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Geometry optimization of synchronous machines used on ship shaft generator systems

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Abstract. In this paper, the geometry optimization and analysis of two synchronous machines for ship shaft generator applications was carried out. The use of shaft generators in marine applications is a convenient and effective way to supply electric energy to the ship, operating in conjunction with conventional diesel generators. On a first step, state of the art topologies of shaft generator systems are identified and evaluated. In addition, potential improvements in shaft generator systems are proposed. On a second step, a low-speed, direct-driven Permanent Magnet Synchronous Generator (PMSG) for shaft generator applications is designed and optimized in terms of torque production as well as efficiency. The PMSG is compared with an equal power Salient-Pole generator driven by a step-up gear, which is a set-up commonly used in shaft generator systems. The machines are evaluated and optimized in terms of torque production, efficiency and electromotive force's (EMF) harmonic content in nominal operating conditions.

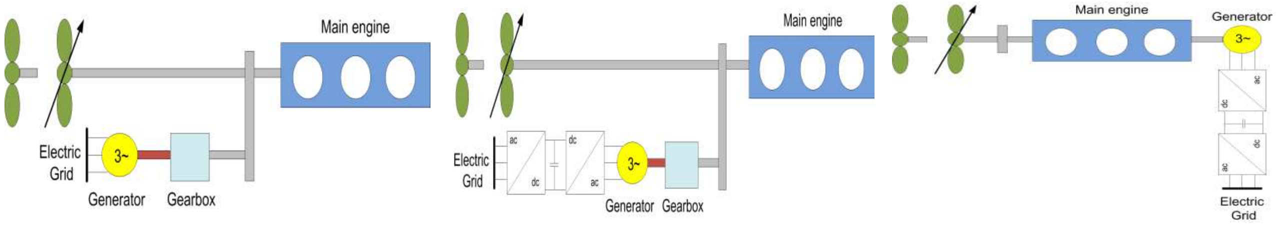
Introduction

Nowadays, shaft generator (SG) systems are gaining increased interest in ship propulsion, due to a number of advantages over conventional diesel generator (DG) systems [2]. Generally, SGs are mounted on the propeller shaft between main propulsion engine and propeller and thus convert part of the power produced by the main engine to electrical. SGs are thus used in conjunction with DGs and other non-conventional sources for generating power on ships. Therefore, their design should be carried out taking into consideration performance and efficiency issues. In addition, the evaluation of their electromagnetic characteristics plays an important role in the analysis of SG systems. In this paper, a low-speed direct-driven PMSG is designed and compared with a salient-pole synchronous generator (SPSG) of the same nominal power but greater speed, for implementation on an actual Ro-Ro ship [5]. These machines are geometrically optimized and compared in terms of their main operating characteristics. Generally, there are three main types of SG topologies [2], [8]:

- Power Take Off/Gear Constant Ratio (PTO/GCR), which consists of flexible coupling, step-up gear, torsionally rigid coupling, and generator as shown in Fig. 1a. In this type, the electric frequency of the generator is proportional to the speed of the propulsion engine, which means that constant frequency production is possible only when the ship navigates at sea. In order to produce constant frequency, a controllable pitch propeller is installed or an induction generator (IG) is used [8]. In the second condition, the rotor can rotate on variable speed higher than the synchronous speed, producing constant electric frequency on the stator. However, the IG must initially operate as a motor in order to be magnetized and then switch to generator mode, supplying with active power the electric network of the ship. Furthermore, IGs absorb reactive power, necessitating the installation of a synchronous condenser. Alternatively, this topology can operate on standalone condition, with a small margin on the electric frequency (50-60Hz), supplying only some special loads (such as bow thrusters), which are tolerant on frequency fluctuations.
- Power Take Off/Renk Constant Frequency (PTO/RCF), which includes an RCF speed-controlled gear and generator. The schematic of this topology is the same as PTO/CGR, shown in Fig. 1a. In this topology, the gearbox maintains the generator's rotor speed constant. As a result, the electric

frequency of the generator remains stable, enabling the parallel operation with diesel generators. Wound rotor synchronous generators are the most common electrical machine type for this SG topology. One of their main benefits is the ability to produce variable reactive power, unlike induction generators, maintaining the grid voltage constant by adjusting properly their field current. Furthermore, the protection of the machine is possible in short circuit operation by controlling their excitation [1].

- Power Take Off/Constant Frequency Electrical (PTO/CFE), which includes a step-up gear, generator and electrical control equipment, as shown in Fig. 1b. Alternatively, a slow-running generator, directly mounted to the front end of the main engine, with electrical control equipment, could be established, as shown in Fig. 1c. In the first case, there is a gearbox with constant ratio and the electrical control system is responsible to convert the variable electric frequency to constant frequency. The power converter generally consists of a rectifier and an inverter which take up the role of keeping the electric frequency and voltage of the grid bus constant. In the second case, the gearbox can be eliminated by choosing a slow-running alternator with a high number of poles. In this topology, PMSGs can be considered.



(a) (b) (c)

Fig. 1. Schematic of a) PTO/GCR & PTO/RCF with conventional or controllable pitch propeller b) PTO/CFE with gearbox and conventional or controllable pitch propeller c) PTO/CFE with a slow running generator and conventional or controllable pitch propeller.

Nowadays, PMSGs are gaining increased interest in SG systems. Their main benefits include the elimination of the field winding, brushes and slip-rings, higher efficiency, since copper losses in the rotor are eliminated, and larger torque density. Radial field Surface Mounted Permanent Magnet (SMPM) generators are the most common topology though more complex topologies, such as axial field PM generators and transverse flux PM generators, are also considered. PMSGs with fractional-slot concentrated winding (FSCW) are gaining great interest in direct-drive applications, such as wind turbines, electric vehicles and electromechanical actuators [3]. Additionally, recent trends in power electronics might enhance the establishment of direct-driven PMSGs in SG applications, connected to the electric grid via an AC/DC/AC converter. However, there are several issues to be addressed regarding PMSG operation, the most notable of which being the lack of control of the excitation, especially under short circuit operation. Also, the rotor geometrical configuration (surface/internal magnets) should be chosen according to the nominal speed and the risk of demagnetization.

Shaft generator design and geometry optimization methodology

In a first step, a preliminary design has been implemented, in order to choose the main design parameters of the generators. More specifically, the main specifications of the synchronous machine are determined i.e. nominal speed and power. Particularly, the nominal speed is modified if the machine is directly mounted to the main engine or driven by a gearbox [2]. Furthermore, the generator's nominal power and phase voltage is determined according to ship's electric network data. In a second step, the machine's main dimensions are calculated, taking into consideration typical electric and magnetic loadings. More specifically, the electromagnetic torque is expressed by means of Maxwell's stress tensor as follows:

$$F_t = P_t \cdot A \tag{1}$$

$$T_e = D \cdot F_t/2 = \pi \cdot D^2 \cdot L \cdot P_t/2 \tag{2}$$

$$P_t = \frac{1}{\mu_0} \cdot \oint B_n \cdot B_t \cdot dc \tag{3}$$

where F_t is the tangential component of the magnetic force, T_e is the electromagnetic torque, P_t is the mean tangential pressure, D is the air-gap diameter, L is the generator's active length, A is the air-gap surface and B_n, B_t are the normal and tangential mean flux density components respectively.

In a third step, a parametric 2D finite element (FE) model was employed to after the generator's initial geometrical configuration for a detailed calculation of machine electromagnetic properties. Afterwards, a parametric design process for was developed in order to perform sensitivity analysis with variables being the machine's main geometrical parameters. The optimization algorithm is shown in Fig. 2. The algorithm's main variables for the PMSG and the SPSG are:

$$\boldsymbol{X_1}=[t_w,\ m_w] \tag{4}$$

$$\boldsymbol{X_2}=[I_f,\ tw,\ d_{sy}] \tag{5}$$

where t_w and m_w are the tooth and magnet width respectively. In addition, I_f, tw and d_{sy} are the field current, tooth width and stator yoke. Initially, the preliminary design is considered and the torque capability is evaluated. The next step involves the evaluation of the machine's total losses. These consist of stator winding's copper losses (P_{Cu}) and iron losses (P_i). It should be noted that for the SPSG field winding's copper losses are included in the total copper losses. An upper limit for the total losses is established to maintain the machine's efficiency relatively high. An objective function [4] is also assigned, which measures the relative deviation of the torque from the nominal value and total losses from the defined upper limit. The parameters are modified to the direction that the objective function is minimized.

$$T_{calc} = f_1(\boldsymbol{X}) \tag{6}$$

$$P_{calc}= f_2(\boldsymbol{X}) \tag{7}$$

$$f = w_1 \cdot \left|\frac{T_{nom}}{T_{calc}}\right| + w_2 \cdot \left|\frac{P_{nom}}{P_{calc}}\right| \tag{8}$$

where w_1, w_2 are weight coefficients and T_{calc}, P_{calc} are the measured torque and total losses respectively. It should be noted that the design parameters are constrained within specified limits, e.g. an upper limit for the magnet width was defined, taking the magnet's cost into account.

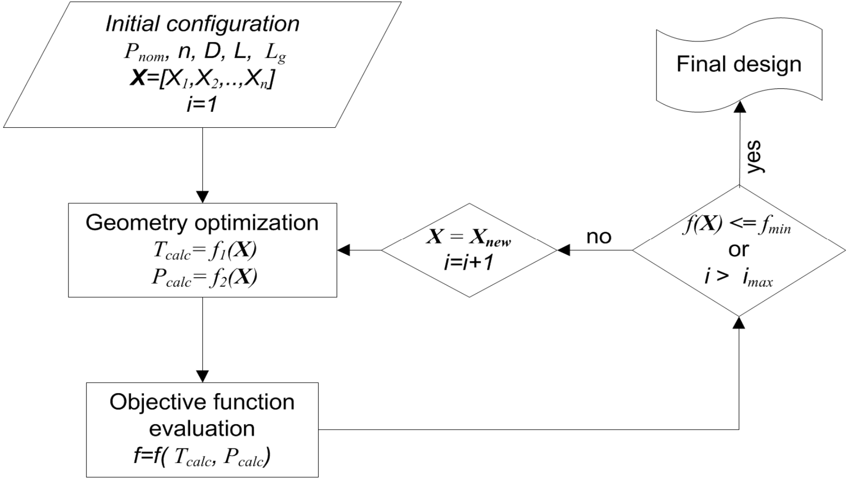
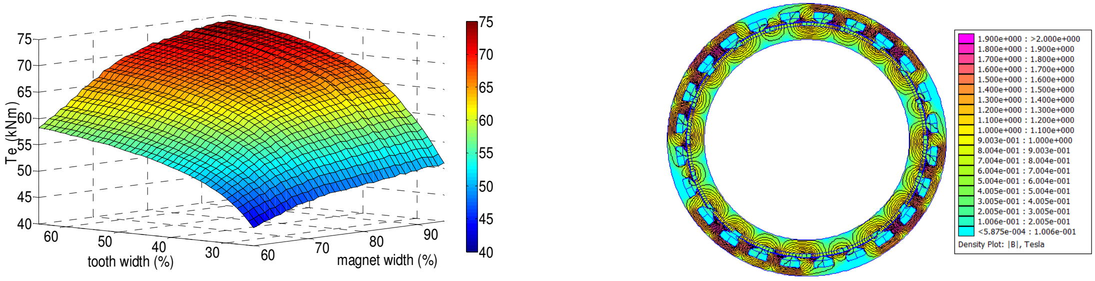


Fig. 2. Flowchart of the proposed algorithm.

Permanent Magnet Synchronous Generator case

Using the parametric design algorithm described above, a PMSG was designed for PTO/CFE SG application. In a first step, the main specifications of the machine are determined: nominal speed 400 RPM and power 2.4 MW. Since the generator is designed for direct-drive application, the nominal speed was determined at the same value as the main propulsion engine's of an actual Ro-Ro ship [5]. A surface-mounted PM configuration is chosen, because of its simplicity and low cost [6]. A 20-pole machine is considered, in order to maintain the frequency relatively high, which is important aspect for the power converter's design and operation [6]. A double-layer FSCW is proposed, owing to the lower iron losses in the rotor and more sinusoidal EMF waveform than the single-layer winding [7]. In the implementation of the proposed algorithm, the torque's nominal value is set to the lower limit of the machine's torque capability and the total losses upper limit is 2% of the nominal power. The torque at nominal speed is calculated about 57.3 kNm. It should be mentioned that additional losses of the power converter are not taken into account. In Fig. 3a, electromagnetic torque map is depicted as a function of tooth and magnet widths, expressed as a percentage of slot-tooth period and pole pitch, respectively. In Fig. 3b the PMSG's magnetic flux density distribution is illustrated for nominal operating conditions.

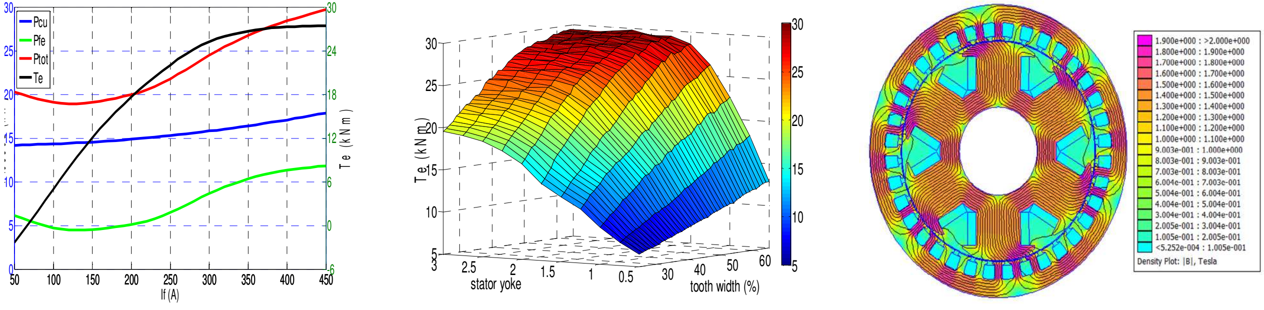


(a) (b)

Fig. 3. a) Electromagnetic torque distribution as a function of the tooth and magnet width b) Magnetic flux density distribution under full load operation.

Salient Pole Synchronous Generator case

In a second step, a Salient-Pole synchronous machine of the PTO/RCF topology was designed. The generator's nominal power and voltage are the same as the PMSG's, with nominal speed 1000 RPM. This is a typical configuration for used in ship shaft generator systems [5]. A 6-pole machine was designed to produce 50 Hz nominal electric frequency. A full-pitch distributed winding with 2 slots per pole per phase was adopted. Moreover, a sensitivity analysis was performed to define the final configuration. Specifically, the algorithm was executed in two steps: initially, the nominal field current (I_f) was determined. Afterwards, the optimization procedure was implemented with variables the tooth width and stator yoke (t_w and d_{sy} respectively). The total losses upper limit was the same as the PMSG's. The nominal torque calculated for the machine's nominal speed is 22.9 kNm. The results of the described procedure are shown in Figs. 4a & 4b. The flux density distribution at full load operation for the final geometry is shown in Fig.4c. The final configuration's parameters for both machines are summarized in Table 1.



(a) (b) (c)

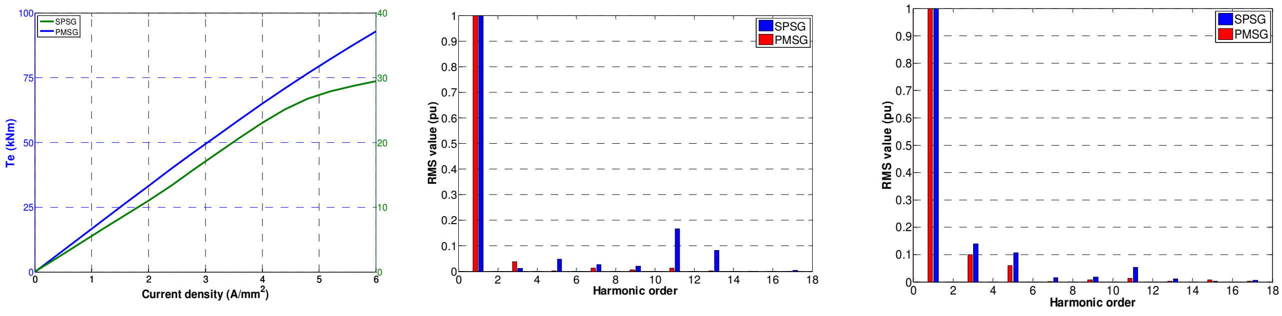
Fig. 4. a) Torque and losses versus the field current (b) Torque distribution as a function of the tooth width and stator yoke (c) Flux density distribution at full load operation .

Table 1. Parameters of PMSG and SPSG

Parameter	***PMSG***	***SPSG***	***Parameter***	***PMSG***	***SPSG***
P(MW)	2.4	2.4	Air gap diameter (cm)	150	90
n(rpm)	400	1000	Gap width (mm)	5	5
f(Hz)	66.7	50	Axial length (cm)	48	63
Nom voltage (V)	900	900	Tooth width (%)	43	44
Current density (A/mm^2)	4	4	Magnet width (%)	76	-
Poles/Slots	20/24	6/36	Field Current (A)	-	340

Comparative analysis

Finite element analysis has been carried out for both machines in order to accurately calculate electromagnetic characteristics. The nominal current density in both cases is 4A/mm^2. PMSG's torque versus current density characteristic is almost linear as illustrated in Fig. 5a, which means that the machine operates at the non-saturation region. On the other hand, SPSG's magnetic circuit is saturated during overloading (current density > 4.5 A/mm^2).



(a) (b) (c)

Fig. 5. a) Torque versus current density b) FFT analysis for the no-load voltage c) FFT analysis for the full-load EMF

Torque ripple and cogging torque coefficients are also displayed in Table 2. They are calculated by the following equations:

$$t_c = \frac{T_{cog}}{T_{av}} \cdot 100\% \tag{9}$$

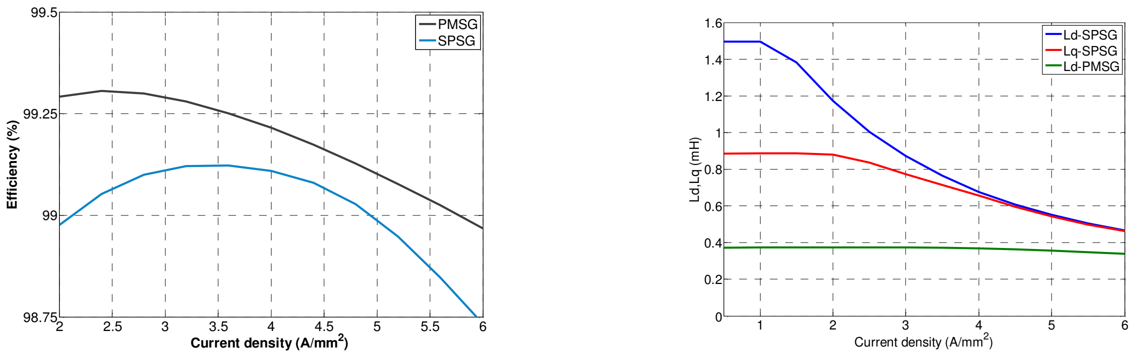
$$t_r = \frac{T_{\max} - T_{\min}}{T_{av}} \cdot 100\% \tag{10}$$

where T_{cog} is the maximum value of the cogging torque, T_{av}, T_{max}, T_{min} are the mean, maximum and minimum values of instantaneous torque under full load respectively. These values where obtained by the rotor's synchronous rotation over two pole pitches for both machines. Respective results are summarized in Table 2.

Table 2. Torque ripple, cogging torque coefficients and EMF THD (%)

	t_c (%)	t_r (%)	No load	Full load
PMSG	1.08	6.1	4.296	11.927
Salient-Pole SG	13.23	10.2	19.505	18.86

From Table 2, it can be concluded that the PMSG displays reduced cogging torque and torque ripple. The PMSG's lower cogging torque coefficient is due to the presence of a fractional-slot concentrated winding [7]. Additionally, the electromotive force's FFT analysis is displayed in Figs. 5b,c for no load and full load operation respectively. Their values are expressed in per unit values of the fundamental component. From Table 2, it can be observed that PMSG's THD coefficient is much lower than SPSG's, both in no-load and full-load operation. Furthermore, the SPSG's no-load voltage has very high 11th harmonic component, which is justified by its high winding factor for this harmonic order. Efficiency versus current density for both machines is illustrated in Fig. 6a. Both machines have a high efficiency (greater than 98.5% for the measured current density region). This was expected because it was one of the main objectives in the optimization procedure analyzed above. Finally, the PMSG is slightly more efficient. Figure 6b shows the inductances in the d and q-axis of the two machines versus the current density. It should be noted that the PMSG's inductances are almost equal due to the specific rotor configuration i.e. surface mounted PMs [7]. From Fig. 6b, it can be concluded that PMSG's inductance is almost constant with respect to the current density, which confirms that PMSG operates at the non-saturation region. On the other hand, SPSG's inductances decrease significantly with the current density, which implies the saturation of its magnetic circuit.



(a) (b)

Fig. 6. a) Efficiency with current density b) Inductances with current density

Summary

In this paper, two synchronous machines for an SG application have been designed and evaluated. A low-speed direct-driven surface mounted PMSM of the PTO/CFE topology is proposed and its final design was determined by an optimization procedure. Additionally, an SPSG of the PTO/RCF topology is designed in a similar way. The comparison of the main operating characteristics between the two machines has shown that the PMSG configuration is advantageous in terms of torque ripple, EMF harmonic content and efficiency. As a result, a low-speed PMSM with fractional-slot non-overlapping winding, connected to the ship's electric grid via a power converter, can be considered as an attractive option for SG systems.

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