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Calculation of PWM-Induced Rotor-Can Losses in Flooded Generators

Faisal Wani, Udai Shipurkar, Jianning Dong, and Henk Polinder

Abstract—**Improving availability of tidal turbines has been identified as a key area to lower the levelized cost of energy from tides. One of the approaches suggested to achieve high reliability is to use a flooded permanent magnet (PM) generator. Flooded PM generators are designed to operate with a seawater filled stator-rotor gap in the generator. Using such generators will prevent frequent maintenance required for the high pressure rotary mechanical seals between the turbine shaft and the nacelle enclosure. Flooded generators are conventional generators with additional stator and rotor-can material to protect the active parts of the generator against water ingress. Normally, stator-can is made of an electrically non-conductive material to prevent excessive losses from the PM field. On the other hand, choice of the rotor-can is more flexible. If the rotor-can of the flooded generator is made of stainless steel or any other electrically conductive material, this may give rise to substantial losses in the rotor-can due to the space and time harmonics of the stator magneto-motive force. The time harmonics arise from the pulse-width modulated inverter used to control the torque/speed of the generator. This paper aims at quantifying losses in the rotor-can of the flooded generator due to the time harmonics of the stator current. Results show that the rotor eddy current losses due to the space harmonics are not always negligible. However, losses due to the time harmonics, under normal operating conditions, can be assumed to be negligible.**

Keywords—**Eddy current losses, flooded generator, permanent magnets, pulse width modulated inverter, tidal turbines,.**

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Fig. 1. Nova M100 tidal turbine.

I. Introduction

ENERGY from tidal turbines has recently been gaining traction among renewable sources of energy. One of the main reasons for that is its periodic and predictable nature [1]. This attention towards tidal energy is despite the technological and economical challenges faced in harnessing tidal energy. Improving reliability and/or minimizing maintenance of the subsea equipment is crucial for decreasing the levelized cost of energy (LCOE) from tides [2]. A typical tidal turbine is shown in Fig. 1 [3]. The shown Nova M100 turbine is rated at 100 kW, and uses fixed-pitch blades with a geared drivetrain.

Generators for tidal turbines are usually placed in a nacelle sealed by a high pressure rotary mechanical seal. Over time the leakage from the mechanical seals can cause faults in the generator due to corrosion, insulation failure, etc. To avoid these faults due to leakage, some tidal turbines use the bilge pumping systems inside the nacelle with dehumidifying systems. This adds to the cost and the reliability issues for the power take-off (PTO) system. In order to minimize failure modes and improve reliability, a flooded permanent magnet (PM) generator has been proposed in the literature [4], [5], [6]. To improve the efficiency and availability, direct-drive PM generators are preferred over other generator types [7].

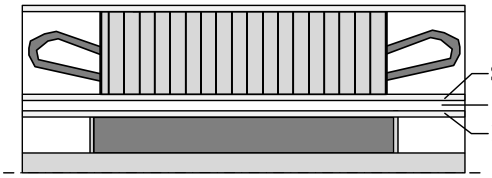

Fig. 2. Stator and rotor-can in a Flooded PM generator.

The flooded generator is similar to the conventional airgap generator, except that it has a stator and a rotor can to protect the stator and the rotor materials from seawater, as shown in Fig. 2. If the can material is electrically conductive, it can lead to high losses inside the generator, compromising the efficiency [4]. From an electromagnetic viewpoint, a conductive material experiences losses when exposed to time-varying magnetic field. These losses are mainly the eddy current losses in non-magnetic materials. As explained in [4], using a conductive material as a stator-can is ill-advised; however, the choice of the rotor-can is more flexible. Both electrically conductive as well non-conductive materials have their pros and cons [4], and have precedence for use in similar applications [6]. Metallic materials, such as steel, are better against water ingress than say composites. In other words, thinner cans may be used which improve power density of the machine, possibly leading to lower cost. On the other hand, they may experience high eddy current losses. Therefore, it's important to estimate these rotor losses prior to the manufacture. Since the rotor-can rotates at the same speed as the principal torque producing magnetic fields, it is less likely to have significant eddy current losses. However, there are other components of magnetic fields in the permanent magnet (PM) generator, which travel at non-synchronous speeds. These asynchronous magnetic field components can give rise to eddy-current losses in the rotor-can.

Previously, rotor losses due to the space harmonics of the stator current were shown to vary significantly in case of integer slot windings and fractional slot windings [4]. Higher rotor losses were estimated in the latter case. Another cause for the same losses could be the higher order harmonics of currents in the generator, which arise from the power electronic converter connected to the generator [8]. To complete the argument from this perspective, this paper looks at the time harmonic induced rotor losses. Again the losses will be compared for the integer slot and fractional slot windings. In addition to calculating the time harmonic rotor eddy current losses, we also look at characterizing these losses in terms of switching frequency.

Because of the switching nature of the converter, the voltage and currents in the generator are not purely sinusoidal, and contain several higher order time harmonics. The stator magneto-motive force (MMF) wave setup by these higher order harmonics are asynchronous with the rotor speed. As a result, the rotor runs at a certain slip with respect to these MMF wave components. These losses can occur both in the rotor-can as well as permanent magnets.

In the next section, we describe the tidal turbine power take-off system on which the analysis is done. Section III explains the methodology adopted to calculate the time harmonics of the stator current and the corresponding rotor-can losses. Section IV gives the results from the aforementioned analysis. Section V summarises the conclusions from this study.

II. System Description

To analyse the eddy current losses in the rotor-can of the generator due to the pulse width modulation (PWM)-induced time harmonics, we shall use 300kW tidal turbine power take-off system, with PM generator. For the sake of brevity, we assume that the turbine is operated at constant speed of 30 rpm at tidal velocity of 3 m/s. The turbine is assumed to be active-speed stall controlled [9]; this gives higher reliability by doing away with pitch controlled system.

The rating and dimensions of the generator are same as those used in [4]. The generator design parameters are listed in Table I. As mentioned earlier, two PM machines will be analysed. Machine-I has integer slot windings, and Machine-II has fractional slot windings (12slots/10poles combination in a single layer configuration). In this paper, a two-level back-to-back converter is used as a low voltage drive. Also, an active speed stall controlled turbine assumed in this analysis implies that the converter and the generator need to be overrated to account for sudden surges in speed [10]. Here we have assumed an overrating of 30% in torque rating of the generator, or in the kVA rating of the converter. This overrating is calculated from assuming a surge of 0.5 m/s in speed at cut-out speed of 3.5 m/s. The outer speed control gains (PI-controller) and the inner current control gains (again PI) are tuned to achieve fast response and not to let the turbine over-speed for a temporary surge in tidal velocity [10].

Since the electrical time constant of the converter-generator is smaller than its mechanical time constant, the variations in current due to speed fluctuations about the reference speed are not considered to have significant impact on the pulse width modulated eddy current losses in the generator.

TABLE I
DESIGN PARAMETERS FOR PM GENERATORS

Symbol	Quantity	Value
P	Rated Power	300 kW
ω_m	Rated Speed	30 rpm
B_r	Remanent density in PM	1.25 T
σ_{PM}	Magnet conductivity	5.56e5 S/m
σ_{steel}	Conductivity of Non-magnetic Stainless Steel 304L	1.3e6 S/m
R_s	Watergap radius	1.2 m
c_{tr}	Rotor-can thickness	2 mm
c_{ts}	Stator can thickness	3 mm
G	Watergap radial length	8 mm
α_m	Magnet-arc to pole-pitch ratio	0.7
h_m	Magnet height	24 mm
P	No. of pole pairs	55
Q_s	No. of stator slots (Machine-I)	330
Q_s	No. of stator slots (Machine-II)	132
L	Stack length	0.7 m
h_{yoke}	Stator and rotor yoke heights	20 mm
k_{fil}	Slot fill factor	0.5

Machine-I has integer slot windings; Machine-II has fractional slot windings.

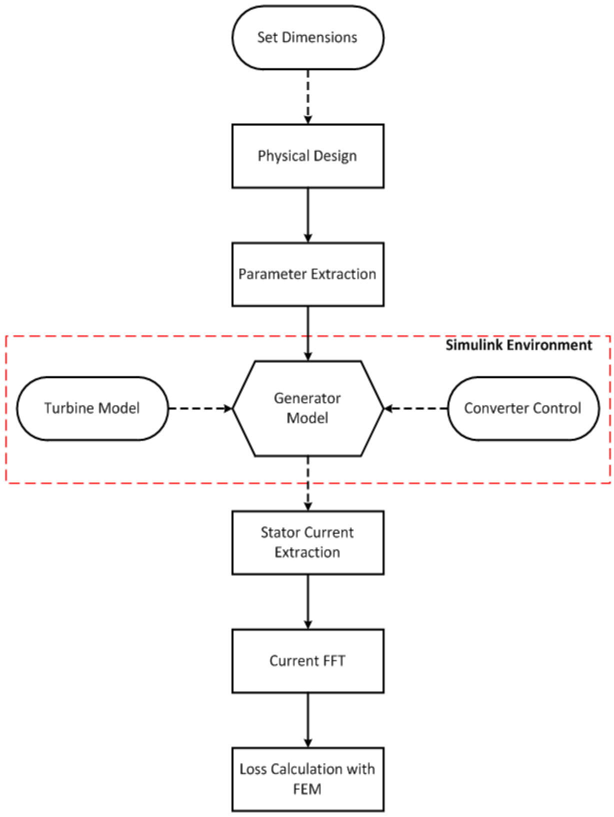

Fig. 3. Flowchart to illustrate the calculation of PWM-induced eddy current losses in the rotor-can of the flooded PM generator.

III. METHODOLOGY

The following approach is followed in order to calculate the rotor eddy current losses in the flooded PM generator. First, the speed and torque inputs to the generator electromagnetic model are estimated from the turbine model. Then, the stator phase currents are calculated from the generator model. Subsequently, a time-domain fast Fourier transform is used to calculate higher order frequency components in the currents. The rotor eddy current losses from each time harmonic component is calculated using the finite element model. Each of these steps is explained in detail below. A flow chart of the process is shown in Fig. 3.

A. *Simulink Model*

The turbine, PM generator and a 2-level voltage source converter are modelled using in-built blocks in MATLAB Simulink environment.

The turbine is modelled using the following equations:

$$P = \tfrac{1}{2} C_p \rho U^3 A, \tag{1}$$

$$J \frac{d\omega_m}{dt} = T_m - T_e, \tag{2}$$

where P is the power generated by the blades, C_p is the power coefficient of the turbine, ρ is the density of water, U is the tidal velocity, A is the swept are of the turbine, J is the moment of inertia, ω_m is the rotational velocity and T_m and T_e are the mechanical and electrical torques.

Assuming that the rotor eddy current field has negligible effect at the stator bore, the stator current is calculated from the following differential equations (in dq frame):

$$\frac{di_d}{dt} = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} p\omega_m i_q \tag{3}$$

$$\frac{di_q}{dt} = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q - \frac{L_d}{L_q} p\omega_m i_d - \frac{\lambda}{L_q} p\omega_m \tag{4}$$

$$T_e = 1.5p[\lambda i_q - (L_d - L_q) i_d i_q] \tag{5}$$

where i_d, v_d, L_d are the direct axis components of the stator quantities. Similarly i_q, v_q, L_q are the quadrature-axis quantities. Also, p is the number of pole-pairs of the generator and λ is the rotor flux linkage. The electrical parameters for the two machines are given in Table II.

The assumption that eddy current field of the rotor-can has negligible effect on the stator current could only be valid if the rotor-can losses are rather low (although not negligible). The gate signal inputs to the pulse-width modulated inverter are calculated based on the speed control algorithm mentioned in the previous section. A simple PI-controller in dq frame is used to control machine speed/torque values.

B. *Rotor Eddy-Current*

The stator current is obtained from the Simulink model. Subsequently, a time-domain fast Fourier transform (FFT) current is performed to derive different time harmonic components.

TABLE II
ELECTRICAL PARAMETERS FOR PM GENERATORS

Symbol	Quantity	Value
P	Machine-I (integer slot winding)	300 kW
R_s	Resistance per phase	0.0047 ohm
L_s	Inductance per phase	0.3 mH
E	No-load phase emf (rms)	196.83 V
V_{dc}	DC-link voltage	660 V
J	Inertia	5900 kg.m^2
P	Machine-II (fractional slot winding)	300 kW
R_s	Resistance per phase	0.002 ohm
L_d or L_q	Inductance (d and q axes)	0.24 mH
E	No-load phase emf (rms)	209.64
V_{dc}	DC-link voltage	660 V
J	Inertia	5900 kg.m^2

The rotor eddy current losses are calculated for each time harmonic component by using the rotor-only model, explained in [11]. The model uses a linear current density boundary condition at the stator inner radius, as shown in Fig. 4. The assumptions involved in rotor loss calculation include linear iron permeability, laminated rotor iron, negligible end-effects and no influence of rotor eddy current field on the magnetic field near the stator inner radius.

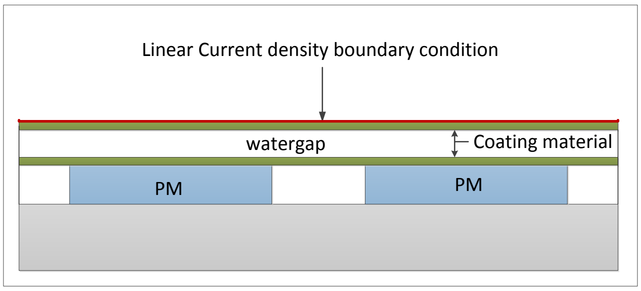

Fig. 4. Calculation of rotor eddy losses by imposing current density on the stator bore.

The rotor loss method used in this paper calculates the losses due to all space harmonics corresponding to a single time harmonic in a single frequency domain computation (stator frequency). For multiple time harmonic components, method needs to be repeated as many times as the number of time harmonic components present in the stator current.

IV. RESULTS

In this section, the stator phase current and the associated rotor eddy current losses are analysed. The analysis is carried out for a mean tidal velocity of 3 m/s, at which the generator rotates at a speed of 30 rpm and generates around 300 kW of power.

The rotor eddy current losses are calculated at two different switching frequencies: 2 kHz and 4 kHz. Two PM machines, one with integer slot windings and the other with fractional slot windings were analysed.

The time harmonic components of the stator current for Machines-I and II at 2 kHz switching frequency are shown in Figs. 5 and 6. The corresponding rotor eddy current losses due to each time harmonic component are shown in Figs. 7 and 8. Similar results for both the machines with switching frequency of 4 kHz are given in Figs. 9 to 12. The losses in the rotor include both the losses in the rotor-can as well as permanent magnets. The bulk of the losses occurs in rotor-can both due to its higher conductivity as well as non-segmented nature.

It is observed that the eddy current losses in case of the integer slot windings is negligible due to both the space and the time harmonics of the stator current. However, in the case of the fractional slot windings, the rotor eddy current losses are substantial. The losses are mainly due to the space harmonics of the fundamental current component, which has the highest magnitude. The substantial space harmonic components are a consequence of the fractional slot concentrated winding layout. Some of the loss is also due to the fifth and the seventh time harmonic components. However, their contribution to the total eddy current loss in the rotor is rather small. Loss contribution due to time harmonic components near the switching frequency is negligible. This is primarily because of the low magnitude of the current components near switching frequency. Furthermore, at very high frequencies, skin depth reduces significantly limiting the losses in the rotor.

It is evident from the results that including losses due to higher time harmonic components does not add much to the total rotor eddy current losses. This conclusion holds both for the integer as well as fractional slot windings, which otherwise have different resistance and inductance for the similar machine dimensions and power.

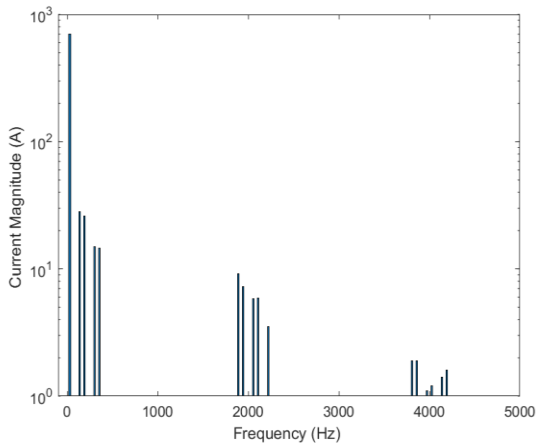

Fig. 5. Time harmonics of stator phase current. Switching frequency of the converter is 2 kHz. Machine-I with integer slot windings.

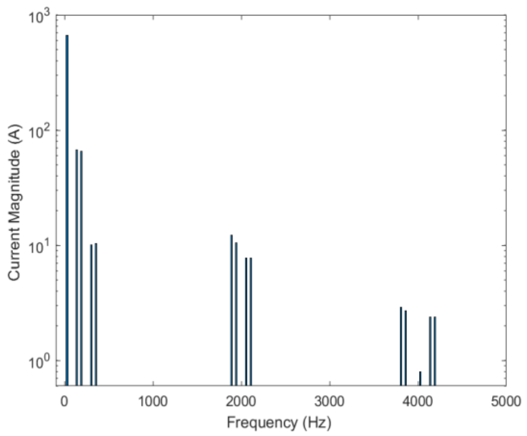

Fig. 6. Time harmonics of stator phase current. Switching frequency of the converter is 2 kHz. Machine-II with fractional slot winding 12/10 SL.

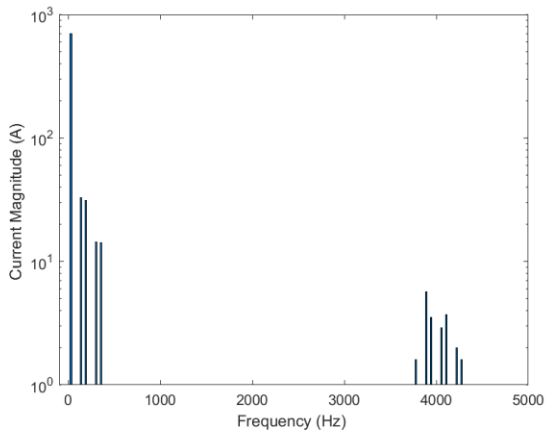

Fig. 9. Time harmonics of stator phase current: switching frequency of the converter is 4 kHz. Machine-I with integer slot windings.

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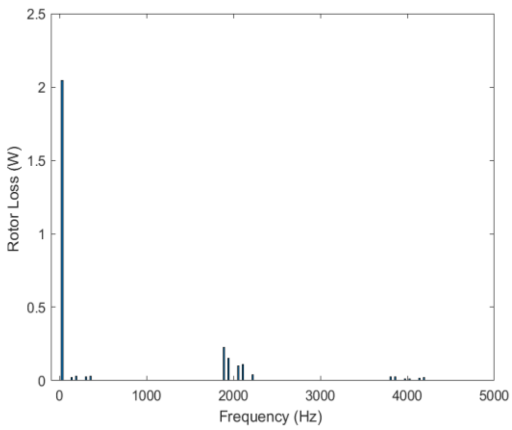

Fig. 7. Total rotor eddy-current loss in Machine-I as a function of time harmonic component of current. Switching frequency is 2 kHz.

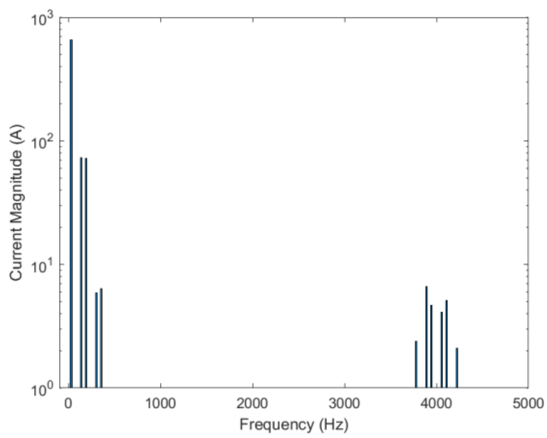

Fig. 10. Time harmonics of stator phase current: switching frequency of the converter is 4 kHz. Machine-II with fractional slot winding 12/10 SL.

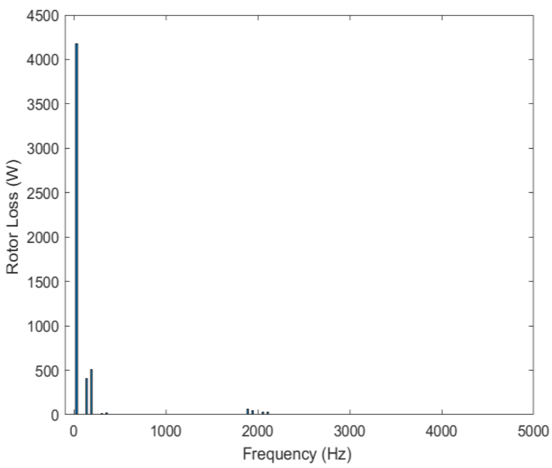

Fig. 8. Total rotor eddy-current loss in Machine-II as a function of time harmonic component of current. Switching frequency is 2 kHz.

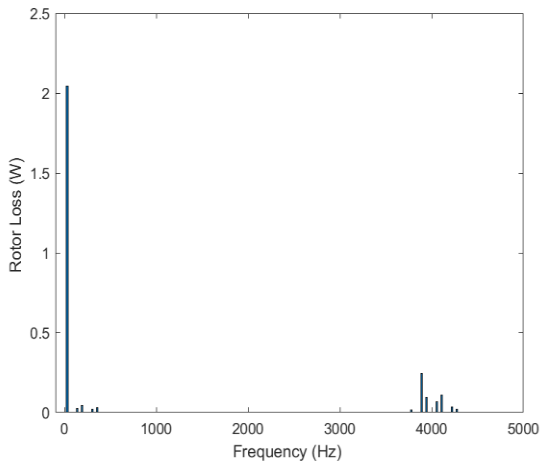

Fig. 11. Total rotor eddy-current loss in Machine-I as a function of time harmonic component of current. Switching frequency is 4 kHz.

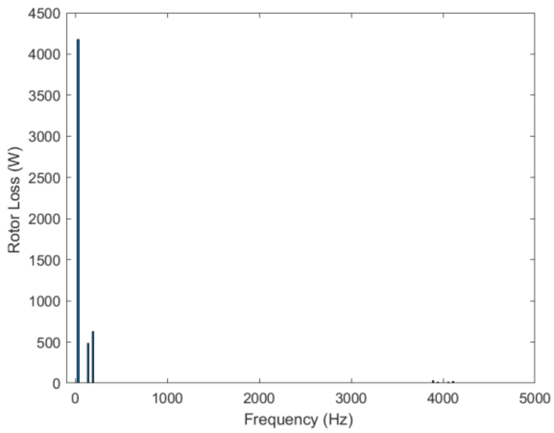

Fig. 12. Total rotor eddy-current loss in Machine-II as a function of time harmonic component of current. Switching frequency is 4 kHz.

V. CONCLUSIONS

The paper analysed the eddy current losses in the rotor-can as well as the magnets of the flooded PM generator. The source of the loss was the time harmonics of the current arising from the pulse-width modulated inverter controlling the generator. From the results we observed that the losses due to the time harmonics of the stator current are negligible. This conclusion does not change with the switching frequency and winding configuration of the generator. On the other hand, space harmonics of the fractional slot winding machine can cause induce substantial eddy current losses in the rotor.

From this we can conclude that for design purposes the converter induced losses in the rotor could be neglected, and focus should be more on the space harmonic induced losses. This also implies that increasing the switching frequency (reducing the harmonic distortion in current) has almost no effect on the rotor losses. On the contrary, it might reduce the drive efficiency by increasing the converter switching losses. Another observation is that because the losses are not substantial, the eddy current field effect is negligible. This assumption was made in the beginning and is validated by the loss results.

For the correct choice of the rotor-can material, studies should be conducted based on waterproofing properties of different materials, required thickness of the can, structural integrity of the material, and the manufacturability together with the rotor of the generator.

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