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Identification of Some Tubular Topologies of Linear Switched Reluctance Generator for Direct Drive Applications in Ocean Wave Energy Conversion

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***Abstract*—In this work, 4 structural configurations are proposed, and analyzed, to be used as linear switched reluctance generators with tubular topology. For the 4 models under assessment, inductance change with the mover part position is assessed to quantify the machine capabilities as generator. 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.**

***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. 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 [4], 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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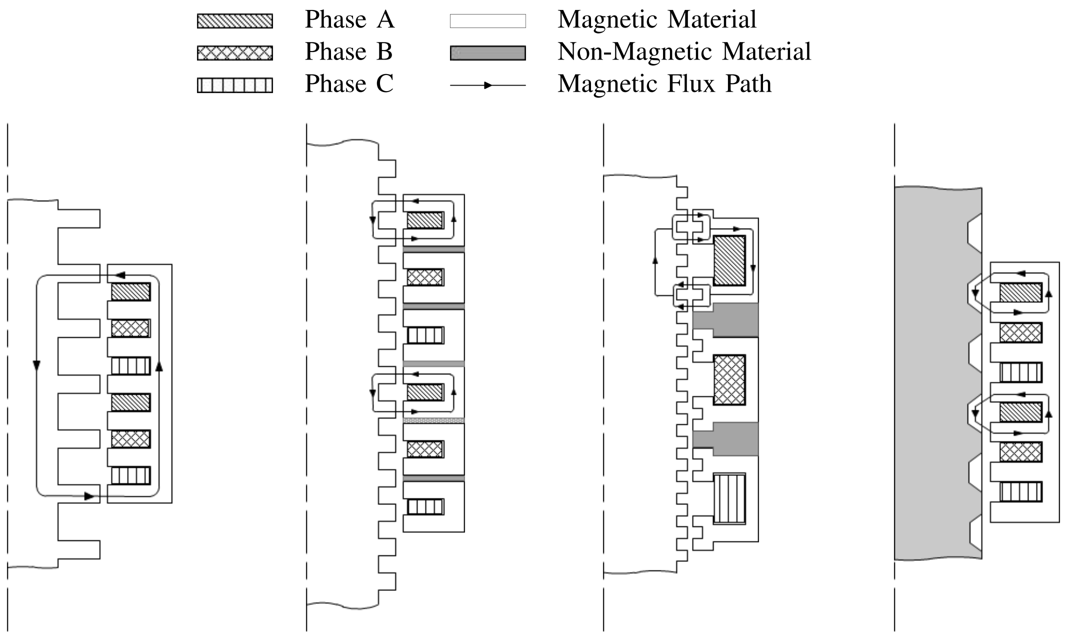
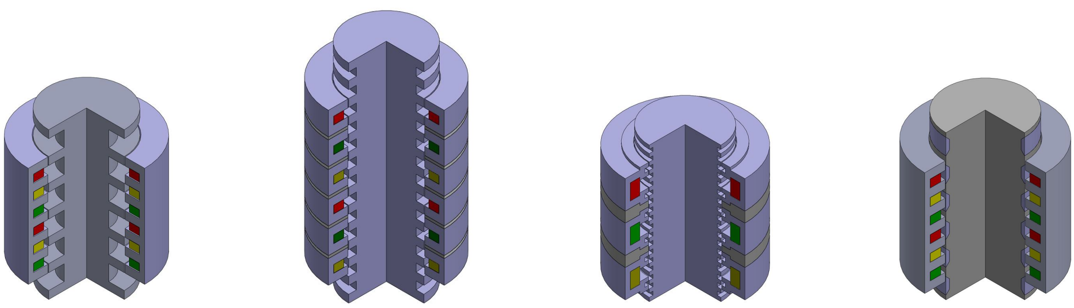


(a) Model A (b) Model B (c) Model C (d) Model D

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 [5], 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 [6] for precision manufacturing applications. The same structural principle is adopted in [7] for a switched reluctance actuator with application in levitated linear transporters and in [8] 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 [9]. 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 cross-sectional profile is used where the segments are carefully distributed along the translator in compliance with the stator

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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 [10], 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. 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. Regarding the size of the numerical model, the dimensions provided in [3] are adopted for the structural model A. The main dimensions, for a 3 phase generator, are indicated in Table I. As no analytical procedure has been performed to the proposed structures, the remaining models were designed with approximate dimensions in order to perform a numerical evaluation of the different configurations, allowing a first approach in the comparison between them. 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.

TABLE I: Model A main dimensions.

Teeth Width	30 mm
Primary Slot With	30 mm
Secondary Slot Width	60 mm
Primary Teeth Width	56 mm
Secondary Teeth Width	60 mm
Primary Outer Diameter	293 mm
Secondary Outer Diameter	449 mm
Number of Turns per coil	86

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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 II. According to the obtained results, the highest value of Q was found for model B (2.56) followed by model A with a value of 2.27. Model D was classified by the lowest Q value (1.66) while model C stands as 3rd classified with a Q value of 1.73. 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 unligned positions are presented in Fig.3 and Fig.4, respectively, 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.

TABLE II: Results for Q.

Model	Δx (mm)	$L_a - L_u$ (H)	Q (H/m)
A	45	0.103	2.27
B	30	0.077	2.56
C	15	0.027	1.73
D	45	0.074	1.66

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, as can be observed in the color maps of Fig.4.

Comparing the obtained results indicated in Table II, 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, despite presenting the second best Q value also seems to be the more favorable to operate under high saturation levels which is not desirable once these operating conditions promotes the material degradation.

Also, a high saturation level is an indicator of high nonlinear magnetic characteristics which, in practice, will reduce the value of Q diminishing the machine's generation capabilities. Thus, model A may not be the optimal choice among the structural configurations under assessment. How-

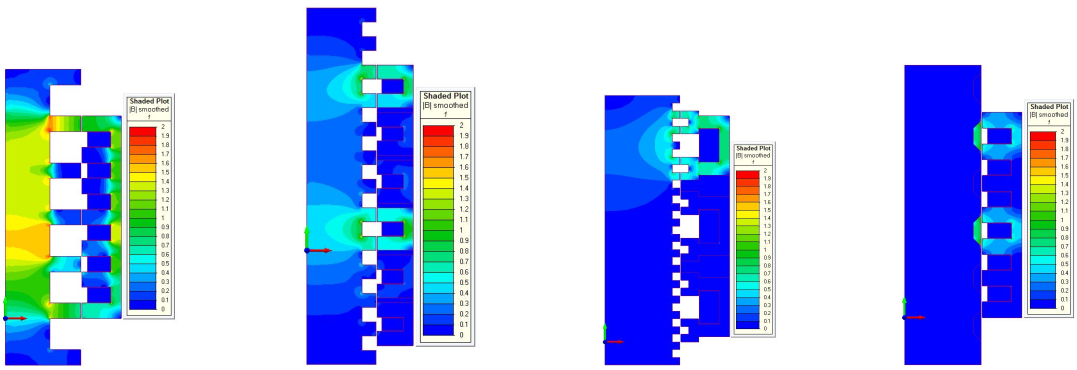

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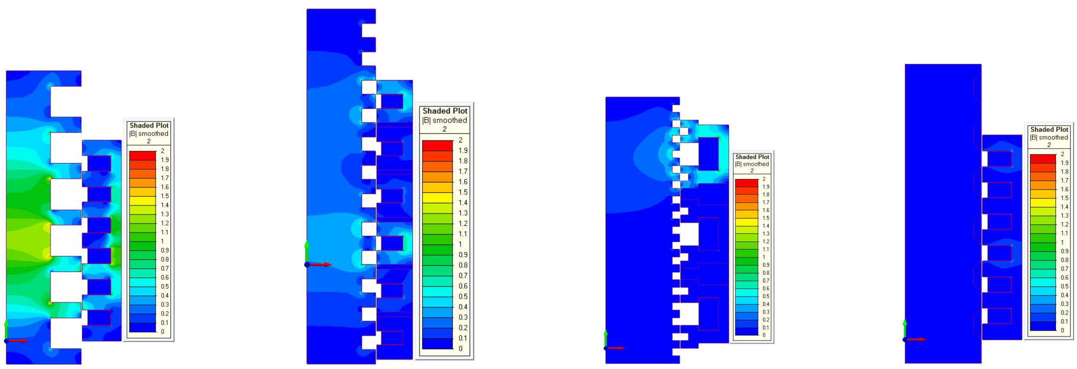
Fig. 3: Magnetic flux density color maps of the models in the aligned position.



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

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

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ever, 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.

V. 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 the adaptation of existing linear switched actuator configurations to a similar type of machine with tubular topology. Only the structural concept for the models 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, despite the fact of being classified as second according to Q value criteria, 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 3rd 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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