Wind turbine emulation using permanent magnet synchronous generator

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***Abstract*—This paper aims to presents the results obtained in electromechanical wind speed emulator of distributed low power system. The results are obtained in insulated regime with a step up/down converter, battery bank and resistive load. All the operating regions are aimed, namely optimization and power limitation one, and also an intermediate operating region is considered in order to ensure smooth transition between these two regions. For control purpose an improved strategy is proposed. Hardware implementation is done under DS1103 controller board running under Matlab and ControlDesk® software. This paper present results from a functional low power wind system, part of a distributed multisource low power system, which offer also the possibility of implementing the behavior and the control of such systems, in grid-connected or disconnected from the national grid. Experimental results show the effectiveness of the proposed system under various conditions.**

Keywords—small wind energy conversion system, autonomous low power wind system emulator, PMSG, intelligent hierarchical system

I. Introduction

In the past decades small wind turbines has been subjects of thousands of researches envisaging a variety of issues, most of them pointing the wind turbine system operation depending on the main exogenous variable value, the wind speed. The EU directives encouraged the researches in this area due to the imposed shear of each member states that must be fulfilled in the nearly years.

According to the technical literature, small systems architecture is based mainly on PMSG, fixed pitch and variable speed operation [1], [2], [3]. The present paper presents also a setup based on PMSG, see Figure 1. It is an experimental system for the intelligent hierarchical control of distributed systems, for producing and using electrical energy. Two main sources are connected to the system: a wind turbine with permanent magnets synchronous generator and photovoltaic panels, both supplying, via DC-DC converters with MPPT function into a 48V DC Bus, further to electrochemical batteries and an active power filter (APF) connected to the three-phase national grid, through a 1:1 galvanic isolation transformer.

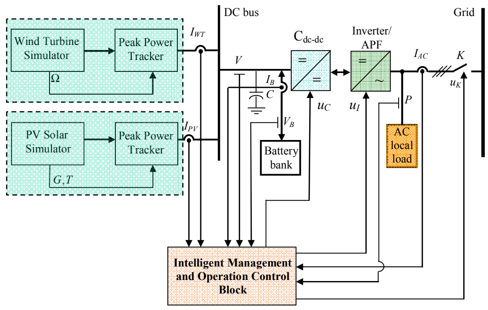


Fig. 1. Structure of the distributed multisource low power system [4]

The experimental rig represents a strong support for further testing scenarios that regards hierarchical management of electrical power flows and/or battery life saving. In the present paper, only wind turbine side contribution is evaluated enclosing the transmission to the DC Bus and the supply of the DC loads. The power electronics is represented by a DC converter and an uncontrolled rectifier. DC converter plays his role in the transmission and already been presented in [5], therefore will not be detailed. An overview of how it works the wind side subsystem is given based on first approach that envisages an open loop control with DC loads. This approach is based on changes in commands to chopper's duty-cycle which acts then on the DC load. The second approach, a more complex one, is based on two control loops, both loops having only one controller with one pair of parameters, each helping to support system operation, not only on the optimal regime characteristic (ORC) [6], but also in power limitation at high wind speed. This approach was improved because the controller used for limitation is a classical PI that has parameters values kept identical no matter if the operating point is in the optimization or the limitation region. Thus is ensured operation in region 2 where power maximization must be ensured by maintaining the operating point on the ORC and region 3 where the captured power must be limited to the rated value. In most of the control solutions region 2 is divided into 2 regions, like in this paper. Thus we have two regions, region 2a and region 2b (see Figure 2). The former provides a smooth transition to region 3 by keeping the rotational speed in limitation. At transition, system phase shift occurs that causing controller command forward and backwards jump. Thus keeping rotational speed in limitation is avoiding any side effect and providing smooth transition.

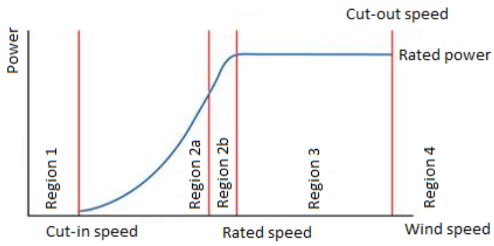


Fig. 2. Wind turbine power curve

II. Theoretical aspects

A classic PI approach is used for controlling the rotational speed of the wind turbine shaft. The reference signal of this control loop is:

$$\Omega_{opt} = \lambda_{opt} \frac{R}{v} \tag{1}$$

where λ is the tip speed ratio, R is the blade length and v is the wind speed value.

The controller parameters are calculated by identifying process response to chopper duty-cycle step commands. A first order process is identified with the following transfer function:

$$H(s) = \frac{K}{Ts+1} = \frac{10{,}8}{4s+1} \tag{2}$$

Based on (2) closed loop transfer function is:

$$H_o(s) = \frac{\frac{K}{Ts+1} \cdot \frac{K_p(T_i s+1)}{T_i s}}{\frac{K}{Ts+1} \cdot \frac{K_p(T_i s+1)}{T_i s}+1} \tag{3}$$

and can be reduced to the next expression, considering $T_i = T$,

$$H_o(s) = \frac{K \cdot K_p}{K \cdot K_p + T_i s} = \frac{1}{T_o s+1} \tag{4}$$

where $T_o = \frac{T}{K \cdot K_p}$. Gain constant can be calculated as:

$$K_p = \frac{T}{K \cdot T_0}. \tag{5}$$

For power limitation in region 3, is used a power control strategy that brings wind turbine operation in stall mode by reducing the rotational speed shaft when the wind speed increases over the rated value. Stability of the system at transition from region 2 to region 3 is ensured. The solution is to consider an intermediate region, interleaved in region 2, where power optimization is still aimed but rotational speed is kept constant.

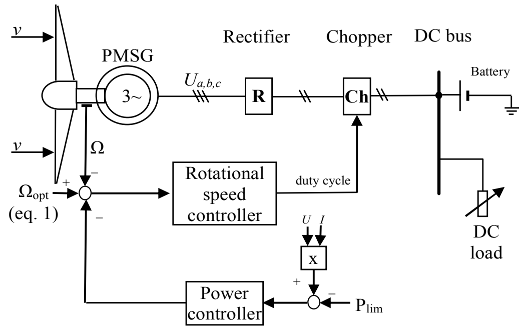


Fig. 3. Control structure for wind system side of the distributed multisource low power system

Figure 3 presents this power loop. The loop reference is a constant value $P_{\lim}$ to which captured power must be limited while the measured power signal is generated by multiplying current and voltage measured values from chopper side. The power controller command is transferred to rotational speed controller and compared with the reference. The command is limited to a value smaller than the rated value, enough to generate region 2b used for transition. This region has certain variability depending on the system and its variables that must be manipulated.

III. Experimental rig

The wind energy conversion system (WECS) are systems for which the real-world validation of various control laws through off-line simulations involves new technical approaches concerning the outside wind speed, but in controlled wind speed regime [7], [8], [9], [10], [11].

Figure 4 displays physical elements of the experimental setup used in this paper. The experimental rig is composed of: a 3 kW squirrel cage 3ph asynchronous motor, a 5kW frequency converter Danfoss VLT 5000 Flux, an encoder, a PMSG GL-PMG-1500 type with a rated power of 1.5 kW, a step up/step dawn converter with MPPT function, batteries and a computer connected to the dSPACE® controller board DS1103. Based on Matlab software and ControlDesk „Hardware-In-the-Loop” – HIL simulation concept [6], [8], [9], [13], [14], [15] is ensured. The acquisition board was embedded into a box DSpace PX4 connected to a PCI Express board of the PC through an optical cable. A PV emulator based on a Magna-Power programmable DC power supply was also considered. An electrical connection ensures electrical energy transfer from the wind turbine and PV emulators to a battery bank and to a group of mono phase local loads via an inverter.

The 5kVA galvanic isolation 1:1 was considered for connecting the rig to the national three phase network.

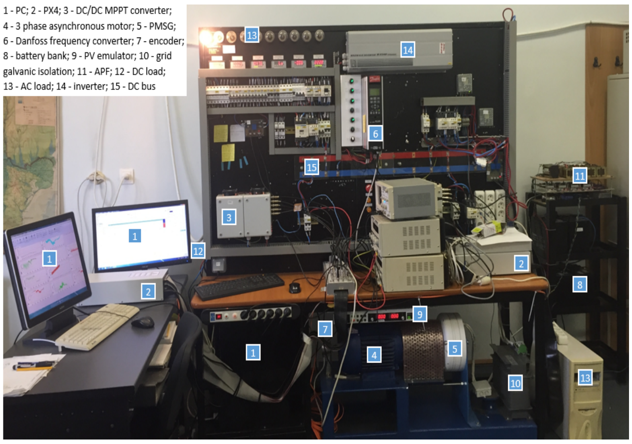


Fig. 4. Distributed multisource low power system experimental setup

IV. Experimental results

Two control approaches have been studied. A first approach consists in modifying in open loop the operating point based on DC resistive load values when DC converter command remains unchanged.

More precisely have been verified the followings experiments:

- the voltage – rotational speed characteristic of the electromechanical part of the wind turbine emulator (the asynchronous motor supplied via Danfoss VLT 5000 frequency converter and directly coupled to PMSG via wind turbine shaft, which generates electrical energy through an uncontrolled three phase rectifier) was tested when no load is existent and the result is presented in Figure 5.a. The obtained characteristic corresponds to offered dates from the PMSG producer [16].

- the operation of the electromechanical wind turbine emulator when load exist and consist of a rheostat with the maximum resistance 15,5Ω and 10 A maximum current. In Figure 5.b were presented the characteristics voltage – rotational speed (rpm) obtained when loads are 6Ω, 6.5Ω and 12.3Ω. In Figure 6.a are presented the characteristics power - rotational speed for the same loads. The generator supplies the load via an uncontrolled rectifier. In Figure 6.b were presented the characteristics current-voltage for this experiment. From the second experiment, can be observed that the obtained electrical power is higher when the load value is smaller (R=6 Ω).

In the second approach chopper duty cycle is variable and the load is constant. The duty-cycle is controlled via two control loops considered for rotational speed and electrical power. This approach is more complex because envisages not only operation in the optimization regime, but also transition from region 2 to region 3. The controllers parameters used in rotational speed loop and power loop are: $K_{p\Omega} = 0.37$, $T_{i\Omega} = 0.25$, and $K_{pP} = 0.005$, $T_{iP} = 0.26$ respectively. The wind speed profile is a ramp with a variation limited to 10 m/s. When the simulation time is t=200 s the power optimization loop start to operate, the command value moves to 2, the tip speed riches the optimal value $\lambda_{opt} = 7$, the power coefficient is to the maximum value ($c_{p\max} = 0.476$), all this showing that the rotational speed follows the optimal rotational speed, this can be seen in Figure 7.d. From Figure 7.b can be seen that after 420 seconds of simulation, the intermediate region, region 2b, is reached. Here the rotational speed is limited to a value smaller than the rated value. Even the rotational speed is limited, the power optimization is still ensured, power increasing as the wind speed increases. At 520 seconds of simulation, the power is almost 400 W, identical with the value imposed as rated power value; therefore, the power loop starts to limit the captured power even the wind speed still increases.

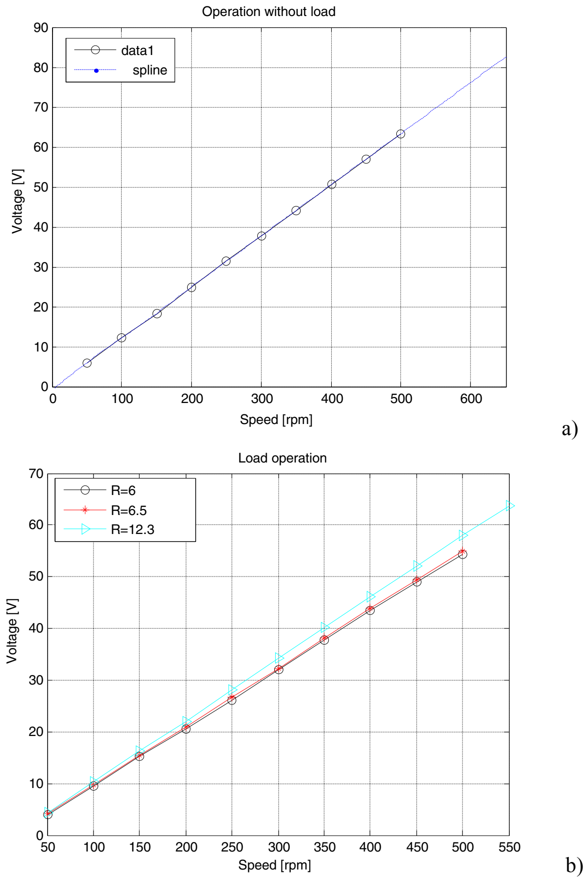
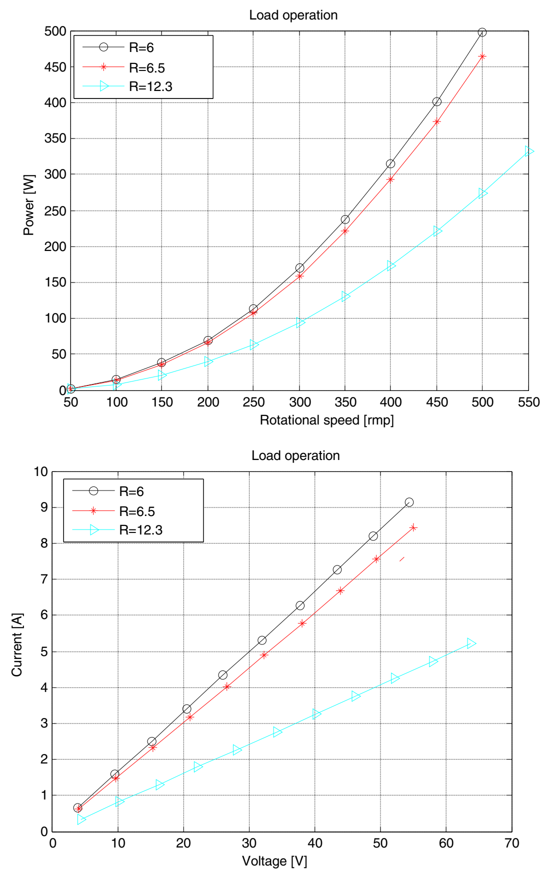


Fig. 5. Rotational speed – voltage characteristic of the wind speed emulator: a) when no load is considered; b) when different load values are considered

Power limitation in stall regime can be observed from tip speed evolution (Figure 7.d) that decreases while the wind speed increases.

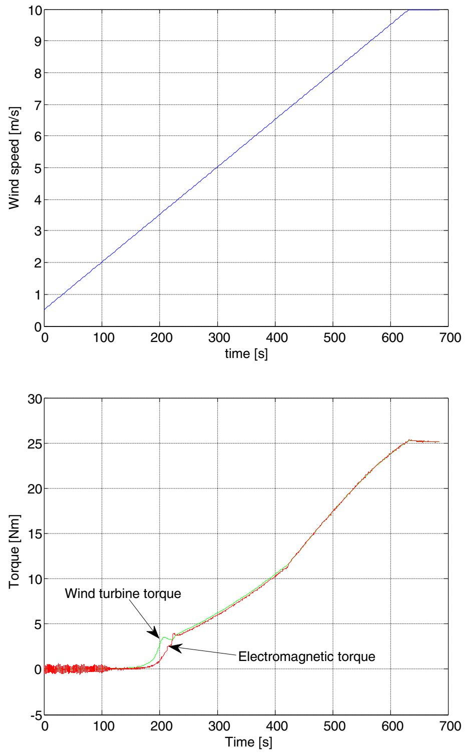
In Figure 8 are presented the evolution of the electromechanical wind system main variables when the wind speed has an evolution in step continued immediately with a ramp.



a)

b)

Fig. 6. a) rotational speed – electrical power characteristic when electromechanical wind speed simulator operates with load; b) voltage – current characteristic when electromechanical wind speed simulator operates with load



a)

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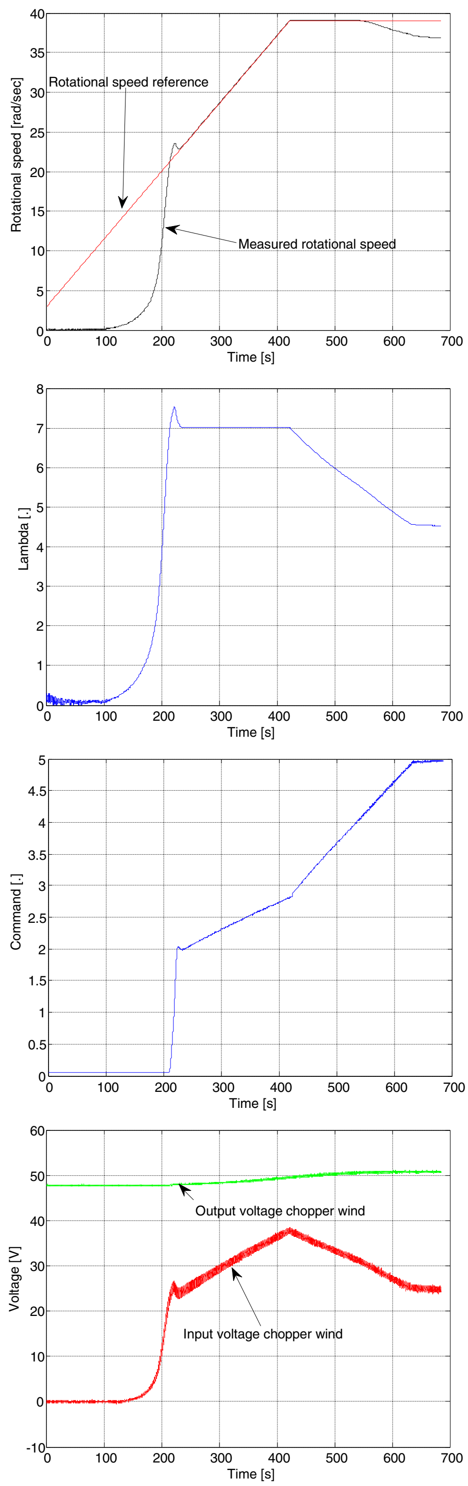

c)

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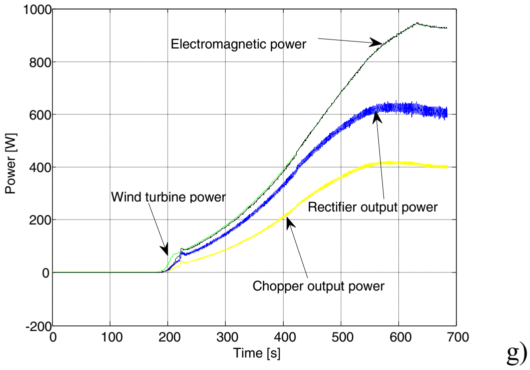
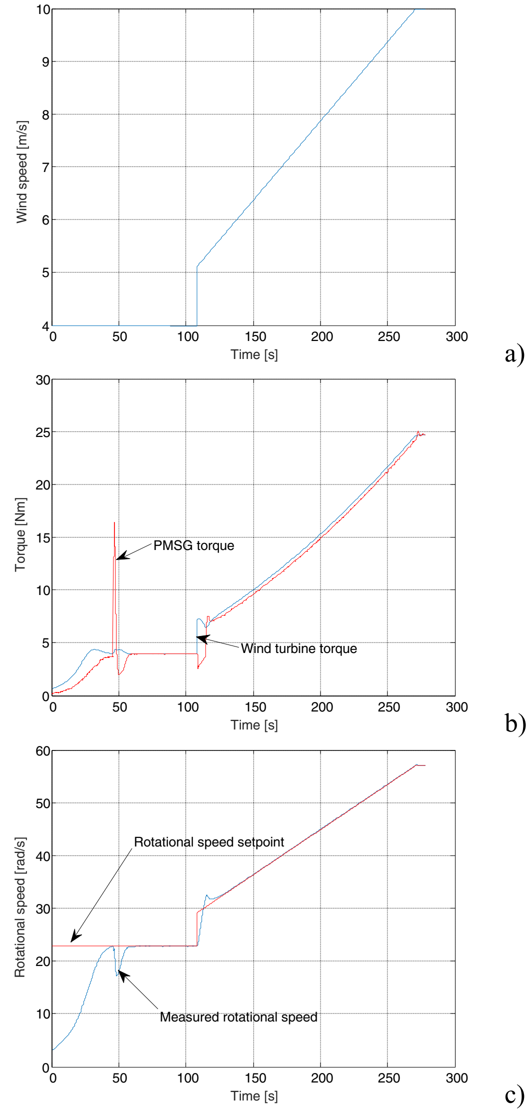


Fig. 7. The evolution of main wind system variables when passing from region 2 to region 3, the operation being in presence of a battery bank and a resistive load, while the used wind speed profile is a linear ramp



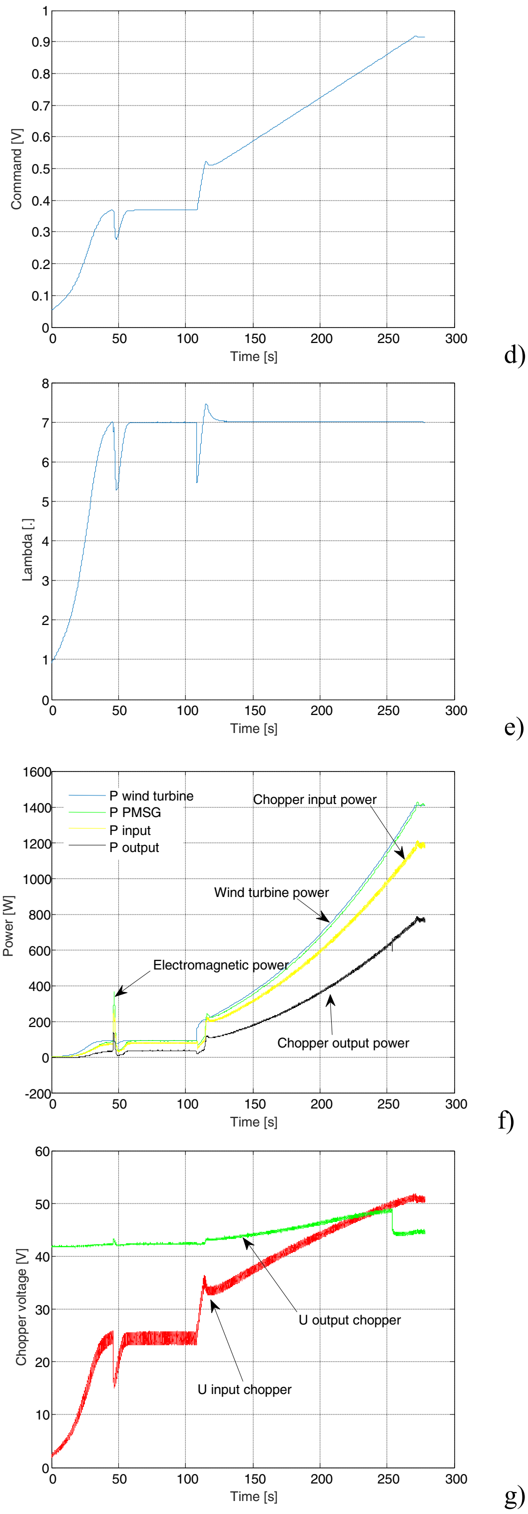
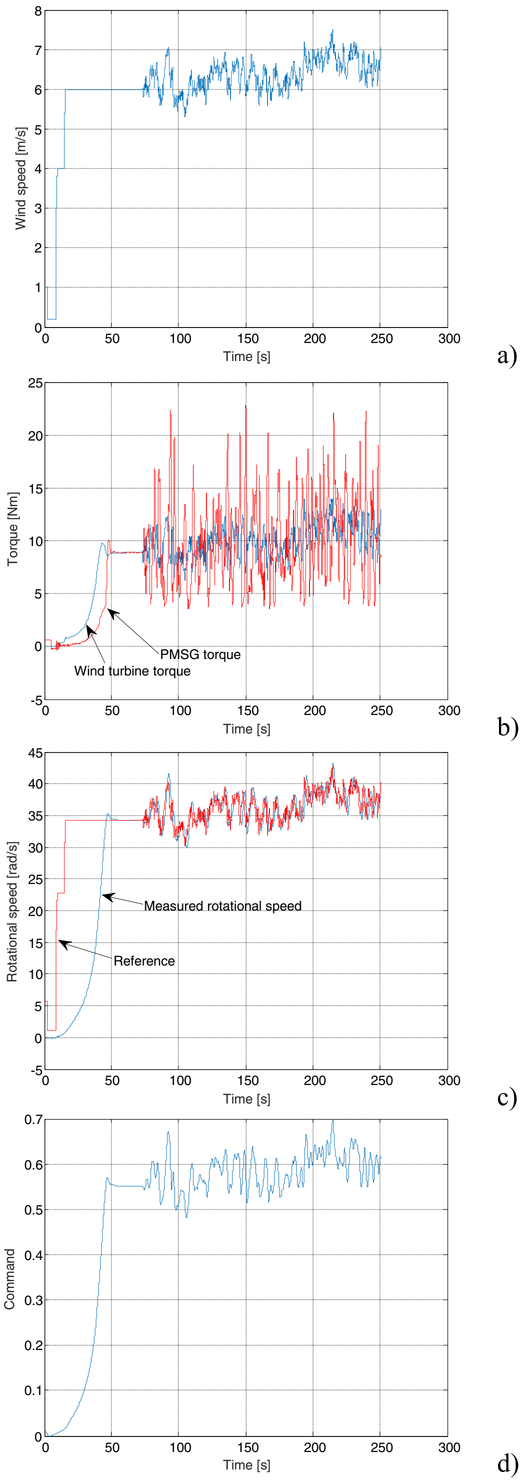


Fig. 8. Evolution of main wind system variables when PI controller is used for the optimization control loop, the operation is with bank capacitances and resistive load, while the used wind speed profile is a linear ramp interleaved with steps

The former statement is valid regardless of wind speed profile, thus system was tested also to a variable profile. At the begin wind speed has a constant value and system starts operating with the control loop decoupled, practically in open loop (see Figure 9). After some seconds the rotational speed loop is coupled and when wind speed reaches 6 m/s the wind profile is changed to one variable. Figure shows the evolution of main system variables for this case. It can be seen that system stability is kept and operating point remains on the ORC (see rotational tip speed kept around the optimal value in Figure 9.e.



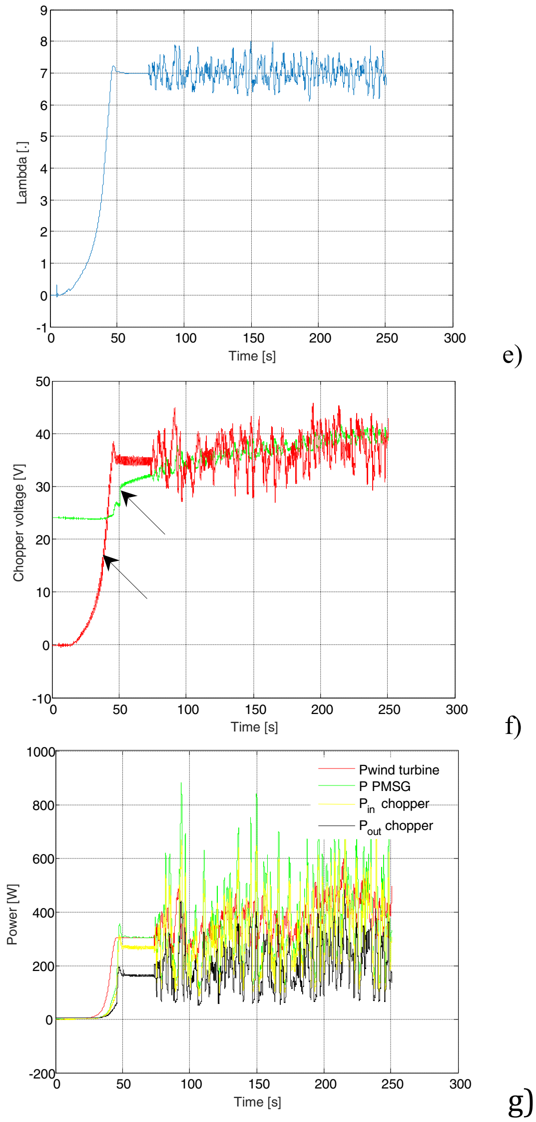


Fig. 9 Evolution of main wind system variables when PI controller is used for the optimization control loop, the operation is with bank capacitances and resistive load, while the used wind speed profile is variable

V. CONCLUSION

The present paper presents the performances of a wind turbine electromechanical simulator of a hierarchical distributed multisource system. The test rig is a result of a research grant. The presented results are only for wind system side operation in insulated regime with battery bank and DC load. A step up – step down chopper is used for controlling the operation regime. For control is used a control structure with two control loops, based on reference signals (1) dependent of the wind speed measured value. Different results are obtained for different wind speed profiles. Regardless of wind speed profile the system performances are kept, system stability is always ensured and nevertheless each regime operation is followed as it is expected. In the optimization region the operating point is kept on ORC and in limitation region captured power is limited to the value imposed by the user, which not overpass the rated value. These results offer a valid support for further testing approaches that will aim not only insulated regime, but also distributed regime. Further it is also aimed to find solutions for increasing battery life time used in the system in case of grid connection.

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