Continuously Variable Transmission (CVT) Optimal Regulation Curves in a Small Wind Energy Conversion (WEC) System

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ABSTRACT: *In the current work, we have given a simple parameter-based analytical approach for calculation of continuously variable transmission (CVT) optimal regulation curves in a small wind energy conversion (WEC) system. A CVT is placed between turbine's rotor and an induction generator directly connected to the power system, enabling better utilization of available wind power. We have developed methods to calculate the optimal CVT regulation curve in details and has been applied to the small WEC with rated power of 55 kW. Effects of generator's winding resistance variation, caused by temperature change, have been studied further. During the testing we found that there is no impact of the calculated curves on the normally expected changes of the winding's resistances.*

Keywords: Wind turbine, Induction Generator, Winding Temperature, CVT, Optimal Regulation

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1. Introduction

The crucial part of any wind energy conversion system (WEC) is a wind turbine itself, being an element, whose role is to accept kinetic energy of the airflow and to convert it to the driving mechanical torque on the generator's shaft. Accepted aerodynamic theory defines that there is the absolute maximum of a wind turbine's efficiency that cannot be exceeded under any circumstances (0.596), which is also known as the Betz limit ([1]). From the historical point of view, efficiency of energy conversion in older designs of wind turbines (such as Savonius turbine or American farm wind turbine), could not reach neither the half of the mentioned theoretical limit. Even in contemporary engineering solutions, obtained by intensive usage of computer-aided design methods, there are no significant breakthroughs that could be regarded as an efficiency "very close to the Betz limit". For example, modern designs of three-blade horizontal axis wind turbines (HAWT) allow the wind energy conversion with the maximum efficiency of about 0.5.

Described problem is further complicated by the fact that the efficiency of the wind energy conversion is, in general, a highly-nonlinear function, depending on both actual angular speed of the rotor and actual velocity of the wind. In order to reach the optimal operating point, characterized by the maximum efficiency, it is necessary to achieve exact, optimal ratio between rotor's angular speed and actual wind velocity. The value of this ratio differs from one type of wind turbine to another, but it is obvious that, when wind velocity varies, angular speed of the rotor also has to be varied. Otherwise, the wind turbine will not extract the maximum of available kinetic energy from the wind.

Since the rotor of the driven generator has to rotate at constant, or almost constant speed (depending on if a synchronous or an induction generator is applied), in order to deliver power to the electric power system (EPS) with constant frequency, it is necessary to exploit some additional technical devices for solving of the mentioned problem. Contemporary solutions are mostly based on intensive usage of power electronic devices that enable some type of indirect coupling between the EPS and the generator. This approach enables that, despite of constant frequency in the EPS, angular speed of the generator's rotor can be varied in considerably wide range. However, these solutions also have significant drawbacks, at the first line regarding very complex control of power electronic devices and harmonic distortion of generated power .

Although the commercial use of continuously variable transmission (CVT) was introduced by automotive industry more than a half century ago, in recent decades this concept has also occupied the interest of researchers and producers in the area of WEC systems ([2],[3]). There are several studies indicating that an CVT incorporated with a wind turbine can completely substitute power electronics in performing the task of optimal operating point tracking, while the generator is directly connected to the EPS. Main concerns related to wider usage of CVT in small WEC systems are questions about reliability, durability, and also limited capacity for transfer of mechanical energy. However, in [4] was shown that, with innovative approach and careful design of CVT, these problems could be mitigated. In [5], utilization of cage rotor induction generators in CVT based WEC systems has been suggested and some issues related to synchronization with EPS have been discussed. In [6] method for calculation of optimal CVT regulation curves for a WEC system with an induction generator directly connected to the EPS has been proposed, and also effects of the EPS voltage variations on calculated curves have been studied.

The goal of this paper is to study effects that variations of generator's windings resistance, caused by changes of their temperature, could have on optimal CVT regulation curve. The method used for calculation of optimal CVT regulation curves is similar to the one described in [6], however, analysis is directed to different aspects of the problem.

2. Identification of the Problem

Layout of the WEC system studied in this paper is presented in Figure 1.

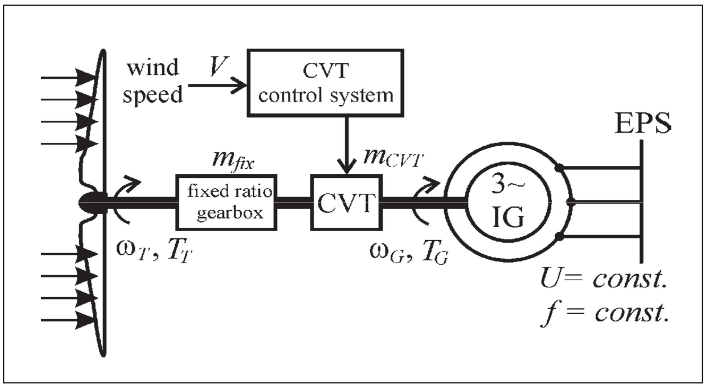

Figure 1. Layout of the analyzed WEC system

It consists of a HAWT, a fixed-ratio drive train, a CVT and a three-phase cage-rotor induction generator (IG), connected directly to the electric power system.

Induction generator can be represented by its equivalent circuit, shown in Figure 2. The main difference that can be noticed, compared to the standard equivalent circuit is that stator and rotor resistances, R_S and R_R are considered as variable elements, whose values depend on the actual temperature of the winding θ.

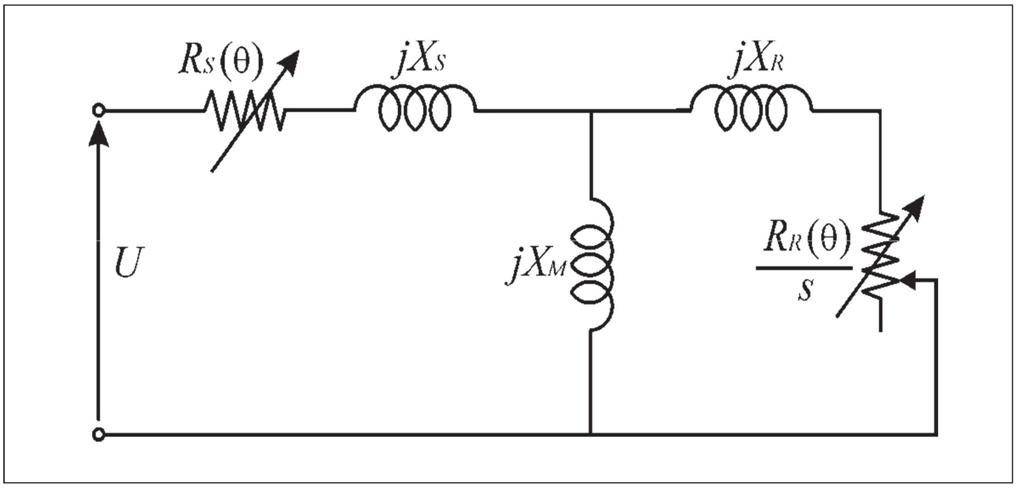

Figure 2. Equivalent circuit with variable stator and rotor resistances

This approach is justified by the fact that wind is very unpredictable and uncontrollable source of mechanical power, and as a consequence, operation of IG cannot be considered as stationary operation with constant load. Instead, it is likely that IG would operate in unpredictable cycles, while winding temperature could vary from ambiental temperature θ_a, to the maximum allowed value θ_{hMAX} defined by the temperature tolerance class of insulation material.

Such variations in temperature will result in variations of actual winding resistances, according to the equation

$$R_h = R_a \frac{A+\theta_h}{A+\theta_a} \tag{1}$$

where $R_h\,[\Omega]$ is resistance of the hot winding, related to the increased temperature $\theta_h\,[^oC]$, $R_a\,[\Omega]$ is resistance of the winding at the ambiental temperature $\theta_a\,[^oC]$, and $A = 235$ (if windings are made of copper), or $A = 255$ (if windings are made of aluminum).

Mentioned changes of winding resistances will further cause slight degeneration of generator's torque-speed curve, and will affect the optimal CVT regulation curve in some extent. In the next section of the paper, basic mathematical model of the analyzed WEC system is presented.

2.1. Mathematical Model

Mechanical power extracted from the wind by HAWT is given as:

$$P_T = 0.5\rho\pi R^2 V^3 C_p(\lambda,\beta) \tag{2}$$

where ρ is the density of the air $[kg/m^3]$, R is the radius of the turbine's rotor $[m]$ and V is the wind speed in $[m/s]$. In Eq. (2), $C_p(\lambda,\beta)$ is non-dimensional power coefficient, depending on the actual tip speed ratio:

$$\lambda = \frac{\omega_T R}{V} \tag{3}$$

and on actual rotor's blades pitch angle β. In the normal operating region, where optimal regulation is exploited, angle $\beta = 0$ and the power coefficient is a nonlinear function of tip-speed ratio only. Producers of wind turbines usually give function $C_p(\lambda)$ in the form of look-up table, but there are also different analytical expressions that are exploited for WEC system studies. The curve used in this paper is shown in Figure 3.

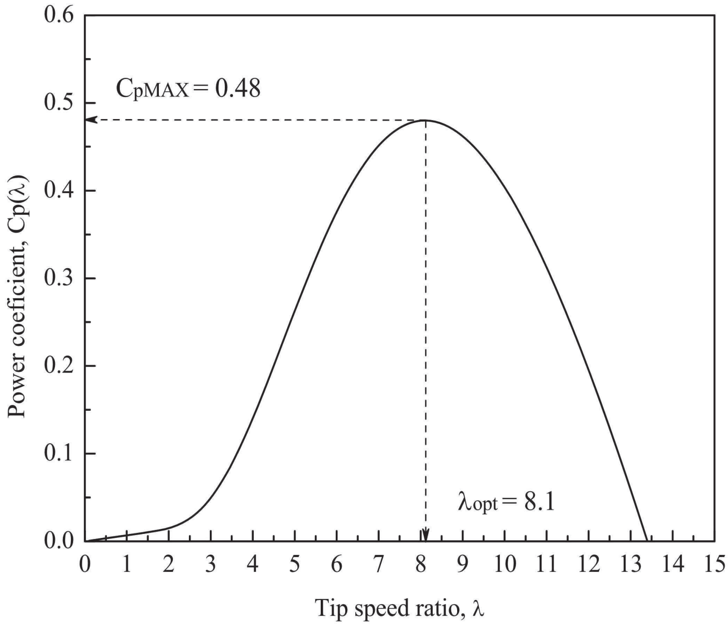

Figure 3. Power coefficient curve of the analyzed wind turbine

It is very important to understand that the complete shape of the power coefficient curve and its accurate mathematical formulation are not necessary for the analysis presented in this paper. It is enough to know accurate coordinates of the optimal operating point $(\lambda_{opt}, C_{pMAX})$.

Using the general definition of a mechanical torque, and also Eqs. (2) and (3), the actual torque developed by HAWT can be expressed as:

$$T_T = \frac{\rho \pi R^3 V^2}{2\lambda} C_p(\lambda) \tag{4}$$

The electromagnetic torque of the induction generator (which acts as braking torque) is defined by the actual value of voltage U in the EPS, but also depends on the actual angular speed of the generator's shaft ω_G which is not constant, and also on parameters of the machine's equivalent circuit. It is defined as:

$$T_{eG} = \frac{3}{\omega_S} \cdot \frac{R_R}{s} \cdot \frac{U^2}{\left(R_S + \nu \frac{R_R}{s}\right)^2 + \left(X_S + \nu X_R\right)^2} \tag{5}$$

where R_S is stator resistance, R_R is rotor resistance, X_S is stator leakage reactance and X_R is rotor leakage reactance.

Synchronous angular speed of the generator ω_S depends on number of the machine's pole pairs p and, for the constant frequency f in the EPS, it is defined as $\omega_S = 60 f / p$.

The value of generator's relative slip s can be calculated as

$$s = (\omega_S - \omega_G) / \omega_S \tag{6}$$

and finally, stator's leakage coefficient ν figuring in Eq. (5) can be determined as $\nu = 1 + X_S / X_M$, where X_M is the magnetizing reactance of the generator.

$$m_{tot} = m_{fix} \cdot m_{CVT} \tag{7}$$

where m_{fix} is the transfer ratio of the fixed drive train, and m_{CVT} is the actual transfer ratio of the applied CVT, which can take arbitrary value between the limits defined by the construction. In order to simplify analysis at this stage, it is considered that transmission is ideal and that all friction losses can be neglected. With such assumptions, static equilibrium of the analyzed WEC system is defined by

$$T_T + m_{tot} T_{eG} = 0 \tag{8}$$

2.2. Method for Calculation

Using Eqs. (3) (4), (5), (6), and also the Eq. (9) connecting angular speeds ω_G and ω_T,

$$\omega_G = m_{tot} \omega_T \tag{9}$$

Equation (8) can be rewritten as:

$$0 = \frac{\rho \pi R^2 V^2 C_p(\lambda)}{2\lambda} + \frac{3 m_{tot} R_R}{R\omega_S - m_{tot} V\lambda} \cdot \frac{U^2}{\left(R_S + \frac{\nu R_R R \omega_S}{R\omega_S - m_{tot} V\lambda} \right)^2 + \left(X_S + \nu X_R \right)^2} \tag{10}$$

Substituting values for $\lambda = \lambda_{opt}$ and $C_p(\lambda) = C_{pMAX}$ into the Eq. (10), and considering U, f and all parameters of the equivalent circuit except $R_S(\theta)$ and $R_R(\theta)$ are constant, we obtain function

$$g(V, m_{tot}, R_S, R_R) = 0 \tag{11}$$

describing the optimal operation of the analyzed WEC.

Previous relation allows possibility that stator and rotor winding resistances are not constant. If Eq. (11) is solved for a chosen, arbitrary combination of R_S and R_R as parameters, and for an arbitrary value of wind speed V, obtained solution for $m_{tot} = m_{opt}$ represents the optimal total transfer ratio, desired for reaching the optimal operating point. If chosen combination of parameters R_S and R_R is kept, further solving of Eq. (11) for different discrete values of V results in identification of points that describe functional dependency $m_{opt} = h(V)$, valid for the chosen combination of *RS* and *RR* . Finally, it is now possible to calculate another set of optimal CVT transfer ratios $m_{CVTopt} = f(V)$, using Eq. (7) and known fixed gear transfer ratio m_{fix}.

It is not necessary to derive the exact solution of Eq. (11) in a closed form. Instead, it is possible to exploit *fzero* function from the *Matlab Optimization Toolbox*, whose application for chosen R_S, R_R and V successfully leads to the identification of the optimal total transfer ratio m_{opt}.

3. Calculated Results

The explained analytical approach was used to calculate optimal CVT transfer ratios for the small WEC system consisted of 3-blade HAWT whose parameters are $P_{Tn} = 55\ kW$, $R = 5.9\ m$, $V_n = 12\ m/s$, $C_{pMAX} = 0.48$, $\lambda_{opt} = 8.1$, $m_{fix} = 14$, and of 4-poles, three phase cage rotor induction machine with nameplate data (given for motoring mode of operation) $P_n = 55\ kW$, $U_n = 400V$, $f_n = 50\ Hz$, $I_n = 101.5$ A, Δconnection, thermal tolerance class F. All reactances from the equivalent circuit shown in Figure 2 are considered as constant and their values are $X_S = X_R = 0.754\ \Omega$ and $X_M = 20.83\ \Omega$. Stator and rotor resistances are treated as variable parameters, depending on the actual temperature rise in windings. The first pair of resistances (R_{Sa}, R_{Ra}) that has been used for calculation were resistances valid for the supposed ambiental temperature of $\theta_a = 20^o C$, and their values have been taken as $R_{Sa} = 0.14\Omega$ and $R_{Ra} = 0.19\Omega$. The second pair of resistances used for calculation (R_{Sh}, R_{Rh}) has been related to the temperature of hot windings $\theta_{hMAX} = 155^o C$, which is the maximum allowable operation temperature for the temperature tolerance class F. Using Eq. 1, and knowing that stator winding is made of copper, while rotor cage is made of aluminum, resistances of hot windings have been determined as $R_{Sh} = 0.214\Omega$ and $R_{Rh} = 0.283\Omega$. Values of wind speed have been varied in the range between the cut-in speed $V_{ci} = 5\,m/s$ and the nominal wind speed $V_n = 12\,m/s$, using incremental steps of $\Delta V = 0.1 m/s$. Calculated results for optimal regulation of CVT transfer ratio $m_{CVTopt} = f(V)$ are shown in Figure 4.

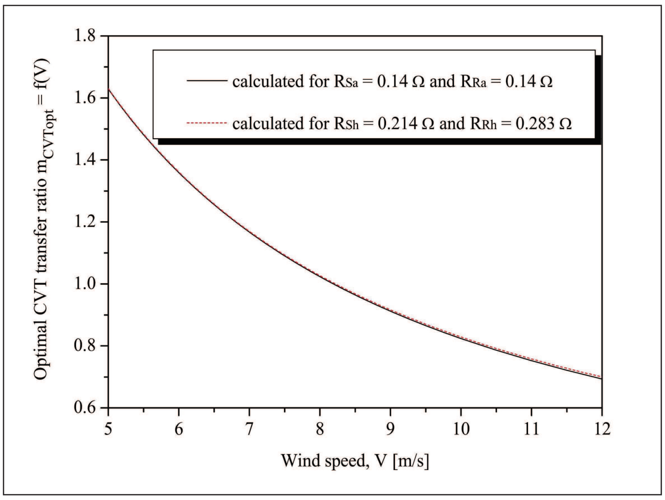

Figure 4. Calculated optimal CVT regulation curves

At low wind speeds, total transfer ratio *mtot* has to be high in order to enable optimal operation of wind turbine. In such regimes, turbine should rotate slowly, extracting maximum of available mechanical power from the wind. As the wind speed increases, turbine's angular speed has also to be increased; otherwise, it will not operate with power coefficient $C_p = C_{MAX}$ anymore. Since generator's angular speed can not be increased in a desired amount, due its direct connection to the power system, the total transfer ratio has to take lower values. This action can be performed using a control system for achieving the optimal transfer ratio of the exploited CVT, according to the calculated optimal regulation curve, $m_{CVTopt} = f(V)$. In the region of low wind speeds, CVT has to be controlled in the way that its transfer ratio is greater than 1. As the wind speed is increased, transfer ratio of the CVT has to take lower values, keeping the wind turbine in the optimal operating point. Information shown in Figure 4 can be of great interest during synthesis of any CVT control system. In the region characterized by low wind speeds (i.e. in the region where $m_{CVTopt} > 1$), it is almost not possible to notice any difference between calculated curves. Small drift occurs only in the region of wind speeds close to the V_n, but it is still less than 1%, although the rise in resistances of about 50% has been taken into consideration. It is obvious that if temperature of windings is increased to the highest value acceptable for normal operation, optimal CVT transfer ratio should be just slightly increased. This can be explained by the nature of the induction generator's torque-speed curve, because with higher resistance of windings, machine will develop optimal electromagnetic braking torque at somewhat higher rotational speed, compared to the situation when windings are cold.

4. Conclusion

Applying the methodology presented in the paper, for any WEC system with a cage rotor induction generator directly connected to the electric grid, the optimal CVT transfer ratio can be calculated as the function of actual wind speed. As the presented approach does not require complete shape of the turbine's power coefficient curve, it can be very useful tool for synthesis of a control system. Although temperature changes can cause significant variation of resistances in stator and rotor windings, presented results clearly show that such variation has no significant impact on calculated optimal CVT transfer ratio regulation curves. Obtained information is very important, since it enables more comfort during the design process of an appropriate CVT regulator.

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