Power split transmissions for wind energy systems

POWER SPLIT TRANSMISSIONS FOR WIND ENERGY SYSTEMS

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ABSTRACT

To optimize the power produced in a wind turbine, the turbine speed should vary with the wind speed. Currently, in order to match the grid requirements, variable speed wind turbines incorporate expensive power electronics to convert the variable frequency power to a constant frequency.
This paper deals with the performance of power split transmissions in wind energy systems. Through such systems it is possible to bring significant benefits to the turbine and the generator. Indeed, the turbine could operate at maximum efficiency levels and the generator could produce electric power at a desired frequency. The aim of this paper is to identify the power split configurations that require the minimum rated power of the control system (mechanical CVT or servo-motor/generator), to reduce costs and the power losses.

1. INTRODUCTION

The conversion of the wind energy into electric power is particularly problematic due to the variations of the wind speed. Wind turbine rotors achieve their maximum efficiency at a particular tip-speed ratio [1]. Wind turbines with constant speed, in which the rotor is connected to a generator at a fixed speed ratio, operate at very low efficiency. To increase the efficiency of the wind turbines, variable speed systems are normally applied in order to change the angular speed of the rotor according to the wind speed profile [1, 2].In these systems, the turbine runs at a tip speed ratio which ensures its maximum efficiency.

Variable speed systems present other advantages in that the turbine can be operate as a flywheel, smoothing the torque variations caused by varying wind conditions, it is less sensitive to the wind pattern of a given location and emits less noise [1, 3].

Currently, an overgear is used to connect a wind turbine to an electric generator. The main technologies used today are doubly-fed induction generators and converter drive synchronous generators [2, 4]. The generator is decoupled from the grid by a converter that works at the same rated power. In such configurations the generator rotates with variable speed thus operating, in many cases, in conditions characterized by low efficiency. Therefore, these configurations are particularly expensive. The development of novel, more reliable and efficient wind turbine systems is of fundamental importance in order to optimize the wind energy recovering [5-7].

The feasibility of incorporating a Continuously Variable Transmission (CVT) between a wind turbine and an electric generator (GEN) has been examined in Ref [8-10]. This solution brings benefits in terms of energy recovering since the transmission can vary automatically the speed ratio according to any variation of the wind speed and reduces the costs associated with the expensive power electronics since the generator is able to produce electric current at constant frequency. However, the CVT has low efficiency compared to the one of a fixed gear transmission system [9].

Power split transmissions are often employed to improve the performance of a continuously variable transmission [11, 12]. Their basic scheme includes a Planetary Gear train (PG) and a CVT, be it mechanical, electrical or hydraulic. Power Split Continuously Variable Transmissions (PS-CVT) have been investigated in many studies, which focused on the efficiency [12-14], experimentally verified through a test bench [13, 15], the functional design and the original types of PS-CVT [16]. There are two possible configurations of PS-CVT [12]: input split (IS), obtained if the PG is placed at the input shaft and Output split (OS), obtained if the PG is placed at the output shaft.

Recently some papers have suggested to connect a wind turbine rotor to a generator through a power-split hydrostatic transmission [17, 18] to maximize the turbine efficiency. In other previous papers [19-23], hybrid CVT transmissions have been proposed for variable speed wind turbines, in which the transmissions consist of a single PG controlled by a servo-motor.

This paper compares the performance of the IS and OS power systems, for variable speed wind turbines. For each configurations, the possible power flows and, in particular, the power of the control system with respect to the input power is presented. The aim of this work is to identify configurations that require the minimum rated power of the control system (mechanical CVT or servo-motor/generator), to reduce costs and power losses.

2. WIND TURBINE WITH OUTPUT SPLIT TRANSMISSION

In this section the OS configuration is described. The PG is placed downstream of the wind turbine and the CVT is between the PG and the wind turbine (fig. 1). The internal power circulation of an OS transmission follows the classification given by Mantriota in [13] and it is depicted in figure 1.

It has been shown that three possible power flows occur within the transmission system: the type I and II, characterized respectively by a forward and backward power re-circulation, and the type III in which the power is split in two branches and no recirculation occurs. In Mantriota [13] it has been shown that type II power flow appears only if the CVT ratio range is smaller than the global one. Generally, in wind energy systems, the regulator (mechanical CVT or servo-motor/generator) has a greater ratio range with respect to the global one, therefore in this work, only type I and type III power flows will be considered.

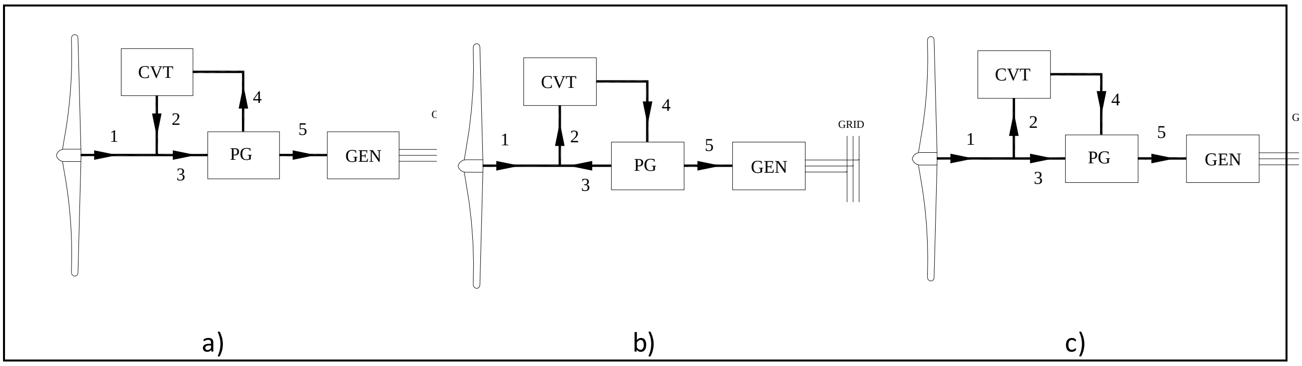

Fig. 1: Output split configuration: a) type I power flow; b) type II power flow; c) type III power flow

Following the nomenclature indicated in figure 1, the transmission ratios of each single elements are:

$$\tau_{CVT} = \frac{\omega_4}{\omega_2}; \tau_{15} = \frac{\omega_1}{\omega_5}; \ \omega_1 = \omega_2 = \omega_3; \ rr = \frac{\tau_{CVTM}}{\tau_{CVTm}}; \ \tau_W = \frac{\omega_5 - \omega_3}{\omega_4 - \omega_3} \quad (1)$$

ω_i denotes the angular velocity of the ith path and τ_{CVT}, τ_{15}, τ_W are the speed ratio of the CVT, global and the Planetary gear respectively. CVTs have a transmission ratio ranging from a minimum value τ_{CVTm}

and a maximum value $\tau_{CVT\,M}$, depending on the particular choice of the CVT drive type (belt, toroidal, hydraulic, electric). "rr" is the ratio range of the CVT .

Then the global transmission ratio becomes (eq. 1):

$$\tau_{15} = \frac{1}{\tau_W \tau_{CVT} - \tau_W + 1} \tag{2}$$

and:

$$\tau_{CVT} = \frac{1 - \tau_{15} + \tau_W \tau_{15}}{\tau_W \tau_{15}} \tag{3}$$

Mangialardi and Mantriota [23] showed that the overall speed ratio (τ_{15}) is a monotonically increasing or decreasing function of the speed ratio of the CVT. In fact, from eq. 2:

$$\frac{\partial \tau_{15}}{\partial \tau_{CVT}} = \frac{-\tau_W}{\left(\tau_W \tau_{CVT} - \tau_W + 1\right)^2} \tag{4}$$

Therefore, τ_{15} is always a monotonic function because the sign of equation does not change if τ_{CVT} is subjected to variations. As described in [24], the direct or inverse proportionality between the CVT speed ratio, τ_{CVT}, and the overall speed ratio, τ_{15}, establishes directly if a type I or type III power flow will characterize the operations of the system.

If a specific minimum value τ_{15m} and maximum value τ_{15M} were required for the global transmission ratio with a given CVT ($\tau_{CVT\,m}$ and $\tau_{CVT\,M}$ known) it would be possible to univocally calculate the transmission ratio of the planetary gear train [13-24].

If a direct proportion between τ_{15} and τ_{CVT} is imposed, the value of τ_W may be determined (type I power flow [24], (fig. 1a)). Namely (eq. 3):

$$\tau_{CVT\,M} = \frac{1 - \tau_{15M} + \tau_W \tau_{15M}}{\tau_W \tau_{15M}} \; ; \; \tau_{CVT\,m} = \frac{1 - \tau_{15m} + \tau_W \tau_{15m}}{\tau_W \tau_{15m}} \tag{5}$$

Than:

$$\tau_W = \frac{-rr\,\tau_{15M}\left(1 - \tau_{15m}\right) + \tau_{15m}\left(1 - \tau_{15M}\right)}{\tau_{15M}\tau_{15m}\left(rr - 1\right)} \tag{6}$$

In this work, the efficiency of the PG will be considered equal to 1. This assumption is generally accepted because the efficiency of the CVT and of the generator is very low compared with the one of the Planetary gear. Therefore, it is easy to demonstrate that the torque ratios become (fig. 1):

$$\frac{T_4}{T_5} = -\tau_W \; ; \; \frac{T_4}{T_3} = \frac{\tau_W}{1 - \tau_W} \tag{7}$$

and the power ratios:

$$\frac{P_{CVT}}{P_T} = \frac{P_4}{P_1} = -\tau_W \tau_{15} \tau_{CVT} \tag{8}$$

Where P_{CVT} and P_T are the CVT and Input power (turbine power), respectively.

Using the equations 3, 6 and 8 , we obtained:

$$\frac{P_{CVT}}{P_T} = -1 + \tau_{15} \frac{rr\tau_{15M} - \tau_{15m}}{\tau_{15M}\tau_{15m}(rr-1)} \quad (9)$$

Typically, there are three main operational regions for variable-speed wind turbines [1, 25]. Figure 2 shows the turbine power vs. wind speed (V_W) curve (i.e., the power curve) together with the operational regions of a variable-speed wind turbine. Region 1 is the low wind speed region for which the turbine does not produce any power, the rotor is still standing and the turbine is disconnected from the grid. The rotor rotates until the threshold value V_{W_S} is reached, and the turbine moves into the region 2. The second region is the region between the wind speed at which the turbine starts to operate (V_{WS}) and the wind speed at which the maximum power (rated turbine power: P_{TR}) is produced (V_{WR}, rated wind speed).

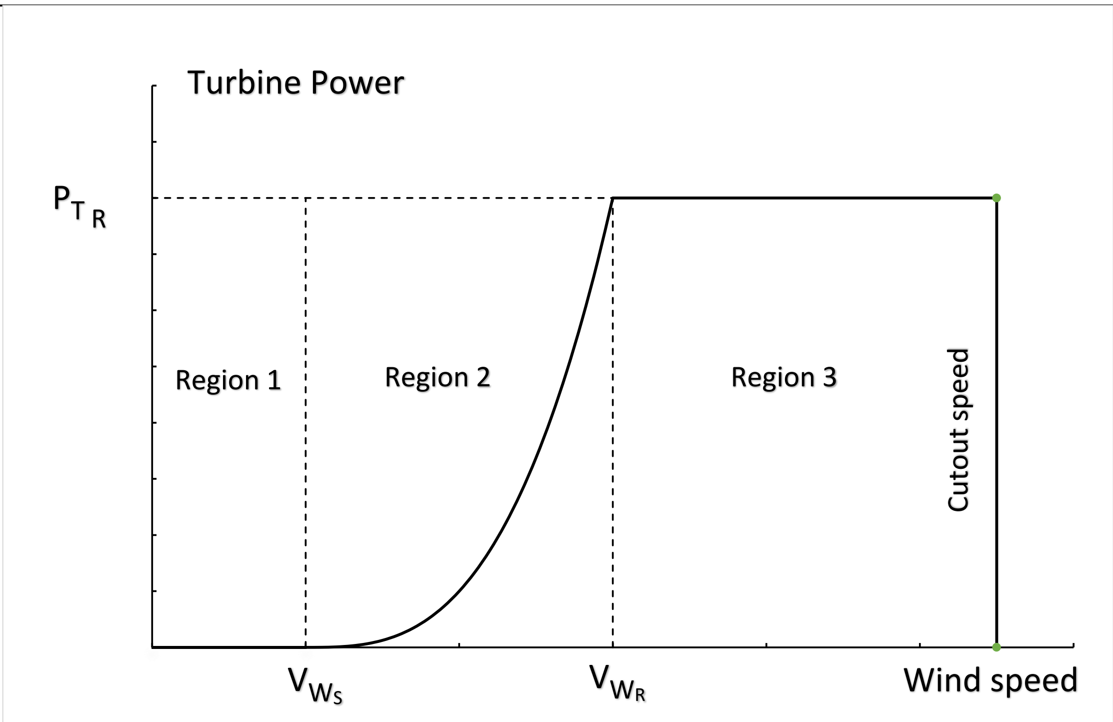

Fig. 2: Typical turbine power

The main control objective when operating at region 2 is to maximize the wind energy recovering. To achieve this, the rotor speed of the wind turbine is controlled such that the characteristic power coefficient (C_p) is maximized.

Region 3 refers to a condition when the turbine operates at high wind speed and the output power is maintained constant at its maximum, independently from the wind speed [1, 25]. A typical control objective in this region is to prevent the output power exceeding the rated value in order to protect the system from power overloading, which can bring damages to the wind turbine. This control action can be realized by changing the blade pitch angle to decrease the power coefficient. If the wind speed exceeds the cutout speed (fig. 2), the wind turbine is shutdown. The optimal control of the turbine speed is then necessary in region 2, in which, the turbine power is [1]:

$$P_T = \frac{1}{2} C_P S \rho V_w^3 \quad (10)$$

where ρ indicates the air density, C_P the power coefficient and S the wind turbine frontal area.

The power coefficient is a function of λ defined as the ration between the peripheral speed (*u*) of the turbine and the wind speed. In formulas, [1]:

$$\lambda = \frac{u}{V_W} = R\frac{\omega_T}{V_W} = R\frac{\omega_1}{V_W} \quad (11)$$

with R the turbine radius and ω_T the turbine angular velocity.

The trend of the power coefficient C_P in figure 3 is related to a fixed-blade horizontal axis turbine.

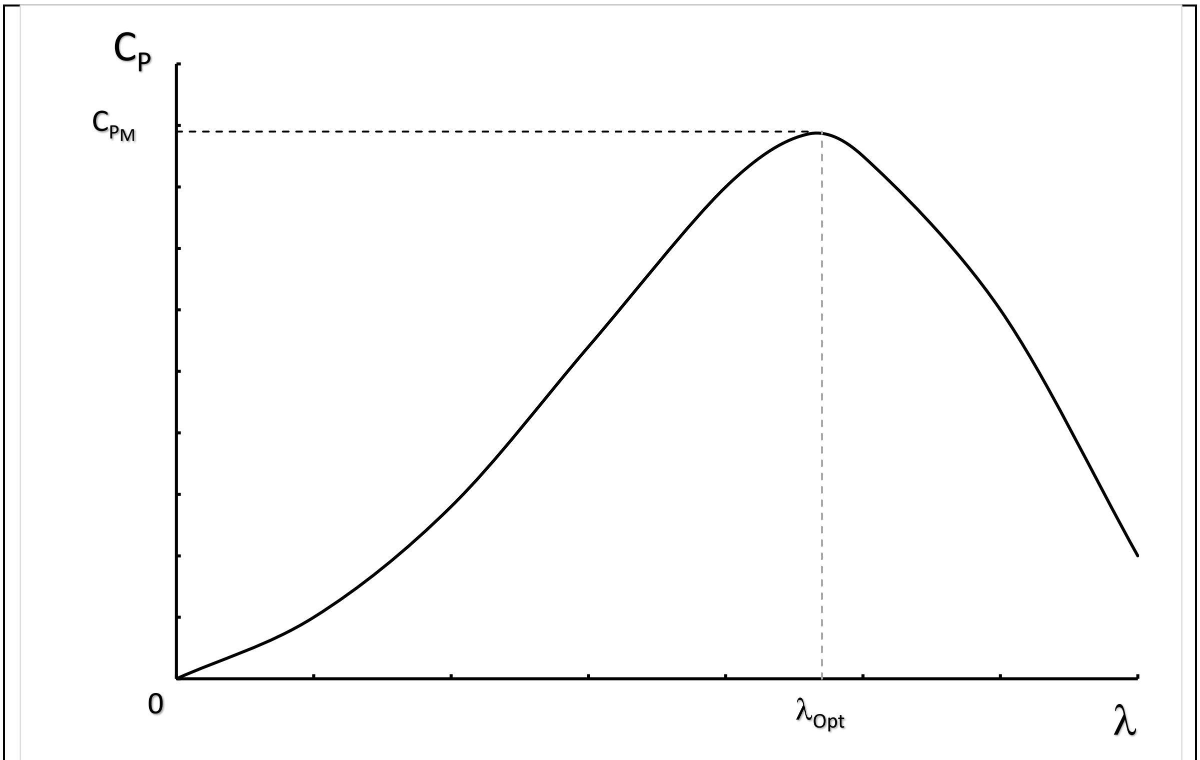

Fig. 3: Power coefficient

For each wind speed, the maximum turbine power is obtained when C_P always assumes its maximum value (C_{PM}), then the turbine must always work in λ_{opt}. This means that (eqq. 10, 11):

$$P_{tOpt} = \frac{1}{2} C_{PM} S \rho V_w^3 = k_1 V_w^3 = k_1 \left(\frac{R}{\lambda_{Opt}} \right)^3 \omega_1^3 = k_2 \omega_1^3 \quad (12)$$

With k_1 and k_2 constants.

Induction and synchronous electric generators are generally used in wind power systems to produce AC electric power and deliver it directly to the electricity mains [1, 2]. In order to generate a constant frequency current, a synchronous device must strictly rotate at synchronous speed while an operating induction generator rotate at an angular speed which is greater than the synchronous speed at slip values generally lower than 10%. In this work, we assumed a synchronous electric generator connected directly to

the mains (without inverter device). This paper examines a novel architecture introducing a power split CVT between an electric generator and a wind turbine. Through the variation of the transmission ratio between the wind turbine and the electric generator, it is possible to deliver power directly to the grid.
Considering a synchronous electric generator rotating at constant speed (ω_5 =const), we obtained (eqq. 1, 12):

$$P_{T\,Opt} = k_1 V_w^3 = k_2 \omega_1^3 = k_2 \omega_5^3 {\tau_{15}}^3 = k_3 {\tau_{15}}^3 \tag{13}$$

With k_3 constant.

From the equation (9), in this condition it is obtained that:

$$P_{CVT} = \left[-1 + \tau_{15} \frac{rr\tau_{15M} - \tau_{15m}}{\tau_{15M}\tau_{15m}(rr-1)} \right] k_3 {\tau_{15}}^3 = \left[-1 + V_W \frac{rrV_{WR} - V_{WS}}{V_{WR}V_{WS}(rr-1)} \right] k_1 V_w^3 \tag{14}$$

Making the derivative of eq. (14) with respect to V_W:

$$\frac{\partial P_{CVT}}{\partial V_W} = k_1 {V_W}^2 \left[4V_W \frac{rrV_{WR} - V_{WS}}{V_{WR}V_{WS}(rr-1)} - 3 \right] \tag{15}$$

Then the maximum or minimum value of the CVT power (eq. (15)) is obtained when:

$$\frac{\partial P_{CVT}}{\partial V_W} = 0 \Rightarrow V_{W\,P_{CVT}Max/Min} = \frac{3}{4}\frac{V_{WR}V_{WS}(rr-1)}{rrV_{WR} - V_{WS}} = \frac{3}{4} V_{WS} \frac{rr \cdot rr_W - rr_W}{rr \cdot rr_W - 1} < \frac{3}{4} V_{WS} \tag{16}$$

$$\text{with } rr_W = \frac{V_{WR}}{V_{WS}} \tag{17}$$

It is easy to show that the wind velocity in eq. (16) determines the minimum CVT power. Then, the maximum value of the CVT power (Output Split and type I power flow: $P_{CVT\,M}\big|_{OS}^{I}$) is obtained when the wind speed assumes the maximum value, then (eq. (14)):

$$P_{CVT\,M}\big|_{OS}^{I} = \left[\frac{rr(rr_W - 1)}{(rr-1)} \right] P_{TR} > P_{TR} \tag{18}$$

Where P_{TR} is:

$$P_{TR} = k_1 {V_{WR}}^3 \tag{19}$$

The eq. (18) shows that in this case the maximum CVT power is greater than the maximum Input Power (rated turbine power).

If a reverse proportion between τ_{15} and τ_{CVT} is imposed (type III power flow [24], fig. 1c), the eqq. (6) and (14) become:

$$\tau_W = \frac{-rr\tau_{15m}(1-\tau_{15M}) + \tau_{15M}(1-\tau_{15m})}{\tau_{15M}\tau_{15m}(rr-1)} \tag{20}$$

$$P_{CVT} = \left[-1 + V_W \frac{rrV_{WS} - V_{WR}}{V_{WS}V_{WR}(rr-1)} \right] k_1 V_w^3 \tag{21}$$

Making the derivative of eq. (21) with respect to V_W :

$$\frac{\partial P_{CVT}}{\partial V_W} = 0 \Rightarrow V_{W\,P_{CVT}Max} = \frac{3}{4} \frac{V_{WS}V_{WR}(rr-1)}{rrV_{WS} - V_{WR}} = \frac{3}{4} V_{WR} \frac{rr-1}{rr - rr_W} \tag{22}$$

Naturally the eq. (22) is true if $V_{W\,P_{CVT}Max} < V_{WR}$, namely:

$$rr > 4 \cdot rr_W - 3 \tag{23}$$

In this case, the eq. (22) indicates the wind speed with the maximum CVT Power. If eq. (23) is true, the maximum CVT power (Output Split and type III power flow: $P_{CVT\,M}\Big|_{OS}^{III}$) becomes (eqq. (21) and (22)):

$$P_{CVT\,M}\Big|_{OS}^{III} = -0.105 P_{TR} \left[\frac{rr-1}{rr - rr_W} \right]^3 \tag{24}$$

In particolar, if $rr >> rr_W$ we obtained (eqq. (22) and (24)):

$$V_{W\,P_{Mot}Max} = \frac{3}{4} V_{WM} \tag{25}$$

$$P_{CVT\,M}\Big|_{OS}^{III} = -0.105 P_{t\,Max} \tag{26}$$

Therefore, the maximum CVT power (CVT rated power) is only about 10% of the maximum input power (turbine rated power).

It is possible to note (eq. (24)) that the maximum CVT power is only a function of the CVT ratio range (rr) and rr_W . In particular the result does not depend on the size of the turbine (for ex. diameter) or the generator characteristics (for ex. synchronous speed).

In conclusion, for an output split power it is more convenient to design the transmission in order to obtain a type I power flow. With type I power flow, the CVT rated power will be approximately only 10% of that of the electrical generator.

3. WIND TURBINE WITH INPUT SPLIT TRANSMISSION

In this section, we examine the input split configuration. In this case, the CVT is between the planetary gear and the generator (fig. 4).

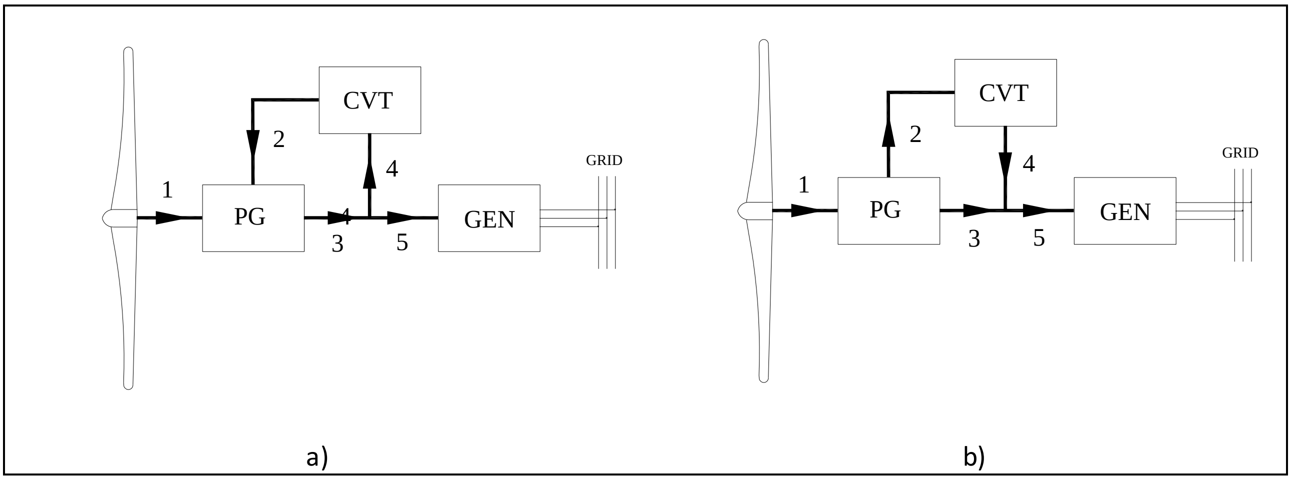

Fig. 4: Input split configuration: a) type I power flow; b) type III power flow

Rather than CVT, the system may be constituted by an electric regulator (servo-motor or servo-generator) connected to the planetary gear train and to the grid (fig. 5).

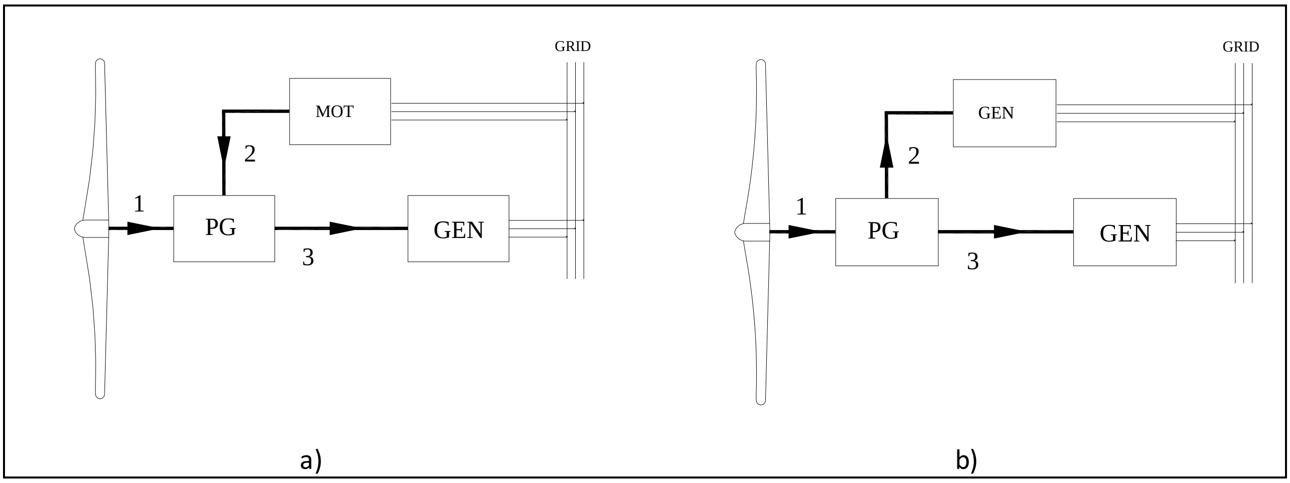

Fig. 5: Input split configuration with servo-motor/generator: a) type I power flow; b) type III power flow

Following the nomenclature indicated in figures 4 and 5 the transmission ratios of the single elements are:

$$\tau_{23} = \frac{\omega_2}{\omega_3}; \tau_{13} = \frac{\omega_1}{\omega_3};\ rr = \frac{\tau_{23M}}{\tau_{23m}} \tag{27}$$

$$\tau_W = \frac{\omega_3 - \omega_1}{\omega_2 - \omega_1} = \frac{1 - \tau_{13}}{\tau_{23} - \tau_{13}} \tag{28}$$

Than:

$$\tau_{13} = \frac{\tau_W \tau_{23} - 1}{\tau_W - 1} \tag{29}$$

$$\tau_{23} = \frac{(\tau_W - 1)\tau_{13} + 1}{\tau_W} \tag{30}$$

Making the derivative of τ_{13} with respect to τ_{23} (eq. (29):

$$\frac{\partial \tau_{13}}{\partial \tau_{23}} = \frac{\tau_W}{\tau_W - 1} \tag{31}$$

τ_{13} (global transmission ratio) is always a monotonic function because the sign of equation (31) does not change if τ_{23} is subjected to variation. As in previous section ($rr > rr_W$), the two possible flows, type I and III, [12] occur when there is respectively inverse and direct proportionality between τ_{23} and the τ_{13}.

If a direct proportion is imposed, the value of τ_W may be determined. In this case a type III power flow [12]is obtained (figg. 4b, 5b) and the electric regulator works as a generator.

Namely (eq. (29):

$$\tau_{13M} = \frac{\tau_W \tau_{23M} - 1}{\tau_W - 1}\ ; \quad \tau_{13m} = \frac{\tau_W \tau_{23m} - 1}{\tau_W - 1} \tag{32}$$

then:

$$\tau_W = \frac{rr(1 - \tau_{13m}) + \tau_{13M} - 1}{\tau_{13M} - rr\tau_{13m}} \tag{33}$$

With:

$$rr = \frac{\tau_{23M}}{\tau_{23m}} \tag{34}$$

As in the previous case, if we neglect the losses of the PG , the torque ratios are:

$$\frac{T_2}{T_3} = -\tau_W \quad \frac{T_2}{T_1} = \frac{\tau_W}{1 - \tau_W} \tag{35}$$

Therefore, using eqq. (27), (33) and (35) , the ratio between the regulator power (branch 2) and input

power is:

$$\frac{P_{\mathrm{Reg}}}{P_T} = \frac{T_2}{T_1}\frac{\omega_2}{\omega_1} = \frac{1}{\tau_{13}(1 - \tau_W)} - 1 = \frac{\tau_{13M} - rr\tau_{13m} - \tau_{13}(1 - rr)}{\tau_{13}(1 - rr)} \tag{36}$$

As in the previous case, assuming a synchronous electric generator operating at constant speed (ω_3 =const) in optimal condition, the turbin power is:

$$P_{T\,Opt} = k_1 V_w^3 = k_3 \tau_{13}{}^3 \tag{37}$$

Then (eqq. (36) and (37))

$$P_{\mathrm{Reg}} = \left(\frac{\tau_{13M} - rr\tau_{13m}}{\tau_{13}(1-rr)} - 1 \right) k_3 \tau_{13}^{\ 3} = \left(\frac{V_{WR} - rrV_{WS}}{V_W(1-rr)} - 1 \right) k_1 V_W^{\ 3} \quad (38)$$

Making the derivative of P_{Reg} with respect to the wind speed:

$$\frac{\partial P_{\mathrm{Reg}}}{\partial V_W} = 2k_1 V_W \frac{V_{WR} - rrV_{WS}}{(1-rr)} - 3k_1 V_W^{\ 2} \tag{39}$$

Thereby:

$$\frac{\partial P_{\mathrm{Reg}}}{\partial V_W} = 0 \Rightarrow V_{W\,P_{\mathrm{Reg}}Max/Min} = \frac{2}{3}\frac{V_{WR} - rrV_{WS}}{(1-rr)} \tag{40}$$

It is easy to show that the wind velocity in eq. (40) determines the minimum CVT power. The maximum value of the power (Input Split and type III power flow: $P_{\mathrm{Reg}\,M}\Big|_{IS}^{III}$) is obtained when the wind speed assumes the maximum value, then (eq. (38):

$$P_{\mathrm{Reg}\,M}\Big|_{IS}^{III} = \left(1 - \frac{(rr - rr_W)}{rr_W(rr-1)} \right) P_{TR} \tag{41}$$

If $rr >> rr_W$, the maximum regulator power is (eq. (41)):

$$P_{\mathrm{Reg}\,M}\Big|_{IS}^{III} = \frac{rr_W - 1}{rr_W} P_{t\,Max} \tag{42}$$

If a reverse proportion between τ_{13} and τ_{23} were imposed (type I power flow [12], figg. 4a, 5a), the electric regulator works as a servo-motor. The eqq.(33) and (40) become:

$$\tau_W = \frac{rr(1-\tau_{13M}) + \tau_{13m} - 1}{\tau_{13m} - rr\tau_{13M}} \tag{43}$$

$$V_{W\,P_{\mathrm{Reg}}Max} = \frac{2}{3}\frac{V_{WS} - rrV_{WR}}{(1-rr)} \tag{44}$$

The power in the branch 2 is (eq. (38) (Input Split and type I power flow: $P_{\mathrm{Reg}\,M}\Big|_{IS}^{I}$) :

$$P_{\mathrm{Reg}\,M}\Big|_{IS}^{I} = \left(\frac{V_{WS} - rrV_{WR}}{V_W(1-rr)} - 1 \right) k_1 V_W^{\ 3} \tag{45}$$

By using the eqq. (44) and (45), the maximum power of the servo-motor is:

$$\frac{P_{\mathrm{Reg}\,M}\Big|_{IS}^{I}}{P_{TR}} = 0.148\left(\frac{rr \cdot rr_W - 1}{(rr-1)rr_W} \right)^3 \tag{46}$$

If $rr >> rr_W$, the maximum regulator power is (eqq. (44) and (46)):

$$V_{W\,P_{Reg}M} = \frac{2}{3} V_{W\,R} \quad (47)$$

$$P_{Reg\,M}\Big|_{IS}^{I} = 0.148 P_{T\,R} \quad (48)$$

Again (eq. (46)) the servo-motor rated power is function only of the servo-motor ratio range (rr) and rr_W. Therefore, the results are independent on the size of the machines. For an input split transmission, the rated power ratio of the regulator for type I and III power flows is (eqq. (41) and (46)):

$$\frac{P_{Reg\,M}\Big|_{IS}^{I}}{P_{Reg\,M}\Big|_{IS}^{III}} = 0.148 \frac{(rr \cdot rr_{gl} - 1)^3}{(rr_{gl} - 1)(rr - 1)^3 rr_{gl}^{\,2}} \quad (49)$$

If $rr >> rr_W$, the equation (49) becomes:

$$\frac{P_{Reg\,M}\Big|_{IS}^{I}}{P_{Reg\,M}\Big|_{IS}^{III}} = 0.148 \frac{rr_{gl}}{rr_{gl} - 1} \quad (50)$$

Then it is more convenient to design the system with type I power flow. In conclusion, for an input split transmission with type I power flow, the regulator rated power is only about 15% of the input one (eq. 48).

4. COMPARISON OUTPUT/INPUT SPLIT TRANSMISSION

This section deals with the performance of the architectures discussed in the previous sections. The following data of the turbine are considered as input:

D= 25 m; λ_{Opt} = 8.5; $C_{P\,Max}$ = 0,5; $n_{gen=}$ **1000 RPM;** V_{WS}=4.5 m/s; V_{WR}=12 m/s (51)

Through these data set, we will show the benefits deriving from the adoption of a power split transmission in wind turbine systems.

4.1 Output split configuration

The output split configuration with type I power flow (fig. 1a) is here considered. Figure 6 reports the CVT transmission ratio as a function of the wind speed (eqq. (3),(6)) for different values of the CVT ratio range (rr). From the figure 6 it is possible to note that the CVT speed ratio and the wind speed increase with direct proportion and for different values of *rr*, the curves are practically parallel to each other. In figure 7 the CVT power respect to the turbine rated power is reported (eq. (14, 19)). It is possible to note that the CVT power increases, reaching a value of about twice the turbine rated power. So, in this case, the CVT should have a rating power of approximately twice that of the turbine. This result indicates that it is not convenient the type I power flow.

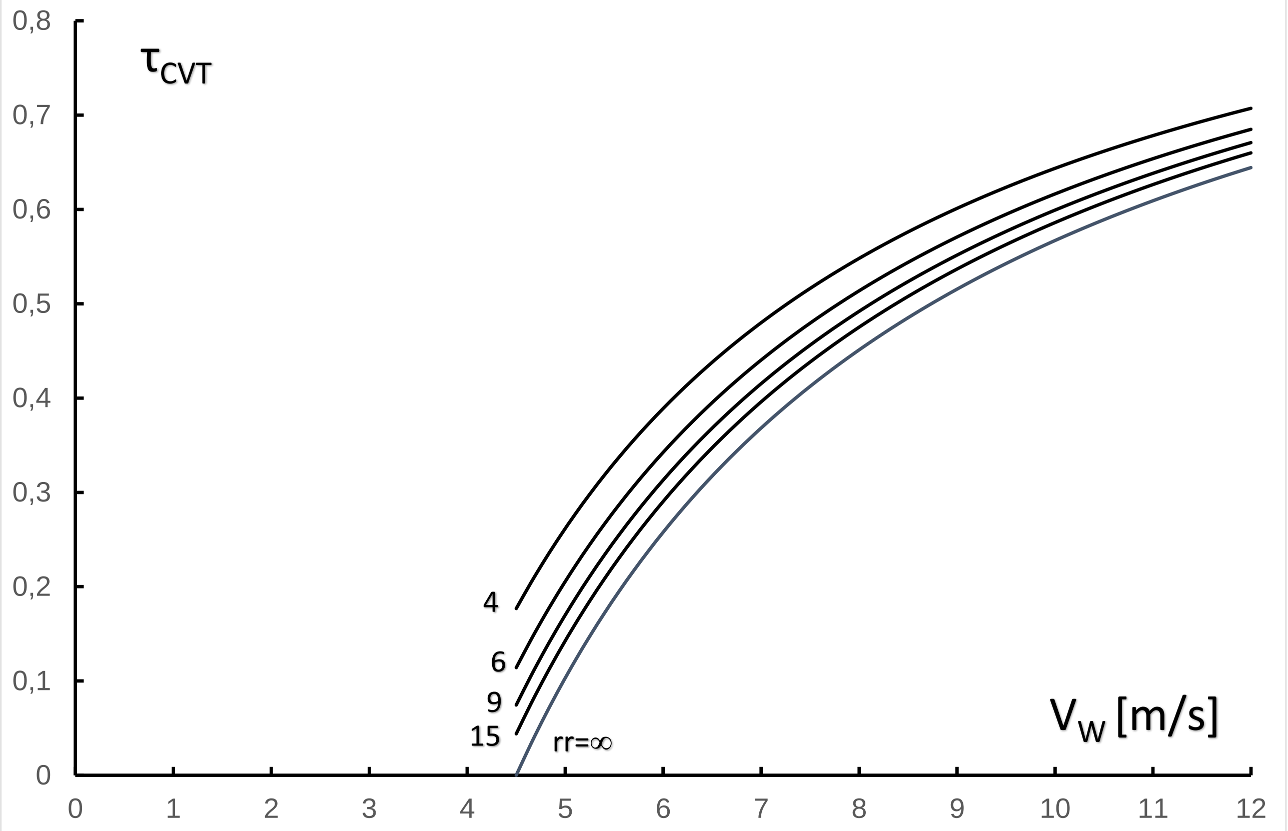

Fig. 6: Output split configuration with type I power flow: CVT transmission ratio vs. wind speed

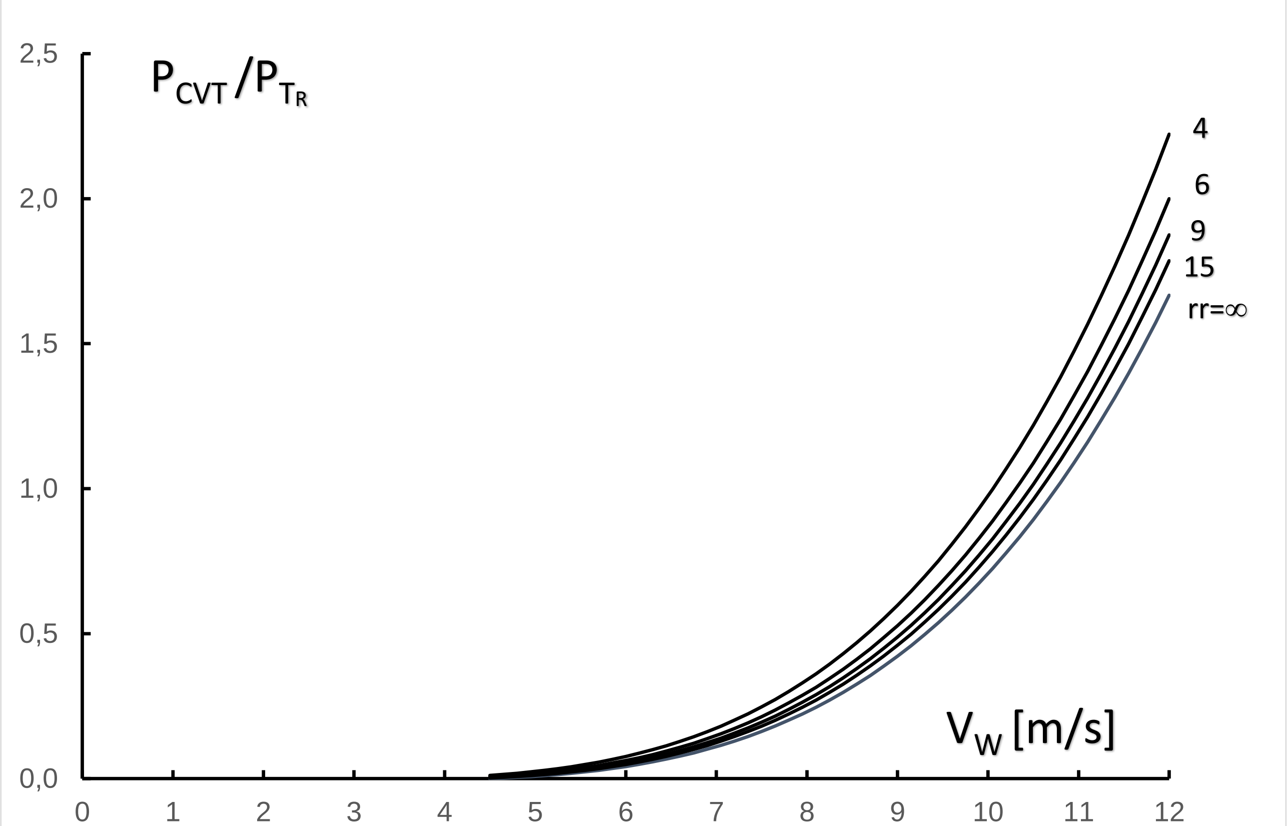

Fig. 7: Output split configuration with type I power flow: Power ratio vs. wind speed

An inverse proportionality (eqq. (3), (20)), the type III power flow is obtained (fig. 1c). The CVT transmission ratio(eq. (3)) decrease with the wind speed (fig. 8). In particular, when *rr* tends to infinite the τ_{CVT} tends to zero.

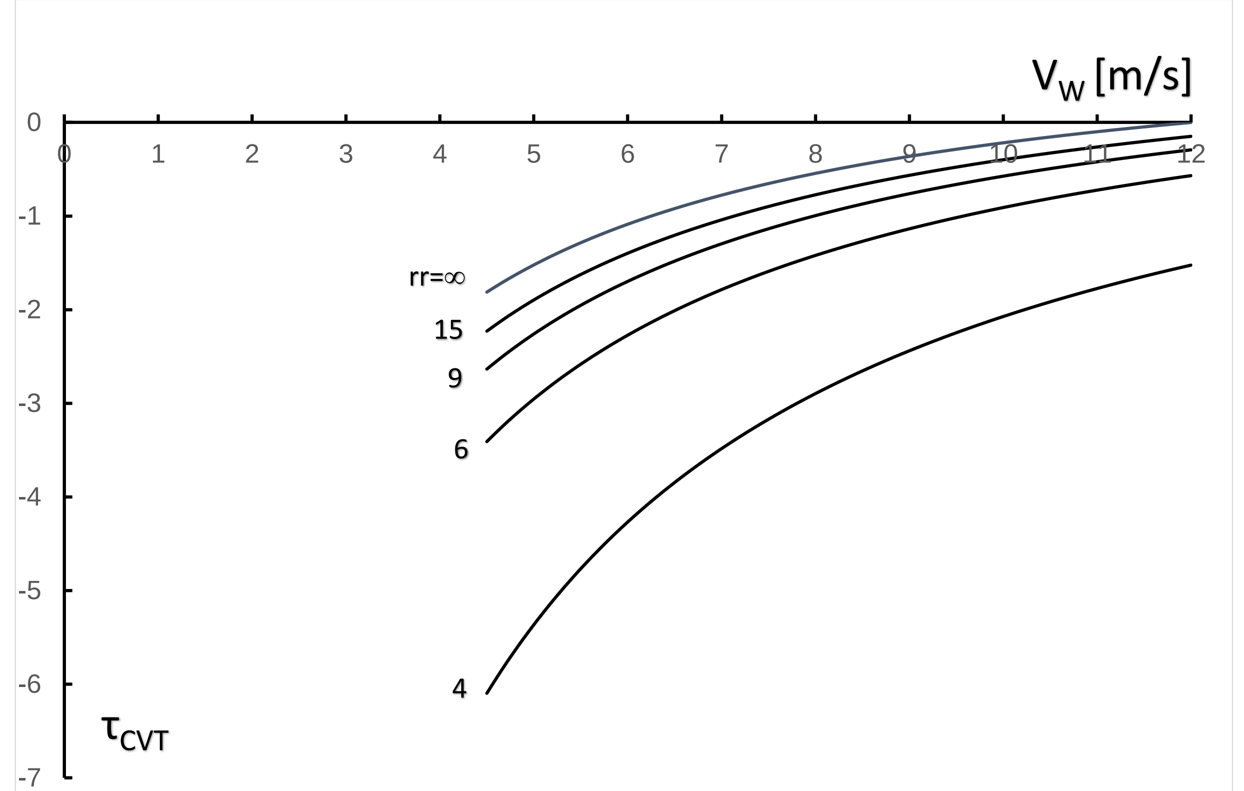

Fig. 8: Output split configuration with type III power flow: CVT transmission ratio vs. wind speed

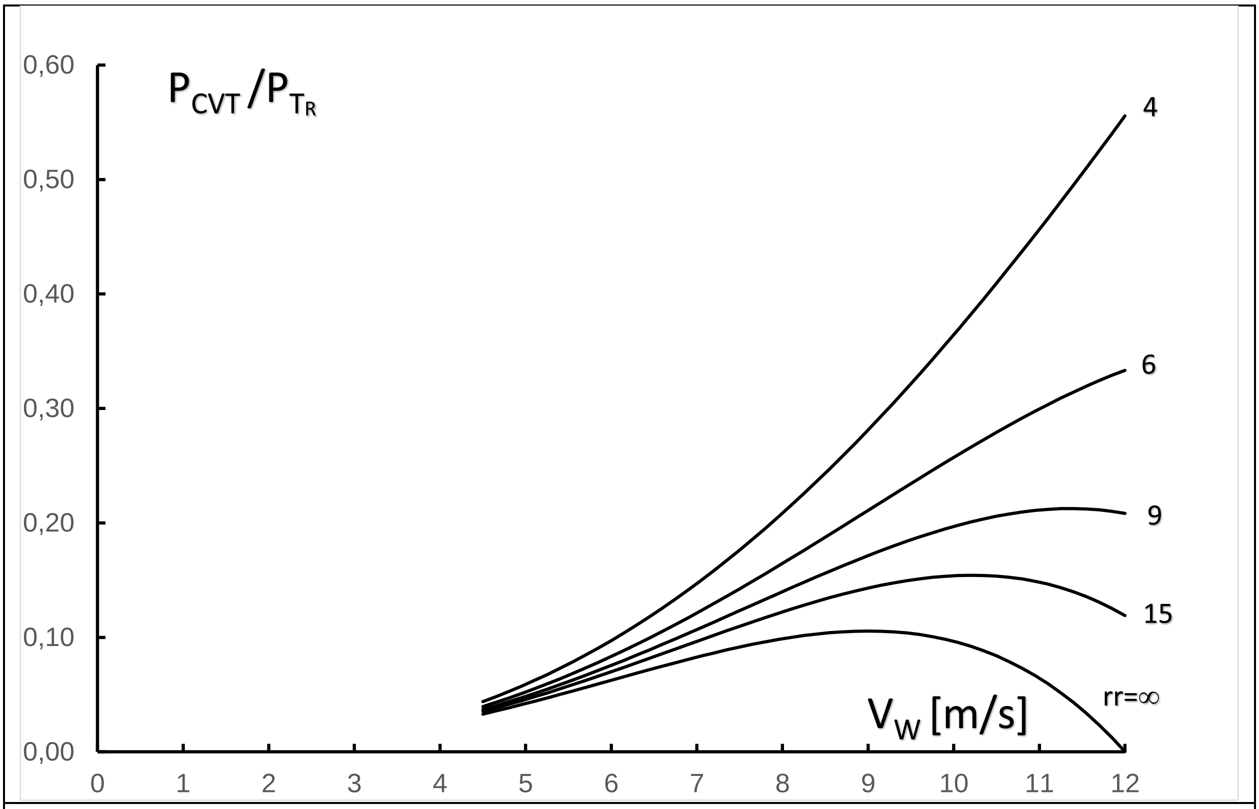

Fig. 9: Output split configuration with type III power flow: Power ratio vs. wind speed

Figure 9 reports the CVT power flow shown as a function of the turbine rated power (eq. (19, 21). For any particular value of the wind speed, the CVT power decreases as *rr* increases. The wind speed at which the maximum CVT power is delivered can be calculated through equation (22). When $rr >> rr_W$, the maximum power of the CVT is 0.105 of the rated turbine power when the wind speed is equal to 9 m/s.

Therefore, the configuration with type III power flow is particularly advantageous as it would require a CVT with a much lower rated power of the generator.

4.2 Input split configuration

Figures 4 and 5 show the power flows in an input split configuration. In the first case (type III power flow), the CVT transmission ratio (fig. 10) linearly increases when the wind speed increases (eqq. 3, 33).

The power of the CVT (fig. 11) increases with the wind speed, reaching maximum values ranging from 60 to 80% of the rated turbine power (eq. (38)). This architecture is therefore not particularly advantageous.

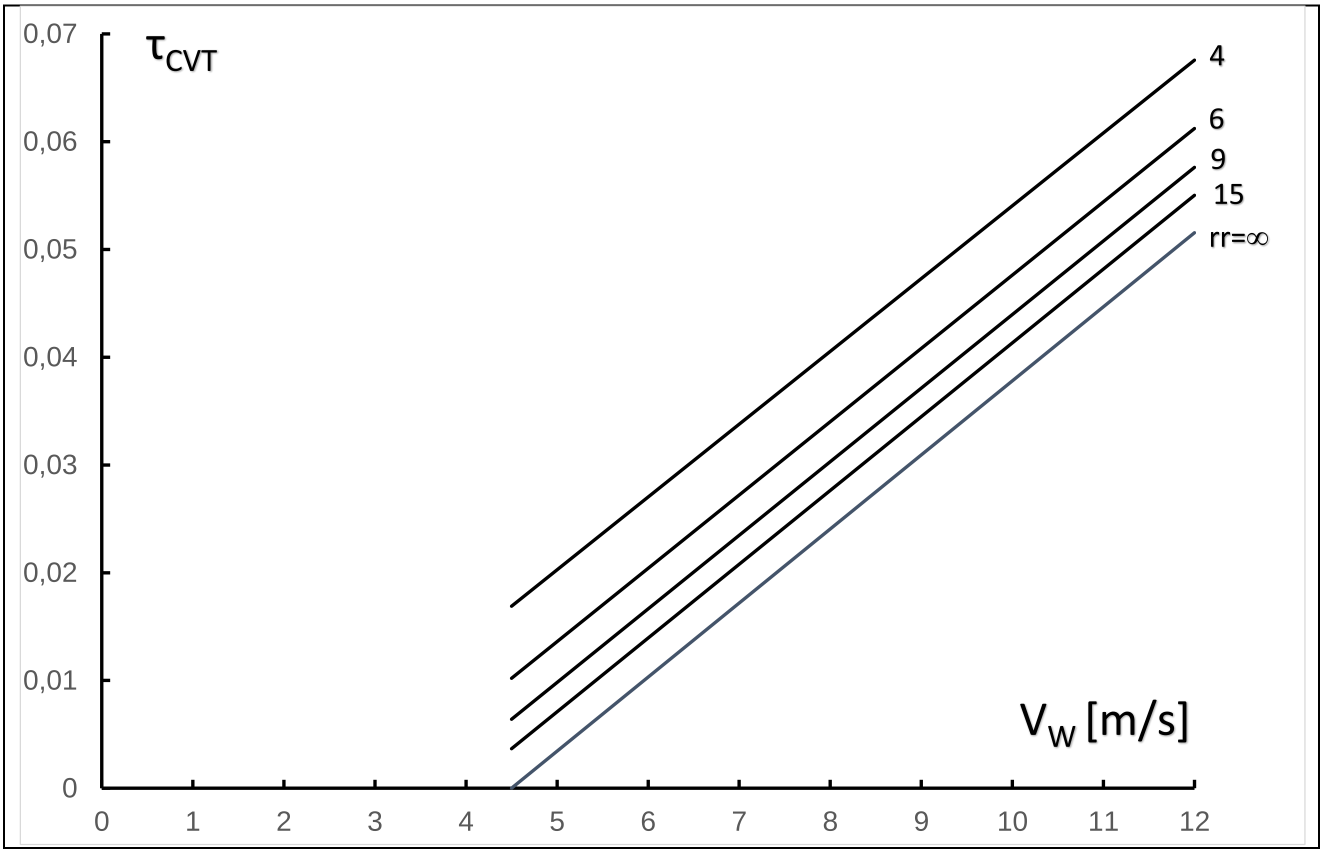

Fig. 10: Input split configuration with type III power flow: CVT transmission ratio vs. wind speed

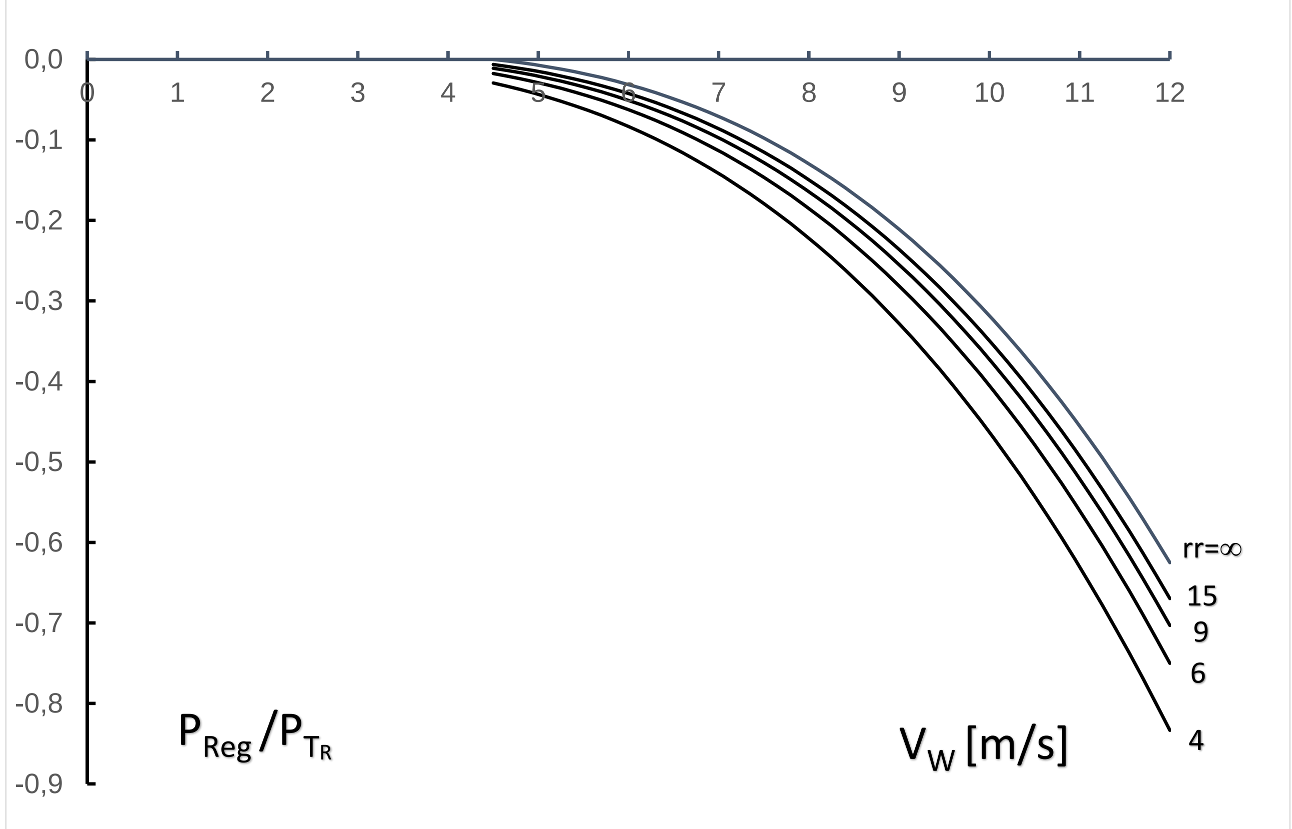

Fig. 11. Input split configuration with type III power flow: Power ratio vs. wind speed

Now we examine the input split configuration with Type I power flow (figg. 4a and 5a). In this case (eq. 3, 43) there is inverse proportionality among τ_{CVT} and the global transmission ratio (fig. 12). The absolute value of the τ_{CVT} linearly decreases and the trend is similar for each value of the CVT ratio range.

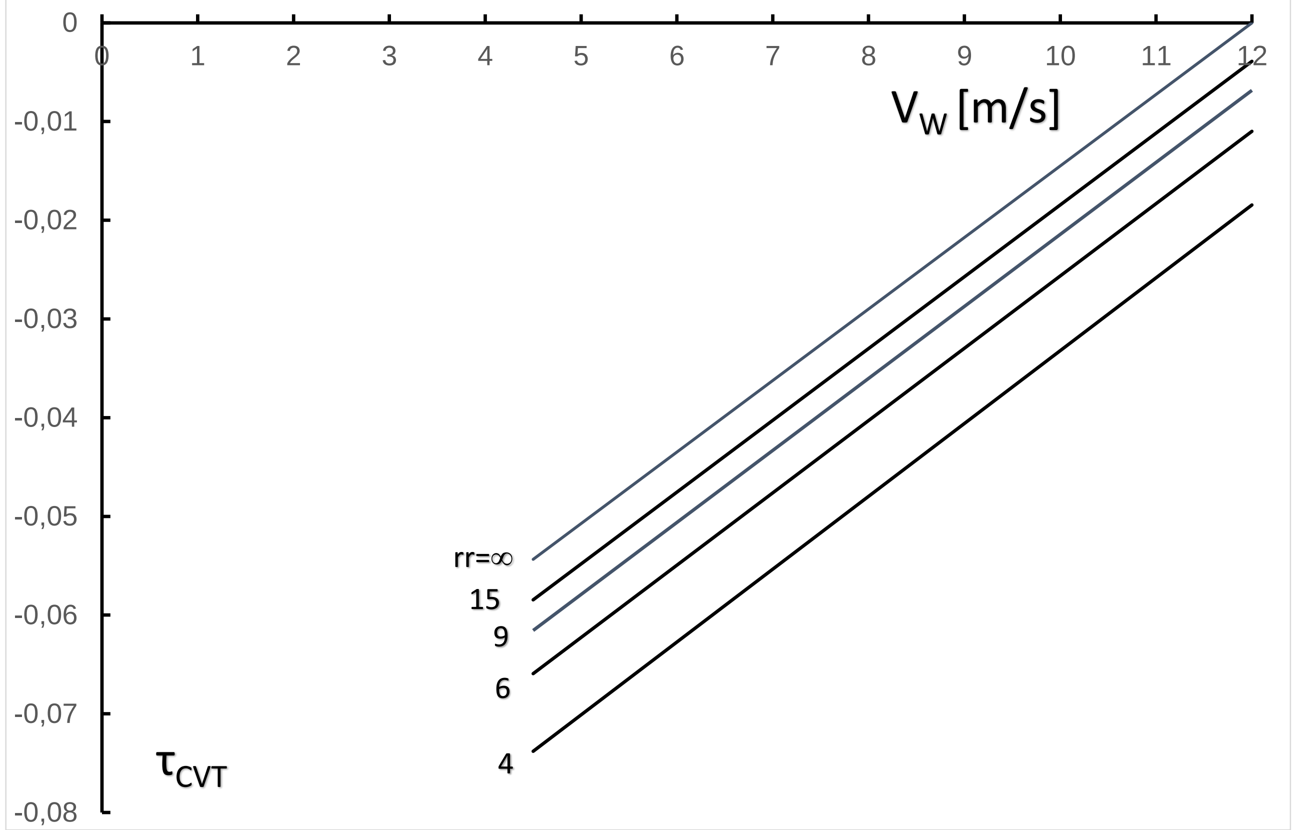

Fig. 12: Input split configuration with type I power flow: CVT transmission ratio vs. wind speed

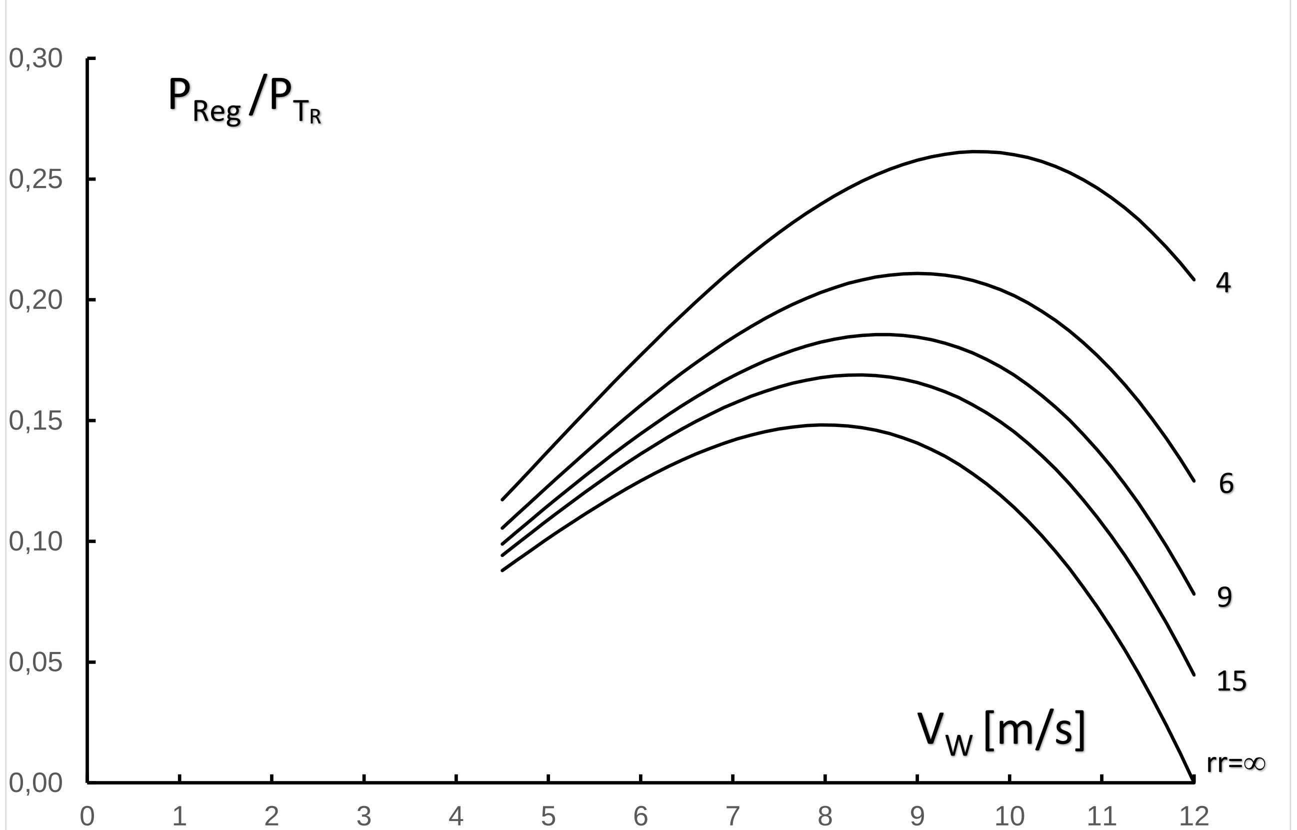

Fig. 13. Input split configuration with type I power flow: Power ratio vs. wind speed

The power ratio (CVT power/rated power of the turbine) reaches a maximum value (fig. 13) that is function of the CVT ratio range (eq. 46). It is interesting to note that the power of the CVT is always much lower than the maximum input. For $rr >> rr_W$, the CVT power is only 15% of the rated turbine power. Also, for low values of rr, for example rr = 4, the ratio among the power is low (0.25).

This configuration is therefore very advantageous in that the rated power of the CVT is considerably lower than the turbine power.

In the input split configuration, it is possible to use an electric regulator to vary the speed of the branch 2 (fig. 5). For the type III power flow (fig. 5b), the electric regulator operates as a generator, whilst as a motor in the type I power flow (fig. 5a). In both cases, the power of the branch 3 (generator) does not coincide with the input power. In the type III power flow, the input power is sum of the power in the branch 2 (electric regulator) and 3 (generator). If we neglect the power loss, figure 14 reports the generator and regulator power in the case $rr >> rr_W$. In this case, the maximum power of the generator is approximately twice that of the controller.

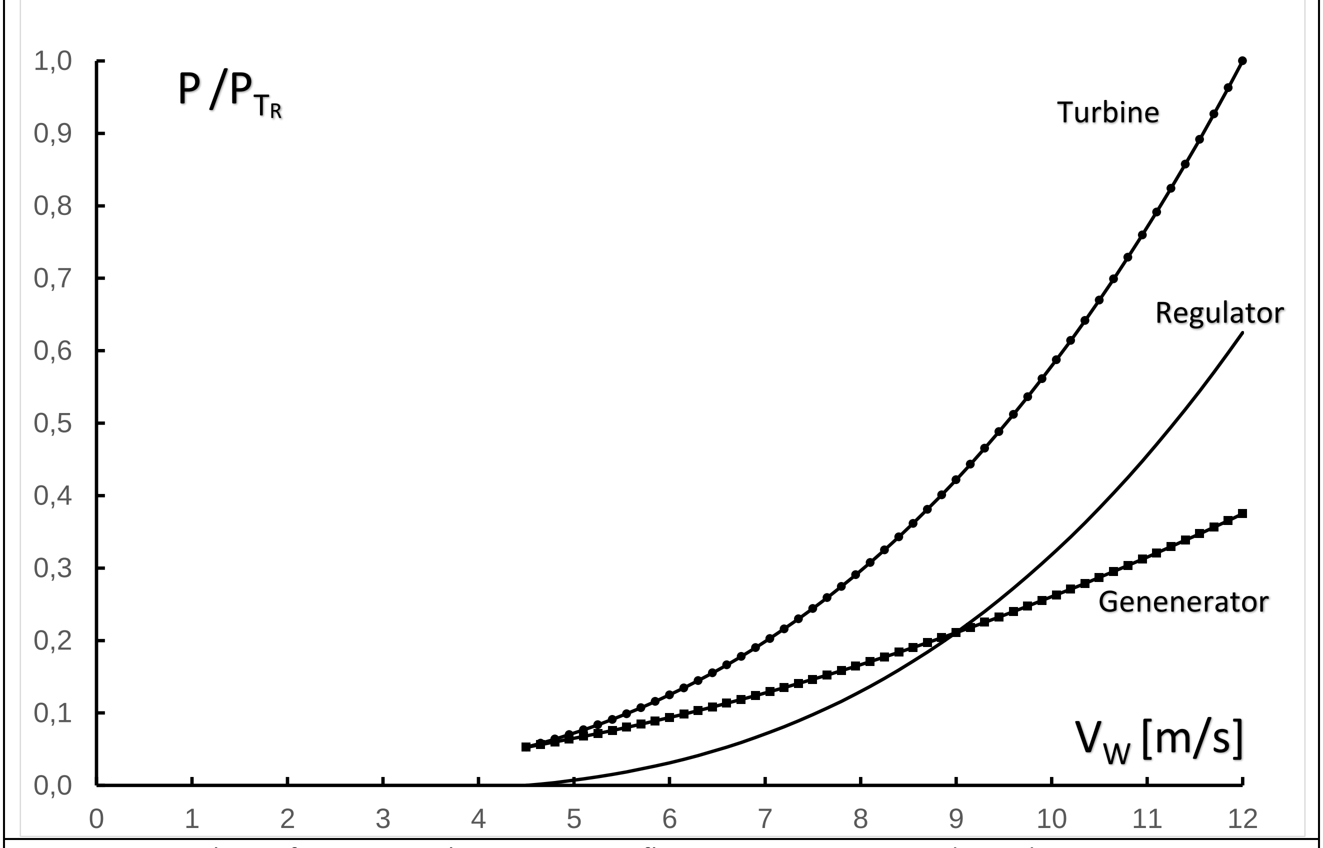

Fig. 14. Input split configuration with type III power flow: Power ratio vs. wind speed

In the type I power flow (fig. 15) the maximum power of the generator is always greater than the input.

However, with the increasing of the wind speed, the difference between input power and that of the generator decreases. At the rated wind speed, the regulator power is zero, therefore the rated power of the generator coincides with the rated turbine power.

In conclusion the best configurations that guarantee a regulator power much lower than that of the generator are the Output Split with type III power flow and Input Split with type I power flow, in the latter case, the controller may be constituted by a servo-motor.

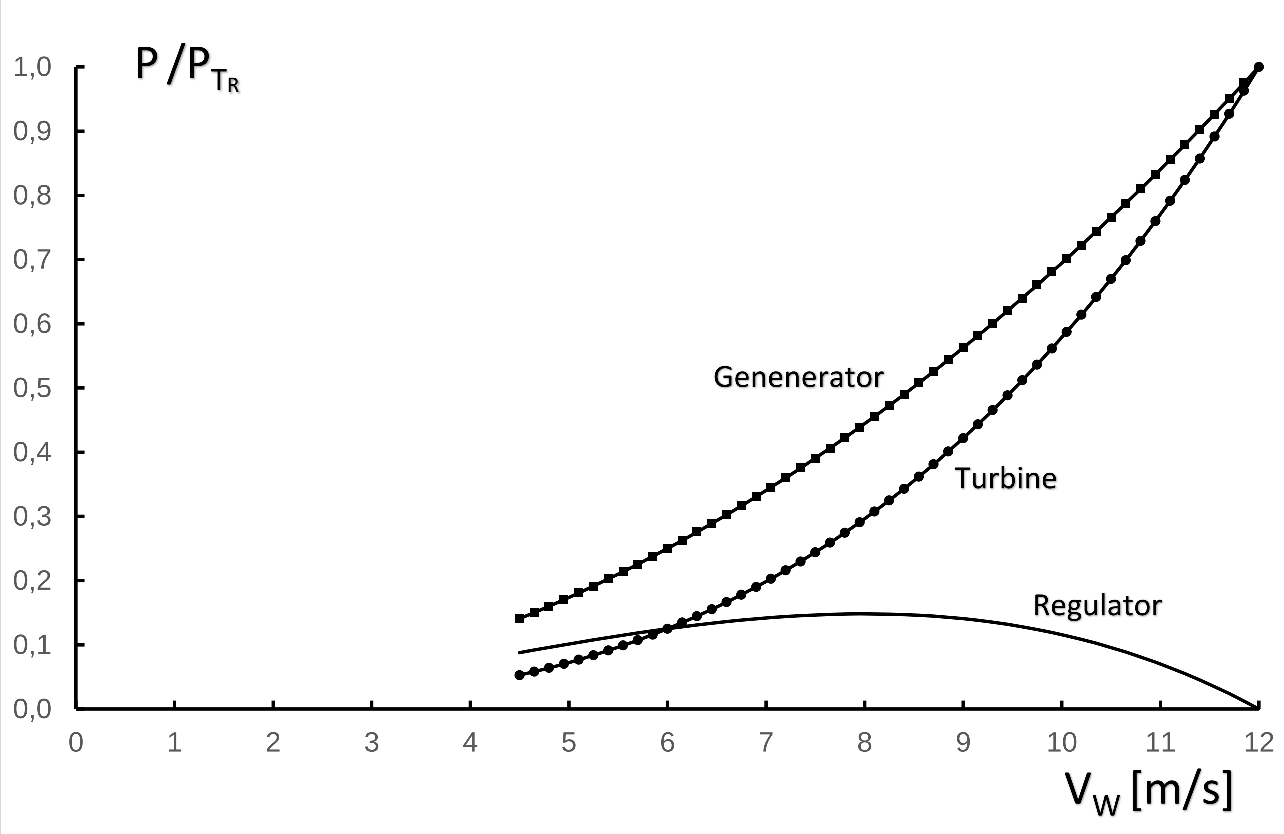

Fig. 15. Input split configuration with type I power flow: Power ratio vs. wind speed

CONCLUSIONS

A variable speed wind system normally incorporates advanced power electronics components that increase overall turbine costs. These components are required to change varying AC power to constant frequency.

This paper compared the performance of the Input and output split power systems for variable speed wind turbines. Through these architectures the turbine could operate at maximum efficiency levels and the generator could produce electric power at a desired frequency.

For each configuration, we studied the possible power flows and the power of the control systems (mechanical CVT, servo-motor/generator or hydraulic system). The minimum rated power of the control system has been identified for each of the configuration described in order to reduce costs and the power losses.

Respect to the rated power of the turbine, the results have shown that the maximum power of the control system is function only of its ratio range. That is, the result does not depend on the size of the turbine or the generator characteristics.

In particular, for an output split power it is decidedly more convenient to design the transmission in order to obtain a type III power flow. In this case, the power of the control systems will be approximately only 10% of that of the electrical generator. Therefore, the configuration with type III power flow is particularly advantageous as it would require a regulator with a rated power much lower of the generator.

For the input split configuration with type I power flow, the rated power of the control system is only 15% of the maximum input power. In the latter case, the controller may be constituted by a servo-motor.

In conclusion, the proposed transmissions offer the advantage of having a generator which always works with a constant speed and therefore at the maximum efficiency, while the regulation is made with a system that has a rated power much lower than that of the generator, which means lower cost and greater efficiency.

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