The Control of the Wind Power Systems by Imposing the DC Current

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Abstract - **In this paper, we present a method for controlling a wind system consisting in a wind turbine (WT) and a permanent magnet synchronous generator (PMSG) so as to achieve the operation in the optimum energy efficient zone at time-varying speeds of wind. It analyzes the operation of a WT in the maximum power zone by changing the generator load, while the wind speed varies significantly over time. The coordinates of the maximum power point (MPP) changes over time and they are determined by the values of the instantaneous wind speed and mechanical inertia. So not always the wind system can be brought quickly to operate in the MPP zone. By measuring wind speed, the optimum dc current ($I_{CC\text{-}OPTIM}$) can be obtained, the generator load can be controlled and thus it can extract the maximum mechanical energy at time-varying wind speeds.**

I. Introduction

In the literature [1-21] various mathematical models of wind turbines (MM-WT) offered by building companies and/or obtained under laboratory conditions are presented, far different from those in real conditions operation [7, 12, 19]. For this reason the final result, especially the obtained electrical energy has a value less than the maximum possible at the maximum power point (MPP) operating at optimal mechanical angular speed (MAS). In most of the work is treated the operation of the wind turbine (WT) at MPP. [3, 5, 11, 21] .In some cases, [7, 9, 15, 11, 21], there are used mathematical models which are only partially valid, because of the continuous varying weather conditions. The laboratory conditions where they have obtained the turbine characteristics are different from those in real operation [11, 15, 17].

Recent works [1, 2, 3, 4] use control algorithms based on the measurement of wind speed and prescribing optimal speed of the mechanical angular speed in the MPP region. The estimation of the optimal MAS on the basis of the wind speed is a complex problem solved by mathematical calculations and with specialized simulation software [2, 3, 5].

Method of bringing the wind system operating point in the MPP region, by appropriately modifying the electric generator load requires the measurement of the wind speed and is quite powerful, [17,19,21], in certain circumstances. It can analyze these variations in time by knowing the wind speed and given the values of the moments of inertia.

There are geographical areas where the wind speed changes its value in less time [8, 9, 17]. In Romania, the wind speed varies in time and therefore the method can be applied in certain areas only after a prior study.

The method is based on the dependency of the power of WT on MAS, that means the function $P_{WT}(\omega)$ has, at a certain speed, a maximum value for MAS, ω_{OPTIM} (Fig. 1).

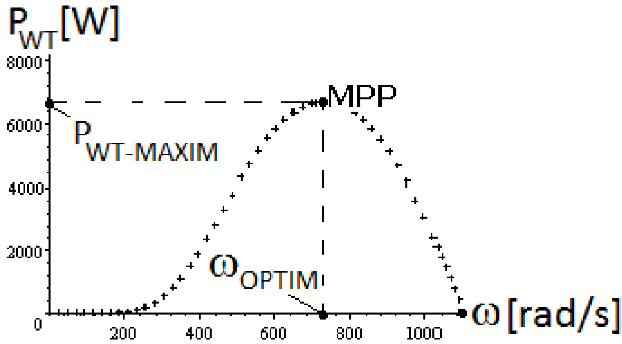

Figure.1.Power characteristic of the WT

For wind speed which does not change his value over time, the operation in the MPP region can be performed quite simply. For wind speeds which significantly vary over time, the problem becomes complex and sometimes unsolvable (if the wind quickly changes the speed).

Analysis of the MPP operation is done by simulation using specific mathematical models for WT and PMSG

By changing the PMSG load, the system tries to reach the MPP region and the transient phenomena can be visualized by solving the movement equation of the WT+PMSG system.

II. The Mathematical Model of the Wind Turbine

We will use a classical turbine model [14], which allows the estimation of the reference angular speed ω_{ref}. **The mathematical model of the WT** allows also the calculation of the optimal speed, so as the captured energy will be a maximum one.

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The power given by the WT can be calculated using the following equation:

$$P_{WT} = \rho\pi R_p^2 C_p(\lambda) V^3 \quad (1)$$

where: ρ - is the air density, R_p – the pales radius, $C_p(\lambda)$ – power conversion coefficient, $l = R\omega/V$, V- the wind speed, ω– mechanical angular speed (MAS).

The power conversion coefficient, $C_p(\lambda)$, could be calculated as follows:

$$C_p(\lambda) = c_1\left(\frac{c_2}{\Lambda} - c_3\right)e^{-\frac{c_4}{\Lambda}}, \quad (2)$$

$$\frac{1}{\Lambda} = \frac{1}{\lambda} - 0.0035, \quad (3)$$

$c_1 – c_4$ are data-book constants.

$$\frac{1}{\Lambda} = \frac{1}{\lambda} - 0.0035 = \frac{V}{R\omega} - 0.0035 = \frac{V}{1.5\omega} - 0.0035$$

By replacing, we can obtain the the power conversion coefficient as follows:

$$C_p(\lambda) = c_1\left(\frac{c_2}{\Lambda} - c_3\right)e^{-\frac{c_4}{\Lambda}} =$$

$$c_1\left(c_2\left(\frac{V}{1.5\omega} - 0.0035\right) - c_3\right)e^{-c_4\left(\frac{V}{1.5\omega}-0.0035\right)} \quad (4)$$

And the power given by the wind turbine can be calculated as follows:

$$P_{WT}(\omega, V) = \rho\pi R^2 C_p(\lambda)V^3 = 1.225\pi 1.5^2 c_1\left(c_2\left(\frac{V}{1.5\omega} - 0.0035\right) - c_3\right)e^{-c_4\left(\frac{V}{1.5\omega}-0.0035\right)}V^3 \quad (5)$$

or

$$P_{WT}(\omega, V) = \rho\pi R^2 C_p(\lambda)V^3 = k_1\left(k_2\left(\frac{V}{\omega} - 0.0525\right) - c_3\right)e^{-k_3\left(\frac{V}{\omega}-0.0525\right)}V^3 \quad (6)$$

Where $k_1 = 1.225\pi 1.5^2$, $k_2 = c_2/1.5$, $k_3 = c_4/1.5$.

For the wind turbine WT, the producer gives the experimental power characteristics, $P_{WT}(\omega, V)$, or torque characteristics $T_{WT}(\omega, V)$, the last ones being known as mechanical experimental characteristics.

$$T_{WT}(\omega, V) = {P_{WT}(\omega, V)}/{\omega} = k_1\left(k_2\left(\frac{V}{\omega} - 0.0525\right) - c_3\right)e^{-k_3\left(\frac{V}{\omega}-0.0525\right)}V^3/\omega. \quad (7)$$

The maximum value of the function $P_{WT}(\omega, V)$ is achieved for a reference MAS ω_{ref}, as follows:

$$\frac{dP_{TV}}{d\omega} = \frac{d}{d\omega}\left(k_1\left(k_2\left(\frac{V}{\omega} - 0.0525\right) - c_3\right)e^{-k_3\left(\frac{V}{\omega}-0.0525\right)}V^3\right) = 0 \quad (8)$$

and it yields

$$\omega_{ref} = \omega_{OPTIM} = 400 \cdot k_3 \frac{k_2}{400\cdot k_2 + 21\cdot k_3 k_2 + 400\cdot k_3 c_3} \cdot V = k_4 \cdot V \quad (9)$$

This result proves the direct link between reference speed and wind speed.

By replacing this result, it yields:

$$P_{WT-MAX}(V) = k_P \cdot V^3 \quad (10)$$

This result proves a cubic dependency of the WT power on the wind speed.

If the wind speed has large variations, this result must be reanalyzed.

The mathematical model of the PMSG

To analyze the behavior of the system WT-PMSG for the time-varying wind speeds, it uses orthogonal mathematical model for permanent magnet synchronous generator (PMSG) given by the following equations [5]:

$$\begin{cases} -U\sqrt{3}\sin\theta = R_1 I_d - \omega L_q I_q \\ U\sqrt{3}\cos\theta = R_1 I_q + \omega L_d I_d + \omega\Psi_{PM} \\ T_{PMSG} = p_1(L_d - L_q)I_d I_q + I_q\Psi_{PM} \end{cases} \quad (11)$$

where: U – stator voltage

I_d, I_q – d-axis and q-axis stator currents

θ – load angle

R_1 – phase resistance of the generator;

L_d - synchronous reactance after d axis;

L_q - synchronous reactance after q axis;

Ψ_{PM} - flux permanent magnet;

T_{PMSG} - PMSG electromagnetic torque

III. Operating control in the MPP region

The study of operation in the MPP region will be performed by simulation using the following mathematical models

The mathematical model for the WT (MM-WT)

For the wind turbine, the producer provides the experimental power characteristics [14], $P_{WT}(\omega, V)$

$$P_{WT}(\omega, V) = 1191.5 \cdot (V/\omega - 0.02) \cdot e^{-98.06\cdot(V/\omega)} \cdot V^3 \quad (12)$$

The reference MAS, ω_{ref}

The maximum value of the function $P_{WT}(\omega, V)$ is obtained for the reference MAS, ω_{ref}, by differentiation:

$$\frac{dP_{WT}(\omega, V)}{d\omega} = \frac{d}{d\omega}\left(1191.5 \cdot (V/\omega - 0.02) \cdot e^{-98.06\cdot(V/\omega)} \cdot V^3\right) = 0 \quad (13)$$

$$\omega_{ref} = 31.115 \cdot V \quad (14)$$

For this value of MAS, the maximum power is obtained:

$$1191.5 \cdot (V/\omega - 0.02) \cdot e^{-98.06\cdot(V/\omega)} \cdot V^3 = 0.61884 \cdot V^3 \quad (15)$$

$$P_{WT-MAX} = 0.61884 \cdot V^3 \quad (16)$$

The mathematical model for the PMSG (MM-PMSG)

From the nominal values of the PMSG [1], for the nominal power: $P_N = 5$ [kW], it yields $R_1 = 1.6$ [W], $L_d = 0.07$ [H], $L_q = 0.08$ [H], $\Psi_{PM} = 1.3$ [Wb].

From the equations of the PMSG, it obtains

$$\begin{cases} -R\,I_d = 1.6 I_d - \omega \cdot 0.08 \cdot I_q \\ -R\,I_q = 1.6 I_q + \omega \cdot 0.07 \cdot I_d + \omega\Psi_{PM} \\ T_{PMSG} = -0.01 \cdot I_d I_q + I_q \Psi_{PM} \\ \Psi_{PM} = 1.3 \\ P = \left(I_d^2 + I_q^2\right) \end{cases} \quad (17)$$

$$P_{PMSG} = 4225R\omega^2 \frac{4\omega^2+625R^2+2000R+1600}{(1250R^2+4000R+3200+7\omega^2)^2} \quad (18)$$

$$T_{PMSG} = 845\omega(5R+8) \cdot \frac{4\omega^2+625R^2+2000R+1600}{(1250R^2+4000R+3200+7\omega^2)^2} \quad (19)$$

$$U_{CC} = 500\ [V] \quad (20)$$

$$P_{PMSG} = U_{CC} \cdot I_{CC} \quad (21)$$

$$I_{CC} = P_G/U_{CC} \quad (22)$$

The value of ICC results from the wind speed.

In order to operate in the MPP region, the control method has two aspects:

- wind speed is constant over time
- wind speed varies over time

3.1 Case study at constant wind speed v=22 [m/s]

The optimal values for MAS and $P_{WT\text{-}MAX}$ are obtained from (14) and (16):

ω_{OPTIM} = 728.54 [rad/s], and

$P_{WT\text{-}MAX}$ = 6696.3 [W]

It shows further two control methods for wind systems

1) by imposing the current Icc;

2) by using regulators

3.1.1. The control system by imposing the current Icc

By imposing the conduction angle of the converter between PMSG and the network, different values for load resistance and thus for the current Icc are obtained.

For a load resistance of R_0 = 33 [Ω] , the mechanical characteristic of the generator has the following expression, from (19):

$$T_{PMSG} = 845\omega(5 \cdot 33+8) \cdot \frac{4\omega^2+625 \cdot 33^2+2000 \cdot 33+1600}{(1250 \cdot 33R^2+4000 \cdot 33+3200+7\omega^2)^2} \quad (23)$$

And for an initial speed value of ω_0 = 800 rad/s, the WT motor torque is lower than the resistant PMSG torque $T_{WT} \ll T_{PMSG}$ and the operating point will follow the WT mechanical characteristic starting from the initial point F0, to the maximum point MPP(728.54,6696.3) (Fig.2.)

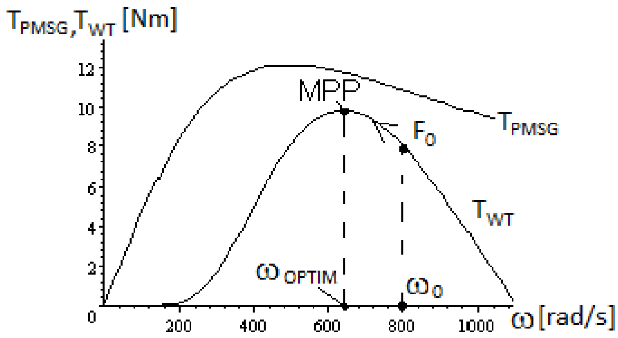

Figure 2. Mechanical characteristics for WT and PMSG

The analysis of the dynamic regime is performed by simulations, starting from the movement equation:

$$J\frac{d\omega}{dt} = T_{WT} - T_{PMSG} \quad (24)$$

where J is equivalent inertia moment, T_{PMSG} is the torque of PMSG, T_{WT} is the torque of WT .

The power acquired by the PMSG is found in the intermediate circuit power and, from this equation, the I_{CC} current is obtained.(18) and (20) - (22)

$$I_{CC} = \frac{P_{PMSG}}{U_{CC}} = \left(4225R\omega^2 \frac{4\omega^2+625R^2+2000R+1600}{(1250R^2+4000R+3200+7\omega^2)^2}\right)/500 \quad (25)$$

The movement equation for the load resistance R_0 = 33 [Ω] is the following:

$$\begin{cases} 45\frac{d\omega}{dt}\omega = 1191.5 \cdot (22/\omega - 0.02) \cdot e^{-98.06 \cdot (22/\omega)} \cdot \\ 22^3 - 845\omega(5 \cdot 33+8) \cdot \frac{4\omega^2+625 \cdot 33^2+2000 \cdot 33+1600}{(1250 \cdot 33R^2+4000 \cdot 33+3200+7\omega^2)^2} \\ \omega(0) = 800 \end{cases} \quad (26)$$

From this we can obtain the variation of MAS and current ICC. (Fig.3 and Fig.4)

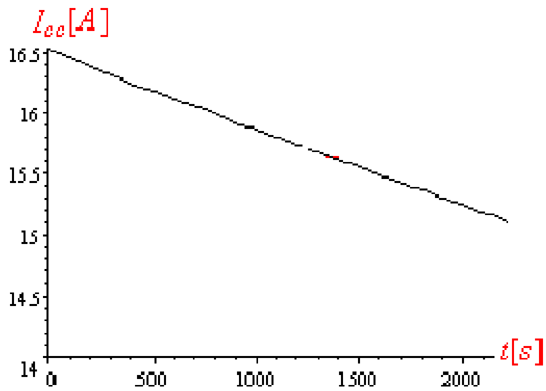

Figure 3. Time variation of the current *Icc*

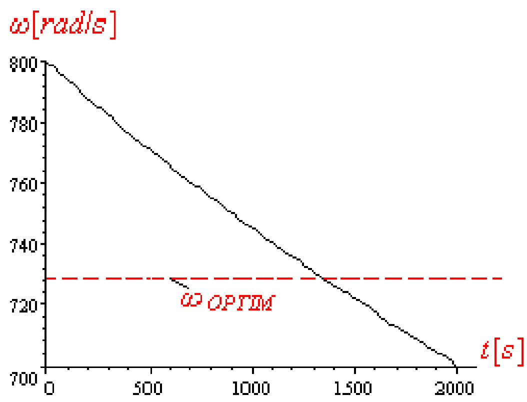

Figure 4. Time variation of the MAS

It can observe that the optimal values for MAS and I_{CC} are at t=1333 [s].

After that, the load resistance is imposed at its optimal value, obtained from

$$P_{WT} = P_{PMSG} \quad (27)$$

with v=22 [m/s], ω = 728.54 .[rad/s].

The solution is

$$R_{OPTIM} = 109.27\ [\Omega] \tag{28}$$

The time variation of MAS at R=109.27 is presented in Fig. 5

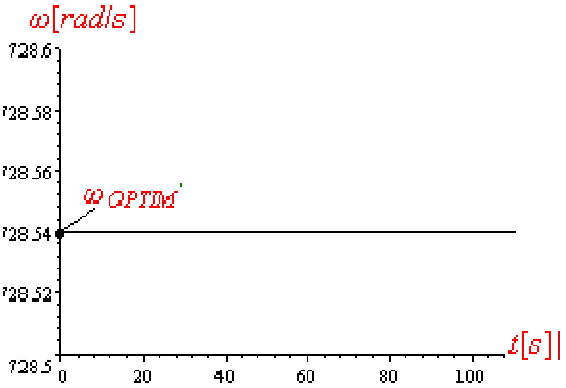

Figure 5. Time variation of the MAS for R = 109.27 [Ω]

Is can see from Fig.5 that we have a steady-state process, the MAS is constant.

$I_{CC\text{-}OPTIM}$ is obtained for R_{OPTIM} = 109.27 [Ω] and ω_{OPRIM} = 728.54.[rad/s] from (28):

$$I_{CC\text{-}OPTIM} = 13.2\ [A] \tag{29}$$

The current $I_{CC\text{-}OPTIM}$ is obtained by (Fig.6) measuring the wind speed with the anemometer (AN). This value is imposed by controlling the switches from the power converter (PC).

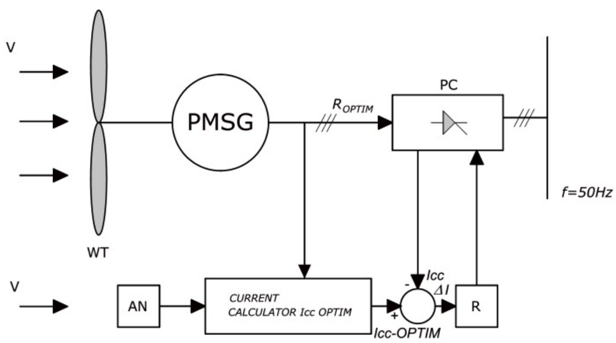

Figure 6. Block diagram of the wind system with imposed dc current.

3.1.2. The control system using regulators

The starting point is the movement and the regulator equations:

$$\begin{cases} 50\dfrac{d\omega}{dt} = T_{WT} - T_{PMSG} \\ \dfrac{dR}{dt} = K_1\dfrac{d\omega}{dt} + K_2(\omega - \omega_{ref}) \end{cases} \tag{30}$$

The initial conditions are:

$\omega(0)$ = 800 [rad/s] and R(0) = 46 [Ω]

PI controller error has as input the current error Δt and as output the switching angle. The reference value is $I_{CC\text{-}OPTIM}$. The tuning of the regulator is a complex problem and is not discussed now. It can be done by successive simulations.

3.2. Case study at variable wind speeds.

For a variable wind speed with the period T, [2], as presented in Fig. 7, it can consider:

T = 35 [s], A = 7 [m/s], V_{MED} = 15 [m/s].

$$V(t) = 15\text{-}7\sin 0.17943t \tag{31}$$

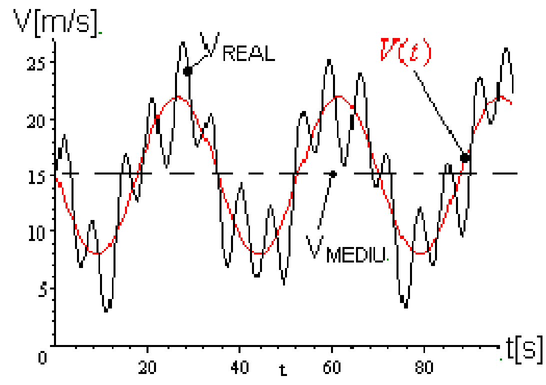

Figure 7. Wind speed over time

$$W_{mec} = \int_0^T P_{WT}\cdot dt = \int_0^T 1191.5\left((15-7\sin 0.17943t)/\omega - 0.02\right)e^{-98.06((15-7\sin 0.17943t)/\omega)}(15-7\sin 0.17943t) \tag{32}$$

With the approximation ω = ct, the optimum speed is obtained

$$\omega_{OPTIM\text{-}2} = 571\ [rad/s] \tag{33}$$

3.2.1 The control system by imposing the current Icc

First step is to obtain different steady-states of the system, by simulation using different load resistances.

The problem to be solved is: which is the value of load resistance when the process enters into the steady-state regime?

It can see that for R = 260 [Ω] the process is in steady-state regime (Fig. 8a and 8b)

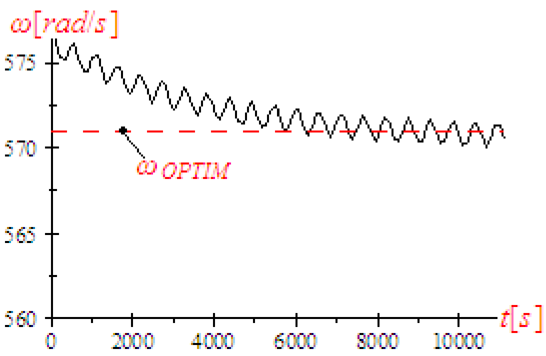

Figure 8a. Time variation of the MAS at ω(0) = 577 [rad/s]

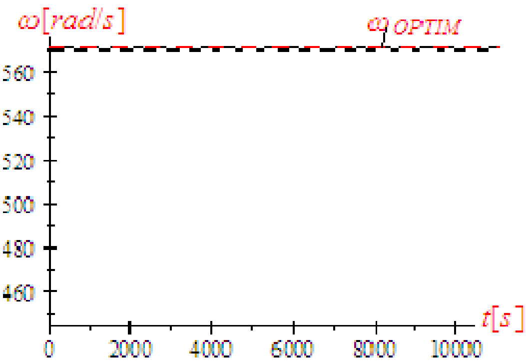

Figure 8b. Time variation of the MAS at ω(0) = 571 [rad/s]

For the load resistance R_0 = 260 [Ω] and at optimum MAS $\omega_{OPTIM\text{-}2}$ = 571 [rad/s], from (21) and (23)-(25) it yields:

$$I_{CC\text{-}OPTIM\text{-}2} = 4.0932 \text{ [A]} \tag{34}$$

Determination of $I_{CC\text{-}OPTIM}$ based on the wind speed

The direct link between the wind speed and the current $I_{CC\text{-}OPTIM}$ can lead to shorter regulation periods. Further, will check for an equation as follow:

$$I_{CC} = k_1 \cdot V_{ECH}^3 \tag{35}$$

where k_1 is the constant of the system WT+PMSG and V_{ECH} is the equivalent wind speed. The constant k_1 is obtained at V=22 [m/s]. For $I_{CC\text{-}OPTIM\text{-}2}$ = 4.0932 [A] the system enters into the steady-state regime and the MAS remains at its optimal value $\omega_{OPTIM\text{-}2}$ = 571 [rad/s]. So, for a wind speed given by (34) it yields an equivalent wind speed

$$V_{ECH} = 14.89\ [m/s] \tag{36}$$

Since WT power depends on the cube of the wind speed and WT performs an integration of speed (by the equivalent inertia moment), the integration of the function V(t) on a time interval T= 35[s] is proposed. The time is imposed by the wind speed oscillation period.

$$V_{ECH} = \left(\frac{1}{T}\int_0^T \sqrt[n]{(V(t))dt}\right)^n \tag{37}$$

With (34), (38) and (39), the optimum current is obtained:

$$I_{cc} = 1.2397 \cdot 10^3 \cdot \left(\frac{1}{T}\int_0^T \sqrt[1.15]{(V(t))dt}\right)^{3.45} \tag{38}$$

3.2.2 **The control system using regulators**

The equations are identical with (33) with the initial conditions ω(0) = 577 [rad/s] and R(0) = 266 [Ω]. The approach is similar with paragraph 3.2.1 (constant wind speed), with the observation that the wind speed is given by (31).

Some results are presented in Fig. 9a, 9b, 10a and 10b.

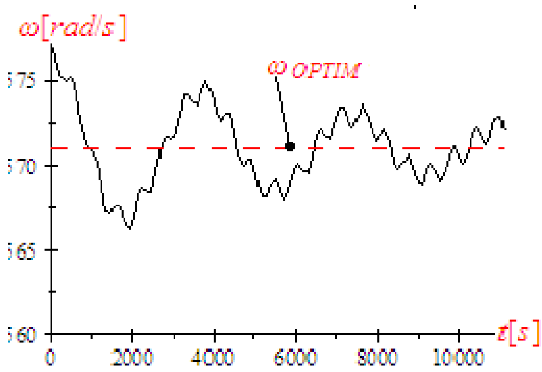

Figure 9a. Time variation of the MAS for K_2=-0.01 and ω(0) = 577 [rad/s]

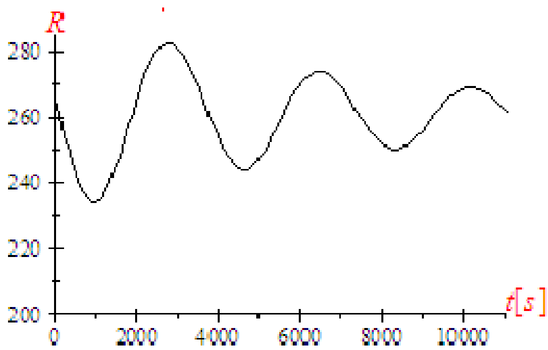

Figure 9b. Time variation of the load resistance for K_2=-0.01 and ω(0) = 577 [rad/s]

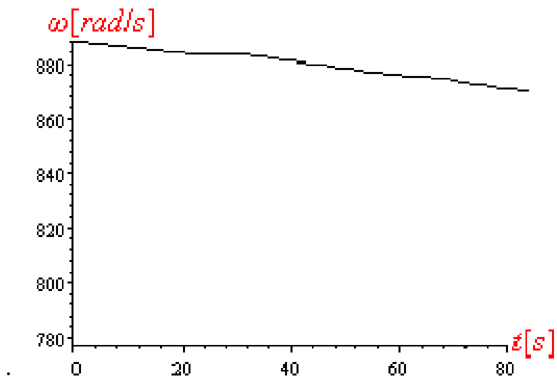

Figure 10a. Time variation of the MAS for K_2=-0.01 and ω(0) = 888 [rad/s]

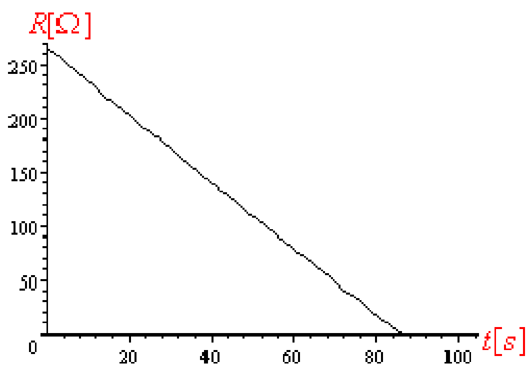

Figure 10b. Time variation of the load resistance for K_2=-0.01 and ω(0) = 888 [rad/s]

From these simulations we can conclude that the initial MAS, ω(0) determine the system behavior, as follows:

-for ω(0) = 577 [rad/s] the system is stable

-for ω(0) = 888 [rad/s] the system is became unstable

IV. CONCLUSIONS

From the simulations performed in this paper we were able to observe the differences in WT behavior caused by imposing different loads on PMSG. The best results are obtained by imposing the optimal value of the current Icc_{-OPTIM}. The PI regulator introduces some oscillations and a longer period of time to get the stabilized regime. Using regulators at the time-varying wind speeds and various values for the initial MAS introduces some difficulties For different initial MAS, the controllers must be re-tuned. By knowing the optimal load current value, the generator load can be controlled to achieve the maximum energy. By analyzing several cases we were able to establish basic parameters that lead to optimal behavior and this can be achieved by measuring wind speed and calculate the optimal load current.

We determined the relationship between wind speed and optimum dc current at which the system must operate so that the captured wind energy has a maximum value. By knowing the value of the optimum dc current the generator load can be adjusted so as to achieve the maximum energetic operation. Based on the motion equation, the optimal value for MAS has been obtained, ω_{OPTIM}, for wind speed variations. Also the dependence of $I_{CC-OPTIM}$, by wind speed was determined.

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