A Novel Mechanical Hardware in the Loop Platform for Distributed Generation Systems

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ABSTRACT

The growing number of distributed generation (DG) plants has emphasized the need to perform tests before the plants begin to operate. DG systems are complex enough that setting up of an experimental phase requires high costs and efforts. Moreover, renewable energy sources are intrinsically intermittent as they vary randomly with the time of day, the season and the weather. Consequently, the possibility of emulating the behavior of the whole renewable generation system in a real time environment, where a part of the real system, the natural energy source, is replaced by a real time computer simulation allows one to test the actual system in all the operating conditions, optimizing the control strategy before its service entrance, overcoming the randomness of renewable energy sources. This article proposes a mechanical hardware in the loop approach applied to a renewable energy generating system, where the whole drive (control, power electronics and electric machine) is tested and the mechanical part is simulated in real time environment. The problem of emulating the inertial torque, which can have a significant high value, is solved through an approach that relaxes the high dynamic requirements of the electrical drive that emulates the mechanical part. The hardware in the loop test bench emulates two energy sources (hydro and wind). In addition, a control strategy that emulates the inertial torque is implemented. An experimental phase in which different energy sources are modeled and emulated in a real time environment is presented as well. The underlying hardware-in-the-loop energy source emulation and experimentation scheme is shown to accurately represent real systems performance, under various control strategies and varying operating conditions.

Keywords: Hardware in the loop; distributed generation; low voltage, power quality, real time test bench.

INTRODUCTION

The strong growth of Distributed Generation (DG) systems installed on Low Voltage (LV) electrical power networks (with a typical power range of 1 to 400 kW) has emphasized the need to perform preliminary tests before they are put into service to check their efficiency and validate Power Quality (PQ) functions. Typically, these tests are made on DG system prototypes that entail high experimental costs and effort. In addition, it is often very hard to perform significant tests in a short time because DG systems use renewable energy sources, like wind, sun or sea, which vary widely or aren't always available. A hybrid approach, using a Hardware-In-the-Loop (HIL) simulation, has turned out to be an effective tool for the evaluation of these systems and various methods have been proposed in scientific literature. Here, HIL simulation refers to a system in which parts of the real system are replaced by a computer simulation running in real time.

Hardware in the loop simulations (HILS) are not new [1]-[4], but have been used extensively for controller assessment for a long time. The aerospace industry has been using this technique ever since software became a safety critical aspect of flight control systems. More recently, however, a combination of several factors has led to a sharp increase in its use, principally thanks to the reduced cost and greater availability of HIL products and the intense pressure to reduce development time and costs.

More recently, HIL simulations have also been used to test distributed generation systems, e.g., to validate control algorithms or Maximum Power Point Tracking (MPPT) strategies [5]-[10]. Generally, these HIL techniques are limited to control applications, i.e., there is only signal coupling between the hardware and the virtual system. This approach, even if it is very useful during the control design stage, it presents some deficiencies when it is used to develop electrical drives for DG renewable low power energy generators. As a matter of fact, a DG system has an intrinsic complex nature and can rely on both renewable and non-renewable sources, such as wind turbines, photovoltaic generators, small hydro, fuel cells and gas combined heat and power (CHP) stations. Thus, various DG/CHP hybrid schemes can be achieved. Figure 1 shows a simplified schematic of a complete DG system.

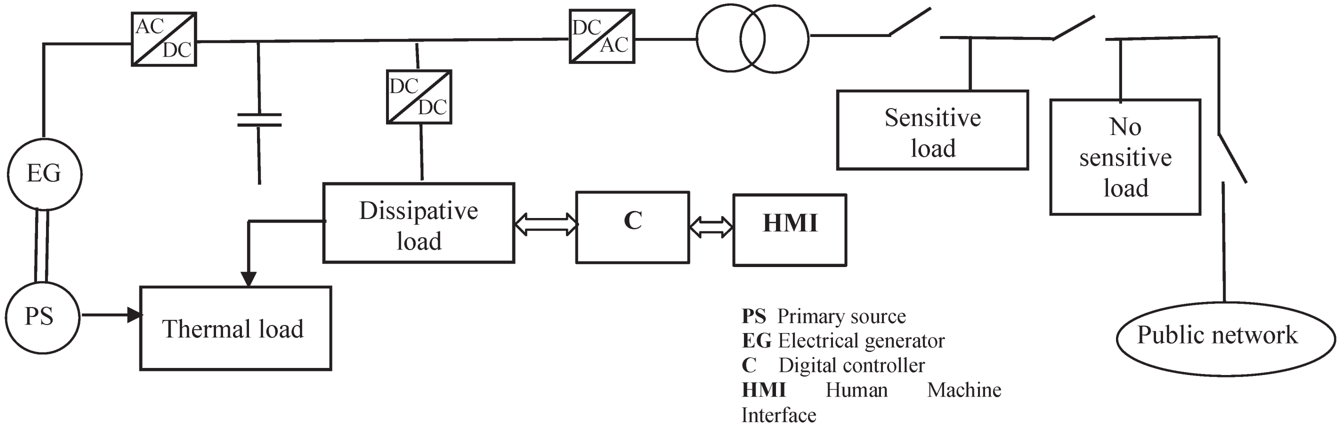

Figure 1. The simplified architecture of a generic Distributed Generation (DG) system.

In these systems, it is very important to evaluate the interactions between the electrical drives and the mechanical components in order to avoid dangerous working conditions and, moreover, to estimate precisely the system's energy efficiency. In particular, this parameter is an important variable in a renewable energy plant because these systems are quite expensive and a small increase in global efficiency can drastically reduce the payback time. For this reason, different kinds of HIL simulations can be used to meet these requirements reducing the cost and the infrastructure.

HIL approach has been successfully adopted in wind energy systems to test wind turbine control strategies [11], [12]-[23]. In particular in [17] a HIL simulator dedicated to real time validation of specific control laws for variable speed wind energy conversion systems is discussed. In [18] a real time simulator is adopted to study a hybrid system constituted of a hybrid energy storage system and a wind turbine generator, while in [19] HIL approach is adopted to test a hydrogen production process for assessment of an active wind energy conversion system.

In [27]-[29] three different kinds of HIL simulations for electrical drives have been evidenced:

1. Signal level HIL simulation, where only the control board is tested and the other parts are simulated in a real-time environment. In this case, only a signal coupling between the real time simulator and the hardware tested is needed. This kind of HIL simulation has very often been employed in aerospace and automotive applications for the assessment of controller boards (Fig. 2).

2. Power level HIL simulation [24]-[26], where the control board and the power electronics converter are tested and evaluated. Here both the electrical machine and the mechanical load are simulated in the real time environment (Fig. 3). In this case, signal and power variables are required at the interface between the system under test and the real time simulation environment. This kind of simulation is often referred to as power HIL (PHIL).

3. Mechanical level HIL simulation. In this case, the whole drive (control, power electronics and electrical machine) is tested and the mechanical-energy part (source/load) is simulated in a real time environment (Fig. 4).

Figure 3. Power Level HIL or PHIL simulation

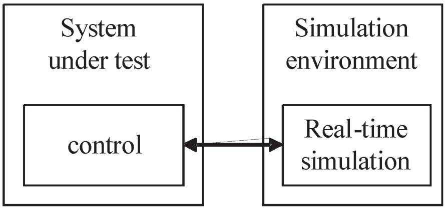

Figure 2. Signal Level HIL simulation

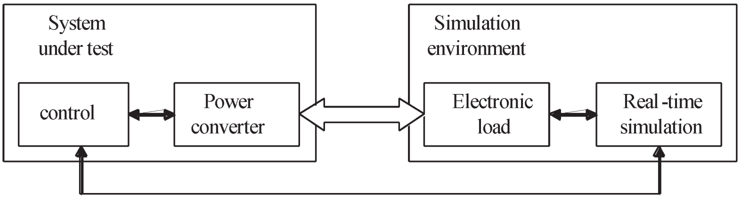

Figure 3. Power Level HIL or PHIL simulation

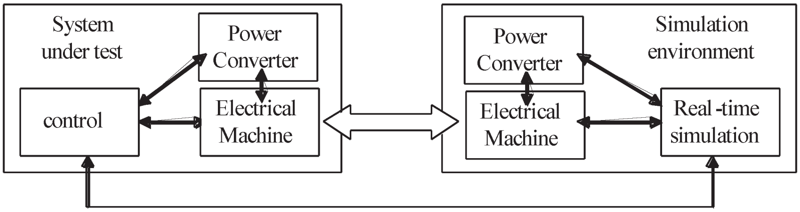

Figure 4. Mechanical Level HIL simulation

Each of these simulations can be used to test a DG electrical drive, although peculiar aspects characterize each of them.

This article proposes a real time mechanical level HIL approach able to emulate a DG system. The proposed approach is intrinsically general and can be applied to different renewable and not renewable energy sources. The possibility of emulating the behavior of a DG system using the real generator connected to the real grid also with other generators, simulating the mechanical part and physical source of energy, in a real time environment, allows us to verify system behavior in all the operating conditions even in the more critical ones. Moreover, it allows us to test and validate different control laws for various energy source regimes, irrespective of the actual meteorological context. Furthermore, the problem of emulating high inertial torque of a renewable energy source is solved adopting an original approach. The article is organized as follows: Section II presents mechanical level HIL and its peculiar general aspects, in particular two different energy sources are analyzed (wind and hydroelectric). Section III presents the HIL test platform, while experimental results are discussed in Section IV.

MECHANICAL LEVEL HIL

Mechanical HIL can be particularly interesting in the area of DG systems, where the infrastructure necessary to set up an experimental platform is quite relevant in terms of cost and complexity and the nature of the controlled process does not allow deterministic tests in its natural environment. In a DG mechanical HIL, the whole drive (control, power electronics and electric generator) is the real one, while the mechanical behavior of the energy source is simulated and realized through an electrical drive mechanically coupled with the real electrical generator (Fig. 4). Let us refer to the real drive as the system under test, and to the other as the simulated one. The real time simulation system gives the mechanical inputs to the simulated system (the electrical machine which emulates the mechanical torque of the energy source system) according to the renewable energy system operating conditions which should be simulated. Moreover, measurements on the mechanical part have to be sent to the controller board under test, as all field measure should be emulated too. The electrical machine used to simulate the mechanical behavior of the energy source is supplied by a second power electronics set. A second controller board (real-time simulation) is required to control the load machine and to send fictitious mechanical "measurements" to the controller board under test.

In a mechanical HIL simulation, the presence of a real electrical drive removes the very small time step boundaries typical of signal level and of PHIL simulations and introduces new boundaries that depend on mechanical dynamics expressed by equation (1).

$$T_m = T_r + J\frac{d\omega}{dt} + B\omega \tag{1}$$

where T_m is the electromagnetic torque, T_r is the load torque, J is the equivalent inertia, B is the load damping factor and ω is the actual rotor speed. Equation (1) shows that the electrical drive used to emulate the mechanical load should supply not only the load torque but also the inertial torque, which could present high values and dynamics. To satisfy this requirement, it is necessary to use a high performance drive, which is not very simple to implement and control. To avoid this problem, a different approach can be used, as proposed in [30-31]. In particular, the DG power source presents a low dynamic speed variation due to a high damping factor and inertia, so it is possible to modify the mechanical emulator control of the electrical drive from torque to speed control. In this way, the mechanical model could be reduced to a quasi-steady-state model by considering the DG power source speed as a constant during an integration step. This is possible because the integration model step is very small compared with the mechanical time constants. Using this approach, the acceleration torque, T_{acc} equal to $T_m - T_r$, can be calculated by subtracting the load power (P_l) from the available mechanical source power (P_s) and dividing the result by the actual speed ω_{act}. The load power is measured by the electrical drive to take into account all the mechanical losses in the power train. Thus, the acceleration torque is

$$T_m = T_r + J\frac{d\omega}{dt} + B\omega \tag{2}$$

The new speed reference (ω_{ref}) for the electrical drive that emulates the DG power source is calculated by dividing the acceleration torque by the system equivalent inertia, as it is indicated in (3) and (4).

$$\frac{D(\Delta\omega_m)}{dt} = \frac{1}{J}T_{acc} - B\omega_{act} \tag{3}$$

$$\Delta\omega_m = \int_0^{\Delta t}\left(\frac{T_{acc}}{J} - B\omega_{act}\right)dt \Rightarrow \omega_{ref} = \omega_{act} + \Delta\omega_m \tag{4}$$

The proposed approach (Fig. 5) simplifies the modeling of high inertia loads, allowing the test of control strategies under dynamic conditions, avoiding the measurement of load acceleration. Moreover, it is possible to use a less sophisticated electrical drive, control board and emulation board, thus reducing the test bench cost.

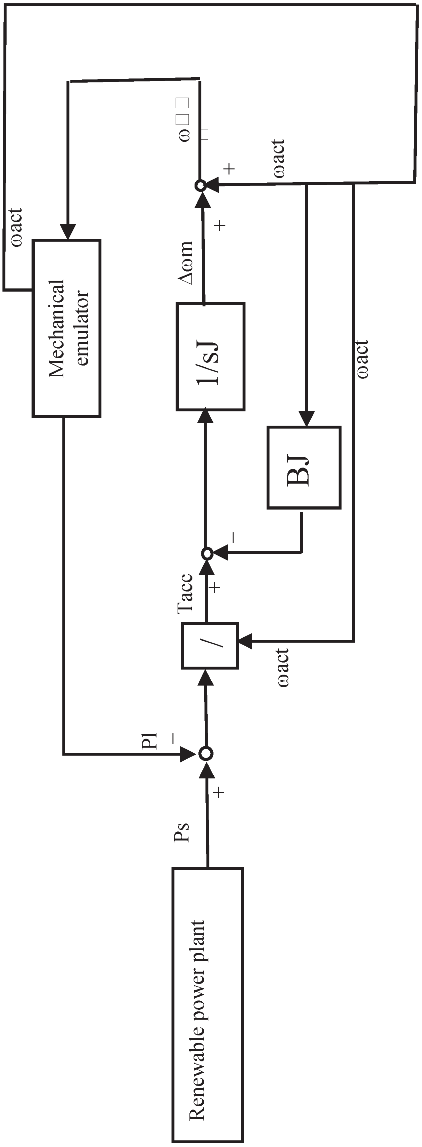

Figure 5. HIL test bench speed reference generation

A different approach was proposed in [32], where the simulation of load variation was introduced by adding a virtual load signal to the output of the electrical motor controller. Even though this approach is very interesting, it is very difficult to implement, because it is necessary to modify the controller software of the system under test. On the other hand the approach presented in this article allows to obtain a good performance without modifying the control architecture.

Two different DG systems have been emulated using an HIL mechanical level test bench.

- Small-scale hydropower generator
- Small scale wind turbine source

Small Scale Hydropower Generator

Hydroelectric generation has been well recognized as environmentally friendly and socially beneficial for many applications, but large-scale hydroelectric plant developments have become more and more difficult because of the shortage of undeveloped suitable sites and concerns about global environmental protection. However, there are many sites where it is possible to install a small-scale hydroelectric plant.

These systems normally adopt highly efficient but more expensive Kaplan turbines that allow optimal control of the water flow. Kaplan turbines have adjustable pitch angles in both inlet vanes (wicket gates) and propeller blades. In order to reduce plant costs in small-scale plants, it is preferable to use fixed-angle blade propeller water turbines.

This choice can reduce the plant power efficiency because typically in traditional hydroelectric power plants, the speed of the generating unit remains constant to keep it synchronized with the grid, neglecting turbine discharge variation over time [33]. Moreover, this situation becomes critical in stand-alone operation mode, where keeping the speed of the generation unit constant reduces the power plant efficiency drastically. In these cases, a variable speed operation mode and maximum power efficiency operation point tracking is welcome, but it presents numerous design problems regarding the definition of the hardware architecture and power management strategies. Such small-scale hydroelectric plants generally use a permanent magnet synchronous machine (PMS) as an electrical generator. In the test bench proposed in the article the PMS has been replaced by a DC generator, as the behavior of the mechanical HIL emulator does not depend on the electrical generator under test.

Small Wind Turbine Generator

Wind energy is one of the renewable sources with the largest utilization. Furthermore variable speed wind turbines (WT) allow to optimize the energy captured from the wind and to easily control the active and reactive generated power, when a static power converter is used to interface the grid [34]. Variable speed wind turbine technology has some advantages with respect to fixed speed one:

1. It allows an annual energy capture 5% greater than the fixed-speed technology;
2. The active and reactive powers generated can be easily controlled
3. Less mechanical stress
4. Poor power fluctuations, thanks to the rotor that acts as a flywheel (storing energy in kinetic form)
5. Absence of flicker problems
6. Controllability of the grid voltage by varying the reactive-power generation.

As disadvantages, variable-speed wind turbines need a power converter that increases the number of components and make the control system more complex. Variable-speed operation can only be achieved by decoupling the electrical grid frequency and mechanical rotor frequency. This aim is obtained using power-electronic converters, such as an ac–dc–ac converter combined with advanced control systems.

THE HIL TEST BENCH

Each of these applications presents similar peculiarities. In particular, it is very important to evaluate the mechanical performance and, moreover, it is necessary to evaluate the global efficiency (converter and motor) with a good approximation. Among the different HIL approaches the mechanical HIL represents the best solution. As a matter of fact, it allows to set up a real time test bench for the two energy sources under analysis where the only component that changes is the real time software emulation of the mechanical part, while the hardware under test is always the same.

The mechanical test bench hardware architecture is shown in Fig. 6, which includes:

- A motor drive, including an inverter controlled squirrel cage induction motor. This motor is used to emulate the static and dynamic mechanical behavior of the DG power source. An incremental optical encoder is used to feedback the speed signal for control and emulation purposes.

- A DC motor (D) is used to emulate the generator side of the DG system. The choice of a DC generator allows an easier control of the electric load connected to the generator, other kinds of electrical generators can be adopted maintaining the approach proposed in the present article. The rated parameters of the induction motor and generator are listed in Table 1.

A desktop PC with a dSpace 1104 board implements the DG power source model. A dedicated interface board was used to acquire measure-

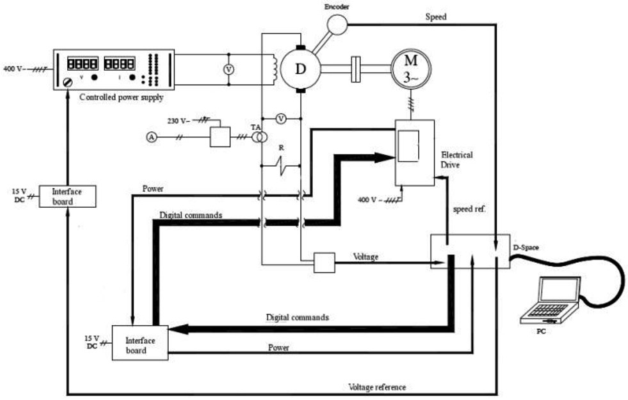

Figure 6. Example of mechanical HIL test bench

Table 1. Induction Motor and DC Motor rated Parameters

Induction Motor		**DC Motor**	
Rated voltage	380 V	Rated voltage	240 V
Rated current	35.1 A	Rated current	60 A
Rated Power	18.5 kW	Rated power	14 kW
Power factor	0.88		
Rated speed	1465 rpm	Rated speed	1500 rpm
Wound connection	Δ		
N° of poles	4	N° of poles	4

ment signals from the field and the motor drive and to transmit control reference signals from the dSpace board to the motor drive. A passive load dissipates the generated power. Figure 7 represents a photo of the HIL test bench.

EXPERIMENTAL RESULTS

According to the previous discussion, when simulating the power sources, it is necessary to evaluate the equivalent inertia and damping factor, along with the generated power vs. rotational speed curve. A simplified equivalent model of each energy source has been studied and operation curves have been deduced.

Small-scale Hydropower Plant

With regard to the small-scale hydropower plant, the fixed blades turbine can be modeled as explained in [35]. The turbine discharge (Q) and efficiency (η) depend on the parameters distributing valve opening vs. speed. The values for such parameters are obtained using the steady-state curves. Next, these values and the turbine head (H) are used in equation (5) to calculate the available mechanical power P_{hyd}, where g is the gravitational acceleration. Table 2 shows the parameters used.

$$P_{hyd} = HQg \cdot \eta \tag{5}$$

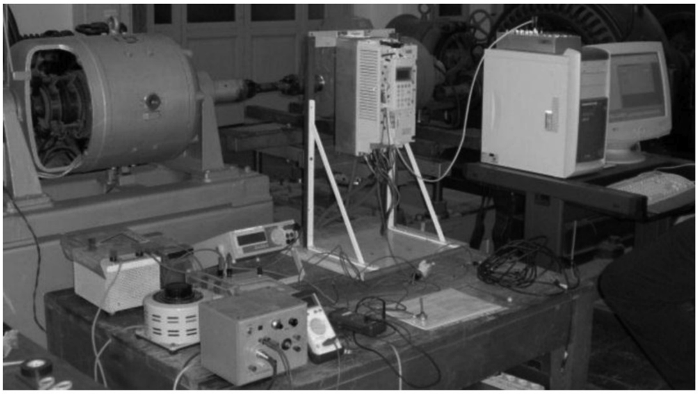

Figure 7. The Hardware in the Loop emulator test bench

Table 2. Hydro turbine mechanical data parameters used

Rated power, P_{hyd}	3.2 kW
Rated discharge, Q	0.1 m^3/s
Design head, H	5.2 m
Rated Rotational Speed, n	180 rpm

The estimated inertia and damping factor of the motor are indicated in (6).

$$\begin{aligned} J &= 4kg/m^2 \\ B &= 50J/(rad/s) \end{aligned} \tag{6}$$

The efficiency of the system depends on the opening of the distributing valve and the speed as indicated in Fig. 8, and the turbine speed is considered to have a constant value during the integration step (in this case it was set to 100 ms).

Small-to-medium-size WT Systems

Let us consider small-to-medium-size (10-100 kW) WT systems. The aerodynamic power P_{aero} of a wind turbine is given by

$$P_{aero} = ½ \rho \pi R^2 \nu^3 C_p \tag{7}$$

Where ρ is the air density, R is turbine radius, ν is wind speed, and C_p is turbine coefficient which represents the power conversion efficiency of a

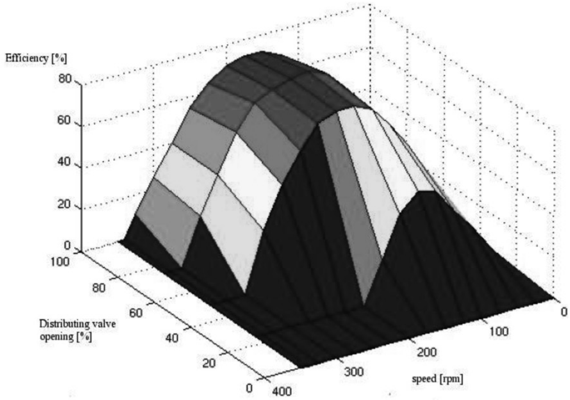

Figure 8. Efficiency vs. turbine speed and distributing valve opening.

wind turbine. C_p is a function of the tip speed ratio (λ), as well as of the blade pitch angle (β) in a pitch controlled wind turbine. Equation (8) defines λ as the ratio between blade turbine tip speed R.Ω and wind speed ν.

$$\lambda = \frac{R \bullet \Omega}{v} \tag{8}$$

Where Ω is the rotational speed of the wind turbine. Once Ω is measured, λ and P_{aero} can be estimated for a particular value of wind speed ν. The estimated inertia and damping factor of the motor are indicated in (9).

$$\begin{aligned} J &= 10\text{kg/m}^2 \\ B &= 50\text{J/(rad/s)} \end{aligned} \tag{9}$$

Experimental Tests and Results

Figures 8 to 12 show the results of the mechanical HIL tests. In particular, for all the energy sources mechanical, power is calculated once energy source speed and parameters are known (according to relations (5) and (7), derived from WT and hydroelectric energy source models). Load power (P_l in equation (2)) is calculated once DC machine armature voltage is measured as $P_l = V_{armature}{}^2/R_{load}$, where R_{load} is the passive load on which the generated power is dissipated (Fig. 6). Then the new speed is calculated according to equation (4).

Fig. 9 compares the estimated turbine mechanical power using the HIL WT model and the real generated power (which is equal to the one dissipated on the resistive load of the test bench). The accelerating torque T_{acc} is computed from the difference between the two power represented in Fig. 8 according to equation (1). During this test the AC machine that emulates the WT (Fig. 5) is started till its frequency equals to 39 rad/s, then it begins to emulate the behavior of WT according to equations (1)-(4). The load torque of DC machine and the generated power is changed acting on the excitation voltage of the test bench DC machine at t = 24 s and t = 46 s. Fig 9 represents the actual rotor speed and its reference computed according to relation (4).

Figures 11 to 12 refers to hydropower systems. In this case the AC machine that emulates the hydropower simulator is started till a speed equal to 39 rad/s then (at t = 5 s in the case of Figs 11-12) the emulator begins to operate. The excitation voltage is initially equal to 60 V. To be more precise two cases have been considered:

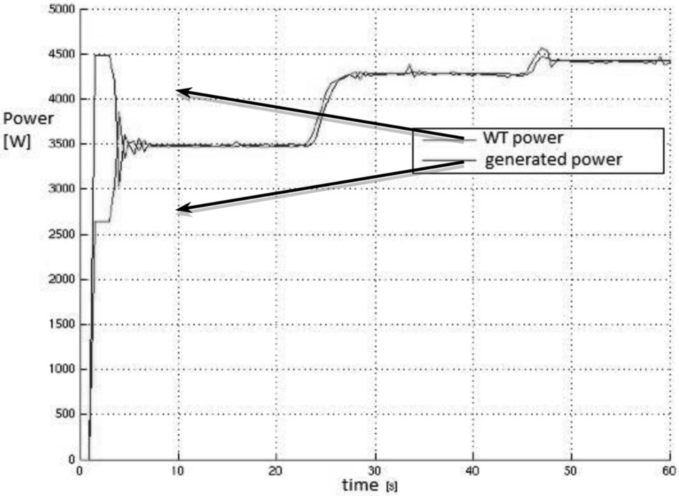

Figure 9. WT mechanical power (blue line) from HIL test bench and generated power (red line)

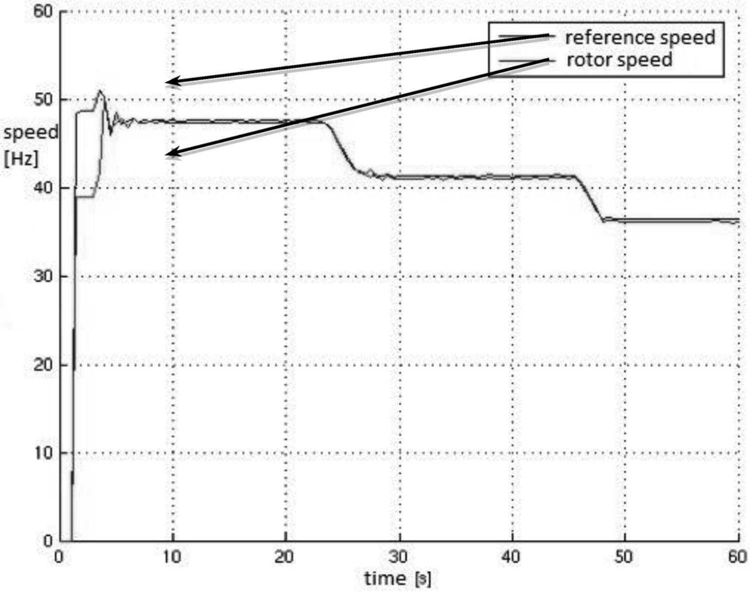

Figure 10. WT mechanical speed (red line)(from HIL test bench) and reference speed (blue line)

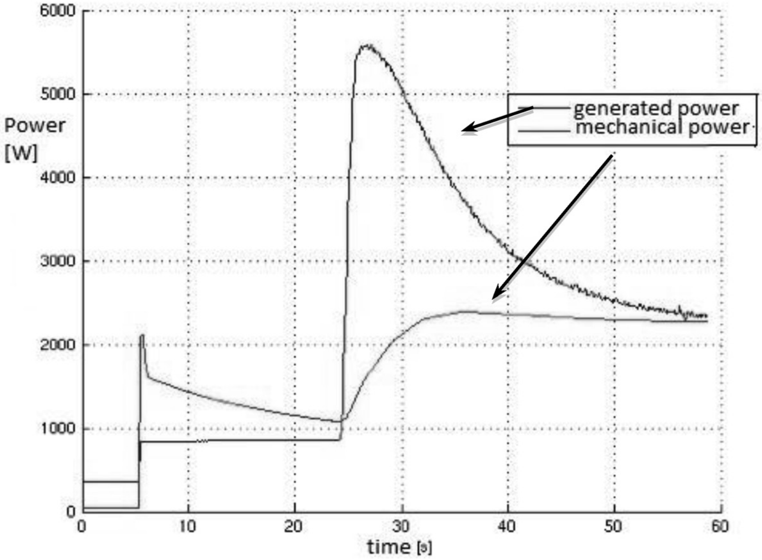

Figure 11. Hydroelectric mechanical power (red line)(from HIL test bench) and generated power (blue line), with $V_{excitation}$ from 60V to 120 V and valve opening equal to 75%

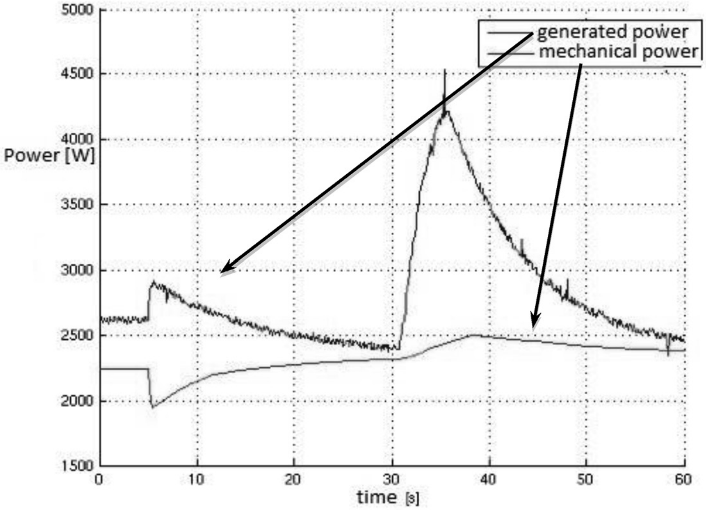

Figure 12. Hydroelectric mechanical power (red line, from HIL test bench) and generated power (blue line), with $V_{excitation}$ from 60V to 120 V and valve opening equal to 100%

— Distributed valve opening equal to 75% with a step of excitation voltage from 60 V to 120 V (Fig. 11).

— Distributed valve opening equal to 100% with a step of excitation voltage from 60 V to 120 V (Fig. 12).

CONCLUSIONS

The present article focused on the main design and realization aspects of an HIL test bench for real time validation of DG systems. The adoption of a HIL architecture allows to replicate the real phenomena, to test the DG system in all the operating conditions even in the most critical ones without the risks for the global operations and the costs required to perform these kinds of tests on a real equipment. The proposed test bench allows us to emulate different energy source with the same HIL emulator adopting a new approach to solve the problem of high inertial torque.

The real time simulation of the prime mover has some critical aspects, as the inertial torque, which should be reproduced, is very high and requires the use a high dynamic electrical drive. This problem is solved in the article introducing a speed control loop in the HIL emulator, consequently a lower performance drive con be adopted with a reduction of the test bench realization costs. Given its flexible structure, the HIL test bench allows the emulation of different energy sources. Among the different possibilities, wind and hydro have been emulated and experimental results are reported in the article. The results show that the test bench can be successfully used not only to test different control strategies but also to verify the whole DG system in all the operating conditions independent of weather context.

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