Analysis of a Permanent Magnet Eddy Current Heater Driven by a Wind Turbine

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***Abstract*—This paper deals with the numerical analysis and optimal design of a Permanent Magnet Eddy Current Heater (PMECH) driven by a wind turbine. This study includes a preliminary sizing of the wind turbine, an optimal design of the PMECH from cost reduction point of view, a heat transfer analysis of the device and a study of the dynamic response of the wind system. The electromagnetic and heat transfer analysis is based on Finite Element Method (FEM) implemented in the Flux software package and the dynamic response of the wind system is analyzed using a dedicated model developed under Matlab/Simulink environment.**

***Index Terms*—eddy currents, design optimization, finite element methods, system analysis, wind energy.**

I. Introduction

Grid-tie or off-grid wind power systems are increasingly used to produce electricity. The evolution of wind power systems in the last decades is quite impressive and the total installed capacity of such systems increases year after year.

After an exponential increase, nowadays the global cumulative installed wind capacity is larger than 369 GW, the estimations being positive for many years ahead [1]. In Romania the cumulative installed windpower capacity at the end of 2014 was about 2954 MW [1].

The classical wind power systems are typically used to convert wind kinetic energy into mechanical rotational energy by means of the wind turbine and then into electric energy by an electric generator. The electric energy is then delivered to the grid, to a battery system or to a local grid using different power converters and control solutions [2-8].

The efficiency of a wind power system depends to a large extent on the wind energy potential at the installation site. An ideal site for wind power systems should fulfill several criteria such as: high and constant wind speeds, small distance to an existing electric power grid, low costs for buying or renting the terrain etc. Once these criteria are fulfilled the investments in wind energy become more attractive and the pay-back period is shorter.

This paper analyzes a vertical axis wind system able to convert the wind kinetic energy into thermal energy. The classical electric generator is replaced here by a Permanent Magnet Eddy Current Heater (PMECH) that converts mechanical energy into eddy currents induced in a steel wall (hollow cylinder shape). At the exterior of the steel wall is welded a copper serpentine that absorbs the heat developed by Joule effect of the eddy currents, Fig. 1. The flow rate of the water injected in the copper serpentine is electronically controlled such that the temperature inside the device to be kept within acceptable limits to avoid permanent magnets irreversible demagnetization. The output thermal energy can be used for other useful purposes. In order to keep the thermal losses low, the PMECH driven by the wind turbine should be placed close to the end-user (e.g. close to buildings or on their rooftops). Long distances from the heater to the thermal loads may increase the thermal losses making the heating system less efficient. Such heating systems could represent a solution for the energy efficient or zero emission buildings [9-12].

Few articles deal with this subject and all of them refer to the generator only [13-19]. This paper covers the preliminary sizing of the wind turbine, the electromagnetic design of the PMECH, the heat transfer analysis and the system analysis.

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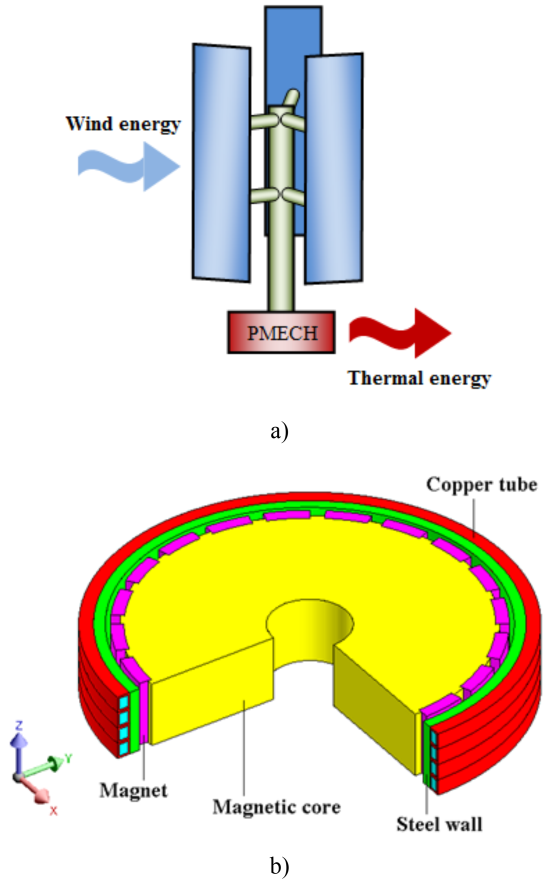


Figure 1. PMECH driven by a wind turbine; a) Operation principle; b) Cut away view of PMECH.

II. CONSIDERATIONS ON THE NUMERICAL ANALYSIS OF THE WIND POWER SYSTEM

The operation of the PMECH driven by a wind turbine is based on a complex interaction between mechanical, electromagnetic and heat transfer phenomena. The permanent magnets mounted on the rotor of the PMECH are moved by the wind turbine and generate eddy currents in the stator conducting wall which heat up by Joule effect. The heating of stator wall will modify the material resistivity since it varies with the temperature. The change of resistivity modifies the induced currents amplitude, the reaction magnetic field structure, as well as the permanent magnets operation points and the inductor field. However the temperature increase of the steel wall is limited because it is in contact with a water cooled copper tube serpentine welded on the outer face of the wall. The eddy currents induced in the stator wall will generate a braking torque decreasing the wind turbine speed, modifying in the same time the inductor field, the induced power and the thermal field.

Based on the above considerations, we can notice that an in-depth numerical modeling of the PMECH driven by wind turbine is a complex task which assumes a coupled analysis of transient electromagnetic, transient thermal and transient mechanical phenomena.

Taking into account that the thermal, mechanical and electromagnetic time constants of the PMECH are very different (minutes, seconds and milliseconds respectively), a coupled analysis of the system would require a huge computation time and resources. Some simplifying measures are therefore necessary in order to decouple the electromagnetic and thermal phenomena so as to make the calculations accessible. That is why the material properties for the electromagnetic field analysis of the PMECH were considered constant and the induced power was computed once for all and used afterward for the heat transfer analysis.

The numerical modeling of the wind system supposes first a preliminary sizing of the wind turbine followed by an optimal design of the PMECH based on transient electromagnetic field calculations, a heat transfer study and a final wind system analysis.

The electromagnetic field calculations are necessary to find an optimal configuration of the PMECH and to determine the torque - speed dependence.

The heat transfer study is carried out to evaluate the temperature field inside the PMECH for different water flow rates so as to avoid the permanent magnet demagnetization due to combined demagnetizing fields and temperature.

The final system analysis based on a Matlab/Simulink model is used to evaluate the dynamic behavior of the PMECH driven by the wind turbine.

III. PRELIMINARY SIZING OF WIND TURBINE

The design of the heating system driven by a vertical axis wind turbine starts from the following main data of the PMECH: rated output thermal power of the heater $P_{oh} = 1$ kW, rated speed $n_n = 180$ rpm (the same as the rated wind turbine speed), rated efficiency $\eta_n = 95$ %. Thus the rated input mechanical power received by the heater is $P_{ih} = P_{oh}/\eta_n = 1000/0.95 \cong 1053$ W. We suppose that the mechanical losses are 20 W and the thermal losses are 33 W.

The conversion system is of direct drive type, which means that the PMECH is directly coupled to the wind turbine shaft (i.e. they have the same speed). Therefore the rated output mechanical power of the wind turbine P_{owt} will be equal to the rated input mechanical power P_{ih} received by the heater as shown below [3]:

$$P_{ih} = P_{owt} = \frac{\rho A V_w^3}{2} C_p(\lambda) \quad (1)$$

where $\rho = 1.225$ kg/m^3 is the air density, $A = 2 \cdot R \cdot H$ is the area swept by the wind, R is the turbine radius, H is the height of turbine rotor, $V_w = 10$ m/s is the rated wind speed and C_p is the performance coefficient of the wind turbine which depends on the tip speed ratio of the blades λ given by the expression:

$$\lambda = \frac{\Omega R}{V_w} \quad (2)$$

where $\Omega = 2 \cdot \pi \cdot n_n/60$ is the angular speed of the turbine.

To size the turbine we choose the rated value of the tip speed ratio of the blades $\lambda = 2$ and the corresponding performance coefficient of the wind turbine $C_p = 0.3$.

From (1) we can evaluate the area of the wind turbine $A = 2 \cdot P_{ih}/(\rho \cdot C_p \cdot V_w^3) = 2 \cdot 1053/(1.225 \cdot 0.3 \cdot 10^3) = 5.73$ m^2.

For a tip speed ratio $\lambda = 2$, from (2) we obtain a turbine radius $R = V_w \cdot \lambda/\Omega = 60 \cdot 10 \cdot 2/(2 \cdot \pi \cdot 180) \cong 1.06$ m and a turbine height $H = A/(2 \cdot R) = 5.73/(2 \cdot 1.06) \cong 2.7$ m.

The analysis of the wind system will be performed using Matlab/Simulink software package where an own turbine model was developed, characterized by the following performance coefficient $C_p(\lambda)$:

$$C_p = 0.4\left(\frac{20}{K} - 4.678\right)e^{-\frac{8}{K}} + 0.13\lambda \quad (3)$$

where $K = 1/(1/\lambda - 0.2185)$.

The output mechanical power of the wind turbine can be computed as function of the wind turbine angular speed:

$$P_{owt} = \rho H R^4 C_p(\lambda)\frac{\Omega^3}{\lambda^3} \quad (4)$$

Based on (3) and (4) the *performance coefficient* $C_p(\lambda)$ and the *wind turbine power - speed curve* $P_{owt}(n)$ are represented graphically in Figs. 2-3.

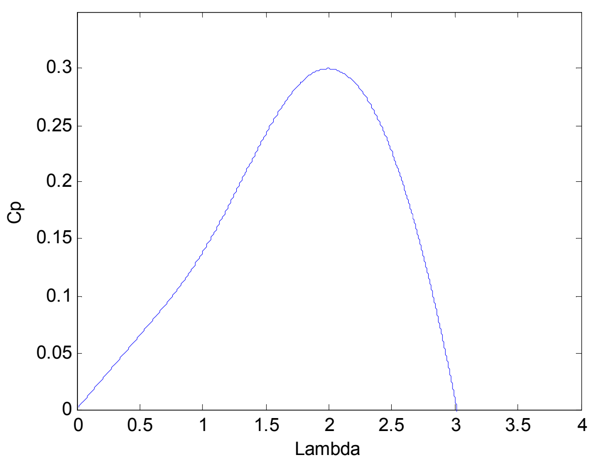


Figure 2. Performance coefficient versus tip speed ratio $C_p(\lambda)$ of the wind turbine.

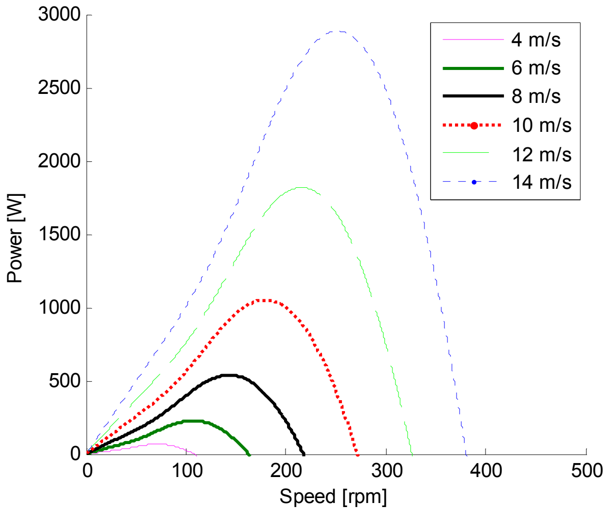


Figure 3. Power - speed curve $P_{owt}(n)$ of the wind turbine.

IV. Electromagnetic Design and Thermal Analysis of PMECH

Being a special device, reliable analytical models able to design PMECHs do not exist so far. There are analytical formulas given in [19] but they do not take into account all complex aspects such as stator wall thickness, magnets operation point etc. Thus the design of the PMECH presented in the paper will be highly based on the Finite Element Method (FEM) which is one of the most versatile numerical methods able to solve partial differential equations. The FEM investigations are carried out using FLUX professional software package dedicated to electric, magnetic, heat transfer and multiphysics applications.

The optimal design of the PMECH from electromagnetic point of view requires the evaluation of induced power in the stator walls and this calculation is carried out using 2D transient magnetic computations described by the following partial differential equation in terms of magnetic vector potential $\boldsymbol{A}$ [18]:

$$\nabla \times \left[\left(\frac{1}{\mu} \right) \nabla \times \boldsymbol{A} - \boldsymbol{H}_c \right] + \sigma \frac{\partial \boldsymbol{A}}{\partial t} = 0 \quad (5)$$

where: μ is the magnetic permeability of magnetic materials, σ is the electrical conductivity electrically solid conductors, $\boldsymbol{H}_c$ is the coercive field strength of permanent magnets.

The transient magnetic analysis of the PMECH allows us also to determine the *torque - speed* characteristic of the device necessary for the final dynamic analysis of the wind system.

In order to find an optimum configuration for the PMECH a series of FEM transient magnetic simulations were carried out in order to identify the influence of the number of poles and permanent magnet thickness on the device performance.

By taking into account the physical symmetries, the 2D FE computation domain of the reference PMECH with $2p$ = 10 poles is represented by 1/10 of the cross-section of the device, Fig. 4.

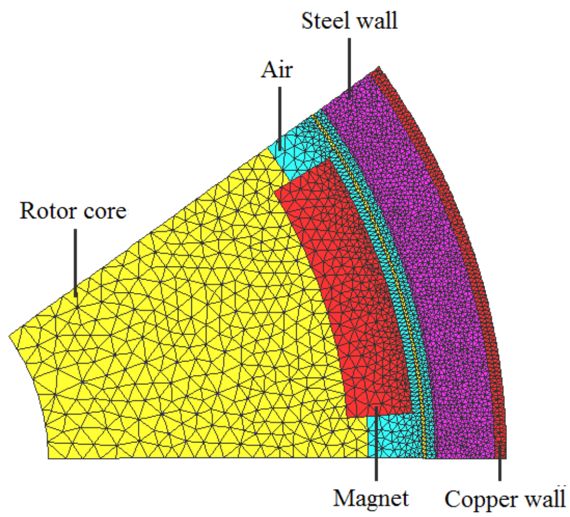
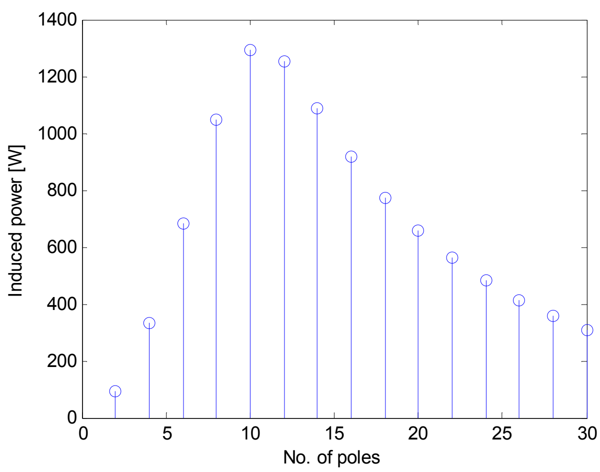


Figure 4. FE computation domain and mesh for the reference PMECH.

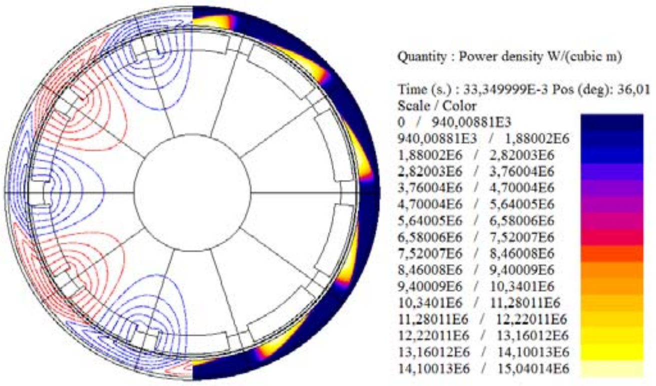
The main dimensions of the reference device are the following: inner diameter of stator wall D_{ist} = 200 mm, device axial length L_a = 50 mm, stator wall thickness S_{thick} = 10 mm made of magnetic steel to attract magnetic field lines, copper wall thickness C_{thick} = 2 mm, distance from PMs to stator wall D_{pms} = 3.5 mm, PMs arc angle $\alpha_{pm} = 0.75 \cdot 180/p$, PMs thickness T_{pm} = 11 mm.

The material properties taken into account for the FE analysis are the following: electrical resistivity of steel (used for stator wall and rotor core) $\rho_s = 1.6 \cdot 10^{-7}$ Ωm, saturation flux density of steel B_s = 1.9 T, initial relative magnetic permeability of steel μ_{rs} = 500, permanent magnet of NdFeB type (N45SH) with a relative magnetic permeability μ_{rm} = 1.038, remnant flux density B_{rm} = 1.28 T, copper electrical resistivity $\rho_{co} = 1.88 \cdot 10^{-8}$ Ωm.

A series of simulations were performed for the rated speed (n_n = 180 rpm) and for different number of pole pairs and the numerical results are shown in Fig. 5. We can notice in Fig. 5 a) that the maximum induced power (P_{indm} = 1291.4 W) is obtained for a PMECH with $2p$ = 10 poles.



a)



b)

Figure 5. Numerical results for reference PMECH and for other number of pole pairs; a) induced power versus no. of pole pairs; b) magnetic field lines and induced power density distribution for reference PMECH (entire cross-section).

The PMECH configuration with 10 poles that provides a maximum induced power, Fig. 5 a), will be the most compact solution. Since the induced power is proportional to the axial length of the device the 10 poles PMECH solution will have the shortest length for a given induced power. Since the rated output power of the PMECH is 1000W and the thermal losses is 33 W, the induced power of the device should be P_{indm} = 1033 W. In order to reduce the induced power of the PMECH with 10 poles from 1291.4 W down to 1033 W the device axial length L_a should be decreased from 50 mm to 40 mm (a 20% size reduction).

In Fig. 5 b) we can notice that the induced power density is located almost entirely in the stator steel wall.

Since the cost of PMs is much larger than the cost of steel, the ideal PMECH solution should be characterized by a small PMs volume but keeping the same performance of the device.

In order to estimate the optimum size of PMs several simulations were performed for different thickness values of the PMs. In Fig. 6 is presented the induced power versus PMs thickness. We can notice that generally thicker PMs lead to larger induced power in the steel wall. However very thick PMs are not justified since they do not determine an important increase of the induced power.

The graphical representation in Fig. 7 shows that a thickness value T_{pm} = 5.5 mm of the PMs provides the highest ratio *induced power/PM volume*.

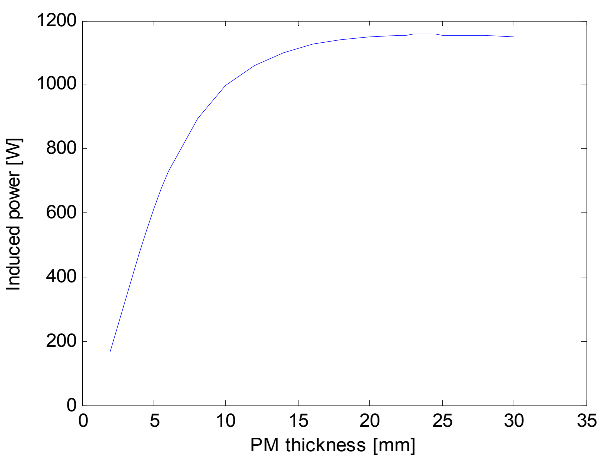


Figure 6. Induced power versus PM thickness.

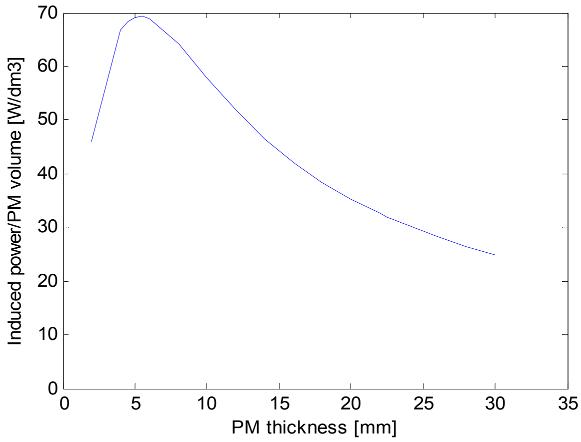


Figure 7. Induced power/PM volume versus PM thickness.

Since the induced power in case of PMECH with PMs of thickness T_{pm} = 5.5 mm is smaller than required, we must increase the axial length of the device from 40 mm up to 61.5 mm in order to reach the target value $P_{ind} \approx 1033$ W.

The final design of the PMECH will have therefore $2p$ = 10 poles and a PMs thickness T_{pm} = 5.5 mm. The *induced power vs. speed* and *torque vs. speed* curves evaluated for this design by FE analysis are shown in Figs. 8 - 9. We can notice in Fig. 8 that the *power-speed* curve of the PMECH fits well enough the maximum points of *power - speed curve* of the wind turbine.

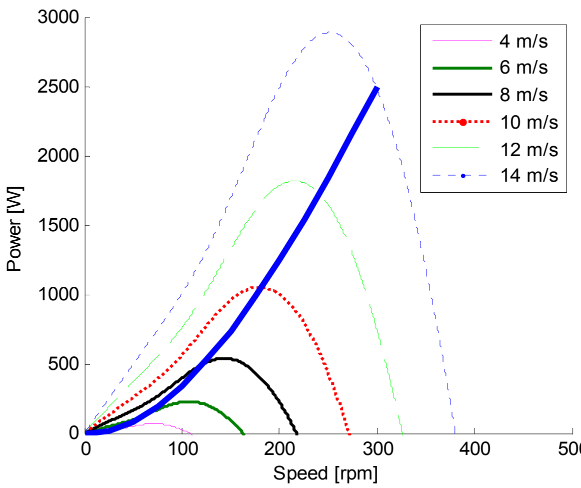


Figure 8. Induced power vs. wind turbine speed for chosen PMECH structure superposed over the *power – speed curve* of the wind turbine.

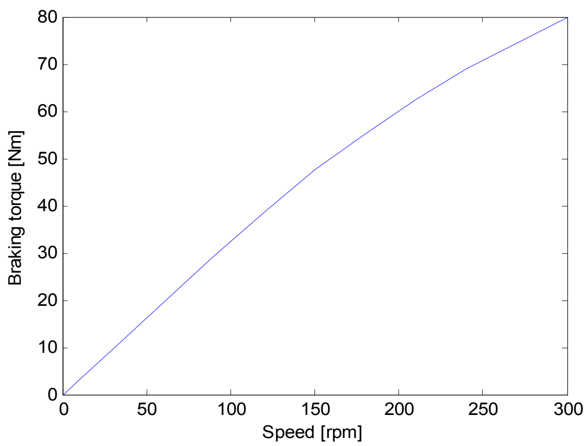


Figure 9. Torque - speed curve for chosen PMECH structure.

The *torque - speed* characteristic of the PMECH shown in Fig. 9 is very important since it represents the load torque T_L of the wind turbine. This curve $T_L(n)$ is approximated with a second order polynomial function (shown below) to be used further for the dynamic analysis of the wind system:

$$T_L(n) = -0.0003n^2 + 0.3588n = 0 \qquad (6)$$

V. Heat Transfer Analysis of PMECH

A heat transfer analysis of the PMECH will be performed in order to verify that the PMs temperature does not increase above a critical value that could entail their irreversible demagnetization.

The heat transfer analysis is based on Fourier's partial differential equation in steady state [15]:

$$\nabla(k\nabla T) + p_J = 0 \qquad (7)$$

where T is the temperature, k is the thermal conductivity and p_J is the induced power density that was considered uniformly distributed in the eddy current regions, its value being taken from the electromagnetic analysis.

The 2D FE computation domain will be the same with the one shown in Fig. 4. The boundary conditions will be of thermal insulation type on all frontiers except for the outer copper wall where a condition of heat transfer by forced convection is imposed (due to the water flowing through the copper serpentine).

The thermal conductivity values used for simulations are as follows: 394 W/mK for copper, 54 W/mK for steel, 7.7 W/mK for PMs and 2.87 W/mK for airgap [20].

The water flow rate was modeled by the value of the heat transfer coefficient by forced convection that was taken in the range 100 ÷ 1200 W/m^{2}K. The numerical results presented in Fig. 10 show that the temperature field of PMECH is highly dependent on the water flow rate used as thermal agent and the temperature field in the PM region is quasi-uniform. This information is very important since it means that by the regulation of water flow rate the temperature of PMs can be kept below reasonable limits.

By the analysis of the results we can mention also that in order to keep the PMs cool enough (below 65 °C) the convection thermal transfer coefficient should be higher than 1060 W/m^{2}K.

VI. Dynamic Response of the Wind System

The dynamic response of the wind system is based on a numerical model developed under Matlab/Simulink environment, as shown in Fig. 11.

The differential equation governing the operation of the wind system is the following:

$$J\frac{d\Omega}{dt} = T_{wt} - T_L - F\Omega \qquad (8)$$

where J = 20 kgm^2 is the moment of inertia of the moving parts, T_{wt} is the torque of the wind turbine calculated based on (4), T_L is the load torque (braking torque generated by the PMECH) given by (6) and F is the viscous friction coefficient F = 0.01 Nm/(rad/sec).

The electromagnetic transient regimes between two speed values due to the eddy currents induced in the stator wall of the PMECH are neglected since the variation of turbine speed is smooth due to the relatively large moment of inertia and thus the electromagnetic time constants are much smaller than the mechanical ones.

For the wind profile shown in Fig. 12 a) we obtain the speed variation of wind turbine presented in Fig. 12 b) and the output power profile shown in Fig. 12 c).

We can notice that the wind turbine speed (equal to the PMECH speed) and the output PMECH power follow properly the wind speed profile with a certain delay due to the relatively important moment of inertia of the system.

The developed dynamic model of the wind system can be therefore used successfully to estimate the performance and the behavior of the PMECH driven by the wind turbine. The design and analysis of larger wind power systems of this type can be performed using the same procedure as described in this paper.

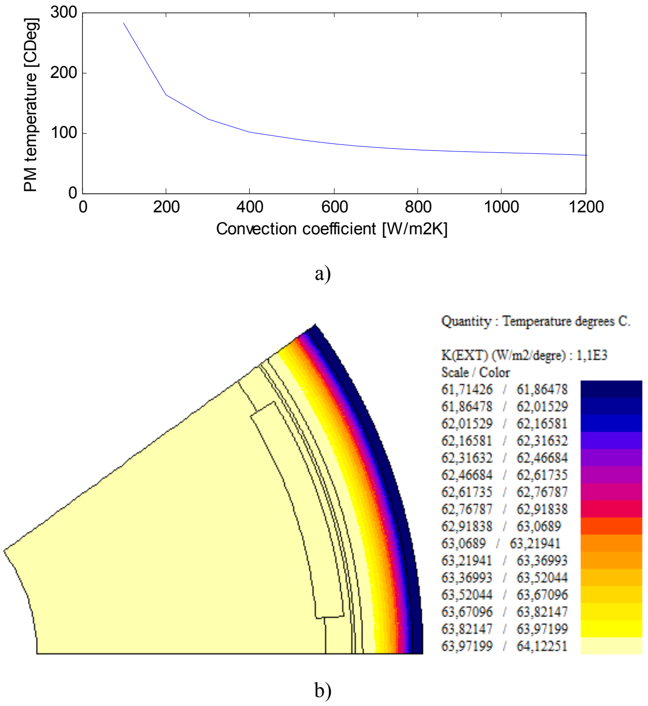
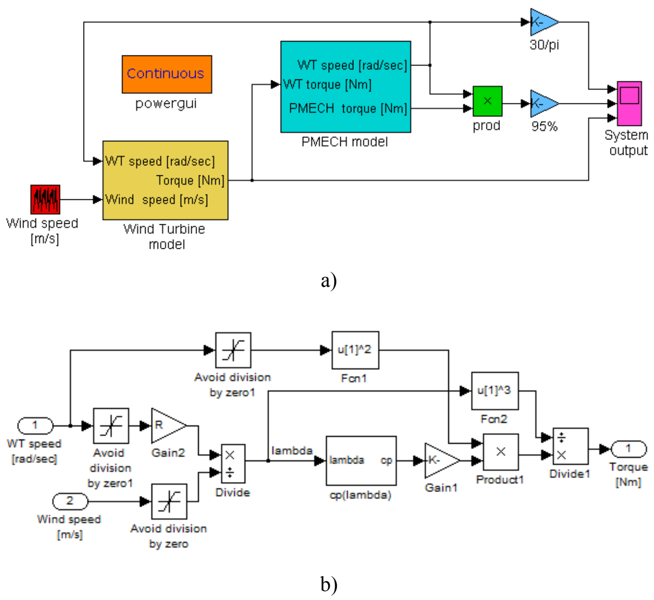


Figure 10. Results of heat transfer analysis; a) PM temperature versus convection coefficient; b) temperature field in the computation domain for a convection coefficient of 1100 W/m^{2}K.



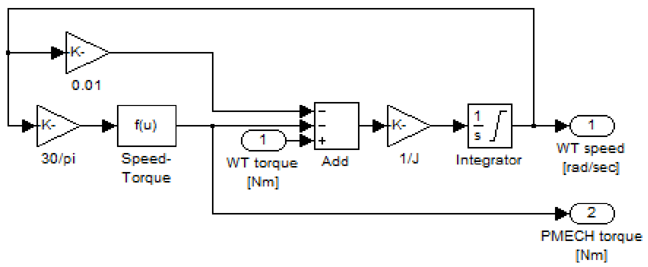


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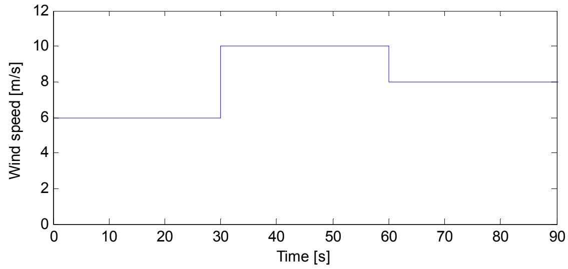
Figure 11. Dynamic model of the wind system developed under Matlab/Simulink environment; a) wind system diagram; b) wind turbine model; c) PMECH model.



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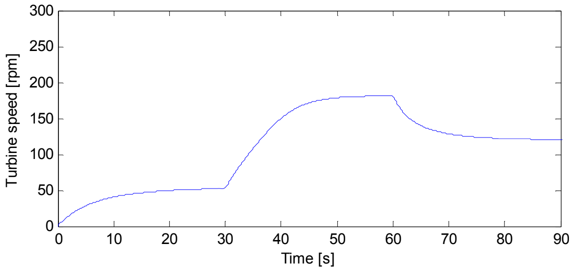

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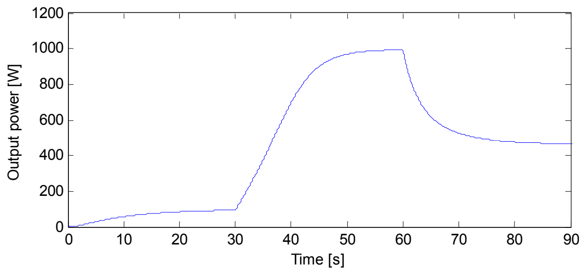

c)

Figure 12. Dynamic model results; a) wind speed profile; b) speed variation of PMECH; c) output power variation.

VII. Conclusion

A numerical analysis of a PMECH driven by a wind turbine was presented in this paper.

The phases of this study were the following: preliminary sizing of wind turbine, optimum design of PMECH from cost reduction point of view, heat transfer analysis of PMECH to estimate the thermal behavior of the device and finally the wind system analysis using a developed Matlab/Simulink dynamic model.

The numerical procedure proposed in the paper is robust and allows the design and estimation of the performance of PMECHs driven by wind turbines.

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