Electric Driven Continuously Variable Transmission for Wind Energy Conversion System

Claudio Rossi, Piero Corbelli, Gabriele Grandi
Dept. of Electrical Engineering - University of Bologna, Italy
Viale Risorgimento 2, 40136 Bologna, Italy. Tel.:+3905193564 Fax:+3905193588
claudio.rossi@unibo.it, piero.corbelli@unibo.it, gabriele.grandi@unibo.it

***Abstract* — This paper investigates the possibility to use a power split electric driven continuously variable transmission as the core of a wind energy conversion system.**
The proposed power split transmission for WECS, called W-CVT, allows to control the speed of the turbine rotor by keeping constant the speed of the electric generator. The W-CVT is constituted by a planetary gear set integrated with a small size electric machine. This device is installed between the step-up gearbox and a fixed speed fixed frequency electric generator. The limitation of the transmissible torque between the rotor and generator due to the introduction of the W-CVT could preserve the system components during wind-gusts or electric faults on the grid side. This paper introduces the W-CVT concept, the dynamic model of a complete WECS transmission based on the W-CVT, a design criteria for sizing the CVT, simulations and experimental results obtained with this system.

I. INTRODUCTION

Wind Energy Conversion System (WECS) is considered one of the most important application of variable speed constant frequency (VSCF) system. Grid integration of the WECS requires to generate electric power at constant frequency. The need to maximize the power with fluctuating wind requires regulation of the turbine mechanical speed.

Among the possible combinations of converter, generator, and gearbox for WECS in the power range 100kW - 3MW, the use of a Wound Rotor Induction Generator WRIG coupled to a fixed ratio gearbox represents the most common solution [1],[2]. Up to now a minor interest seems to be paid to the gearless solutions based on the use of multi-pole synchronous generators. These direct drive solutions are still very expensive due to the full scale AC/AC converter required for grid integration [3],[4].

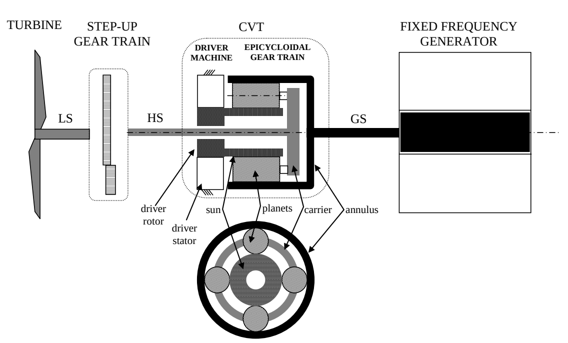

Fig. 1 Scheme of the CVT for WECS

WRIG for WECS are based on a 4 or 6 poles machine with stator phases directly connected to the grid, and rotor phases connected through slip rings to a bidirectional power converter. This configuration allows the WRIG to operate both in sub-synchronous and super-synchronous conditions. In WRIG, for example, to regulate the speed from 50% to 100% of the rated speed, the rotor converter must be sized for 30% of the stator power rating.

This paper deals with a driveline for WECS based on a Continuously Variable Transmission (CVT) placed at the high speed end of the step up gear train. The CVT decouples the variable speed of the gear train output from the fixed (or quasi fixed) speed of the generating machine. In this way the electric generator can be a conventional wound rotor synchronous machine or a squirrel cage induction machine with 4 or 6 pole, directly connected to the grid.

The CVT is constituted by a mechanical differential gearbox integrated with an additional electric machine called driver.

A variable speed control of this driver machine allows to adjust the step up ratio of the CVT in a speed range which is larger than that obtained with traditional WRIG drive systems. This solution was proposed for the first time 25 years ago [5], but the early development stage of variable speed drive did not allow to obtain satisfactory results. More recently the use of a CVT transmission for WECS based on a differential gearbox appeared again [6], [7] but in these cases it is driven by a hydrodynamic system, which determines a high level of complexity and decreases the efficiency.

A schematic drawing of the CVT presented in this paper is shown in fig. 1. The CVT is constituted by a planetary gear stage, where the power from the high speed end (HS) of the step up gear train is supplied to the carrier, the output power delivered to the electric generator is taken from the annulus shaft (GS) and the sun is driven by a variable speed electric drive. In this way the sun acts as driver, adjusting the speed ratio between the carrier and the annulus. This configuration can be considered a simplified version of the electric CVT (E-CVT) now widely developed for hybrid vehicles [8]. In the proposed system the speed control of the driver machine determines the capability to regulate the speed of the turbine across a wide range, by maximizing the power extraction from the wind for wind speed below the rated speed.

In the following Sections a detailed description of the CVT based power transmission of a WECS is given.

II. System Description

A. Wind Turbine Characteristic

Wind turbines are usually modelled by using the following relationship between the wind speed and the mechanical power extracted from the turbine shaft [9]:

$$\boldsymbol{P}_W = \frac{1}{2}\rho \boldsymbol{A}_r \boldsymbol{c}_p(\lambda,\theta)\boldsymbol{v}_w^{\,3}. \qquad (1)$$

Where:

P_W: power extracted from the wind [W];

ρ: air density [kg/m^3];

A_r: cross section of the rotor swept area [m^2];

c_p: power coefficient;

λ: tip speed ratio (ratio between the blade tip speed [m/s] and the upstream wind speed [m/s]);

θ: pitch angle of the blades [deg].

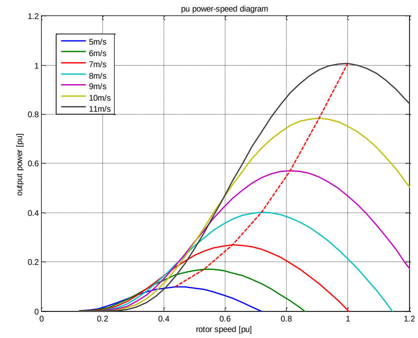

Fig. 2 Power vs. rotating speed, wind speed as parameter

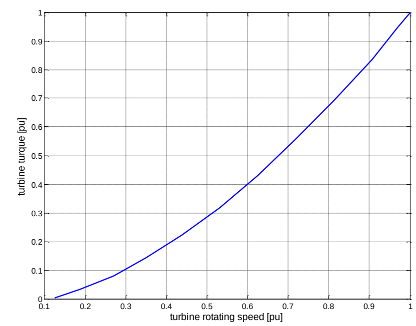

Fig. 3 torque vs. speed at the turbine shaft at MPP

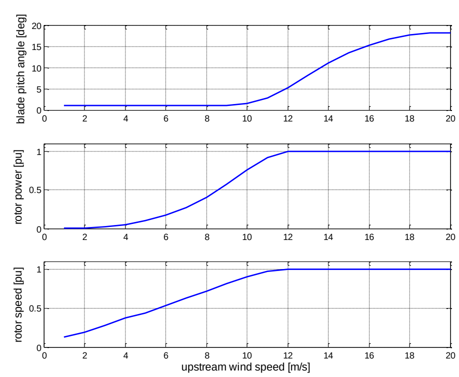

Fig. 4 Blade pitch angle, extracted power at MPP, rotor speed vs. wind speed at MPP

Several numerical representation for $c_p(\lambda,\theta)$ have been given depending on the turbine geometry [10], [11]. In this paper the approximation and coefficients introduced in [12] have been used.

With respect to the wind speed range, in order to optimize energy extraction and to comply with system power rating, a simplified mode of operation of the WECS is the following:

- Below the rated wind speed: regulation of the rotor speed, to maximize power production
- Above the rated wind speed: control of the pitch angle to limit the power at the rated.

Fig. 2 shows the extracted power from the wind vs. rotating speed, the dashed line represents the maximum power tracking.

Assuming the best operation of the maximum power tracking shown in fig.2 the corresponding mechanical characteristic at the turbine shaft is given by the curve shown in fig.3. By considering the whole operating range of a modern WECS the power curve resulting from an optimal control of the system is represented in Fig. 4b.

B. CVT description

The core of the CVT is the planetary gear set, often referred to also as epicyclic gearing shown in fig.1.

The basic equation to consider in analyzing the quasi-static behaviour of a planetary gear set is the relationship between the speed of the three main parts, which can be derived according to the Willis formula:

$$\frac{\omega_S-\omega_C}{\omega_A-\omega_C}=\tau_0 \tag{2}$$

where ω_A, ω_S, ω_C, are the speed of ring (annulus), sun and carrier respectively, and τ_0 is the epicyclic gear ratio

$$\tau_0=-\frac{A}{S} \tag{3}$$

where *S* and *A* are the number of teeth of sun and ring respectively.

Fundamental equation for torque in a planetary gear set can be derived from (2) and from power balance yielding to:

$$\begin{gathered} T_S+T_A+T_C=0 \\ \frac{T_A}{T_S}=-\tau_0 \end{gathered} \tag{4}$$

By eq. (4), at steady state, the torque value transmitted to two members of the planetary gear set is given from the torque of the third member.

C. CVT for WECS

With reference to the scheme of fig. 1, the use of the CVT as one stage of the step up gear set is based on the design of the teeth number of the three element of the planetary gear set. This design procedure can be carried out by normalizing the speeds on the basis of the maximum speed of the carrier ω_{Cr} which is given by the characteristic of the turbine and by the gear ratio of the first stages of the step up gear train. The resulting p.u. representation of the three speeds are:

$\hat{\omega}_C=\frac{\omega_C}{\omega_{Cr}}$ carrier speed in p.u.;

$\hat{\omega}_A=\frac{\omega_A}{\omega_{Cr}}$ ring constant speed in p.u.;

$\hat{\omega}_S=\frac{\omega_S}{\omega_{Cr}}$ sun speed in p.u.;

$\hat{\omega}_{C0}=\frac{\omega_{C0}}{\omega_{Cr}}$ carrier speed in p.u when the sun is at zero speed $\hat{\omega}_S=0$

The relations among the speed of the three elements of the CVT in p.u. is derived from (2) as:

$$\omega_S=\tau_0\omega_A+\omega_C(1-\tau_0)\,. \tag{5}$$

From (5), the speed $\hat{\omega}_{C0}$ of the carrier when the sun is at zero speed ($\hat{\omega}_S=0$), is:

$$\hat{\omega}_{C0}=-\hat{\omega}_A\frac{\tau_0}{1-\tau_0} \tag{6}$$

Eq. (6) can be used to set the epicyclic gear ratio τ_0 depending on the required $\hat{\omega}_{C0}$.

By normalizing with respect to maximum torque at the carrier T_{Cr}, the torque in the CVT annulus and solar are given from the torque at the carrier $\hat{T}_C$ by using (2) and (4):

$$\hat{T}_A = \hat{T}_C\left(\frac{\tau_0}{1-\tau_0}\right) \tag{7a}$$

$$\hat{T}_S = -\hat{T}_C\left(\frac{1}{1-\tau_0}\right) \tag{7b}$$

The application of the CVT to the WECS is based on the control of the driver speed $\hat{\omega}_S$ in order to keep the generator speed $\hat{\omega}_A$ constant all over the operating speed range of the turbine $\hat{\omega}_C$. In this way, for a given value of the gear ratio τ_0, the speed required to the driver $\hat{\omega}_S$ is given from (5) as a function of the turbine speed $\hat{\omega}_C$ only, and the torque applied by the turbine to the driver $\hat{T}_S$ and to the generator $\hat{T}_A$ are than calculated from (7).

From the mechanical characteristic $\left(\hat{\omega}_C, \hat{T}_C\right)$ of the wind turbine operating in MPPT, (fig. 3), by applying (5) and (7) it is possible to determine torque and power curves in both the driver and the generator.

III. Dynamic Model of the W-CVT Transmission

A. Planetary gear-set model

The dynamic equations of the planetary gearbox derive from the relationships between the torques at the gearbox (7), applied at the torque balance equation:

$$T_m - T_{res} = J\frac{d\omega}{dt} \tag{8}$$

Elaborating the eq. (5)-(8) a state-space model of the planetary gear-set has been obtained [13]:

$$\begin{aligned}\dot{\mathbf{x}}(t) &= \mathbf{Ax}(t) + \mathbf{Bu}(t)\\ \mathbf{Y}(t) &= \mathbf{Cx}(t) + \mathbf{Du}(t)\end{aligned} \tag{9}$$

where **x** is the state vector, **u** is the input vector, **Y** is the output vector.

B. Complete transmission model

The complete WECS transmission is modelled using the so-called “two mass model” (fig. 5) which keeps into account the torsion effects for the low speed shaft only. Infinite stiffness can be assumed for the main gearbox and the high speed shaft [14]. Furthermore, the transmission is assumed as ideal, meaning without losses. Using this approximation, the transmission model leads to the following expression for the vectors of the state space equations (9):

$$\begin{aligned}\mathbf{x} &= \begin{bmatrix}\omega_A & \omega_S & \omega_r & \Delta\varphi_r\end{bmatrix}^T\\ \mathbf{u} &= \begin{bmatrix}T_A & T_S & T_r\end{bmatrix}^T\\ \mathbf{Y} &= \begin{bmatrix}\omega_A & \omega_S & \omega_r & \omega_C\end{bmatrix}^T\end{aligned} \tag{10}$$

where:

$$\Delta\varphi_r = \varphi_{ri} - \varphi_{ro} = \int\left(\omega_r - \frac{\omega_C}{r}\right)dt \tag{11}$$

is the torsional angle of the main turbine shaft.

The matrices of (8) **A, B, C, D** have the following expressions:

$$\mathbf{A} = \begin{bmatrix} -\frac{cJ_S\tau_0^2}{hr^2} & \frac{c\tau_0 Js}{hr^2} & \frac{c\tau_0 J_S}{hr}(\tau_0-1) & \frac{k\tau_0 J_S}{hr}(\tau_0-1)\\ \frac{c\tau_0 J_A}{hr^2} & -\frac{cJ_A}{hr^2} & -\frac{cJ_A}{hr}(\tau_0-1) & \frac{-kJ_A}{hr}(\tau_0-1)\\ \frac{c\tau_0}{rJ_r(\tau_0-1)} & -\frac{c}{rJ_r(\tau_0-1)} & -\frac{c}{J_r} & -\frac{k}{J_r}\\ -\frac{\tau_0}{r(\tau_0-1)} & \frac{1}{r(\tau_0-1)} & 1 & 0 \end{bmatrix} \tag{12a}$$

$$\mathbf{B} = \begin{bmatrix} \frac{\boldsymbol{J_C} + (1-\tau_0)^2\boldsymbol{J_S}}{\boldsymbol{h}} & \frac{\tau_0\boldsymbol{J_C}}{\boldsymbol{h}} & 0\\ \frac{\tau_0\boldsymbol{J_C}}{\boldsymbol{h}} & \frac{\boldsymbol{J_C}\tau_0^2 + (1-\tau_0)^2\boldsymbol{J_A}}{\boldsymbol{h}} & 0\\ 0 & 0 & \frac{1}{\boldsymbol{J_r}}\\ 0 & 0 & 0 \end{bmatrix} \tag{12b}$$

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ -\frac{\tau_0}{1-\tau_0} & \frac{1}{1-\tau_0} & 0 & 0 \end{bmatrix} \tag{12c}$$

$$\mathbf{D} = \mathbf{0} \tag{12d}$$

Where:

ω_r is the rotor speed after the hub;
r is the multiplier gear ratio;
ω_c/r is the rotor speed before the multiplier;
φ_{ri} is the low speed shaft angle at rotor hub;
φ_{ro} is the low speed shaft angle at the input of the step-up gearbox;
k is the low speed shaft stiffness

coefficient;

c is the low speed shaft damping coefficient;

T_r is the aerodynamic torque at the input of the low speed shaft;

T_{sh} is the torque at the input of the step-up gearbox;

ω_r is the speed at the input of the low speed shaft;

J_r is the turbine moment of inertia;

J_A Ring shaft inertia;

J_S Sun shaft inertia;

J_C Carrier shaft inertia;

$$\boldsymbol{h} = (1-\tau_0)^2 \boldsymbol{J_A J_S} + \boldsymbol{J_C}(\boldsymbol{J_A} + \tau_0{}^2 \boldsymbol{J_S}) \tag{13}$$

C. Electric machines model

The driver has been implemented by using a IPM-SM controlled in maximum torque per current MTC, all over the speed range. The model of the machine in the d-q synchronous reference frame and the optimal flux weakening control technique have been implemented according to [15].

The electric generator considered in this paper is a squirrel cage induction machine, with the stator phases directly connected to the grid. This machine has been modeled using d-q axis representation written in a stationary reference frame, according to [16].

IV. Design criteria

For analyzing torque and power curve at the CVT elements it is necessary to fix the epicyclic gear ratio τ_0 as defined in (2). Two cases have been considered. In the first case study, τ_0 is selected from (6) in order to have $\hat{\omega}_{C0} = 1$, meaning that, when the driver is at zero speed $\omega_S = 0$, the speed of the turbine is at its maximum speed $\omega_{Cr} = \omega_{C0}$. In the second case τ_0 is selected from (6) in order to have $\hat{\omega}_{C0} < 1$, meaning that when the driver is at zero speed $\omega_S = 0$, the rotating speed of the turbine is lower than its maximum speed $\omega_{C0} < \omega_{Cr}$.

A. $\hat{\omega}_{C0} = 1$

By considering the condition $\hat{\omega}_{C0} = 1$ and then $\hat{\omega}_{\boldsymbol{A}} = (1-\tau_0)/\tau_0$, the power at the carrier $\hat{P}_C$, at the annulus $\hat{P}_A$ and at the sun $\hat{P}_S$, from (6), (7a), (7b) are

$$\hat{P}_C = \hat{\omega}_C \cdot \hat{T}_C \tag{14}$$

$$\hat{P}_A = \hat{\omega}_A \cdot \hat{T}_A = -\hat{T}_C \tag{15}$$

$$\hat{P}_S = \hat{\omega}_S \cdot \hat{T}_S = \hat{T}_C (1 - \hat{\omega}_C) \tag{16}$$

Where $\hat{T}_C$ is given from the turbine characteristic (fig. 3).

The three power curves in p.u. are shown in fig. 6. The dashed line is the input power at the carrier $\hat{P}_C$, the blue line is the output power at the ring (generator) $\hat{P}_A$ and the green line is the input power at the sun (driver) $\hat{P}_S$. From the analysis of (14)-(16) the following considerations can be made:

- The generator is sized for the full power $\hat{P}_A\big|_{MAX} = 1$.
- The driver machine on the sun operates as motor all over the speed range, absorbing a fraction of the generated power. It means that this drive system is an unidirectional converter.

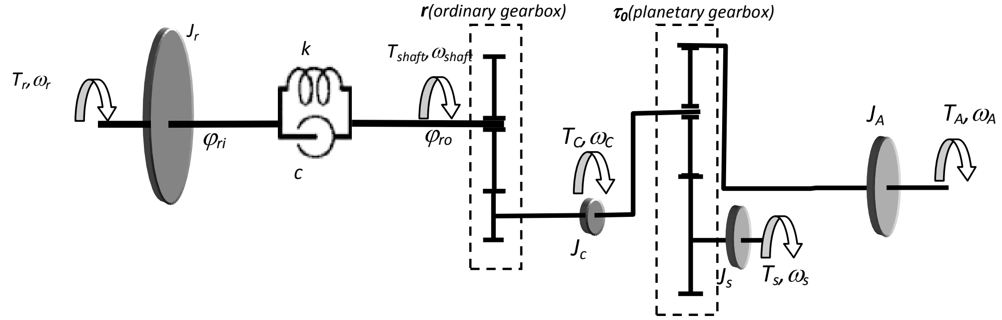

Fig. 5 – WECS drive train with CVT

- The driver power is a small fraction of the turbine power. For the given input $\left(\hat{\omega}_C, \hat{T}_C\right)$ curve, the maximum of the driver input power is $\left.\hat{P}_S\right|_{MAX} = 0.16$. This value represents the power sizing of the power electronic system supplying this machine.
- The sizing of the driver does not depend from gear ratio τ_0, and then from the rated speed of the carrier of the CVT. This means that the power sizing of the CVT is the same, regardless of the stage of the step-up gear where it is inserted.

The capability of the system to regulate the turbine speed at lower values depends on the value of the gear ratio τ_0, and on the possibility to operate the driver at higher speed. In fig. 7 this condition corresponds to the driver torque curve for $\tau_0 = -7$.

B. $\hat{\omega}_{C0} < 1$

By considering the condition $\hat{\omega}_{C0} < 1$ and then $\tau_0 < 1/\left(1 - \hat{\omega}_A\right)$, for a given value of $\hat{\omega}_A$, the power at the carrier $\hat{P}_C$, at the annulus $\hat{P}_A$ and at the sun $\hat{P}_S$, are determined directly from the fundamental equation of the CVT (5) and (7) and can be written as follows

$$\hat{\boldsymbol{P}}_{\boldsymbol{C}} = \hat{\omega}_C \cdot \hat{\boldsymbol{T}}_{\boldsymbol{C}} \tag{17}$$

$$\hat{\boldsymbol{P}}_{\boldsymbol{A}} = \hat{\omega}_{\boldsymbol{A}} \cdot \hat{\boldsymbol{T}}_{\boldsymbol{A}} = -\hat{\boldsymbol{T}}_{\boldsymbol{C}} \hat{\omega}_{\boldsymbol{A}} \frac{\tau_0}{1 - \tau_0} \tag{18}$$

$$\hat{\boldsymbol{P}}_{\boldsymbol{S}} = \hat{\omega}_{\boldsymbol{S}} \cdot \hat{\boldsymbol{T}}_{\boldsymbol{S}} = -\hat{\boldsymbol{T}}_{\boldsymbol{C}} \hat{\omega}_{\boldsymbol{C}} + \hat{\omega}_{\boldsymbol{A}} \hat{\boldsymbol{T}}_{\boldsymbol{C}} \left(\frac{\tau_0}{1 - \tau_0}\right) \tag{19}$$

These three power curves in p.u. are shown in fig. 6 for a given value of the ring (generator) speed $\left(\hat{\omega}_A = 8/7\right)$ as function of the speed of the turbine $\hat{\omega}_C$ and for different values of the epicyclic gear ratio $\left(\tau_0 = -3.5, -4, -5, -6, -7\right)$. The condition $\hat{\omega}_{C0} < 1$, means that the speed of the turbine when the driver is at zero speed is lower than the turbine maximum speed. From fig. 6 it is clearly shown that the driver operates either as motor, for $\hat{\omega}_C < \hat{\omega}_{C0}$ or as generator, for $\hat{\omega}_{C0} < \hat{\omega}_C < 1$.

In particular, when the driver operates as generator, both the generator and the driver itself inject power into the grid determining the following main consequences:

- a reduction of the power sizing of the main generator;
- a reversible power flow in the driver that requires a bidirectional power electronic converter for driver grid interface;
- a reduction of the power sizing of the driver.

In particular this last features can be seen on fig. 6 by observing that the minimum power sizing of the driver is obtained with the epicyclic gear ratio $\tau_0 = -3.5$. With this sizing, the maximum power of the driver is about 0.11 p.u. Even though the design of the CVT transmission with $\hat{\omega}_{C0} < 1$ is convenient in terms of power sizing both for the generator and the

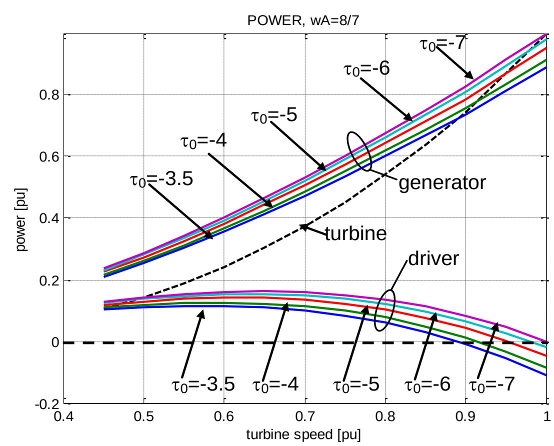

Fig. 6 $\hat{\omega}_{C0} \leq 1$. Power vs. carrier speed in the three elements of the CVT.

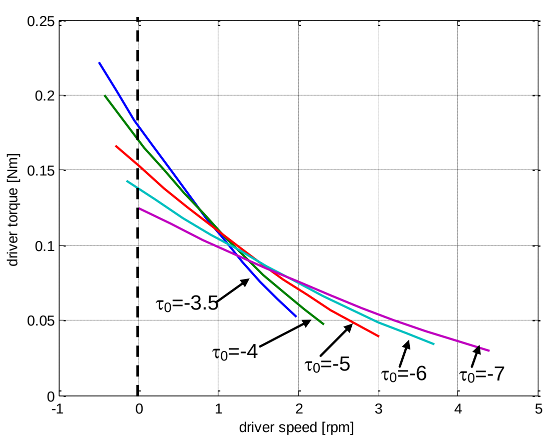

Fig. 7 $\hat{\omega}_{C0} \leq 1$. Driver torque vs. driver speed driver machine, the maximum demanded torque is increased with respect to the case $\hat{\omega}_{C0} = 1$, in fig. 7 represented by the curve $\tau_0 = -7$. In other words the increase of the torque size of the driver yields to increase the weight of the CVT and then could not probably be accepted, even if accompanied by an undersizing of the main generator.

The relevant aspects of both the design choice: $\hat{\omega}_{C0} = 1$ and $\hat{\omega}_{C0} < 1$ are summarized in Tab.I.

V. SIMULATION RESULTS

TABLE I
MAIN CHARACTERISTIC OF THE TWO DRIVER CONFIGURATION

	$\hat{\omega}_{C0} = 1$	$\hat{\omega}_{C0} < 1$
minimum driver power $\hat{P}_S\big\|_{MAX}$	16%	11%
maximum driver torque $\hat{T}_S\big\|_{MAX}$	minimized by the choice of τ_0	always larger than with $\hat{\omega}_{C0} = 1$
generator power $\hat{P}_G\big\|_{MAX}$	100%	89%
power converter for the driver	unidirectional	bidirectional (back-to-back)

A complete model of the WECS has been implemented in a single simulation environment. This model comprises the aerodynamic conversion, the driveline including the CVT, the driver machine, the generator and a simplified grid. A simplified WECS control system have been also developed in order to calculate the reference speed of the driver in any operating condition and the optimal blade pitch angle.

Simulations have been referred to the case study $\hat{\omega}_{C0} = 1$ only. The driver connected at the sun is an electric drive based on a IPM-SM supplied by the grid, operating over two quadrant only, in motoring mode.

A closed loop regulation system based on a PI regulator has been implemented for the speed control of this electric drive.

The first test demonstrates the capability of the system to keep constant the generator speed while the turbine shaft speed is changed. This operating mode is typically referred to wind speed below the rated speed (fig. 8).

The second test demonstrates the capability of the system to limit the transmissible torque between the turbine and the generator. Fig. 9 shows the effect of a sudden gust of wind from 12 to 18 m/s. This wind gust (9a) acts on a turbine rotor with a maximum pitch variation of 3 deg/s (9b). The step increase in the turbine torque (9c) is not transferred to the generator (9f) because of the limitation in the torque that can be applied by the driver (9h). The resulting accelerating torque acts on the turbine rotor speed (9c) and on the driver speed (9g). Acceleration ends as the pitch regulation system cuts the input power and restores the rated turbine speed.

In this condition the limit in the mechanical output torque of the driver acts as a sort of ‘torque limiter’ between the turbine rotor and the generator.

VI. EXPERIMENTAL RESULTS

Experiments have been conducted on the scaled E-CVT prototype of the LEMAD (Laboratory of Electrical Machines and Drives). It is made up of two identical machines (induction machines, 50 kW rated power), one coupled to the ring and the other to the sun of a planetary gear-set. The two machines are controlled by VSI inverters, supplied by a battery bank (80 Vdc). The SUN/DRIVER machine is speed controlled, and torque limited, and the RING/GEN machine is controlled at constant voltage and frequency, to

TABLE II
MAIN CHARACTERISTIC OF THE W-CVT EXPERIMENTAL SETUP

Main characteristics of the machines	
	CARRIER/TURBINE
Rated wind speed (*m/s*)	12
Rated rotor speed (*rpm*)	195
Rated torque (*Nm*)	220
Planetary gearbox ratio (τ_0)	-1,8393

	SUN/DRIVER	RING/GEN
DC link voltage	80	80
Max stator current (A_{rms})	75	200
Max torque (*Nm*)	80	450
Rated torque (*Nm*)	78	144
Speed range(*rpm*)	-323÷0	≈300
Stator voltage (V_{rms})	Variable	54
Stator frequency (*Hz*)	Variable	20

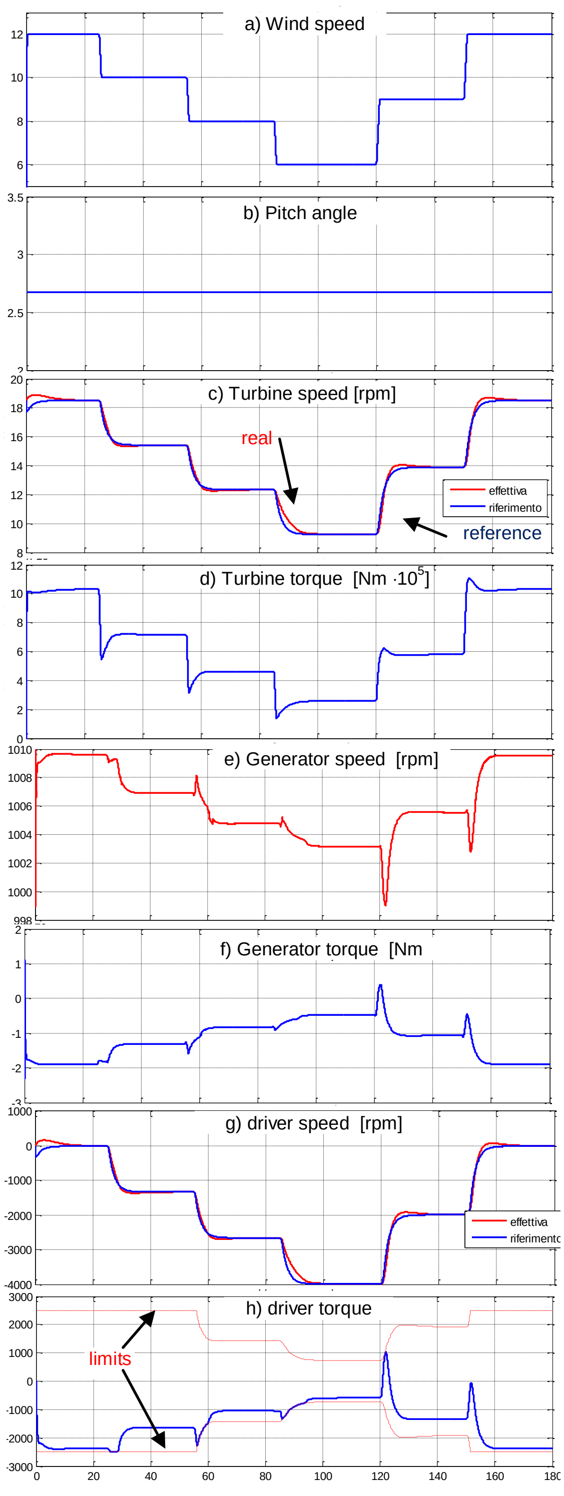

Fig. 8 - WECS operation for wind speed below the rated value

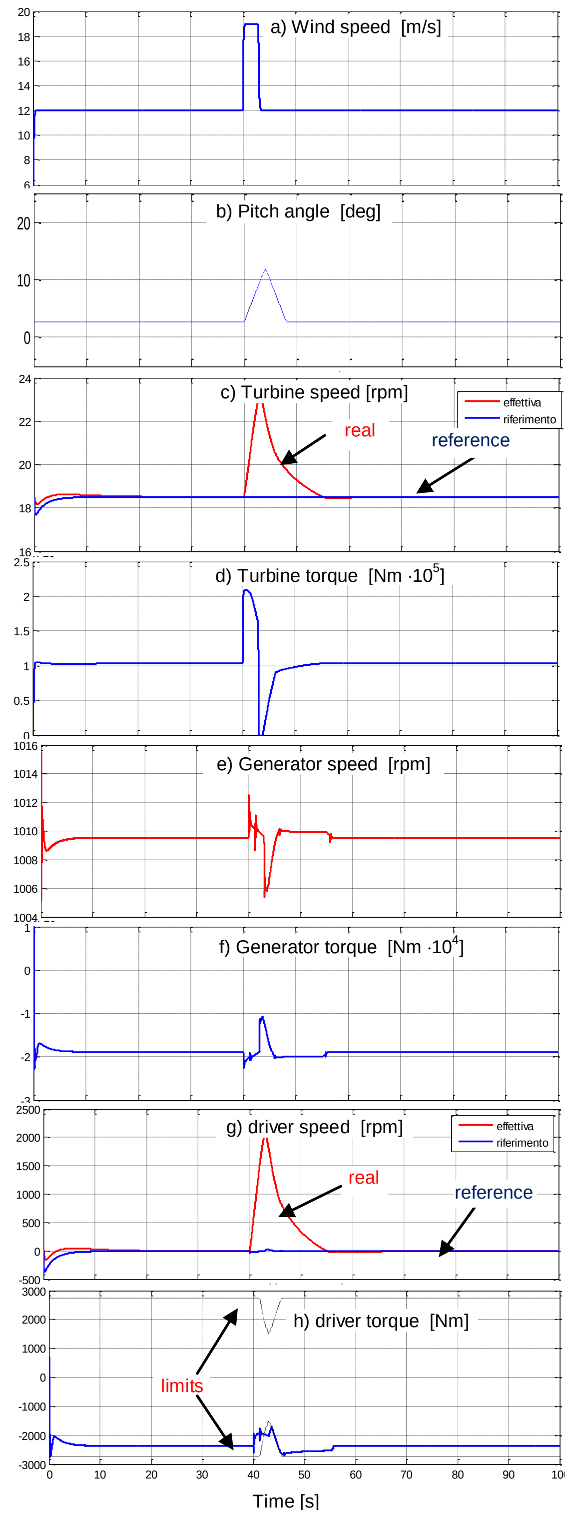

Fig. 9 - WECS operation during wind gust 12→18m/s

simulate real W-CVT conditions.
The input of the W-CVT is another electrical machine, torque controlled, to emulate the wind turbine behavior. It is coupled to the CARRIER wheel. No pitch control is implemented. The main characteristics of the system are presented in the Tab. II.
The high level control unit computes the optimal speed of the CARRIER/TURBINE in order to maximize the wind turbine extracted power, and give the speed setpoint to the driver. No MPPT algorithm was implemented at this stage.
The first test demonstrates the capability of the system to control the turbine speed keeping (quasi) constant the generator speed (fig. 10.c). It can be noted that while the generator speed remains close to 1,6 p.u., the turbine rotor speed varies from 1 p.u. to half the rated speed (fig. 10.b). This is obtained varying the driver speed according to the wind speed variations (fig. 10.e).

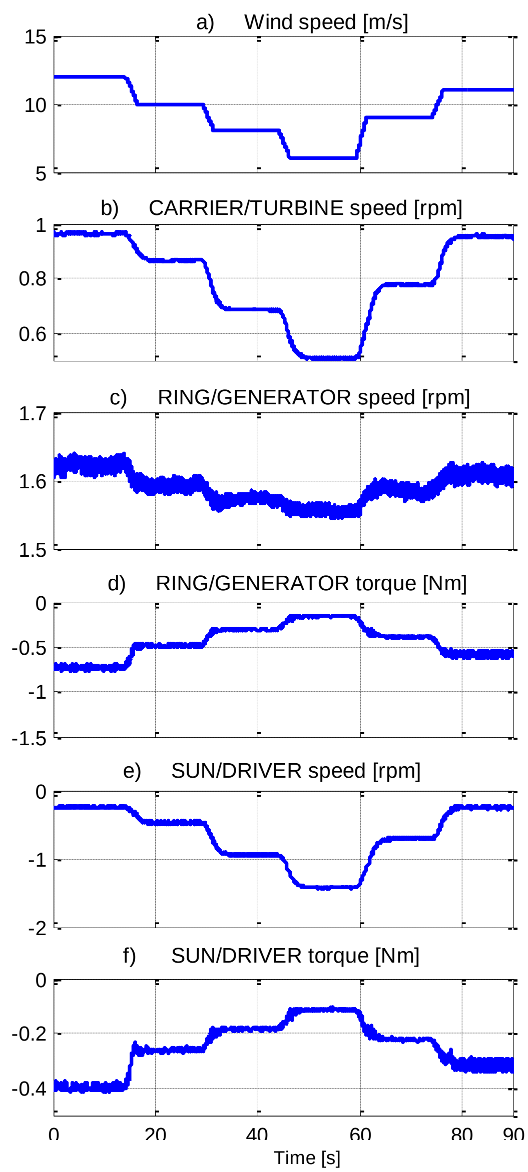

Fig. 10 – Experimental result for CVT WECS operating below the rated wind speed.

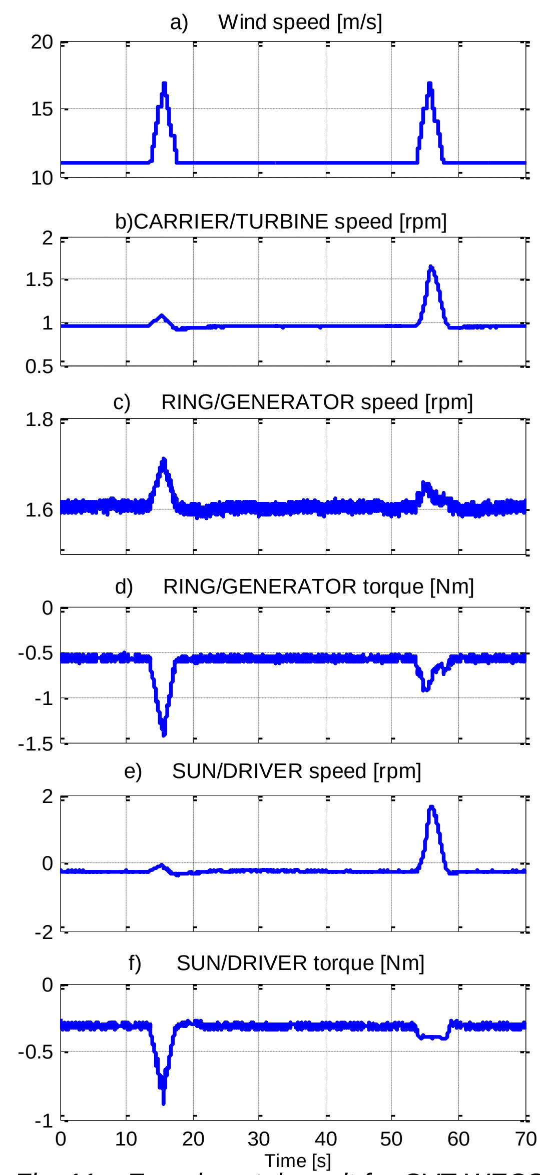

Fig. 11 – Experimental result for CVT WECS operating above the rated wind speed (wind gust).

The second test examine the response of the system to a wind gust (fig. 10.a, 11→17 m/s), in two different cases:

- The first gust (10-20s) simulates the behavior of a stiff transmission, where the SUN/DRIVER transmits all the torque from the CARRIER/ROTOR to the RING/GEN. In this case the over-torque at the generator shaft goes from 0,5 p.u. up to 1,5 p.u. (fig. 11.d).
- In the second gust event (50-60s), the driver transmitted torque is limited to the rated value (as in the real case, fig. 11.f), and it can be seen that the over-torque at the generator reduces of 0,5 p.u. respect to the previous case (fig.11.d). In this condition the turbine is free of accelerating, unlike the previous case (fig. 11.b). This means that the gust power increase the kinetic energy of the rotor, instead of stressing the mechanical parts and the electrical generator.

The results of the simulations are confirmed by the experimental tests.

VII. Conclusion

A power transmission for WECS based on a Continuously Variable Transmission (CVT) placed at the high speed end of the step up gear train has been presented in this paper.

A complete model of the CVT integrated in a conventional WECS transmission (fixed speed generator) has been presented. A design criteria underlying the main sizing aspects related to the choice of the planetary gear ratio τ_0 of the CVT is also discussed. From this discussion, a solution which minimizes the torque request at the driver and operates the driver only in motoring mode $\hat{\omega}_{C0} = 1$ seems to be preferable.

Simulation results have been given in order to show the speed regulation capability of this configuration and the possibility to operate the transmission as a torque limiter between the generator and the turbine rotor. These features have been confirmed by the experimental results. Next steps will regard the realization of a suitable MPPT technique and a strategy for an optimal limitation of the driver torque in wind gust or grid fault conditions, in order to reduce the over-torque related to these events.

References

[1] E.S. Abdin, W. Xu, "Control Design and Dynamic Performance Analysis of a Wind Turbine-Induction Generator Unit" IEEE Trans. On Energy Conversion, Vol. 15, No. 1, pp. 91-96, March 2000.

[2] B. Rabelo, W. Hofmann, "Optimal Active and Reactive Power Control with the Doubly-Fed Induction Generator in the MW-Class Wind-Turbines," Proc. of 4th IEEE International Conference on Power Electronics and Drive Systems, Vol. 1, pp. 53-58, Oct. 2001.

[3] E. Spooner, A.C. Williamson, "Direct coupled, permanent magnet generators for wind turbine applications" Proc. of Electric Power Applications, IEE - Vol. 143, Issue 1, Jan. 1996 Page(s):1 - 8

[4] A. Binder, T. Schneider, "Permanent magnet synchronous generators for regenerative energy conversion - a survey" Proc. of European Conference on Power Electronics and Applications, 2005 11-14 Sept. 2005 Page(s):10 pp.

[5] H. Law, H. A. Doubt, B. J. Cooper, 'Power Control Systems for the Orkney wind-turbine generators' Proc. of Intersociety energy conversion engineering conference; Vol./Issue: 4; 19 Aug 1984; San Francisco, CA, USA

[6] H. Müller, M. Pöller, A. Basteck, M. Tilscher, J. Pfister, 'Grid Compatibility of Variable Speed Wind Turbines with Directly Coupled Synchronous Generator and Hydro-Dynamically Controlled Gearbox' Proc. of Sixth Int'l Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, 26–28 October 2006, Delft, NL

[7] Wikov-Wind W2000 '2MW Wind Turbine' data sheet from Wikov Wind a.s.; www.wikov.com

[8] J. M. Miller, "Hybrid electric vehicle propulsion system architectures of the E-CVT type," IEEE Trans. Power Electron., vol. 21, no. 3, pp. 756–767, May 2006.

[9] S. Heier, "Grid Integration of Wind Energy Conversion Systems", 2nd Ed., Wiley, 2006.

[10] O. Wasynczuk, D. T. Man, and J. P. Sullivan, "Dynamic behaviour of a class of wind turbine generators during random wind fluctuations" IEEE Trans. Power App. Syst., vol. 100, pp. 2837–2845, June 1981.

[11] A. D. Hansen, C. Jauch, and P. Sorensen, "Dynamic Wind Turbine Models in Power System Simulation Tool Digsilent" Risø National Laboratory, Risø, Denmark, Tech. Rep. Risø-R-400(EN), Dec. 2003.

[12] J. G. Slootweg, H. Polinder, S. W. H. de Haan, W. L. Kling, "General Model for Representing Variable Speed Wind Turbines in Power System Dynamics Simulations" IEEE Transactions On Power Systems, Vol. 18, No. 1, Feb. 2003

[13] C. Rossi, P. Corbelli, G. Grandi, 'W-CVT Continuously variable transmission for wind energy conversion system', Power Electronics and Machines in Wind Applications, 2009. PEMWA 2009, IEEE.

[14] Henrik Bindner, "Active Control: Wind Turbine Model". Report number: R-920(EN) Risø National Laboratory, Denmark, 1999

[15] Morimoto, S. Takeda, Y. Hirasa, T. Taniguchi, K. Expansion of operating limits for permanent magnet motor by optimum flux-weakening Proc. of Industry Applications Society Annual Meeting, 1989., Conference Record of the 1989 IEEE , 1-5 Oct. 1989 Page(s): 51 -56 vol.1

[16] Ned Mohan "Advanced Electric drives" MNPERE Minneapolis MN – USA, 2001. ISBN 0-9715292-0-5.