Analysis of the Influence of Different Topologies on a TLSRG Generation Performance for WEC

R.P.G. Mendes, M.R.A. Calado and S.J.P.S. Mariano

Abstract—**In this work, 4 structural configurations are proposed, and analysed, to be used as a tubular linear switched reluctance generators with tubular topology (TLSRG). For the 4 models under assessment, inductance change with the mover part position is assessed to quantify the machine capabilities as generator for an wave energy converter (WEC), namely a point absorber device. This evaluation is supported by a 2D FEM analysis based software through which are determined the inductance values at different alignment conditions as well as the magnetic flux densities for the referred alignment conditions. An analytic design procedure is presented for one structural model and the same procedure is used to size the generator for given nominal power and based velocity, derived from an ocean wave energy assessment based on meteorological data.**

Index Terms—**switched reluctance machine, linear generator, wave energy conversion.**

I. INTRODUCTION

Point absorber ocean wave energy converter devices are, usually, characterized for a direct drive operation as well as for a linear slow motion induced by the ocean waves. In this type of devices, for the concept of direct drive operation to be maintained, the mechanical energy extracted from the waves is directly converted into electric energy through a linear electric generator which comprises the system power-take-off. Usually, the linear generators used for this kind of applications make use of permanent magnets in order to achieve the electricity generation. However, the presence of permanent magnets in this kind of electric machines increases the device costs, which makes this kind of technology less attractive to be applied. The linear switched reluctance machine stands as strong alternative as electric generator to point absorbers wave energy converters due to a more economic, robust and simpler construction in comparison with permanent magnet generators. Planar linear switched reluctance machines have already been proposed as electric generators for direct drive wave energy converters [1, 2] ,where some works have suggested the application of the same machines with tubular topology [3]. Despite its topology, switched reluctance machines can, for the same geometric configuration, operate as motor and/or generator where these two modes of operation only differs on the control strategy applied at the respective electronic power converter. For this reason, linear switched reluctance actuator structures can be a suitable option as generation devices. Ocean wave energy assessment plays an important role in the design of power take-off units for wave energy converters and can be estimated through statical analysis of measured ocean wave parameters [3] or trough prediction models based on wind velocity data [4]. Point absorber wave energy converters are characterized for low speed operations induced by the ocean surface waves. As consequence, since the generator used as power-take-off system is directly driven, the latter should be able to generate electricity at low velocities which is not desirable for this type of electric machines once the electromotive force at the phase windings are reduced for these operating conditions, providing lower electric power conversion. This implies that to guarantee the machine generation capabilities at low velocities, its efficiency must be maximized for a reliable application in direct drive ocean wave energy converters. The performance of electric switched reluctance generators depends on the applied control strategy and geometric configuration of generator parts involved in the power conversion process. However the control becomes more difficult as lower is the generator operating velocity. This implies that a proper geometric configuration should be chosen for a linear tubular switched reluctance machine when operating as electric generator with low operational velocities.

II. PROPOSED GEOMETRIES

The typical linear switched reluctance machine (with planar or tubular topology) is characterized for a double salient structure that comprises two main elements, a stationary part (stator) that contains the machines phase windings and a mover part (translator) that is driven by the external force applied to the generator. In the present work, four different geometric configurations are identified as possible structures to be adopted for a linear switched reluctance generator of tubular topology with application in ocean wave energy converters. The first analysed configuration is based on the linear tubular actuator geometry proposed by [5], which was already suggested in [3] as linear electric generator with application in a point absorber wave energy converter. The structure for this model is obtained through the revolution of the geometry illustrated in Fig.1a. This configuration stands as a 3 phase generator with each phase composed of two conducting wire coils connected in series. Each coil also assumes a ring shape form disposed concentrically with the stator and translator. The both stator and translator should be constituted by a ferromagnetic material in order to provide a path with high permeability for the magnetic flux developed by the machine's phase coils. The next model configuration

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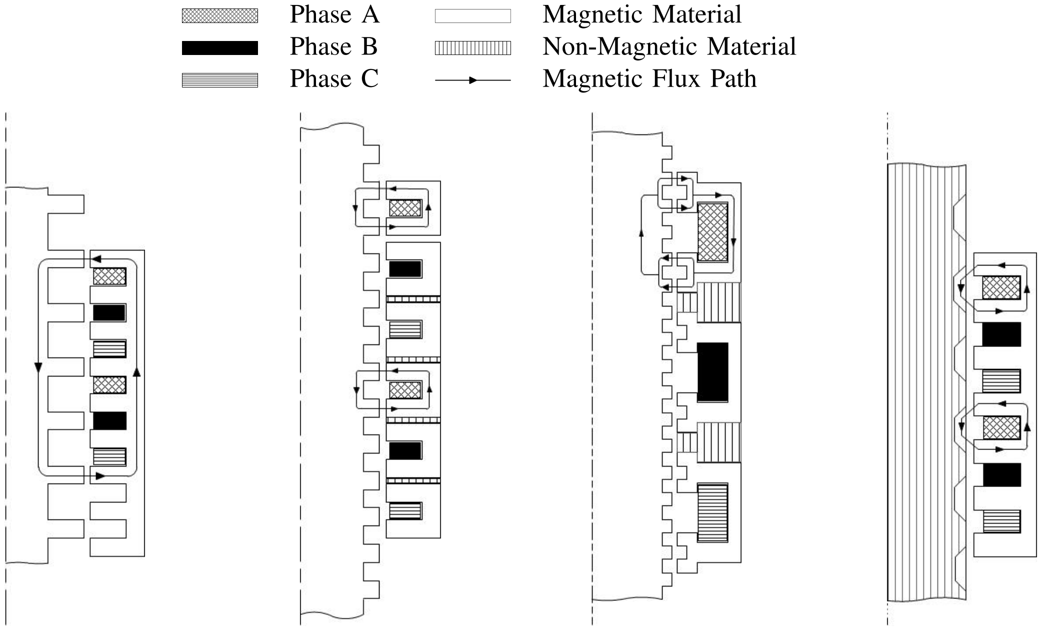
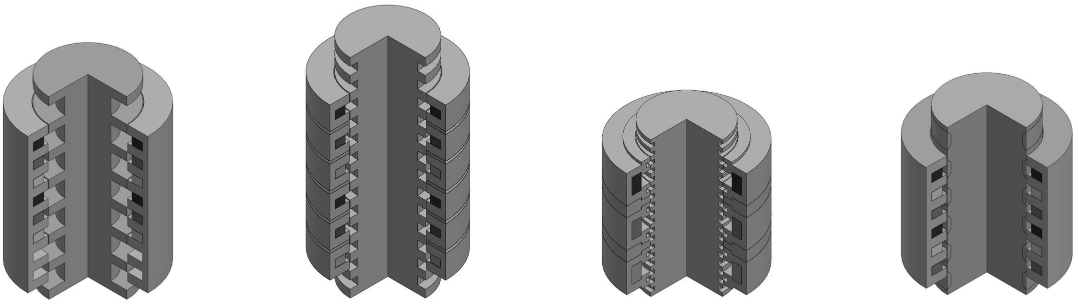


(a) Model A (b) Model B (c) Model C (d) Model D

Fig. 1: Crossectional profile schematics of the proposed models.



(a) Model A (b) Model B (c) Model C (d) Model D

Fig. 2: 3D illustrations of the proposed models.

uses the geometry of a 4 phase linear tubular switched reluctance actuator proposed by [6], which is applied in a heart assistance circulatory device. In this work, an identical three phase machine is proposed. As the 1st model configuration, each electric phase is composed by two coils of conducting wire connected in series as schematized in Fig.1b. However, according to its longitudinal cross-section, this second model is characterized for independent magnetic paths for the linkage flux induced by the respective coil. The magnetic path separation is achieved by ring shaped elements with low magnetic permeability which are located in the primary. In order to achieve non conducting magnetic properties, these elements should be made of paramagnetic or diamagnetic material. The secondary part presents a salient structure where the teeth have the same width as the slots. The third model to be analysed is based on a geometric configuration of a 3 phase linear variable reluctance motor developed by [7] for precision manufacturing applications. The same structural principle is adopted in [8] for a switched reluctance actuator with application in levitated linear transporters and in [9] as a linear generator for ocean wave energy conversion. Although the latter applications make use of a linear machine with planar topology, for the present work the same geometric configuration is adapted for the tubular case, where its crosssectional profile can be observed in Fig.1c. This model is a three phase generator with one electric wire coil per phase. As schematized in Fig.1c, in this model, the primary comprises 3 ring shaped elements of ferromagnetic material in which are located the respective phase coil. As in model B, these ferromagnetic materials are separated by non-magnetic spacers. Each magnetic pole is formed by two teeth with the same dimensions as the ones that compose the salient profile of the secondary. The latter is made of a ferromagnetic material.

The last model configuration candidate results from the adaptation of the linear segmented switched reluctance machine proposed in [10]. This configuration consists on a linear machine of planar topology where the translator, differently from the models presented above, is constituted by a non-magnetic material with segments of magnetic material, which provides the machines reluctance variation according to the translator relative position in respect to the stator. The presence of these segments avoids the need for a salient geometric profile for the translator. Instead, a planar crosssectional profile is used where the segments are carefully distributed along the translator in compliance with the stator teeth position. Based on the existent planar topologies for this type of switched reluctance machine, a new 3 phase tubular model is proposed in this work. As illustrated in Fig.1d, the stator is similar to the stator of model A, with two coils per phase likewise positioned, but with less number of teeth. Each coil has its own path for the respective induced magnetic flux. The translator assumes the form of a cylinder with embedded rings as magnetic material segments. The 3D illustrations of the analysed models are presented in Fig.2.

III. EVALUATION CRITERIA

The 4 tubular linear switched reluctance machine models presented are proposed as generators for ocean wave energy converters. The latter type of devices is characterized as direct drive conversion system which, due to the wave's long oscillation periods, provides the respective electric generator with a slow velocity operation. For this reason, the structural configuration of the generator should improve its electric generation capabilities. According to [11], the electromotive force (e) in each electric phase of a switched reluctance generator, is given by the following relation:

$$e = v\frac{dL}{dx} \tag{1}$$

As expressed in (1) the electromotive force is proportional to the translator velocity (v) and the rate of change of the machines inductance with the translator relative position (x). According to this statement, it can be concluded that low velocities of operation are not desirable for electric generation. Once the translator velocity is not dependent on the generator geometric configuration, the latter can then be classified according to the respective rate of change of the inductance with the position ($\frac{dL}{dx}$). For different relative positions between the translator and the stator, the machine assumes different arrangements with particular inductance values. Therefore, each structural configuration will present a range of inductance values that will be comprised between a maximum and a minimum. Assuming the ideal case where the generator presents linear magnetic characteristics for a given relative displacement of the secondary, as greater is the difference between the inductance at the aligned position (L_a) and the inductance at the unaligned position (L_u), greater will be the electromotive force developed by the generator for a fixed velocity. Likewise, as small is the distance Δx that the secondary should travel between these two alignment positions, larger will be the induced electromotive force at the electric phase coils. In practice, the switched reluctance machines are characterized for operating under nonlinear magnetic characteristics which imply that its linear behavior will, mostly, not be verified, particularly, for high electric currents. Nevertheless, for an initial evaluation, it is reasonable to assume a linear rate of change in the machines inductance with the secondary, specially, for comparison purposes.

Accordingly, to evaluate the electric generation potential for a given structural model, a generation quality factor (Q) is defined by the authors to calculate the ratio between the difference of inductance values at the aligned position(L_a) and the unaligned positions (L_u) and the relative distance (Δx) of the secondary, between the referred positions, as indicated in 2.

$$Q = \frac{L_a - L_u}{\Delta x} \tag{2}$$

Thus, the larger is the value of the ratio Q, greater is the respective machines electric generation potential.

IV. MACHINE DESIGN

To design the proposed models for a given power input, the analytical procedure proposed in [5, 12] for a tubular linear switched reluctance actuator will be adapted for the generator machine. The referred design procedure is directed for the structural configuration represented by model A. This procedure was already applied in [3] for the design o a tubular linear switched reluctance generator for wave energy conversion.

Given an input mechanical power (P_{mec}) into the generator and a base velocity of operation (v), the mechanical force (F) applied to the secondary part of the machine is obtained by:

$$F = \frac{P_{mec}}{v} \tag{3}$$

To achieve a proper reluctance variation with the relative displacement of the secondary in respect to the primary, the following relations:

$$m\tau_p = 2\tau_s \tag{4}$$

where m is the number of electric phases of the machine and τ_p an τ_s are, respectively, the primary and secondary pole pitches. The latter are given by:

$$\tau_p = b_p + c_p \tag{5}$$

$$\tau_s = b_s + c_s \tag{6}$$

In order to satisfy equation **??** for a 3 phase machine, the following geometric relations are adopted the poles and slots of each parts:

$$b_s = b_p \tag{7}$$

$$c_p = b_p \tag{8}$$

$$c_s = 2b_s \tag{9}$$

where b_p is imposed by the designer.

Establishing a tangential force density (F_x) at the primary's teeth surface, the internal diameter of the primary (D_{ip}) is calculated by:

$$D_{ip} = \frac{F}{2\pi b_p F_x} \tag{10}$$

For an excitation voltage of U_0 the peak linkage flux developed a each electric phase is given by:

$$\lambda_p = \frac{U_0}{v}\left(x_f - x_i\right) \tag{11}$$

where x_f and x_i are, respectively, the turn-off and turn-on positions that defines the conduction period for the working electric phase. According to [5], a value of $0.8b_p$ will be assumed for the conduction length in each phase stroke.

Since each electric phase is composed by two coils, the number of turns (N_t) per coil is:

$$N_t = \frac{U_0}{v}(x_f - x_i)\frac{1}{b_p B_g D_{ip}} \tag{12}$$

with B_g, the imposed flux density at the airgap.

The necessary peak electric current (I_p) is determined assuming that the corresponding co-energy (W_c) of the machine equals the input mechanical energy during the phases conduction period. Since this type of electric machine is characterized by a non-linear behaviour due to the presence of magnetic saturation, it is difficult to fully quantify its magnetic co-energy. However, an quasi-linear analytic expression can be used to obtain a reasonable approximation of the latter identity accounting with the referred non-linear effects. According to [13], the co-energy is obtained through the following expression:

$$W_c = k_s\left[\left(\lambda_p - L_u I_p\right) I_p - \frac{\left(\lambda_p - L_u I_p\right)^2}{2\left(L_{au} - L_u\right)}\right] \tag{13}$$

with L_{au} the unsaturated machine's inductance value at the aligned position, L_u its inductance value at the unaligned position and k_s a design safety factor. The machines unsaturated inductance at the aligned position can be approximated as:

$$L_{au} = 2\pi\mu_0\frac{D_{ip}b_b}{l_g}N_t^2 \tag{14}$$

where μ_0 is the constant magnetic permeability of vacuum.

The calculation of the inductance at the unaligned position is not straightforward as it is for the aligned position because at the unaligned the magnetic flux path is more complex to evaluate. However, for initial design purposes, the unaligned inductance directly related to the unsaturated inductance at aligned position. According to [5, 12], for this type of machines the unsaturated aligned inductance at aligned position is, typically, 10 times greater than the unaligned inductance. Thus, we have:

$$L_u = \frac{L_{au}}{10} \tag{15}$$

The input mechanical energy (W_m), during the conduction period of each phase,is calculated by:

$$W_m = F\left(x_f - x_i\right) \tag{16}$$

Assuming that $W_c = W_m$, equation 13 is solved iteratively to find the correspondent peak electric phase current (I_p).

The primary teeth height (h_p) can be obtained as follows:

$$h_p = \frac{N_t I_p}{c_p k_e J} \tag{17}$$

where k_e is the slot fill factor to account the cross-sectional area occupied by the electric phase coils.

According to [5], the secondary teeth height (h_s) shall adopt a value of 20 to 30 times the the airgap length (l_g) and for the primary and secondary core width (n_p and n_s, respectively), a value between 60 to 70 percent of the respective pole width is proposed. Following these recommendations, the referred geometric parameters are calculated as:

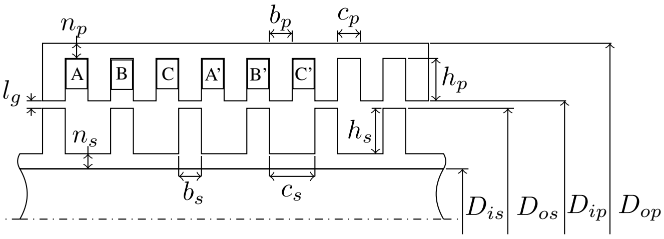


Fig. 3: Tubular LSRG scheme and respective geometric parameters.

$$h_s = 30l_g \tag{18}$$

$$n_p = 0.65b_p \tag{19}$$

$$n_s = 0.65b_s \tag{20}$$

The primary outer diameter (D_{op}) as well the secondary outer and inner diameters and (D_{os} and D_{is}, respectively) are calculated according to:

$$D_{op} = D_{ip} + 2\left(h_p + n_p\right) \tag{21}$$

$$D_{os} = D_{ip} - 2l_g \tag{22}$$

$$D_{is} = D_{os} - 2\left(h_s + n_s\right) \tag{23}$$

The coil wire diameter (d_wire) can be calculated as follows:

$$d_{wire} = 2\sqrt{\frac{k_e c_p h_p}{\pi N_t}} \tag{24}$$

In Fig. 3 is illustrated the schematics of the machine's geometry as well the geometric parameters that are involved in the described analytical design procedure. The latter provides the dimensions for the structural configuration of model A. In the absence of a proper design procedure for the remaining models, these will be sized with similar dimensions and electric characteristics to model A in order to perform an equivalent assessment for all the models under evaluation, allowing a first approach in the comparison between them.

A. Ocean wave energy based design

The main dimensions of the generator models will be conditioned by the results of the energy assessment of point absorber device performed by [3] based on climate ocean wave data of the site of Esposende, in the Portuguese coast. The energy assessment resulted in a device with 4,5 kW nominal power and a base velocity of operation of 0.67 m/s. Since for these characteristics, the resulting generator dimensions are not suitable for implementation, a modular unit with 1.5 kW of nominal power will be designed instead. Thus, the electromechanical conversion will system comprised by

3 of these modular units connected in series to match the mechanical input power provided by the point absorber.

The main characteristics of the generator are presented in table I. In table II are the imposed geometric values and constants used in the analytical design procedure and the respective results are shown in table III.

TABLE I: Generator main characteristics.

Parameter	Value
P_{mec}	1500 W
v	0.67 m/s
b_p	30 mm
U_0	200 V
l_g	2 mm

TABLE II: Imposed design parameters.

Parameter		Value
Primary teeth width	b_p	30 mm
Airgap length	l_g	2 mm
Phase conduction length	$x_f - x_i$	24 mm
Magnetic induction at airgap	B_g	1.5 T
Magnetic permeability of vacuum	μ_0	$4\pi \times 10^{-7}$ H/m
Design safety factor	k_s	0.7
Slot fill factor	k_e	0.4

TABLE III: Analytical design results.

Parameter		Value
Input mechanical energy	W_m	53.7 J
Peak flux linkage	λ_p	7.16 Wb
Unsaturated aligned inductance	L_{au}	0.26 H
Unaligned inductance	L_u	0.026 H
Number of turns per coil	N_t	86
Peak electric current	I_p	25.7 A
Electric coil wire diameter	d_{wire}	4 mm
Primary slot width	c_p	30 mm
Secondary teeth width	b_s	30 mm
Secondary slot width	c_s	60 mm
Primary pitch	τ_p	60 mm
Secondary pitch	τ_s	90 mm
Primary teeth height	h_p	53 mm
Secondary teeth height	h_s	60 mm
Primary core width	n_p	20 mm
Secondary core width	n_s	20 mm
Primary inner diameter	D_{ip}	297 mm
Primary outer diameter	D_{op}	443 mm
Secondary inner diameter	D_{is}	133 mm
Secondary outer diameter	D_{os}	293 mm

V. NUMERICAL ANALYSIS OF THE PROPOSED MODELS

In order to evaluate each structural model candidate, the machines inductance values for the desired relative positions (alignment and unalignment), are obtained from a 2D magneto-static analysis supported by finite element method (FEM) based software. Since the structural models in evaluation are tubular, an axisymmetric analysis will be adopted using only half of the models cross-section, as illustrated in Fig.1. The machine's magnetic characteristics, in respect to the translator's displacement, are identical for the three phases of the generator being only out of phase for the same translator's absolute position. For that reason, to simplify the simulation process, only the generator's phase A will be considered assuming that the same characteristics will be verified for the remaining phases at equivalent alignment conditions. This kind of analysis is useful in the decision on the structure to be adopted in a specific wave energy converter system. The stator of the model A has the same dimensions as the ones of B and D models, with an exception for the former, whereas the its stator's length is superior due to the presence of the non-magnetic 10 mm width spacers. The stator of model C presents the major changes in geometry with a tooth width and minor height of 15 mm and a major height of 75 mm. Its outer diameter is of 487 mm and is 450 mm long. The non-magnetic spacers for this part have width values between a minimum of 22.5 mm and a maximum of 42.5 mm.

The mover part maintains the same outer diameter for all the models. For models B and C, the teeth width and height presents the same values as the primary teeth width. The magnetic segments contained in the secondary of model D have a trapezoidal shape with a major base of 60 mm width and 15 mm height. The segments are spaced from a 30 mm distance.

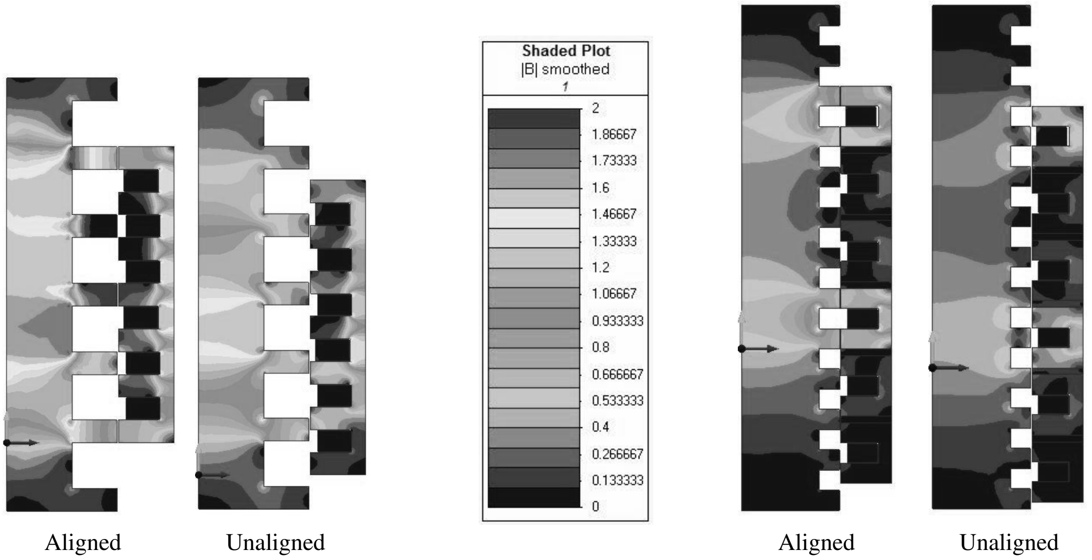
A. Results

The numerical simulations were performed for the proposed structural models where their inductance values were obtained for the respective aligned and unaligned positions. With these values, the ratio (Q) was calculated for each model. The referred values are indicated in Table IV. According to the obtained results, the highest value of Q was found for model B (2.52) followed by model C with a value of 1.68. Model D was classified by the lowest Q value (1.64) while model A stands as 3$^{\text{rd}}$ classified with a Q value of 1.67.

However, attention shall be paid to the fact that B and C models were evaluated with a lower value of displacement between aligned and unaligned positions. Models B and C were evaluated for a displacement of 30 mm whereas the assumed displacement for models A and D was 45 mm. Because lower displacement gives a higher value of Q, the models are not evenly evaluated when considering only the parameter Q as decision criteria. The magnetic flux density should also be evaluated since it gives an indication of the generators susceptibility to achieve higher saturation levels.

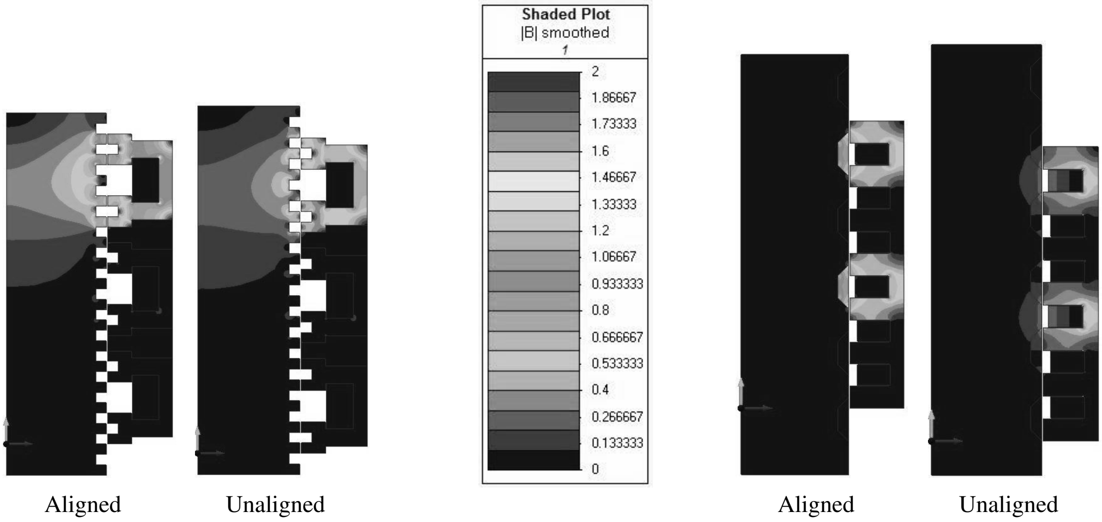
The color maps of the magnetic flux density for the aligned and unaligned positions are presented in Fig.4, considering all the analysed models . According to these figures, it can be stated that model A is characterized for higher magnetic flux density zones for the same value of electric current. This implies that, under the same operating conditions, this machine model will be more susceptible to achieve magnetic saturation and thus attain higher non-linear properties that the remaining models.

For model D were obtained the lowest levels of magnetic flux density specially at the unaligned position where the values are very low in comparison with the remaining models for the same alignment conditions.



(a) Model A

(b) Model B



(c) Model C

(d) Model D

Fig. 4: Magnetic flux density color maps of the models in the aligned position.

The results obtained in this work from the FEM analysis are different from the ones presented in [14], specially in model's rating where, in the latter, model A stands as 2nd best candidate as generator instead of 3rd. The reason for this discrepancy of results are due to the value of electric current used in the numerical models simulation. In this work the calculated peak current (25.7 A) was used for simulation while in [14] a lower electric current of 20 A was adopted for the evaluation of the model's electromagnetic characteristics. As a large current value was used for this work, a higher magnetic saturation was verified specially for model A, which is the most susceptible to attain this electromagnetic phenomenon. For this reason it can be stated that with an increase in magnetic saturation level, the machine's performance as generator diminishes.

TABLE IV: Results for Q.

Model	Δx (mm)	$L_a - L_u$ (H)	Q (H/m)
A	45	0.075	1.67
B	30	0.075	2.52
C	15	0.025	1.68
D	45	0.074	1.64

Comparing the obtained results indicated in Table IV, it can be stated that, according to the performed simulations, the structural model B is the most suitable tubular topology for a linear switched reluctance electrical generator once it presents greater electric generation capabilities while not achieving high magnetic flux densities. Model A, seems to be the more favourable to operate under high saturation levels which is not desirable once these operating conditions promotes the material degradation and as already stated, decreases the generation capabilities of the machine.

Thus, model A may not be a suitable choice among the structural configurations under assessment. However, because only the inductance for phase A was evaluated, if the model A is adopted, the number of teeth on the respective primary should be extended in order to enable the establishment of magnetic paths with minimum reluctance for the flux induced by the electric phases B and C. About model D, regardless having the lesser Q value also shows the lower magnetic flux density and thus, less susceptibility to achieve global saturation levels. In comparison with model B, the difference between the inductance at aligned and unaligned positions are very close. Nevertheless, model B is better classified as electric generator due to a smaller displacement between the aligned and unaligned positions. For this reason, it can be concluded that if geometry with a lower displacement is adopted for model D, its Q value can be increased and, possibly, will approach the electrical generation potential of model B.

VI. Conclusion

In this work were identified 4 possible tubular structural configurations, which could be used as 3 phase linear switched reluctance electrical generator for application in a point absorber wave energy converter. The proposed models resulted from a wave energy based analytical design of model A. For the remaining models, only the structural concept was presented and no analytic design procedure was specified. For the proposed models, a numerical magneto-static analysis was performed and their inductance values were obtained for the aligned and unaligned positions. With the latter results, the ration Q was calculated and presented for the 4 models under assessment. The ratio Q was determined to give a slight information regarding the machine's electric generation capabilities. As no design procedure was done for the models, the respective numerical models were designed with similar dimensions. From the results obtained, and according to the evaluating criteria established, it was concluded that model B is the best candidate as structural configuration to be used as linear switched reluctance generator with tubular topology once its geometry provides high inductance value at the aligned position while a small value its achieved at the unaligned position. Regarding model A, it shows to be highly susceptible to achieve global magnetic saturation which implies that its generation capabilities may not be as greater as indicated by the respective Q value. Model C, classified as 2nd best candidate was evaluated with the lower displacement between the aligned and unaligned positions. As its difference between the inductance values for the referred positions presents the lower value in comparison with the remaining models, if a higher displacement was considered, lesser Q value should be obtained and worst classification would be obtained for model C. Following the same hypothesis, if model D was characterized with a higher displacement, it should be classified with a greater electric generation potential once its difference of inductance values at aligned and unaligned positions is very close to one obtained for model B, whereas the latter was evaluated with a lower displacement. For this reasons, model D could also be a good selection with the need for deeper analysis regarding its dimensional characteristics.

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