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Harvesting the currents power on the Southern Brazilian Shelf

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***Abstract*—Application of marine currents for electricity generation could offer a distinct advantage over other renewable energy sources due to the regular and predictable nature of the resource. This paper details the design of a turbines farm containing ten helicoidal turbines. With three grids a study computing one year of simulation with the TELEMAC-3D model coupled with the energy conversion module was carried out. It was possible to indicate an interest area for trial tests of modelling a turbine farm. The conversion pattern is highly dominated by the wind-driven circulation and for the passage of frontal systems. The configuration settled for this study predicted an annual power output of 59,39 GWh which is equivalent to 0.22% of the whole energetic consumption of the Rio Grande do Sul State in 2010.**

I. INTRODUCTION

The continuous growth of the world population increases the demand and competition for energy, requiring an immense effort for making non-renewable energy sources availability. Therefore, in addition to promoting the development of new technologies, global policies for the generation of renewable and clean energy are being strengthened. Several methods of energy conversion have been developed over the years, especially the turbine-based current energy converter, which demonstrated high energy generation capacity and is already in operation.

The technique used can be described as an underwater wind turbine, having approximately the same principles of function. In Brazil, there is no mapping of the coastal zones regarding the energetic potential viable for conversion using hydrokinetic turbines, however, recent studies have showed two spots of high power availability off the shores of the Rio Grande do Sul state, that can generate 3.5 MW/year of power [1]. [2] studied the influence of hydrodynamic and morphodynamic processes of the installation of six hydrokinetic turbines reaching 5 GW/year annual power.

The Southern Brazilian Shelf (SBS), located between 28ºS and 35ºS (Fig. 1), continentally bounded with the Rio Grande do Sul State, has a slightly rugged shoreline, which is oriented Northeast - Southwest. The bathymetry of this region is quite soft, with the higher slope and shelf break located near the 180 m isobath [3]. Located near the Brazil-Malvinas Confluence zone, this region is known for the high spatial and temporal variability and also for the meeting of several water masses [4]. In addition, the Southwest Atlantic

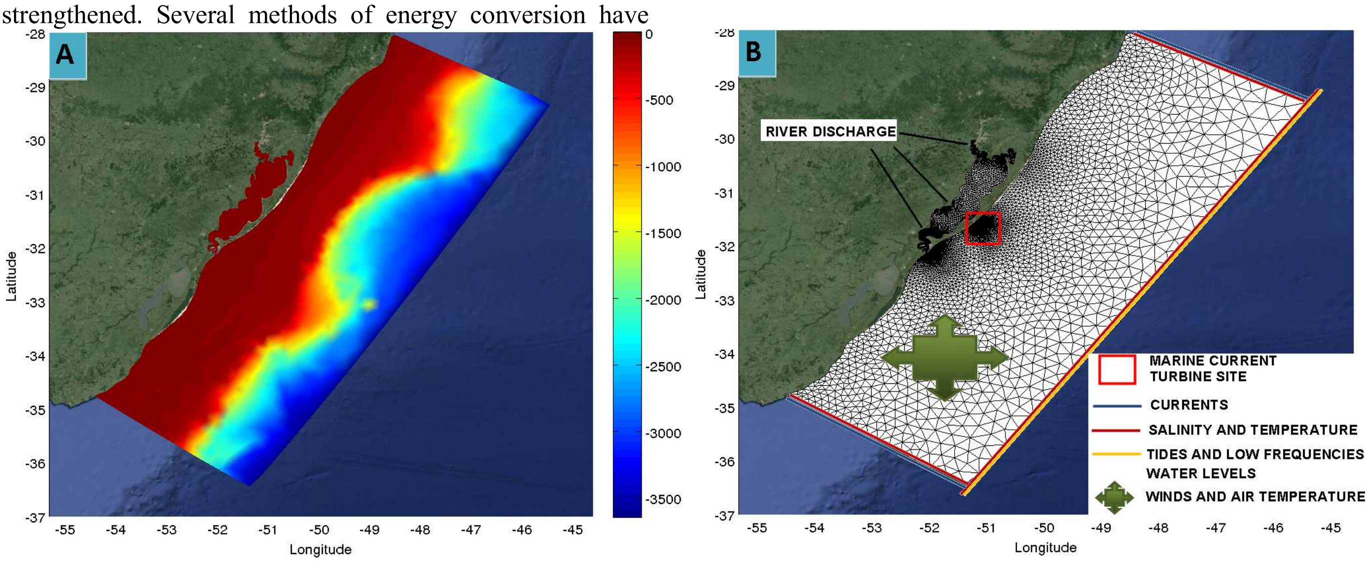


Figure 1. A) Southern Brazilian Shelf, with maximum depth around 3.500 m. B) Grid used on the site simulation. The red square represents the spot of the hydrokinetic turbines farm. Also, the finite elements mesh highlighting the liquid and surface boundaries conditions for the TELEMAC-3D model.

Ocean is one of the most dynamic regions of the global ocean [5], characterized by large thermohaline contrasts and intense mesoscale activity [6].

The high seasonality in the wind fields [7] contributes for dominance of Northeast (NE) winds during Summer and Southwest (SW) winds during Winter, which drive the coastal circulation through the SW and NE, respectively [2,4,8].

Recently, the annual energy report of the Rio Grande do Sul state [9] have briefly mentioned the energy from the marine currents as a possible source for harvesting power, which could easily enhance the Brazilian matrix of energy. Following, the aim of this paper is to study the potential of using energy converters (as turbine type) along the Southern Brazilian Shelf, applying a three-dimensional model of ocean circulation coupled with an energy model, in order to evaluate the energy conversion and the local circulation pattern of a converters farm.

II. Methodology

A. Hydrodynamic Model

The TELEMAC system, developed by the Laboratoire National d'Hydraulique et Environnement of the Company Eletricité de France (CEDF), was used for the hydrodynamic simulations. The TELEMAC-3D model solves the Navier Stokes equations by considering local variations in the free surface of the fluid, neglecting density variations in the mass conservation equation, and considering the hydrostatic pressure and Boussinesq approximations to solve the motion equations. The model is based on finite element techniques to solve the hydrodynamic equation [10] and relies on the sigma coordinate system for the vertical discretization in order to follow the surface and bottom boundaries [11].

A time step of 90s and a Coriolis coefficient of -7.70×10^{-5} rad.s^{-1} (latitude 32°S) were used in all the simulations. The horizontal turbulence process was performed using the Smagorinsky model. This closure turbulent model is generally used in maritime domains with larger-scale eddy phenomena, calculating the mixing coefficient by considering the size of the mesh elements and the velocity field [12].

The mixing length model for buoyant jets was implemented to assess vertical turbulence processes. This model takes into account density effects via a damping factor that depends on the Richardson number to calculate the vertical diffusion coefficients.

B. Energy Conversion Module

The power of the oceanic currents can be transformed, by using converters with similar technology of wind converters, through a submerged rotor that is forced to rotate by the fluid surrounding it. According to [13], in a recent study of equipments available to capture hydrokinetic energy, it was found 76 equipments, among them, turbines in operation or still in the early stages of research were studied.

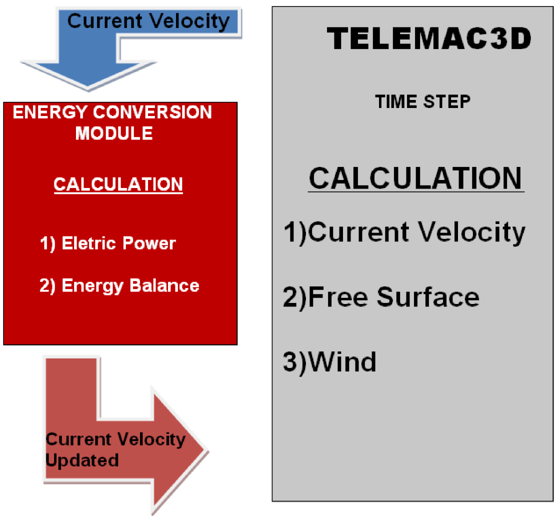


Figure 2. Fluxogram of the interactions between the TELEMAC-3D and the energy module (adapted from [2]).

The hydrodynamic simulations used in this work were performed using TELEMAC-3D model, and the investigations that involved the energy conversion from currents into electrical power were performed with the energy module [2]. This module uses the turbine standard equation to calculate the electric power converted in watts (W), from the incident flow velocity.

Based on the principle of energy conservation, during each time step of the hydrodynamic model (Fig. 2) the current velocity is calculated and transferred to the energy conversion module that converts some part of the energy of the currents into power through the electric power equation (1). In the energy conversion module the current velocity is updated to maintain the energy balance of the TELEMAC-3D model.

According to [2,4,8], among others, the region of the SBS presents a multidirectional and highly dynamic pattern of circulation, which are strongly influenced by the passage of frontal meteorological systems. Due to this pattern, in this work the Gorlov converter will be used [14] because of its advantages on capturing energy in multidirectional currents.

Furthermore, the helicoidal turbine of Gorlov has a sectional area corresponding to a rectangle (h*D) and its efficiency coefficient (η) is smaller, being equal to 0.35 [14]. Therefore, Equation (1) controls the power gained from a helicoidal converter. Table I indicates the turbine technical parameters used into the energy conversion module.

$$P(W) = 0.5.\eta\rho(h^*D)v^3 \qquad (1)$$

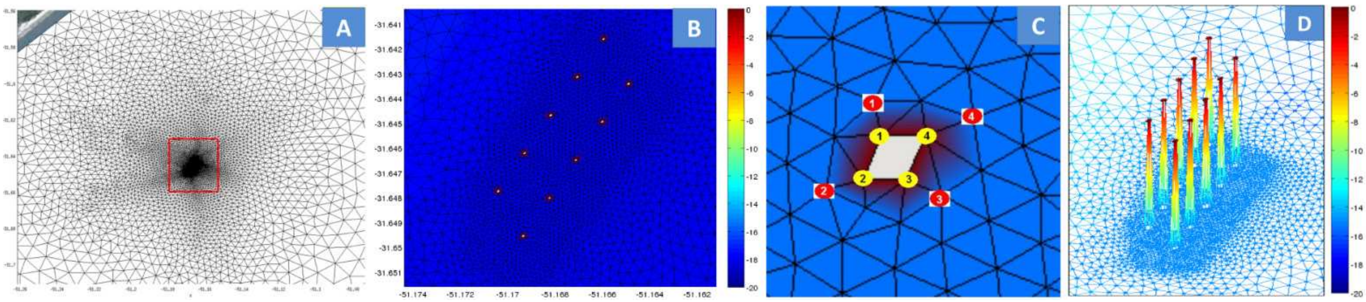


Figure 3. Region of the turbines on the study area. (A) Numerical grid with high degree of refine on the interest region. (B) Converters farm with 10 helicoidal turbines represented with 2 arrays parallel to the coast. (C) Scheme showing the interactions between the energy conversion module and the turbines. (D) Conversion structures represented in a three dimensional shape. The depth of this site is around 18m.

C. Scenario Study

To investigate the potential for energy conversion and the influence of the installation of energy converters in the natural hydrodynamic processes of the SBS, three simulations were carried out over 365 days, applying the physical parameters established in the upcoming section. The simulated period covers from January 1st to December 31st of a climatologic year.

One simulation was conducted using only the hydrodynamic processes. After indicating the interesting areas, another mesh was created with ten turbines (Fig. 3.a).

The farm grid direction (Fig.3.b) was idealized to be parallel to the coast, with 200 m of distance between each turbine on x and y directions. Due to computational limitations the best shape for a turbine was with 4 nodes (Fig. 3.c), with 10 m distance between each node.

The conversion model interacts with the turbine, acquiring the velocity at the node (red bullet at Fig. 3.c), this velocity is converted into power and the loss of kinetic energy is released on the turbine node, represented for the yellow bullets.

In order to improve this scenario, the energy sink for conversion was implemented for two simulations with the farm grid (according to the interactions above). One simulation was without the conversion structures and another simulation contained the three-dimensional physical structure of the turbines (Fig. 3.d), where the turbine nodes depth was changed in the FORTRAN source code.

D. Initial and Boundary Conditions

In order to study the tendency of power generation and the understanding of the processes occurring within a farm of turbines, for this study we used climatology data to impose the initial and boundary conditions. This data was created from long scale data base from the Brazilian National Water Agency (ANA), the Ocean Circulation and Climate Advanced Modeling Project (OCCAM) and also from Reanalysis (National Oceanic Atmospheric Administration - NOAA).

The climatological changes were performed through a monthly mean of temporal data series of discharge since January of 1940 until December 2006. The OCCAM data were treated from 1990 to 2004 for the velocity components, temperature, salinity and sea surface height. The wind and air temperature fields from Reanalysis were gathered from 1948 to 2012 [15].

The oceanic boundary was forced by the astronomical tides, water levels, current velocity, salinity and temperature fields (Fig. 1.b.). Along the surface boundary, the temporal and spatial variability of the winds and air temperature were prescribed. The air temperature data along the ocean's surface have also been used in order to consider the process of heat exchange with the atmosphere in the model calculations.

The numerical model was initialized from the rest and with an initial elevation of 0.50 m, the approximate average tide in the region [16]. Along the oceanic border the amplitude and phase data were also prescribed, through the calculation by the Grenoble Model FES95.2 (Finite Element Solution v. 95.6).

TABLE I. TURBINE TECHNICAL PARAMETERS

Start-in Speed	0.2 $m.s^{-1}$
Cut-in Speed	1.5 $m.s^{-1}$
Nominal Power	170 kW
Turbine Height	14 m
Turbine Ray	10 m

E. Calibration and Validation

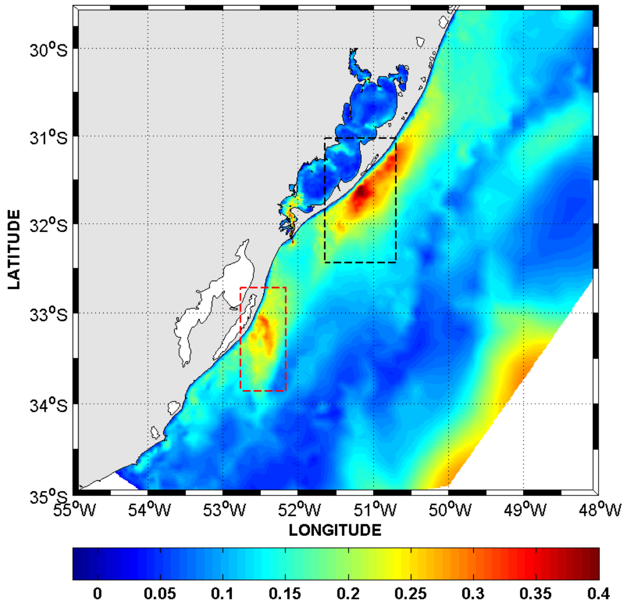


Figure 4. A) Average current velocity (m/s) during the whole period of simulation. In detail, the southern region in the red-dashed area, and the northern region in the black-dashed area.

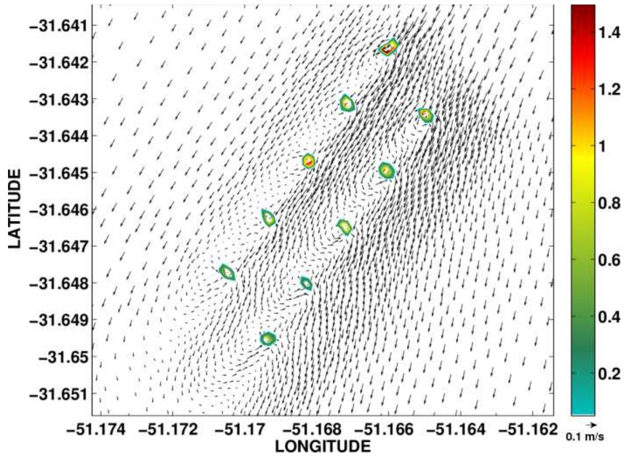
Reference [17] presented results for calibration and validation of the two-dimensional model in the Patos Lagoon estuary. Subsequently, one can find in references [2,8] that a set of simulations for the calibration and validation of the three-dimensional numerical model along the area covered by the Patos Lagoon and the adjacent coastal region has been done. The results of these calibration and validation tests indicated that the TELEMAC-3D model can be used for studies on the SBS with an acceptable degree of accuracy. As a result of these studies of calibration and validation, values of a number of physical parameters (such as wind influence coefficient, friction coefficient and turbulence models) were used to conduct this study.

III. RESULTS

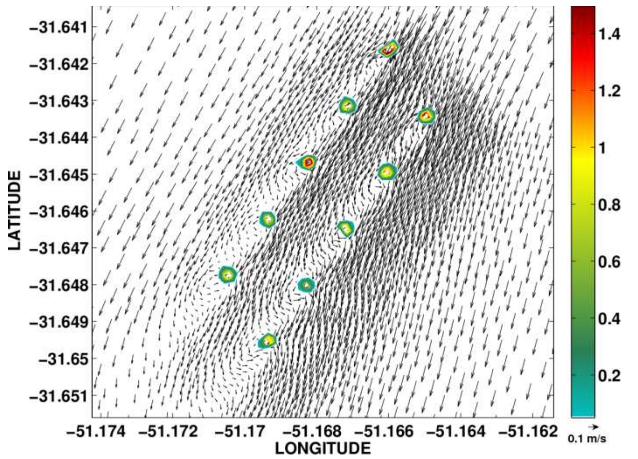
The hydrodynamic conditions of this region are characterized by the clash of different water masses. In these regions the average velocity of the current (Fig 4) was analyzed, and mean values reaching extremes of 0.4 $m.s^{-1}$ in these two highlighted regions were observed.

This mean value is associated with some variability, and thereby the standard deviation of the current velocity is distributed by the same regions of high mean values (Fig 4). This result suggests that: while these regions are appropriate for the location of energy converters, they can also go through periods of low power generation, since the velocity deviation has a closer value to the average.

Reference [1], in previous study, concluded that the southern region has less viability for installation of marine turbine currents in the SBS, while the northern region has emerged as a significant potential power producer reaching mean values of 10 $kWday^{-1}$. Therefore, only the northern region is investigated.



(A)



(B)

Figure 5. Residual velocities and the mean power (kW) generated for the turbines as isolines. (A) Site without the barriers. (B) Site with the presence of the barriers.

A. Current Pattern and Energy Conversion

In order to define which scenario delivers the most efficiency for a farm of turbines (with or without the presence of the structures), the spatial variability analysis was performed considering the temporal variation of the simulation. This analysis relies on the quantification of each turbine on its own capacity of converting the current energy into power according to the hydrodynamic pattern.

The average behaviour of the power generation on both sites was analyzed considering the residual velocity field associated with the mean field power converted (showed in isolines of power in Fig. 5).

The average power converted reaches values higher than 1.4 kW (Fig. 5.a and Fig. 5.b) in some turbines. The simulation without the structure presence (Fig. 5.a) shows the higher mean power on the turbines 1, 2, 3 and 6 (counting from the North-West turbine as first and the South-East as tenth). Despite this, the simulation with the presence of the structures (Fig. 5.b) shows enhanced power generation at the turbines 7, 8 and 10, in addition those cited before.

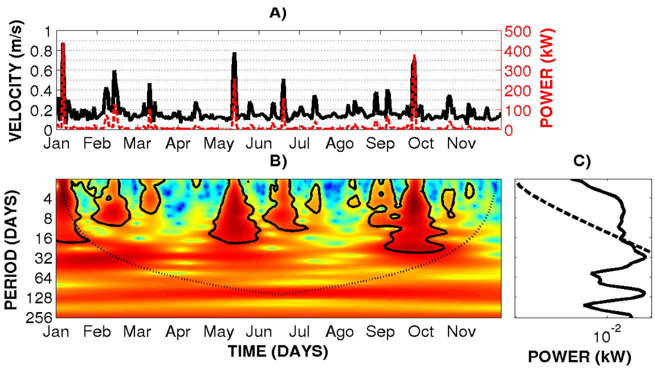


Figure 6. Integrated current velocity and electric power time series (A) used for the cross-wavelet analysis, as well as, the local (B) and the global (C) wavelet power spectrum of the time series using Morlet wavelet. Thick contour lines enclose regions of greater than 95% confidence for a red-noise process with a lag-1 coefficient of 0.95. Cross-hatched regions indicate the cone of influence where edge effects become important.

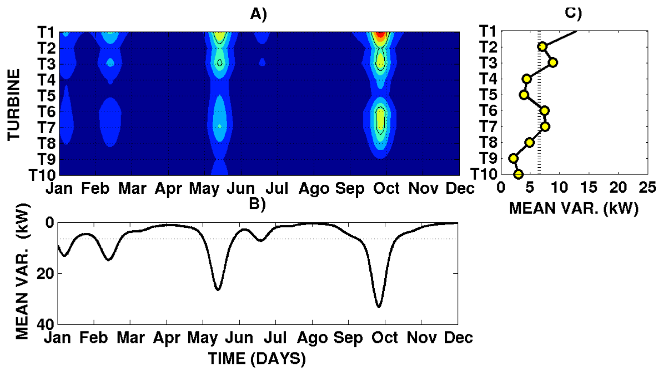


Figure 7. (A) Cross-spectral analysis between power (kW) and current velocity (m/s), for events with scale period higher than 1 day and lower than 30 days. Thick contour lines enclose turbines of greater than 95% confidence for a red-noise process with a lag-1 coefficient of 0.27. (B) Mean variance of the studied period, where values beneath the tendency line represents 95% of confidence. (C) Temporal series of the spacial mean variance of each turbine.

The same South-West circulation pattern can be observed on both simulations, which can be explained by the North quadrant winds dominance during the analyzed period. Besides, there is a slightly intensification at the residual velocity on the simulation that consider the structure effects (Fig. 5.b), with enhanced vectors between the turbine arrays and around them.

Behind the turbines we can observe a “shadow zone” in the circulation pattern, which can be related with the wake generated by the adjacent turbines. On the simulation without the barrier presence, this wake effect is purely hydrodynamic, where variations on the velocity fields occurs due to the conversion of the energy which inputs changes on the local vorticity pattern. On the other hand, on the simulation with the structure effect, this process shows as a contribution of the alterations into the hydrodynamic processes and the effect of the turbine body shape.

B. Temporal Variability Analysis

In order to analyse the temporality of the energy conversion regarding the entire turbines farm, time series (Fig. 6.a.) of electric power accounting for the ten converters were taken to perform the wavelet method described by [18] and [19]. The wavelet method is able to demonstrate the occurrence of events of energy conversion regarding time scales through local and global wavelet power spectrum.

At the analysis of the local power spectrum (Fig. 6.b) positive correlations (red-colored contours) are enhanced for the occurrence of velocities higher than 0.5 $m.s^{-1,}$ increasing the energy conversion. It also shows that the physical processes maintaining the behaviour of the turbines farm are controlled by two main groups of temporal scales. The first group with occurrence around 6 days dominate the period, forced by the cyclic changes of the wind pattern direction.

Otherwise, the second group of temporal scales consists of correlations covering periods above 16 days, suggesting that the physical processes shorter than 20 days were the main mechanisms controlling the electric energy conversion along the inner continental shelf. The global spectrum of energy (Fig. 6.c) corroborate this hypothesis, indicating with 95% of confidence, the occurrence of processes with time scales above 16 days and may be extended in some moments, throughout the study period.

This pattern is similar to the obtained by [2] with respect to the occurrence of the processes and cycles of occurrence. Thus are strongly influenced by the passage of frontal meteorological systems generating further changes in wind direction and intensity of currents.

C. Spatial Variability Analysis

In order to define the importance of each turbine in the farm structure, the correlation between the incident current velocity and the power was performed along the turbine arrays. With this analysis, the efficiency of each turbine was studied in different time scales behalf the usage of bi-dimensional cross-spectral wavelet analysis, considering that the dominant processes occurring on the turbines site have temporal scale higher than 1 day and lower than 30 days.

The importance of each turbine and its variance in time is defined by the high correlation (red colored contours) in the Morlet Wavelet. Values on the right of the tendency line indicate with 95% of confidence the best placed turbines.

For the simulation considering the presence of the structures, through the cross-spectral (Fig. 7a.) it can be observed intensification on the power conversion in several turbines during the main conversion events. The temporal series of mean variance (Fig. 7b.), indicated with 95% of confidence that the four events of great power conversion sustain high power and are also intensified in this scenario.

Variance values above 35 kW (Fig. 7b.) can be observed during the October extreme event, enhancing the greatest power capacity of this scenario. The mean variance of each turbine (Fig. 6 c.) indicates that the higher correlation between the variables maintain average power around 7 kW. Moreover, it suggests that the turbines 1, 2, 3, 6 and 7 are the most efficient of the farm, considering only the energy conversion.

This discrepancy between the turbines efficiency relies on their positions on the farm and the influence of the incident current into the wake patterns.

IV. CONCLUSIONS

The Southern Brazilian Shelf is highly dynamic and constantly influenced by cycling winds (North-East/South-West) and the wind-driven coastal currents. This condition makes the usage of marine current turbines viable, although the recommended helicoidal turbine is to be applied. From this work we can conclude that:

The comparison between the simulations with and without the presence of the physical converting structure demonstrated that, regarding the numerical aspect of these simulations, the effect of the structure does not input changes on the temporal pattern of the energy conversion. The structures presence acted in a positive way in order to promote the intensification of the velocity field surrounding the turbines farm, also increasing the energy conversion.

The presence of the energy converters, on the other way, removed some part of the kinetic energy from the coastal currents, generating divergence and convergence zones in accordance with the dominant direction of the currents. The changes into the hydrostatic balance generated instability on the fluid motion, - part due to the converting energy, and part due to the presence of the structure – generating the wake effect behind the turbines. This effect decrease the energy conversion on the subsequent turbine, although, it also creates an intensification on the surrounding velocity fields.

The turbines farm shows great capacity for converting the currents energy, principally during the four main energetic events observed. Regarding the annually energy capacity, this turbine farm can reach 59,39 GWh (16,5 MW) with ten turbines, which is equivalent to 0.22% of the whole energetic consumption of the Rio Grande do Sul State in 2010.

Further studies shall improve the geometry of the farm and also promote trial test to implement a diffuser structure nearby the turbines to intensity the incident current fields.

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