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Hardware–In–The–Loop Assessment of Robust Fuzzy Control Solutions for Hydroelectric and Wind Turbine Models

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Abstract: The interest towards renewable energy resources is increasing, and in particular it concerns wind and hydro powers, where the key point regards their efficient conversion into electric energy. To this end, control techniques can be used to meet this purpose, especially the ones relying on fuzzy models, due to their capabilities to manage nonlinear dynamic processes working in different conditions, and affected by faults, measurement errors, uncertainty and disturbances. The design methods addressed in this paper were already developed and validated for wind turbine plants, and important results can be achieved from their appropriate design and application to hydroelectric plants. This is the key issue of the paper, which recalls some considerations on the proposed solutions, as well as their validation to these energy conversion systems. Note that works available in the related literature that consider both wind and hydraulic energy conversion systems investigate a limited number of common issues, thus leading to little exchange opportunities and reduced common research aspects. Another important point addressed in the paper is that the proposed control design solutions are able to take into account the different working conditions of these power plants. Moreover, faults, uncertainty, disturbance and model–reality mismatch effects are also considered when analyzing the reliability and robustness features of the derived control schemes. To this end, proper hardware–in–the–loop tools are considered to verify and validate the developed control schemes in more realistic environments.

Keywords: Fuzzy logic, process control, hydroelectric process, wind turbine system, passive fault tolerant control, robustness, hardware–in–the–loop tool.

1. INTRODUCTION

Renewable energy conversion systems have dominated the energy industry over the last few decades, having one of the most efficient strategies (Blanco-M. et al. (2018)). Although there is a theoretical limit to the maximum achievable efficiency, new operational designs continue to progress with larger energy conversion efficiency (Bianchi et al. (2007)). The main capacity factors depend on the renewable source and the conversion technology. Accordingly, the modern plants are designed to have larger turbines, and can be located in remote places, where the availability of renewable energy is higher. This leads to an increase of the converted energy, and consequently, the energy conversion capacity of the power plants.

From the technical point of view, this energy conversion system is a complex highly nonlinear dynamic process. So, in the presence of high variation of the renewable sources, it is challenging to retain their operations with the desired conversion efficiency (Bianchi et al. (2007)). High source power may cause out-of-control operation of these energy conversion processes with catastrophic overspeeding of the turbines. In this case, the system is shut down. In this manner, only a conservative plant control is achieved and the conversion efficiency is cumulatively less than that desired (Blanco-M. et al. (2018)).

The conversion efficiency is a trade-off between converting the maximum energy and satisfying the structural/operational safety (Odgaard et al. (2013); Simani et al. (2014)). In this regard, the modern energy conversion system manufacturers define the so-called ideal power curve, which characterizes the operation of these plants with the optimal efficiency (Bianchi et al. (2007)).

The key solution for the enhancement of their efficiency relies on the development of proper control strategies to retain the operation on the ideal working condition (Bianchi et al. (2007)). According to the ideal case, in high power conditions, the generated power is regulated at its nominal value, despite higher available energy. At the same time, structurally safe operations must be guaranteed, while avoiding over speeding. This region of operation is known as the steady state condition, where the power regulation represents the main objective. In this case, the power regulation is fulfilled by adjusting the orientation of the blades of the turbines, which leads to regulating the generator speed and the generated power (Bianchi et al. (2007)).

So, it is obvious that turbine control is crucial to maintain the efficiency of these energy conversion systems. It is

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worth noting that the shut-down condition can be used in order to avoid hazardous operational mode, in the case of the turbine speeding up, and thus, exceeding the predefined limits. This leads to reducing the generated power, which can be considerably lower than the nominal one. Also, the corresponding fatigue load on the structure increases (Bianchi et al. (2007)). Accordingly, it is beneficial to control the turbine speed such that the speed is kept within the predefined safe-to-operate bound around the nominal value and, consequently, to avoid the conservative energy conversion systems (Odgaard et al. (2013); Simani et al. (2014)).

The aim of the control design for these processes is to improve their conversion efficiency. This requires accurate knowledge of the aerodynamics and hydrodynamics that regulate the evolution of the system, which are represented by nonlinear functions of the control inputs. In addition, the turbine regulation adjusts the aerodynamic and hydrodynamic torque, thus the turbine speed.

The renewable resource behaviour, and in particular its variation, is unknown, thus requiring a stochastic description (Bianchi et al. (2007)). Therefore, the mathematical relationship between the aerodynamic and hydrodynamic systems and the turbine input is not completely known. This is considered as the unknown control direction problem, which affects the conversion efficiency. To this end, the turbine input control design for efficient power regulation represents a challenge, as a result of the uncertain turbine speed variation (Bianchi et al. (2007)).

The power regulation control design has gained significant importance during the last decades. Viable solutions available in the related literature may vary from linear PID, adaptive nonlinear control, robust control, optimal control, linear parameter varying control, fuzzy logic systems, and evolutionary algorithms (Simani and Farsoni (2018)). Consequently, advanced control design has emerged recently and different schemes have been designed, such as robust linear parameter varying control, adaptive sliding mode control, and fuzzy control (Venturini et al. (2017)). Similar schemes were applied to energy conversion systems and different plants, as proposed in (Simani et al. (2021); Castaldi et al. (2021); Farsoni et al. (2021); Farsoni and Simani (2021)).

Note that the main novel contribution of the work is represented by the experimental validation of the proposed method, involving further simulations in a realistic benchmark model and a test–rig implementing the Hardware-in-the-loop (HIL) paradigm, with the aim of integrating the simulation software with the hardware where the control algorithm is real–time executed. The proposed results also show that the proposed advanced control scheme is able to tolerate possible faults in a passive way (Zhang and Jiang (2008)).

Finally, the paper has the following structure. Section 2 provides a brief presentation of the benchmark and simulation models used for describing the accurate behaviour of the dynamic processes. Section 3 summarises the design of the proposed data–driven control techniques that are also able to provide passive fault tolerance capabilities. These control strategies are analysed in terms of the achievable reliability and robustness features also in the presence of faults, disturbance and uncertainty effects. Section 4 illustrates the verification and the validation of the proposed control tools when applied to the HIL test–bed system. Section 5 ends the paper summarising the main achievements of the paper, and drawing some concluding remarks.

2. WIND TURBINE AND HYDROELECTRIC TEST–RIGS

This section briefly summarises the benchmarks and test-rigs exploited for modelling the dynamic processes of the wind turbine plant and the hydroelectric power system used in this work. Moreover, some control techniques already designed for these systems were considered in previous works by the same authors and they will not be summarised here.

The three–bladed horizontal axis wind turbine process proposed in this paper works according to the general principle where the renewable source represented by the wind power moves the turbine blades, such that the rotation of the rotor shaft is generated at lower speed. A higher rotational speed is normally required at the generator level, and obtained by using a gear–box of a drive–train, which is connected between the wind turbine blades and the wind turbine generator.

The wind turbine simulator is based on the benchmark model proposed in (Odgaard and Stoustrup (2013)) and implemented in Matlab and Simulink environment. Such simulator provides a realistic dynamic model the main subsystems involded in the energy conversion process, *i.e.* the blades, the gear-box and the generator. It also considers a set of input wind sequences coming from real acquired data. The simulator has been extended by designing specific Simulink blocks simulating external disturbances (*e.g.* wind gusts) and typical fault scenarios. The block diagram of Figure 1 summarises the complete simulation scheme of the wind turbine system.

A more detailed description of this system is available, for example, from some previous works by the authors, but with the aim of investigating possible falut tolerant control schemes, see *e.g.* (Simani and Farsoni (2018)).

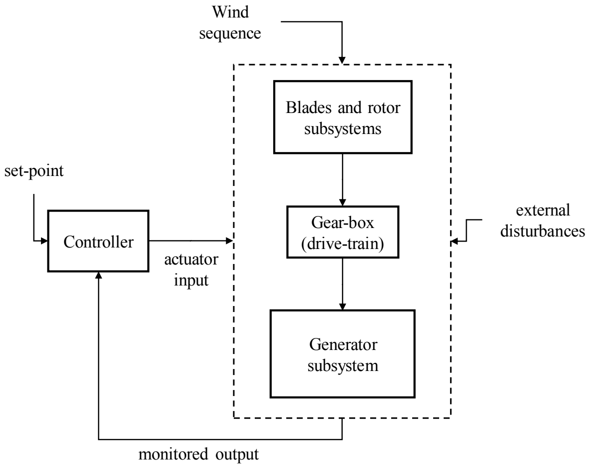

Fig. 1. Wind Turbine simulator model.

On the other hand, regarding the hydroelectric plant system that is considered in this paper in comparison with the wind turbine benchmark, consists of a high water head and a long penstock. It comprehends also upstream and downstream surge tanks, where a Francis hydraulic turbine is connected (Popescu et al. (2003)). This hydroelectric system was proposed in earlier works by the same authors, see *e.g.* (Simani et al. (2019b,c,a)), and was exploited to study the behaviour of the hydraulic process with different control schemes and in presence of faults.

The scheme of this hydroelectric simulator including two surge tanks and the Francis hydraulic turbine considered in this work is recalled in Fig. 2 (Simani et al. (2014)). The hydroelectric simulator includes a reservoir with water level H_R, an upstream water tunnel with cross-section area A_1 and length L_1, an upstream surge tank with cross–section area A_2 and water level H_2 of appropriate dimensions. A downstream surge tank with cross–section area A_4 and water level H_4 follows, ending with a downstream tail water tunnel of cross–section area A_5 and length L_5. Moreover, between the Francis hydraulic turbine and the two surge tanks, there is a the penstock with cross–section area A_3 and length L_3. Finally, Fig. 2 highlights a tail water lake with level H_T. The levels H_R and H_T of the reservoir and the lake water, respectively, are assumed to be constants.

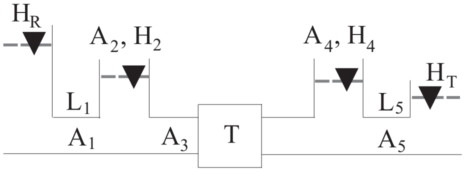

Fig. 2. Scheme of the hydroelectric system.

The mathematical description of the hydraulic system, depicted in Fig. 2, which does not include the Francis hydraulic turbine, was proposed in (Fang et al. (2008)). This model was modified by the authors and presented for the first time in (Simani et al. (2014)), where the authors included the Francis turbine. Its mathematical model and performance curves considered in this work were obtained in order to describe the dynamic behaviour of a realistic hydroelectric process, as addressed in more detail in (Simani et al. (2014)).

Finally, it is worth noting that Sections 3 and 4 will analyse the behaviour of these processes when controlled by means of fuzzy logic strategies and validated with respect to more realistic conditions. In fact, the considered control solutions will be tested with respect to more realistic working situations by means of the HIL tool summarised in Section 4, which motivates the novel aspects of this paper.

3. PASSIVE FAULT TOLERANT FUZZY CONTROL SCHEME

This section recalls the general approach adopted for designing the controller for the wind turbine as well as for the hydroelectric plant simulator, described in detail in previous works by the authors (Simani and Farsoni (2018); Simani et al. (2019b)) also in the presence of faults. It will be shown that the proposed control approaches are able to achieve passive fault tolerant control capabilities.

In both cases, the controller relies on its fuzzy–logic description aimed at providing the actuator signal $u(t)$ for the controlled system so that a given set-point reference signal $r(t)$ is properly tracked by the system output $y(t)$. From an external point of view the controller acts as a block implementing a dynamic function of the monitored system output:

$$u(t) = \mathcal{F}\left(y(t)\right) \tag{1}$$

Where $y(t)$ is the vector containing a certain number of delayed samples of the system output vector, $u(t)$ is the vector containing the current actuator signal and the function $\mathcal{F}$ has to be properly designed by means of a Fuzzy Inference System (FIS). A controller exploiting a FIS is often referred to as a Fuzzy Logic Controller (FLC) and it can provide a solution to cope with the uncertain dynamics of the plant, where strongly non-linear behaviors are expected, such as in a complex system as a wind turbine or a hydroelectric plant.

The FLC has been designed to identify a set of Takagi–Sugeno (TS) fuzzy prototypes using input-output data previously generated by Monte-Carlo simulations.

The choice of using TS is motivated by the fact that the defuzzification process is more computationally efficient compared to that of *e.g.* a Mamdani FIS. Indeed, the output generated by a TS FIS (*i.e.* the actuator signal u in the case of a FLC) is computed as a weighted average of the linear deterministic functions representing the consequents of the fuzzy rules describing the system:

$$u = \frac{\sum_{i=1}^{K} \mu_i(x)\ \left(a_i^T\, x + b_i\right)}{\sum_{i=1}^{K} \mu_i(x)} \tag{2}$$

Where K is the number of fuzzy clusters in which the system domain has been subdivided into, the weights $\mu_i(x)$ are Gaussian membership functions representing the fuzzy degree of fulfillment (whose value is between 0 and 1) of the input vector x with respect to the i-th prototype. The input vector x contains the measurements acquired from the system model, including current and past samples so that the consequent function $a_i^T\, x + b_i$ acts as an Auto-Regressive eXogenous (ARX) dynamic model, whose parameters are the vector a_i, the bias b_i and the number of delayed samples.

The parameter of the FLC has been tuned by means of the Adaptive Neuro-Fuzzy inference System (ANFIS) toolbox of Matlab and fully integrated into Simulink, exploiting the data–driven method proposed in (Jang (1993); Jang and Sun (1997)).

An alternative estimation approach for the estimation of the FLC parameters has been also adopted. Such method exploits the Fuzzy Modelling and Identification (FMID) Toolbox of Matlab and implements the algorithms proposed in (Babuška (1998)), where a set of acquired input-output data is used to estimate the domain regions (fuzzy clusters) and the optimal prototype for each of them.

Note finally that the wind turbine and the hydroelectric system use two FLCs that have been designed to cope with the different dynamics of the two plants. As depicted in the block diagram of Figure 3, the controllers operate on the basis of the current plant condition. It is also

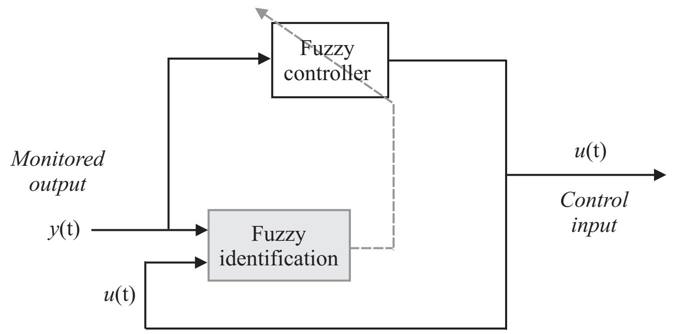

Fig. 3. Design of the robust regulation scheme.

worth observing that the fuzzy identification block can perform an online estimation and optimization of the FLC parameters on the basis of the acquired measurements of the plant model.

The results of the simulation experiments, shown in Table 1, are r eported in this work for the sake of comparison with the HIL experiments of Section 4.

The performances of the FLC designed using the considered fuzzy approach have also been compared to those obtained by a PID controller with gain-scheduling, which represents the most common control strategy in the industry. The adopted performance index is the percent Normalised Sum of Squared Error $NSSE\%$, defined by Equation 3.

$$NSSE\% = 100 \sqrt{\frac{\sum_{k=1}^{N} (r_k - y_k)^2}{\sum_{k=1}^{N} r_k^2}} \tag{3}$$

Where N is the number of the acquired samples taken from the monitored continuous-time signals, r is the tracked set-point, y is the generic controlled output signal.

In more detail, the considered controlled signals are the angular speed of the generator ω_g for the wind turbine and the hydraulic turbine rotational speed n for the hydroelectric plant. The $NSSE\%$ values highlight better capabilities of the developed FLCs with respect to gain–scheduling PID regulators.

Table 1. $NSSE\%$ for the considered control solutions in fault–free conditions.

Test Case	**Gain–scheduled PID**	**FTC Fuzzy**
Wind turbine	11.5%	5.7%
Hydroelectric plant	6.2%	3.1%

Furthermore, Figure 4 and 5 highlight the behavior of the considered systems when controlled using the FLC compared to the gain–scheduling PID approach. In particular, considering the steady–state working conditions for both the wind turbine system (Figure 4) and the hydroelectric plant (Figure 5), the reference signal (dashed line) is constant and the monitored output (continuous grey line) shows a reduced variance when the system is controlled using the FLC (*i.e.* up to 3300 s, when the controller commutes to the gain–scheduling PID).

It is also worth noting that the results obtained by the simulation experiments extend those obtained in previous works by the same authors *i.e.* (Simani et al. (2019b); Simani and Farsoni (2018)), when faults were also considered. In order to highlight the passive fault tolerant control capabilities achieved by the proposed advanced control scheme, Table 2 shows that the $NSSE\%$ maintains limited variations with respect to the fault–free case of Table 1, also with respect to the baseline gain–scheduling PID.

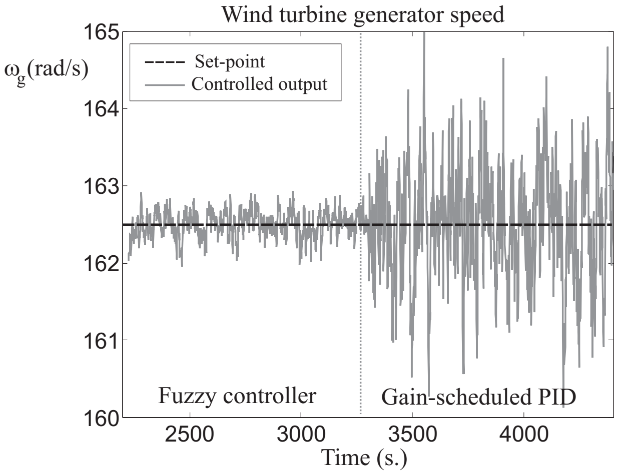

Fig. 4. Wind turbine controller.

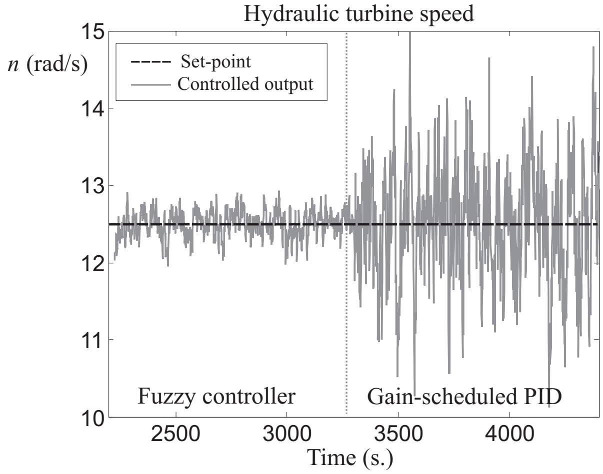

Fig. 5. Hydroelectric system controller.

Table 2. $NSSE\%$ for the proposed control solutions in the presence of faults.

Test Case	**Gain–scheduled PID**	**FTC Fuzzy**
Wind turbine	33.4%	7.9%
Hydroelectric plant	28.9%	5.7%

Indeed in this work addressing the experimental validation of the proposed methods, a set of Monte–Carlo simulations has been performed considering realistic variations of the model parameters and simulating a set of external disturbances affecting the systems, as well as possible fault cases (Simani et al. (2019b); Simani and Farsoni (2018)).

Therefore, the remainder of this paper analyses more in deep the reliability and robustness features of the developed controllers when applied to more realistic simulators of the considered processes, that also take into account a real-time sample rate, connected with the hardware where the control scheme can be executed. These further investigations rely on the Hardware–In–the–Loop (HIL) tool proposed in Section 4.

4. HARDWARE–IN-THE–LOOP SCHEME RESULTS

More realistic operating conditions can be simulated by means of the HIL test-rig. Such an approach consists in the usage of a real control board interfaced with a real–time simulation software.

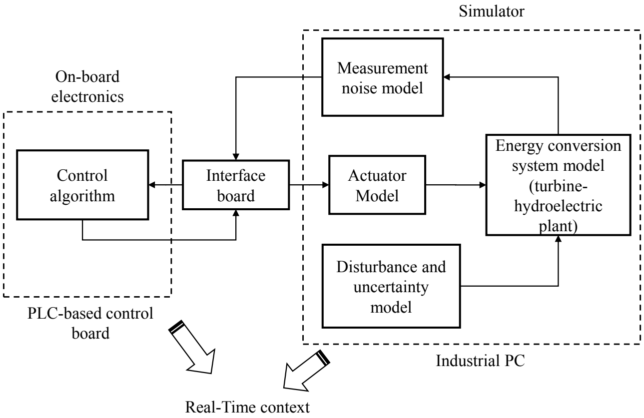

Fig. 6. Hardware–In–the–Loop test–rig.

The scheme of the adopted HIL setup, as depicted in Figure 6, is composed by two main blocks

The block on the left represents the on-board electronics. The control board used in the experiments is the AWC-500, a PLC-based board specifically designed for harsh environments. Its features of robustness towards shocks, adverse temperature and climate allow its usage in a wind turbine as well as in a hydroelectric system.

The block on the right represents the software architecture, that has been implemented in LabVIEW running on an industrial PC. The software simulates the system model, external disturbances and the measurement noise affecting the data acquisition system. It is worth noting that the adopted architecture allows a real-time simulation with a main loop rate of 1 kHz.

The communication between the control board and the simulator software takes place by means of an interface board that takes care of adapting the block input/output signals via the EtherCAT protocol.

Table 3 summarises the results obtained in the HIL experiments, respectively for the wind turbine and the hydroelectric system in terms of the $NSSE\%$ index, compared to those obtained using standard a gain–scheduling PID controller.

Table 3. $NSSE\%$ values with the HIL scheme in fault–free conditions.

Test Case	**Gain–scheduled PID**	**FTC Fuzzy**
Wind turbine system	14.4%	8.1%
Hydroelectric plant	9.9%	6.2%

The results reported in Table 3 are consistent with respect to the pure-simulation achievement reported in Table 1. Indeed, the greater values of NSSE for the HIL experiments are motivated by the usage of a more complex and realistic dynamic simulation model and by the effects of signal transmission on the electronic boards, A/D and D/A conversions and floating-point calculations required by a real-time simulation. However, it is worth observing that such issues are actually not present in the real plants during the normal working conditions, in which the data-transfer between a computer and the on-board electronics is no longer required.

Finally, as in the previous situation, Table 4 reports the results in the presence of faults, as described in (Simani et al. (2019b); Simani and Farsoni (2018)). Table 4 shows that the degradation of the $NSSE\%$ index is limited for the case of the proposed fuzzy controller.

Table 4. $NSSE\%$ values with the HIL scheme with faults.

Test Case	**Gain–scheduled PID**	**FTC Fuzzy**
Wind turbine system	43.7%	12.2%
Hydroelectric plant	39.2%	9.1%

5. CONCLUSION

The paper was focused on renewable energy resources, as their interest is increasing, and in particular it concerns wind and hydro powers, where the key point was represented by their efficient conversion into electric energy. Therefore, the attention went to control techniques, which were used to this purpose, especially the ones relying on fuzzy models. In fact, they showed to be able to manage nonlinear dynamic processes working in different conditions, and affected by errors, faults, uncertainty and external disturbances. It was shown that the proposed solutions presented passive fault tolerance capabilities achieved by means of the considered data–driven methodology. Another point of the work regarded the analysis of the designed control schemes in terms of common issues, exchange opportunities, and common research aspects, when applied to these energy conversion systems. The key point of the work concerned the verification and the validation of the developed control design solutions by means of harware–in–the–loop tools. Under these conditions, the proposed control schemes were able to manage the different working conditions of these energy conversion systems also in the presence of uncertainty, disturbance, faults and model–reality mismatch effects.

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