF lagging. (c) PF leading.

Table 3 BH curve of material 2.

B [T]	H [A/m]	B [T]	H [A/m]
0	0	1.23	287
0.37	66	1.37	637
0.47	74	1.51	2548
0.56	82	1.6	5255
0.66	92	1.7	10035
0.75	104	1.79	19085
0.85	118	1.89	32047
0.9	126	1.98	56529
0.94	136	2.08	103500
0.99	148	2.13	127390
1.08	179	2.18	156050
1.13	203	2.23	191080
1.18	239		



(a)

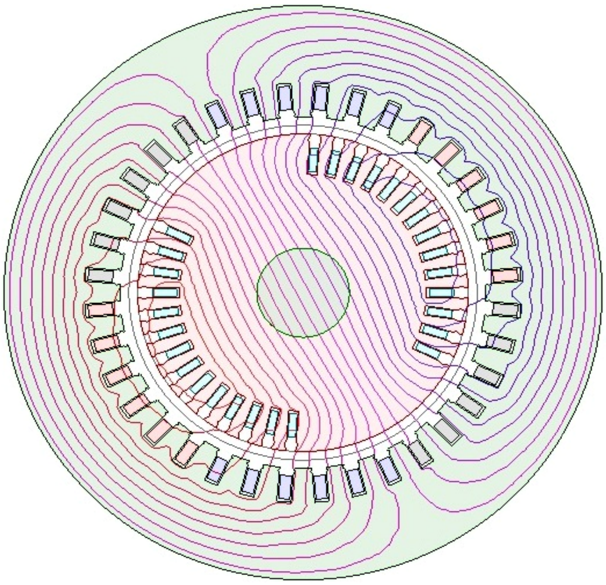


(b)

Fig. 7 Finite element mesh of two designed cylindrical solid rotor synchronous generators. (a) Conventional design. (b) New design.

In fact, the nonlinear relationship between the flux linkage with the excitation current and phase current has made the modeling and analysis of synchronous generator very complicated that was included in this simulation. Finite element based technique allows a precise analysis of electrical machines taking into account geometric details and magnetic nonlinearity [22].

Fig. 8 shows a flux plot of two designed cylindrical solid rotor synchronous generators from FEA in 1000 A excitation current for the healthy condition. It is evident from this figure that magnetic field distribution in synchronous generator under healthy operation is symmetrical (neglecting the insignificant inherent asymmetry in the magnetic field distribution due to the differences in mechanical structures). Also, according to Fig. 8(b), it can be clearly seen that the rotor fluxes are passing through the two different materials of rotor in such a way that the required inductance values are reached to produce reluctance torque. In the following, the results of simulations of these two designed cylindrical solid rotor synchronous generators, i.e., conventional cylindrical generator (CCG) and new cylindrical generator (NCG), is presented. It must be noted, as representative examples of the many simulations performed on these generators, one illustration for each case is presented.



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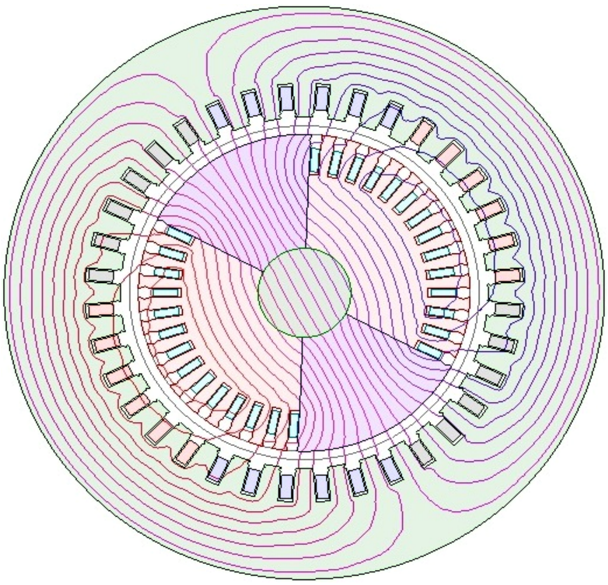


(b)

Fig. 8 Flux lines from FEA in two designed synchronous generators. (a) Conventional design. (b) New design.

Table 4 presents the output power of CCG and NCG synchronous generators, as the excitation current increases from 800 to 1400 A for unity power factor (PF) conditions. In fact, in the conventional generator, the field current is controlled and must be adjusted to the change of load. As shown in this Table, it can be easily seen that the output power of the generator has increased approximately 3% (average) without any increase in total machine size.

On the other hand, Fig. 9 shows the typical current and induced voltage in the stator winding of two designed generators under unity power factor condition with 1400 A of excitation current as obtained by FEA. In this figure, line voltages and line currents are presented.

Also, Table 5 presents the output power of two CCG and NCG synchronous generators, as the excitation current increases from 1100 to 1700 A for lagging power factor condition.

In fact, similar to unity power factor condition it can be easily seen that the output power of the generator is increased without any increase in total machine size and decrease in efficiency. In fact the output power of the generator is increased 7 % (average). Also, it's worth mentioning that the output power of the generator generally follows the load demand from the system. Most of these demands are inductive loads such as transformers and induction motors and because magnetizing current must be supplied to inductive loads, the increase of output power of the machine in this inductive condition is a highly desirable [21].

Fig. 10 shows the typical line current and line induced voltage in the stator winding of two designed generators under lagging power factor condition with 1700 A of excitation current as obtained by FEA.

Fig. 11 illustrates the variation in excitation current with the armature current under the unity and lagging power factor load conditions, respectively. The armature voltages of the conventional generator are maintained at rating (15.7 kV) with 1400 and 1700 A of excitation current. Then the armature voltages and currents of the proposed generator at these excitation currents are calculated by FEA.

It is observed that the rated voltage of the proposed generator, as compared with that of the conventional one, is increased by 2.92 % and 4.1 % under the unity and lagging power factor load conditions, respectively. Also, as illustrated in Figs. 11(a) and 11(b), the armature current is increased by 2.31% and 4.55% under these load conditions, respectively.

On the other hand, Fig. 12 shows the typical line current and line induced voltage in the stator winding of two designed synchronous generators under leading power factor conditions with 880 A of excitation current as obtained by FEA. As stated earlier, in the power network most of the demands are inductive loads. However Table 6 presents the output power of two CCG and NCG synchronous generators, as the excitation current increases from 700 to 880 A for leading power factor conditions. In this condition the output power of the generator is increased 2% (average).

Table 4 Output power of two designed synchronous generators for unity power factor.

Excitation current (A)	Line voltage (kV-rms)		Stator current (kA-rms)		PF=1 Output power of generators (MVA)		
	CCG	NCG	CCG	NCG	CCG	NCG	Increase
1400	15.7	16.17	2.77	2.83	75	79.14	5.513%
1200	14.98	15.28	2.65	2.7	68.74	71.21	3.61%
1000	13.95	14.01	2.49	2.51	59.99	61.07	1.8%
800	12.45	12.48	2.21	2.22	47.67	47.92	0.52%

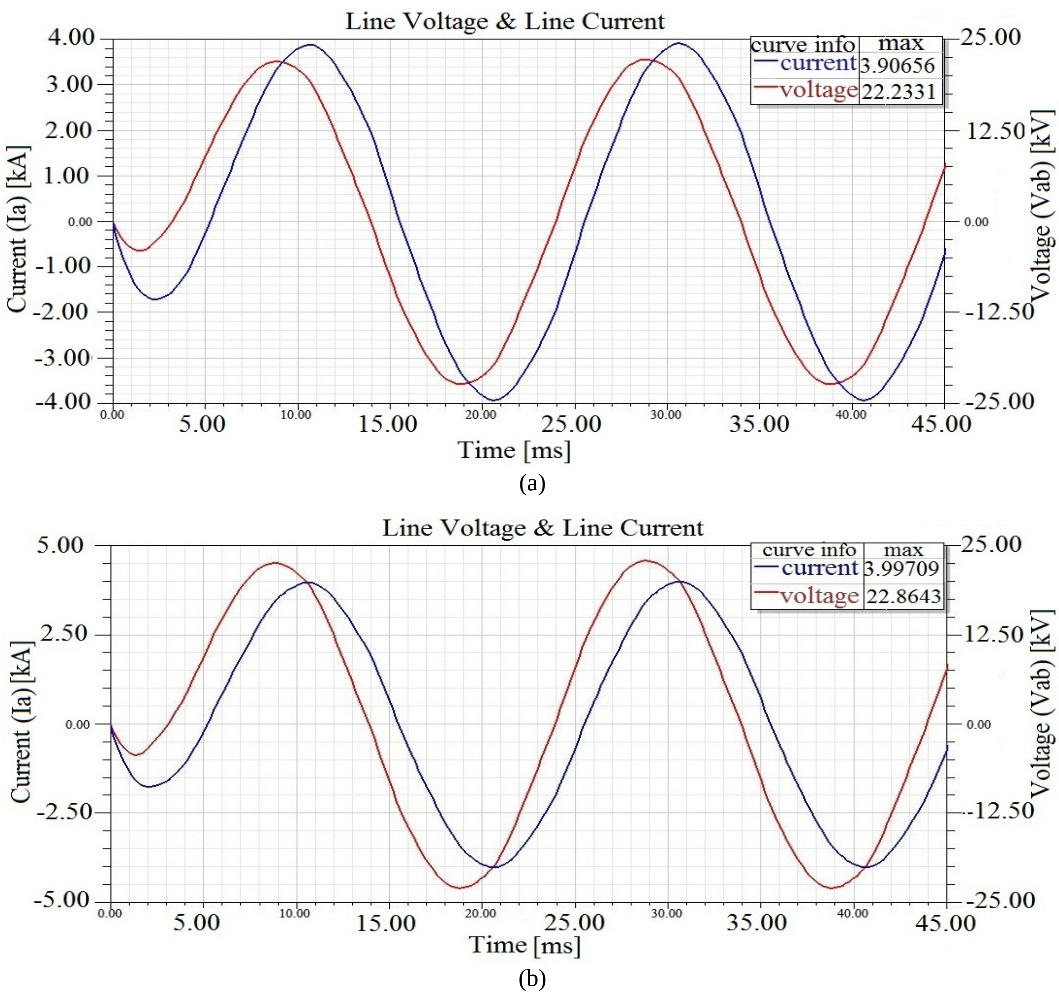
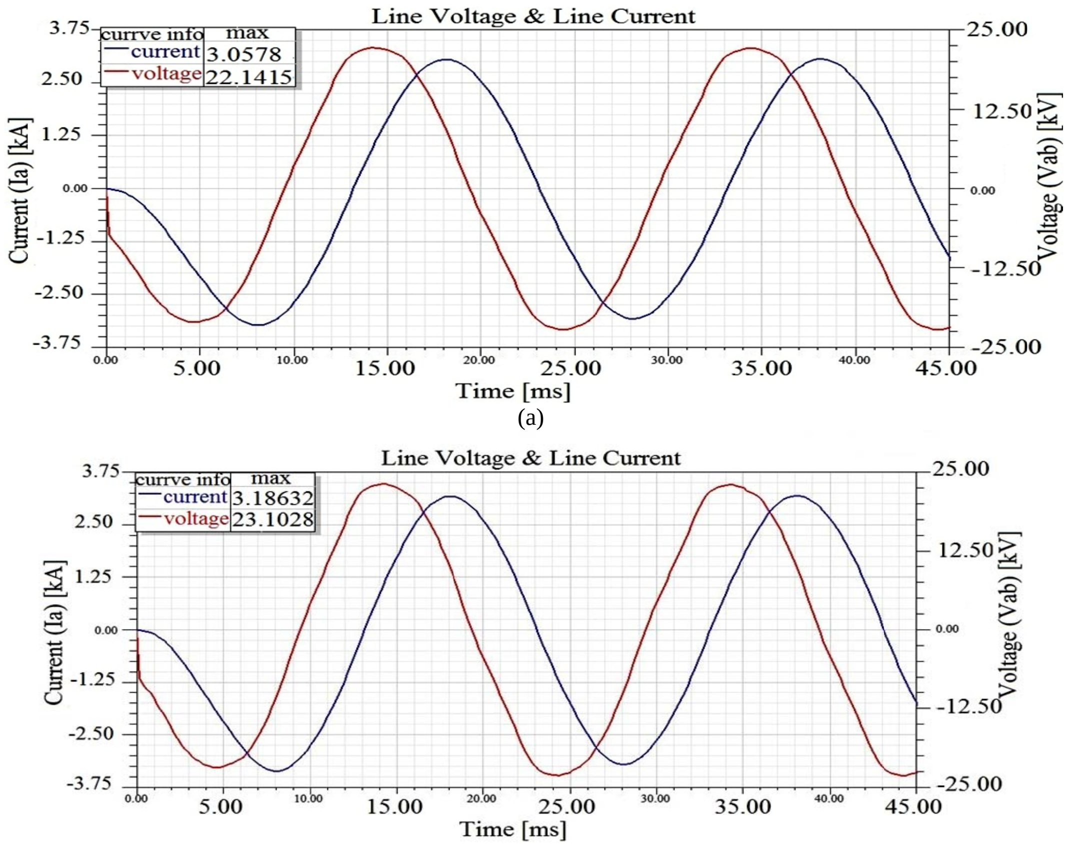


Fig. 9 Line current and line induced voltage in the stator winding of two designed cylindrical solid rotor synchronous generators under unity power factor conditions with 1400 A of excitation current. (a) CCG generator. (b) NCG generator.

Table 5 Output power of two designed synchronous generators for lagging power factor.

Excitation current (A)	Line voltage (KV-rms)		Stator current (KA-rms)		PF lagging-0.86 Output power of generators (MVA)		
	CCG	NCG	CCG	NCG	CCG	NCG	Increase
1700	15.7	16.37	2.16	2.253	58.61	63.75	8.78%
1500	15.21	15.84	2.1	2.176	55.17	59.64	8.2%
1300	14.67	15.16	2.01	2.083	51.27	54.69	6.66%
1100	14.1	14.28	1.92	1.963	46.55	48.56	4.3%



(b)

Fig. 10 Line current and line induced voltage in the stator winding of two designed generators under lagging power factor conditions with 1700 A of excitation current. (a) CCG generator. (b) NCG generator.

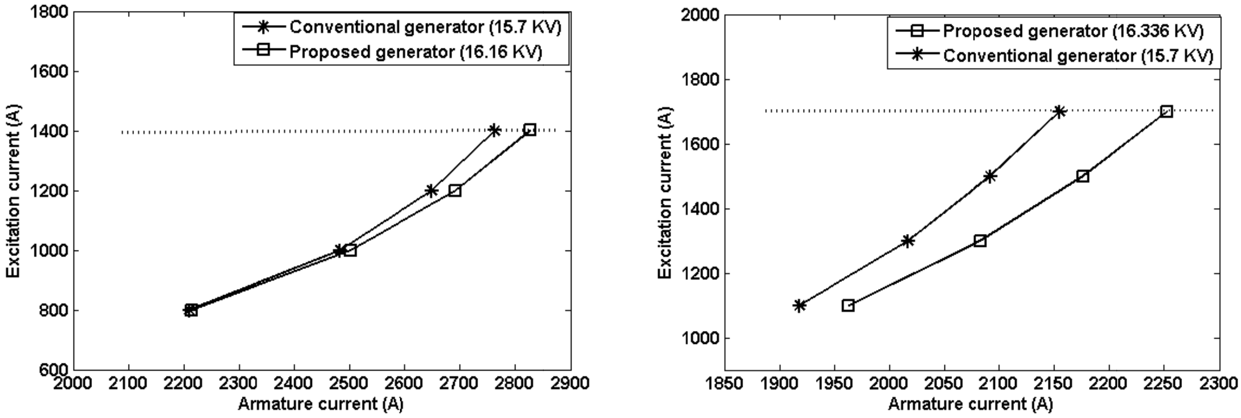
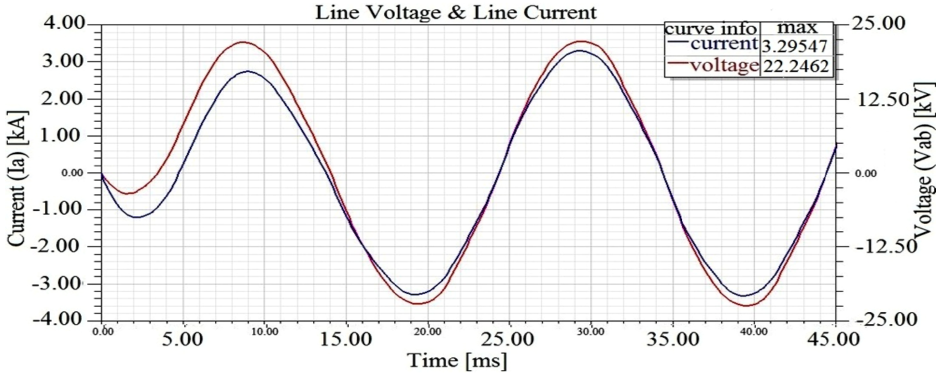
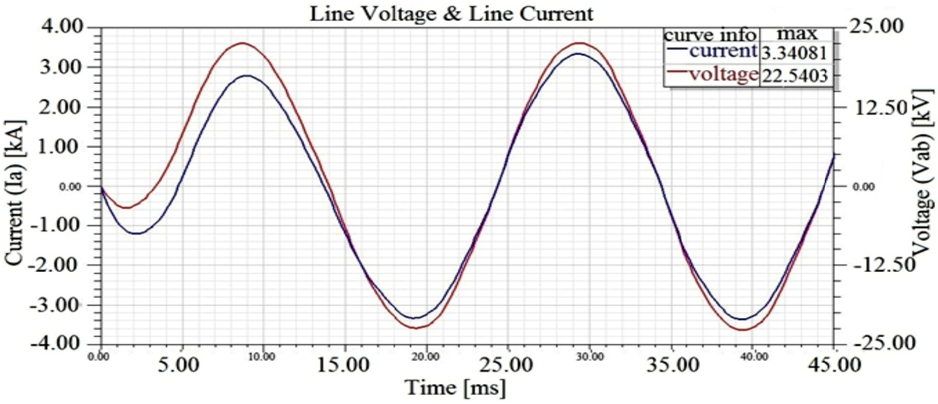


Fig. 11 Variation in excitation currents due to the output. (a) Under unity power factor. (b) Under lagging power factor.



(a)



(b)

Fig. 12 Line current and line induced voltage in the stator winding of two designed generators under leading power factor conditions with 880 A of excitation current. (a) CCG generator. (b) NCG generator.

Table 6 Output power of two designed synchronous generators for leading power factor.

Excitation current (A)	Line voltage (KV-rms)		Stator current (KA-rms)		PF leading-0.86 Output power of generators (MVA)		
	CCG	NCG	CCG	NCG	CCG	NCG	Increase
880	15.7	15.94	2.33	2.37	63.36	65.24	3%
800	15.28	15.46	2.27	2.29	59.94	61.31	2.35%
750	14.96	15.12	2.22	2.24	57.39	58.48	2%
700	14.59	14.75	2.16	2.18	54.55	55.5	1.84%

Also for better comparing, Fig. 13 shows the variation in output power of these two generators with the excitation current under the inductive load conditions. As stated earlier, most of the demands are inductive loads and the increase of output power of the machine in this condition is a highly desirable. As illustrated in Fig. 13, in this condition the output power of the new designed generator is increased 7 % (average) without any increase in total machine size and decrease in efficiency.

Figs. 14(a) and 14(b) shows the variation in output power of these two generators with the excitation current under the unity and leading power factor load conditions, respectively. As stated earlier in these two conditions, the output power of the new designed generator is increased approximately 3% and 2% (average) under the unity and leading power factor load conditions, respectively.

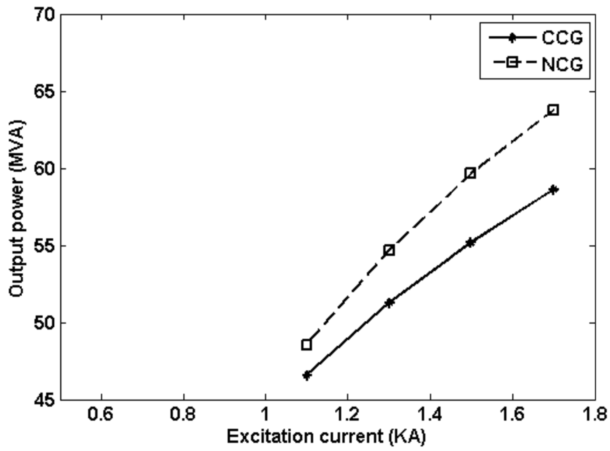
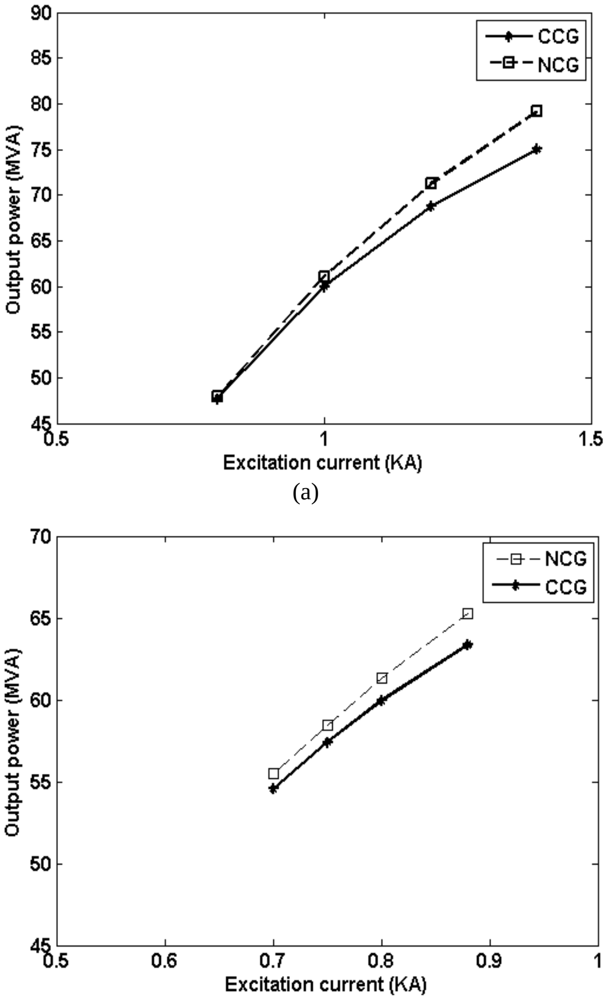


Fig. 13 Variation in output power of two generators with the excitation current under lagging power factor condition.



(a)

(b)

Fig. 14 Variation in output power of two generators with the excitation current. (a) Unity power factor. (b) Leading power factor.

6 Conclusion

It is important to know with the increasing of load in power networks, more and more interest is focused on the large synchronous generator to produce more power. Hence, increasing of output power of synchronous generator without any increase in total machine size is a significant task. In this paper a novel design of cylindrical solid rotor synchronous generator has been presented to produce more power. In conventional cylindrical solid rotor synchronous generator, the direct axis reactance and quadrature axis reactance are equal. Therefore, in this generator, the reluctance torque is zero, but in this new design, the rotor is built of two different materials in such a way that the required inductance values are reached to produce reluctance torque, besides electromagnetic torque due to field excitation. The extensive simulation results show that the proposed method for the design of new cylindrical solid rotor synchronous generator is useful and effective to increase of output power without any increase in total machine size. In fact, the effectiveness of the new cylindrical solid rotor synchronous generator from a magnetic point of view is demonstrated. In this paper, mechanical and thermal aspects of design such as vibration did not analyze.

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