



Kriging Approach Dedicated to Represent Electromagnetic Forces in Salient Pole Generators

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Abstract: The development of multi-physics models can significantly help predict and identify faults in hydropower generating units. In this context, it is crucial to have a good representation of the electromagnetic efforts of the generators. One of the approaches used for determining electromagnetic forces is the finite element method to solve Maxwell's equations. However, the operating conditions of a generating unit can constantly vary, meaning that for each condition the model needs to be solved, thus leading to a high computational cost. In this sense, the Kriging model is formulated to replace the force responses of the finite element model of a generator of a hydropower unit for several operating conditions. The results show that the surrogate model can represent the electromagnetic generator forces to reduce the computational cost.

Keywords: *electric generators, Kriging surrogate model, electromagnetic forces, hydropower unit*

INTRODUCTION

Nowadays, electrical energy has become increasingly indispensable for society. Its consumption has been overgrown (Torres, Martínez-Álvarez, and Troncoso, 2022), considering the Brazilian context according to ANEEL (National Electrical Energy Agency). More than 60 % of Brazilian electrical energy comes from hydroelectric plants. Therefore, to ensure the proper functioning of these systems, it is essential to develop methodologies for analyzing and detecting failures.

Silva (2013) states that defects in a hydropower unit can be divided into three large groups: hydraulic, mechanical, and electrical. The development of multiphysics models that encompass all groups can be of great help in the process of predicting and identifying failures in this system. A good representation of the generator's electromagnetic forces is essential for developing these models. According to Wallin (2013), these efforts result from a non-uniform magnetic flux in the air gap, whether caused by rotor eccentricity or faulty field winding.

Hydropower units are usually large machines operating at low speeds, generally using salient pole generators. These poles are external to the rotor, and their geometry influences the magnetic field distribution (Mohamodhosen, Tounzi and Gillon, 2019). Thus, an adequate way to consider a pole geometry is to use the finite element method to discretize the system's air gap and solve Maxwell's equations.

Hydropower-generating units are connected to the national electricity grid, and according to the demand, their operating parameters can be changed within short periods (Kishor, Saini and Singh, 2007). This variation in the machine's operating parameters brings a necessity to solve the finite element method generator model together with the system's dynamic model for each one of the operating conditions, leading to a possibly very computationally demanding model.

In this sense, this work aims to apply the Kriging surrogate model to represent the electromagnetic forces applied by the generator on the shaft under different conditions. The generator in the analysis has 80 poles, nominal power of 225000 kVA, and is part of the Foz do Chapecó hydropower unit.

MATHEMATICAL MODELS

Electromagnetic model

The proposed approach for the electromagnetic modeling of the salient pole electric generator is to consider a new magnetostatic problem at each instant. Thus, eddy currents that may arise in conductive materials are ignored. In this case, the magnetic field strength \mathbf{H} and the magnetic flux density \mathbf{B} must obey Maxwell's equations (Bao et al., 2022, Andersen, 2012.) Eq.(1) and Eq. (2), where \mathbf{J} , which is a known quantity, is the current density:

$$\nabla \times \mathbf{H} = \mathbf{J} \quad (1)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (2)$$

The relationship between \mathbf{B} and \mathbf{H} is given in Eq. (3) where the proportionality constant μ_p is the permeability of the material:

$$\mathbf{B} = \mu_p \mathbf{H} \quad (3)$$

The magnetic potential approach will be adopted to simplify the finite element problem solution. Therefore, the magnetic flux density is written as the curl of the vector potential, \mathbf{A} , as shown in Eq. (4):

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (4)$$

This definition of \mathbf{B} satisfies Eq. (2), inserting Eq. (4) and (3) in Eq. (1), one can write:

$$\nabla \times \left(\frac{1}{\mu_p(\mathbf{B})} \nabla \times \mathbf{A} \right) = \mathbf{J} \quad (5)$$

Thus, if \mathbf{A} is found, \mathbf{B} and \mathbf{H} can be determined by differentiating \mathbf{A} . With \mathbf{B} , \mathbf{H} , and \mathbf{J} in hand, using Lorentz's force (Eq. (6)) and Amper's law (Eq. (7)), associating the two equations and integrating over the volume of the object, we obtain the expression of force as a function of field \mathbf{B} density alone (Eq. (8)).

$$\mathbf{f} = \mathbf{J} \times \mathbf{B} \quad (6)$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} \quad (7)$$

$$\mathbf{F} = \frac{1}{\mu_0} \iiint_V (\nabla \times \mathbf{B}) \times \mathbf{B} dV \quad (8)$$

To assist in solving the electromagnetic problem, we chose to use the open-source software Finite Element Method Magnetics – FEMM (Meeker, 2020).

Kriging surrogate model

In this work, the Kriging formulation is applied to obtain a surrogate model for the electromagnetic generator forces for different operating conditions as a function of the eccentricity of the rotor about the stator.

The design of surrogate models usually consists of four steps:

- a) Sampling: This step consists of selecting a set of data associated with the original model (inputs and outputs) that will be used to build the surrogate model;
- b) Formulation: selects the function or the set of functions that will be used in the representation of the original model;
- c) Adjustment: in this step, the chosen functions are adjusted to the sampled data set;
- d) Validation: in most cases, this step is done by defining samples not considered in the sampling stage. In this case, the results obtained from the original and surrogate models are compared using precision metrics.

Some features of the adopted Kriging approach are summarized in this section. Interested readers are referred to Simpson (2001) and Wang et al. (2008) for more details. In a Kriging surrogate, the system response $\hat{y}(\mathbf{x})$ is approximated by the sum of an interpolation polynomial $f(\mathbf{x})$ and a Gaussian process $Z(\mathbf{x})$ that effectively interpolates the Kriging model sampled data (Eq. (9)).

$$\hat{y}(\mathbf{x}) = f(\mathbf{x}) + Z(\mathbf{x}) \quad (9)$$

Defining a polynomial approximation function $f(\mathbf{x})$ which is typically zero, first or second order, and a correlation function $R(x_i, x_j)$, normally gaussian, linear, or, exponential, the Kriging surrogate can estimate the model response regarding untrained points (new data) as shown in Eq. (10).

$$\hat{y}(\mathbf{x}) = (\mathbf{f}^T \mathbf{R}^{-1} \mathbf{f})^{-1} \mathbf{f}^T \mathbf{R}^{-1} \mathbf{y} + \mathbf{r}^T(\mathbf{x}) \mathbf{R}^{-1} (\mathbf{y} - \mathbf{f}((\mathbf{f}^T \mathbf{R}^{-1} \mathbf{f})^{-1} \mathbf{f}^T \mathbf{R}^{-1} \mathbf{y})) \quad (10)$$

where $\mathbf{r}(\mathbf{x})$ is the correlation vector between an untrained value of \mathbf{x} and the sampled data points, while \mathbf{R} is the correlation matrix.

RESULTS AND DISCUSSION

Analysis of the surrogate model

This work is dedicated to developing a methodology for representing electromagnetic forces in the most diverse operating conditions of the Foz do Chapecó Hydropower Unit (Fig. 1). This generating unit comprises a Francis turbine, a shaft divided into four parts, a salient pole generator, and three hydrodynamic bearings. The first is positioned just above the turbine, a radial cylindrical bearing, and the second is placed below the generator, which is a tilting pad thrust bearing. And the third is located above the generator, which is a radial tilting pad bearing.

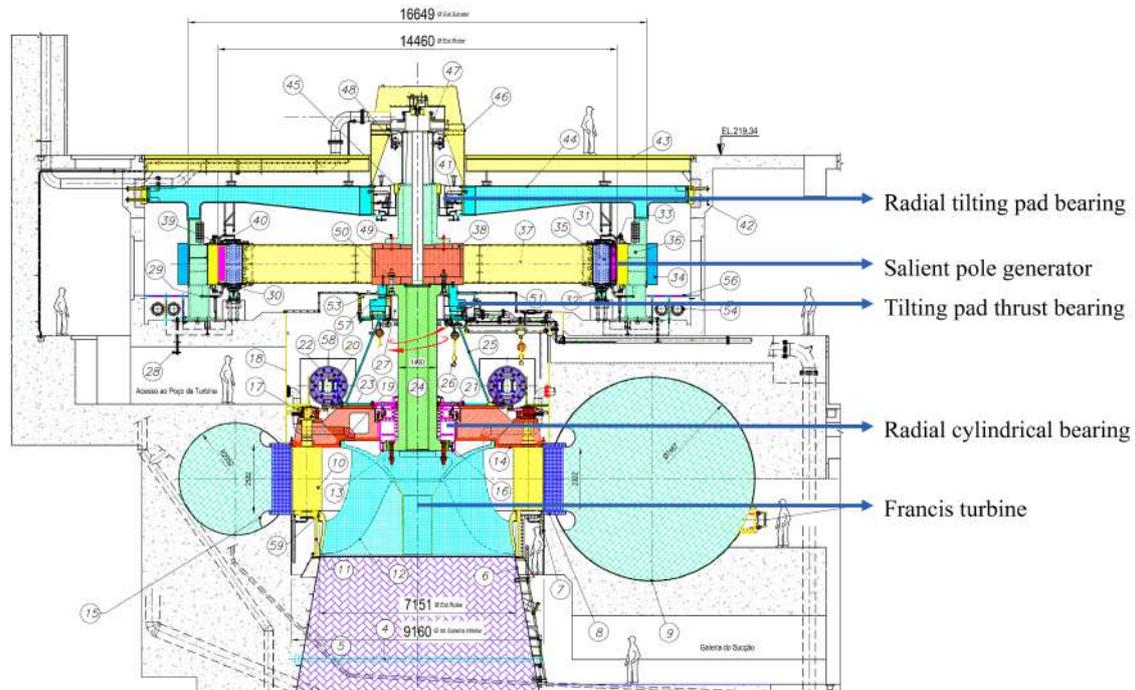


Figure 1 – Foz do Chapecó Hydropower Unit.

The generator under analysis is a salient pole generator. This component's specific geometric and electrical parameters are depicted in Tab. 1, while Fig. 2 shows the generator and a 2D representation of the system, illustrating its main components.

Table 1 – Parameters of Foz do Chapecó Hydropower Unit.

Geometric parameters	
Rotor outside diameter	14 463 mm
Stator inner diameter	14 500 mm
Air gap	18.5 mm
Generator length	1 250 mm
Electrical parameters	
Nominal power	225 000 kVA
Nominal current [RMS]	9 413 A
Rated excitation current	2 537 kVA
Nominal Frequency	60 Hz
Number of phases	3
Number of poles	80
Number of stator slots	672
Busbars per slot	2
Rated speed	90 RPM
Stator winding type	Imbricated

In order to understand the behavior of the electromagnetic force as a function of the rotor eccentricity, a magnetostatic analysis was carried out considering the nominal operating conditions (Tab. 1), in which the rotor was moved in the X

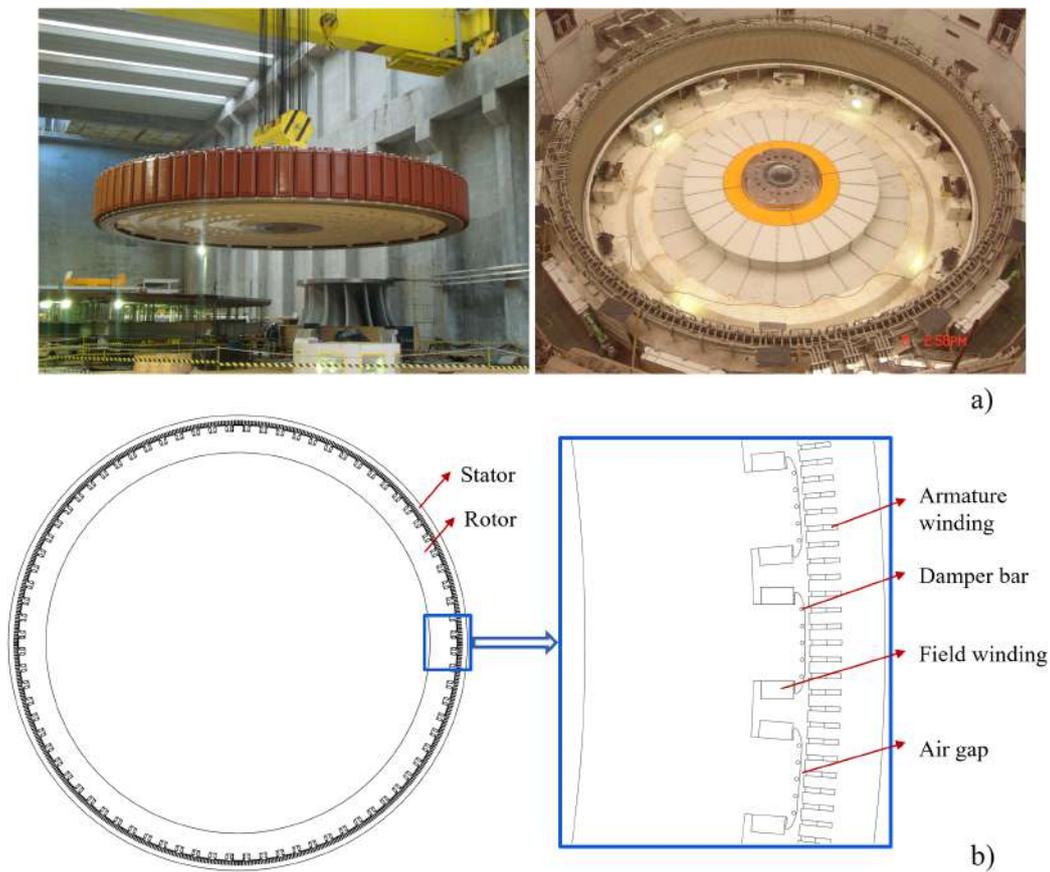


Figure 2 – (a) The physical system of the Foz do Chapecó generator. (b) 2D representation of the electromagnetic model.

direction, varying its eccentricity from $0\mu m$ (perfectly concentric) up to $18000\mu m$. It is possible to observe in Fig. 3 the intensity of the magnetic flux for a rotor eccentricity of $16000\mu m$.

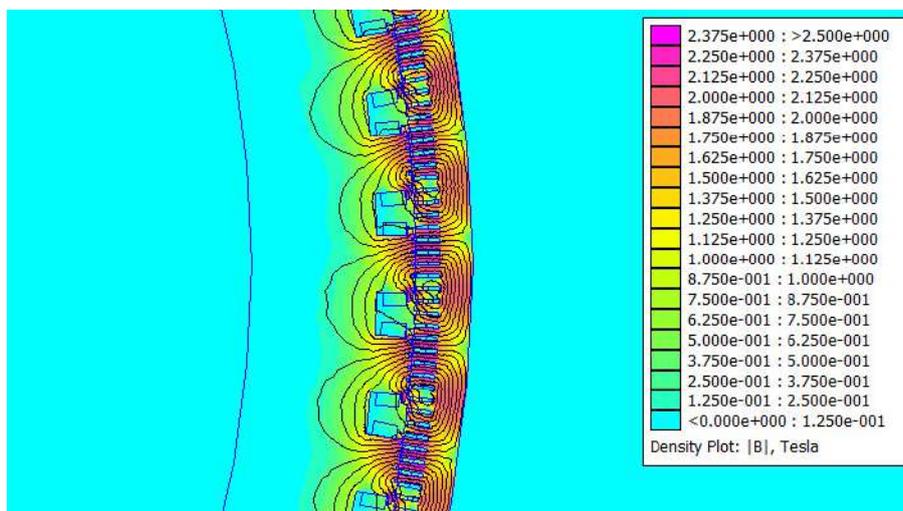


Figure 3 – Flux lines and magnetic flux density.

The behavior of forces as a function of rotor eccentricity is shown in Fig. 4. It is possible to notice that the force in the Y direction remains close to zero. This behavior was expected because the rotor was displaced only along the X direction. Moreover, it is verified that the X force has a linear behavior up to approximately $10000\mu m$, then, for higher eccentricities, becomes nonlinear.

The linear behavior of the force for eccentricities less than $10000\mu m$ is an interesting feature of the system. As the

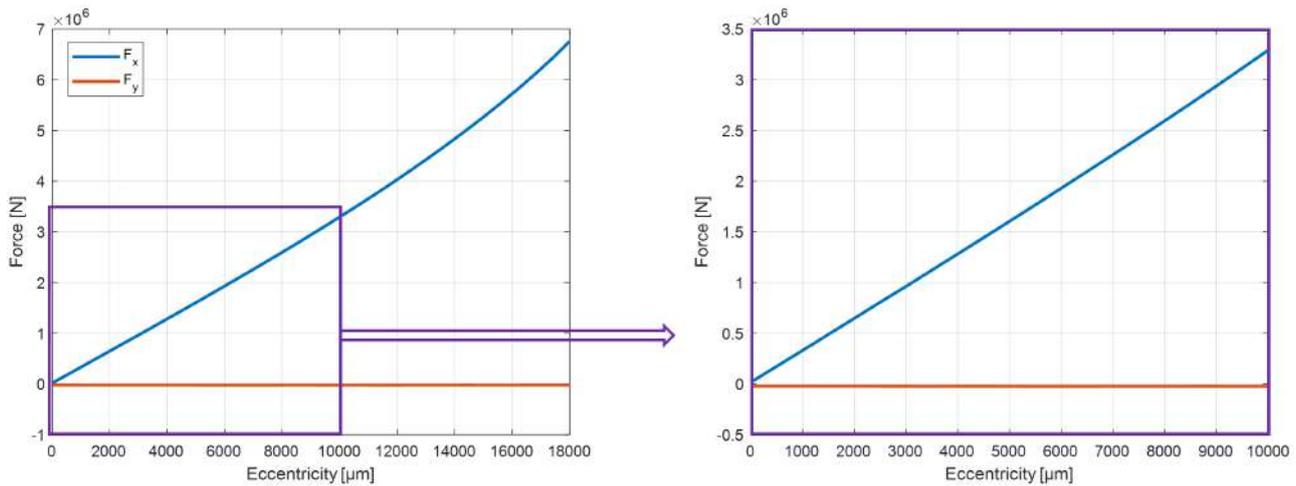


Figure 4 – The behavior of forces as a function of rotor eccentricity.

radial clearance of the tilting pad bearing above the generator is $200\mu m$, this guarantees that the vibration level in the generator will remain in the linear region, allowing the representation of the electromagnetic forces using equivalent force coefficients. The force can be determined by multiplying the eccentricity by the coefficient. For the force response shown in Fig. 4, the equivalent coefficient is $K = 3.174 \cdot 10^8 \frac{N}{m}$.

The methodology of representing the electromagnetic forces through a force coefficient facilitates the generator’s incorporation in the hydropower unit’s dynamic model. However, the generator unit can change its operating conditions according to the demand of the electrical grid, which consequently varies the equivalent coefficient of force. Thus, to construct the representative model of the generating unit, it is necessary to determine the equivalent coefficient of force for the most diverse operating conditions. For that, we chose to use the Kriging surrogate model to determine these coefficients based on historical data of operation.

In order to determine the operating limits of the generating unit, a historical survey was carried out from 05/19/2022 to 08/18/2022. The operating limits are: (i) armature current between 5000 A and 9400 A; (ii) field current between 1600 A and 2630 A; and (iii) active power between 115 MW and 220 MW. The next step consisted of applying the Latin hypercube method (Minasny, and McBratney, 2006) to determine a set of 39 samples with different combinations of field current, armature, and generator active power values. For each of these samples, an analysis was performed using the finite element method using the FEMM to determine the force response as a function of eccentricity and then the equivalent coefficient. Thus, the Kriging surrogate model was fitted to these pre-established samples, where the input parameters are field currents, armature currents, and active power. In contrast, the output parameter is the force coefficient. The objective of this procedure is that the surrogate can determine the force coefficient for any operating condition within the established limits. Thus, there is no need to perform electromagnetic analyses in finite elements with high computational costs. For a better understanding of the procedure, Fig. 5 presents a flowchart with each of the steps.

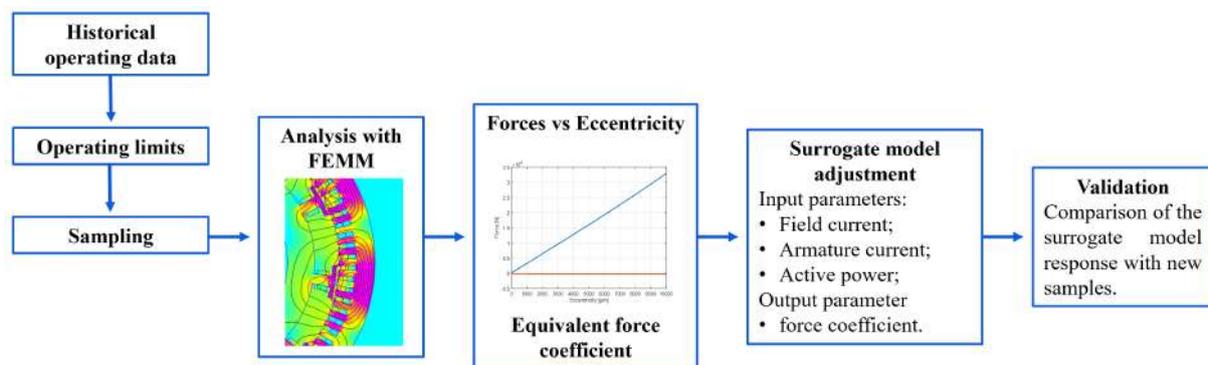


Figure 5 – Flowchart for the construction of the surrogate model.

After building the Kriging surrogate model, the validation stage began, in which 14 samples different from those used initially were selected. For these samples, the equivalent coefficient of forces obtained with the finite element model was

compared with those obtained by the surrogate model. Figure. 6 presents the generator V curve, in which the historical data of operation, the limits found, some samples used in the training of the surrogate model, and the validation samples are presented.

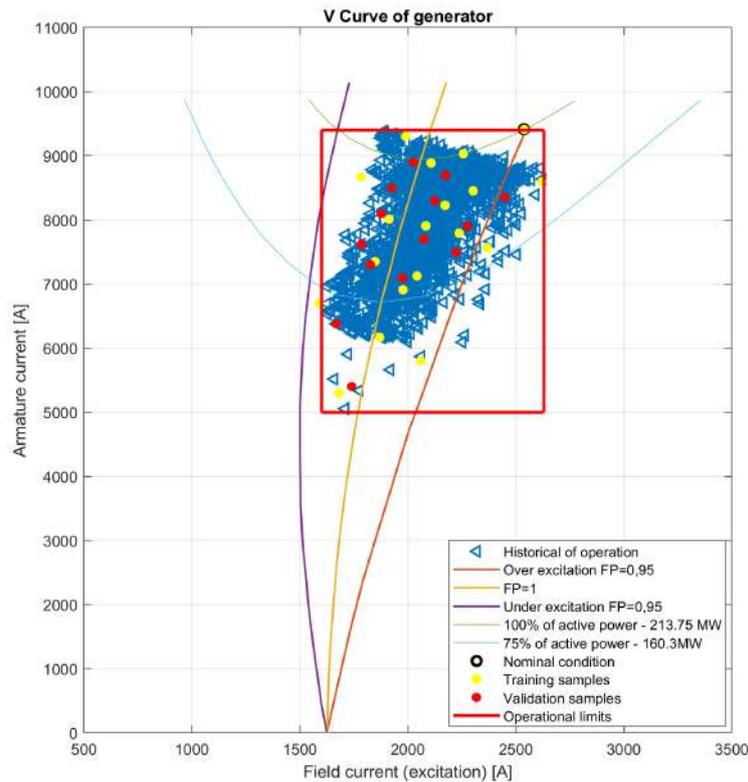


Figure 6 – Generator V curve with historical data, samples, and operating limit.

The surrogate model with the best representation comprises a first-order polynomial function and a Gaussian correlation function. The error metrics calculated for the validation were the Root Mean Square Error of $K = 4.65 \cdot 10^6 \frac{N}{m}$ and the maximum relative error of 1.52%. Both have relatively low values, which guarantees the accuracy of the Kriging surrogate model in representing the equivalent coefficient of generator force.

Dynamic analysis

In order to analyze the influence of the generator's electromagnetic forces on the dynamics of the generating unit, the equivalent coefficients of the forces with the dynamic model of the system were coupled using the Kriging surrogate model.

The mathematical model of the generating unit was built based on the formulation of Lalanne and Ferraris (1998), representing the axis by finite elements (Timoshenko beam) with six freedom degrees per node. The Francis turbine was represented by a rigid disk to which average hydraulic forces were applied, predetermined by simulations in CFD (Computational Fluids Dynamics). The hydrodynamic bearings were represented by equivalent damping and stiffness coefficients obtained by solving the Reynolds equation and energy equation (Barbosa, 2018) and applying the perturbation method (Lund, 1964 and Lund and Thomsen, 1978). A rigid disk represented the generator, and the electromagnetic forces were entered through the equivalent force coefficient determined by the surrogate model. The schematic representation of the generating unit model is shown in Fig. 7.

Three different cases were analyzed to verify the influence of the generator and the operating conditions on the vibration amplitude of the system. At first, the influence of electromagnetic forces was neglected. In the second and third, operating conditions were obtained from the operating history presented in Tab. 2. A temporal analysis of 100 s was performed with a time step of 0.001s.

In Fig. 8, it is possible to observe the generator orbit for the three analyzed cases and the Discrete Fourier Transform (DFT) of the generator displacement in the X direction. Through the analysis of the graphs, it is possible to observe the importance of representing the electromagnetic forces in the model of the generating unit and how the operating

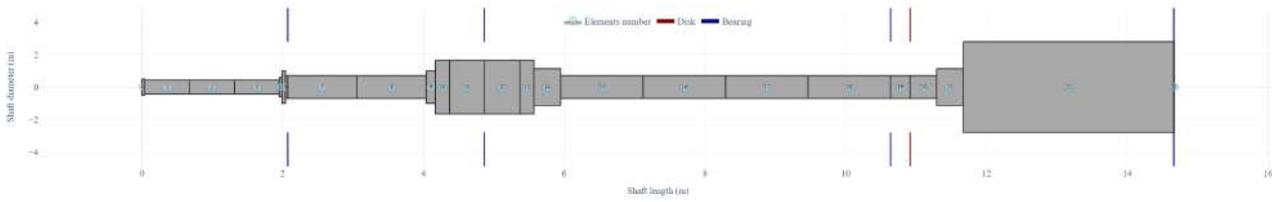


Figure 7 – Representation of the finite element model.

Table 2 – Generator operating parameters in each of the analyzed cases.

Parameters	Case 1	Case 2	Case 3
Field current	-	2300 A	2200 A
Armature current	-	7600 A	9000 A
Active power	-	164 MW	219.7 MW

conditions of the generator can influence the vibration levels of the system. From case 1 to case 2, there was an increase of approximately 40% in the vibration level, and from case 2 to case 3 an increase of 14.4%.

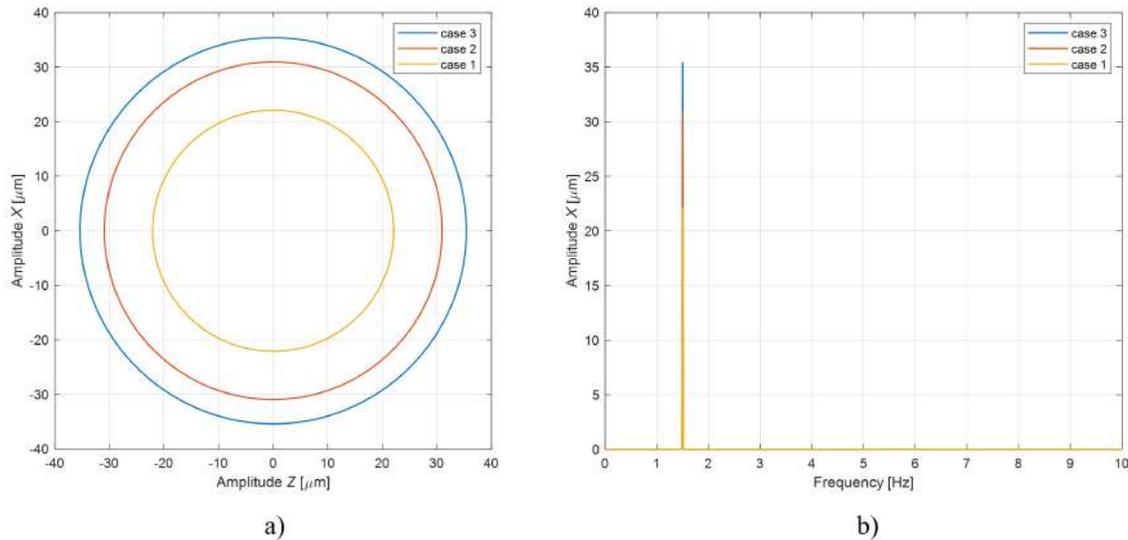


Figure 8 – (a) orbit and (b) FFT of generator displacement.

To visualize the vibration amplitude of the entire generating unit, Fig. 9 presents the three-dimensional orbits of the system, where each orbit represents the displacement of the nodes in the finite element model. It is possible to observe how the electromagnetic forces affect the vibration dynamics of the generating unit as a whole and not only in the generator's node.

CONCLUSION

Multi-physics models can help predict and identify failures in hydropower units. Due to that, it is essential to have a good representation of the generator's electromagnetic efforts. A method widely used to determine these electromagnetic forces is the solution of Maxwell's equations by the finite element method. However, real generating units are typically connected to national power grids, causing their operating parameters to vary constantly according to needs. Such a variation in operating conditions might make the application of multi-physical models difficult due to the high computational cost. Therefore, this work aims to apply the Kriging surrogate model to determine electromagnetic efforts to reduce computational costs.

The developed models were based on the Foz do Chapecó Generator Unit. A historical survey of the machine's operating conditions was carried out over three months to identify the operational limits. From this information, a set

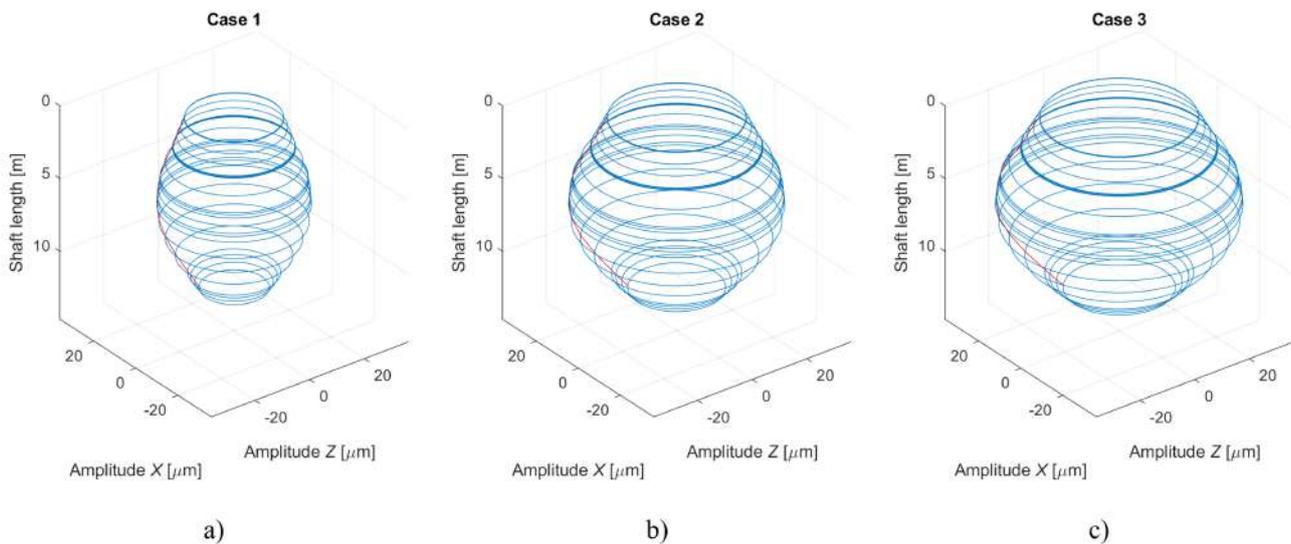


Figure 9 – Three-dimensional orbitals of the generator unit, for the three different cases, analyzed.

of samples was selected in which the electromagnetic forces in the generator and their equivalent force coefficients were determined through the solution of Maxwell's equation by finite elements. A surrogate model was constructed from these samples to estimate the force coefficients accurately.

During its construction, the surrogate model can be demanding, since it needs to evaluate the original model in a wide set of samples with different generator operating conditions. However, after its construction, the surrogate model can reduce significantly the computational time of the generator unit model. To evaluate this computational cost reduction, the execution time of the electromagnetic finite element model was compared with that of the surrogate model and a reduction of approximately 99.6 % in time was obtained. In the validation step, the average relative error of the surrogate model was calculated for a set of 14 extra samples and a value of 0.69 % was obtained, which ensures its reliability.

This surrogate model was incorporated into the dynamic model of the generating unit in which the vibration responses of the system for different operating conditions were analyzed. It verified the importance of inserting the electromagnetic forces in the model and how the vibration levels can be influenced by different operating conditions of the generating unit.

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