Valery I. CHRISANOV[1], Sebastian WISZNIEWSKI[2]

Zachodniopomorski Uniwersytet Technologiczny w Szczecinie, Instytut Elektrotechniki (1)
Zachodniopomorski Uniwersytet Technologiczny w Szczecinie, Instytut Elektrotechniki (2)

Sea Wind-Wave Power Plant on the Base of Permanent Magnet Synchronous Generators

Streszczenie. *W artykule opisano nową strukturę morskiej farmy do pozyskiwania odnawialnej energii wiatru i fal. Zaprezentowano schemat blokowy łączący generatory synchroniczne z magnesami trwałymi do pozyskania energii wiatru i fal morskich i kabel transmisyjny HVDC przeprowadzony pod wodą. Zaproponowano również dwuetapową optymalizacje projektowania generatorów z magnesami trwałymi.* ***(Morska farma wiatrowo – falowa oparta na generatorach synchronicznych z magnesami trwałymi)***

Abstract*. The paper describes a new architecture of an offshore renewable energy plant with wind and wave direct drive energy conversion. A block-scheme of a combined wind and wave power plant on the base of multi-poles PM synchronous generators, power electronic technique and output HVDC underwater cable transmission is presented. Two-stage approach for PM generator design optimization is suggested.*

Słowa kluczowe: energia odnawialna, farmy wiatrowe i falowe, generator synchroniczny z MT, optymalizacja
Keywords: renewable energy, wind and wave plants, PM synchronous generators, design optimization

Introduction

The alternate energy sources play all-growing role in development of economy and environment protection, in solution of energy crisis and a climate change. Offshore wind and wave energy will become a major source of energy across large regions in northern Europe and trend of companies from the traditional to renewable energy generation will continue. The desire to catch a regular and high intensive wind on the one hand and to avoid noise and impact on the landscape on the other hand has been followed out by windmills installation along with wave mills in the high sea.

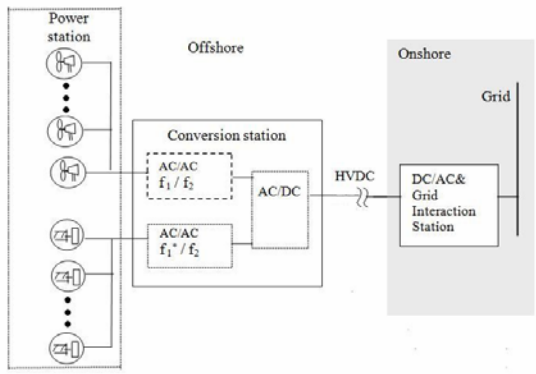

Fig. 1. A block- scheme of power plant with combined system of wind and wave energy conversion.

At present the double-fed induction machines are still the most widely used for wind energy applications. But due to a number of drawbacks (the sliding contacts, complexity of a control system, etc.) they are sometimes replaced with the robust cage induction generators (IG), being more reliable, less size and lower cost [1,2]. However today for the further increase of efficiency and other important performances instead of the IG the new advanced PM synchronous generators (PMSG) of rotating and reciprocating types are developed and designed for application on offshore wind and wave farms [3-8]. Design and construction of combined wind-wave power plant (WWPP) span over many disciplines, including hydrodynamics, mechanics, electrical machinery, power electronics, electrical circuit theory and measurement. A WWPP represents a delicate balance between economy and high technology involved. If the technology is going to be successful, the price of the produced electricity has to be competitive.

The purpose of the paper is to report a new architecture of a high sea combined WWPP with direct drive energy conversion with help of optimized PMSGs.

A power plant with combined system of wind and wave energy conversion

The use of a combined system of wind and wave energy conversion opens a new possibility for increase density and concentration of output electrical power generated at the same exploited sea area of a shelf (Fig.1). On combined WWPP there are two major groups of equipment, consisting of primary drivers on the one hand and generators on the other hand.

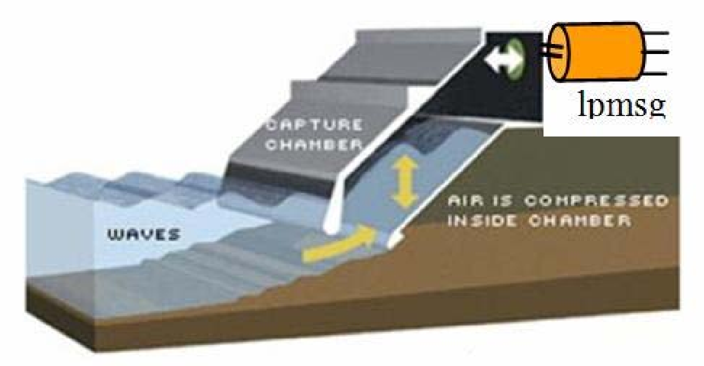

Fig. 2. The wave energy converter of Limpet type.

Wave energy can be converted by different ways (Fig. 2,3) but the Limpet construction is more preferable because all its equipment can be installed on the power station over the sea surface.

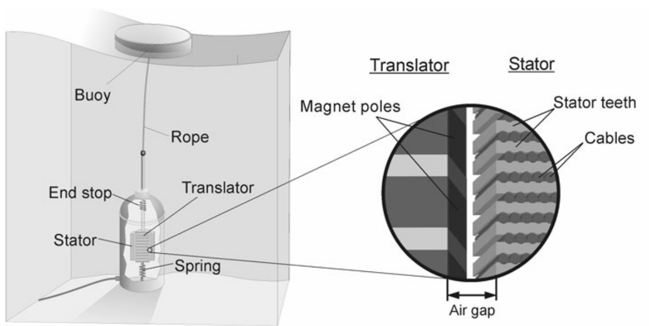

Fig. 3. Conceptual drawing of the wave energy converter together with detailed view of the air gap.

Wave energy conversion is realized with the reciprocating LPMSG, which stator is unmovable and translator is connected to a spring. Permanent magnets are mounted on the moving translator. Moving translator generates electricity which is variable in frequency, amplitude and phase order (Fig. 4). To increase the value and frequency of generated voltage the reciprocating LPMSG is designed as a multipoles machine.

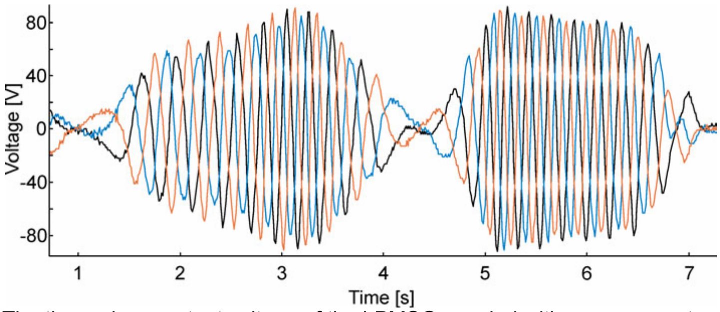

Fig. 4. The three phase output voltage of the LPMSG coupled with wave converter piston.

As a generator for wind turbines it is expedient to use an effective multi-pole axial flux PMSG (APMSG) directly coupled with a turbine (Fig. 5). As the output frequencies of wind and wave mills are different a conversion station has two groups of AC/AC high frequency two-sided PWM converters (Fig. 6) intended to keep unity power factor and to provide soft starting wind turbines.

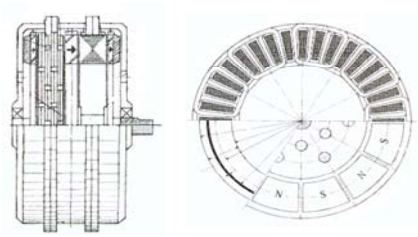

Fig. 5. Multi-disk and multi-pole axial flux PMSG.

All power electronic converters are interconnected among themselves and their operation is synchronized to create an integrated electrical power system of the plant with simultaneous use of wind and wave energy sources on the same site of a marine shelf. It sufficiently improves performances of the power plant, ensuring high efficiency of wind and wave energy conversion, electrical energy transmission and flexible interaction with a grid.

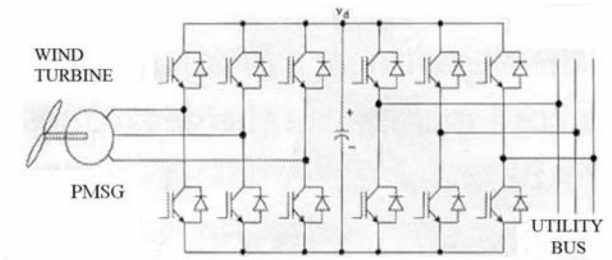

Fig. 6. Two-sided PWM converter.

Optimization of the PMSG designs and performances

Optimization of the PMSG design and performances is a complicated problem, because it should be solved with allowance for of many specifications fulfillment (Fig. 7). According the theoretical methodology the PMSG optimization relates to constrained, multi-objective and multivariable problem.

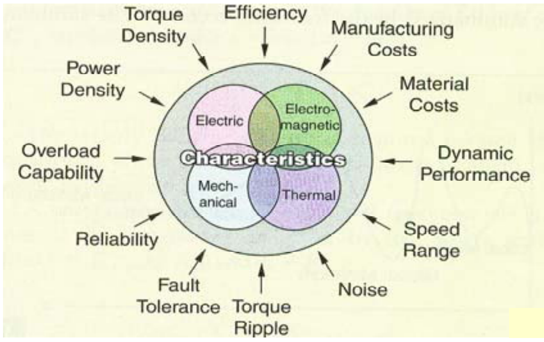

Fig. 7. Typical specifications of PMSGs.

Usually with such kind of problem a two-stage optimization (system and parametrical stages) is used to reduce substantially a computation time [5]. The system (or global) optimization may be considered as an approximating stage and a parametrical optimization as a refining search. An approximation optimization results in a selection of the best candidate from a collection on the base of analytical evaluation by a performance criteria. A refining stage should optimize the geometric parameters of a selected design, using computer modeling and FEM application.

There are several methods of global optimization including direct and indirect methods, stochastic methods that reach their aim only with a certain probability, and deterministic methods. At large, the stochastic evolutionary algorithms have found wide application in treatment of large-scale systems considering them as a black box. Since the PMSG is accessible for observation, mathematical modeling and computation as well, the deterministic approach seems to be more acceptable. Sequentially optimizing the PMSG performances we get a set of maps and the superposition of the maps leads to the global final map with an area of interest.

Global optimization of the PMSG

At the first stage the radial and axial designs of the multipole rotating PMSG are compared with the express method [3,4], based on sizing equations of electrical machines. The same method can be applied for comparison of the reciprocating LPMSG of flat (single and double sided), tubular and octagonal constructions.

The express method has been developed for the rotating PMSM comparison on a criterion of power (torque) density. For the electromagnetic torque of an electrical machine we have the initial sizing equation:

(1) $$T = f_e SR = B_\delta ASR \quad [Nm]$$

where: $f_e = B_\delta A$ – specific force (shear stress), B_δ – flux density (T), A – electric loading (A/m), S – the surface of the air gap (m²) and R – the torque radius (m).

Since the electromagnetic loads are the same of two compared PMSG then their torque are defined by the geometric parameters S and R only. After transformation of analytical expressions for the PMSM volumes of axial (APMSM) and radial (RPMSM) configurations we get their ratio Rar=Va / Vr , which is a nonlinear objective function of two variables p (pole number) and n (ratio of torque radiuses):

(2) $$R_{ar} = \frac{3(\pi/p + 0{,}0355)}{(1 + 0{,}5\pi/pn + 0{,}0152/n)^2}$$

A minimum of objective function (2) in case of unconstrained approach is easily defined by one of well-known classical methods (direct search, gradient methods and second order methods).

At n ≤ 0,6 the APMSG have more high torque density than the radial one at any p. At p≥20 the APMSG torque density is more than twice than at the short length RPMSG. From here it is possible to make a conclusion about the advantages of the multipole APMSG application at the WWPP.

The same method applied for comparison of the reciprocating LPMSG has revealed advantages of a tubular type generator.

Parametrical optimization of the PMSG

Geometric parameter optimization is realized with two steps and at first the conventional method with standard formulas for a machine considered is used [7,8]. The preliminary design of main dimensions is performed by means of the following procedure: the magnetic flux per pole is determined by considering the permanent magnet characteristics and the air gap geometry. The appropriate number of turns of the stator winding is deduced by applying the flux cutting rule in order to ensure the desired voltage and frequency level with respect to the rotor speed. The loading current is then derived by the machine output characteristics while the flux per pole under nominal loading is determined by taking into consideration the armature reaction [7].

Once the geometric parameters of the machine has been determined the second step of the refining optimization is performed by one of appropriate methods of optimization, e.g. by a finite element model on the base of fundamental magnetic field equation.

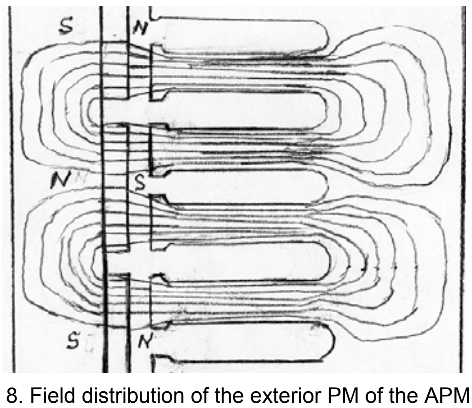

Fig. 8. Field distribution of the exterior PM of the APMSG.

One of the widespread optimization problems is minimization of the width of the exterior positioned PM subject to the constant value of the rated torque. For the sake of simplicity the rectangular shape of the PM is considered here (Fig. 8) and 2D model of magnetic field is simulated with FEM triangular mesh (Fig. 9).

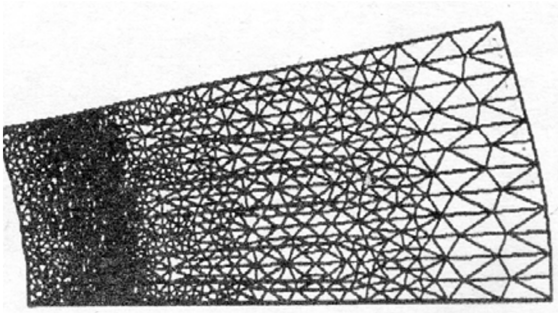

Fig. 9. FEM triangular mesh with 1500 nodes and 3000 elements (arc-wise and axially co-directed cross section).

Through a detailed field analysis the FEM results in the performance determination of the APMSG including the torque ripples as well as design improvement by means of the PM shape modification.

According to [8] the FEM based analysis was carried out to design a 0,25 MW, 60 rpm APMSM. There were some specifications: output frequency f = 30 Hz, the number of poles p= 60, pole pitch τ = 0,05 m, air-gap δ = 2,5 mm, magnet material – alloy NdFeB at magnetic flux density B = 1,15 T, width of the PM b = 0,013 m, outer rotor/stator diameter 1,1m, total length l = 0,21m.

The refining optimization was performed in regard of minimization value b. At b< 0,013m there is a risk of demagnetization of the magnetic material in cases of overloading or operation under abnormal conditions.

Conclusions

1. The new concept of designing renewable energy plants on the base of combined utilization of a wind and sea wave power is offered and a block-scheme of a corresponding plant is described and analyzed. Distinguished features of the plant are: the increase of power equipment concentration on being available area of a shelf or an offshore, unification of the electrical generators and power electronic converters, simplification and convenience of maintenances, etc.
2. It was validated the multipole PM synchronous generators have advantages before the conventional ones due to high technical and operating performances. However the large variety of their constructions hinders process of optimization for consequent application of the best design on power stations.
3. Suggested two-stage method of system and parametric optimizations allows to solve the multivariable and multiobjective problem. With the express method the axial type configuration was selected among the other designs and the FEM based refining optimization has minimized of the PM width at the rated value of torque. Among the LPMSGs the tubular construction is appeared to be the best one.
4. Torque density of PMSG depends mainly on two design parameters: the number of poles p and the sizing coefficient (torque radius ratio n). At p > 8 and n =1 the APMSG have the higher torque density compared with short length RPMSG and at p >20 the torque density is doubled.

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***Autorzy**: prof. dr hab. inż. Valery I. Chrisanov; Zakład Maszyn i Napędów Elektrycznych Zachodniopomorskiego Uniwersytetu Technologicznego w Szczecinie, ul. Sikorskiego 37, 70-313 Szczecin, e-mail: chrisanov@zut.edu.pl*

mgr inż. Sebastian Wiszniewski; Zakład Maszyn i Napędów Elektrycznych Zachodniopomorskiego Uniwersytetu Technologicznego w Szczecinie, ul. Sikorskiego 37, 70-313 Szczecin, e-mail: wisz@zut.edu.pl