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Improvements in Frequency Control of an AC Microgrid by Means of Micro-Hydropower Combined Flow-Reduced Dump Load Control Method

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Abstract. Load Frequency Control (LFC) is an issue of top importance to ensure microgrids (MGs) safe and reliable operation in AC MGs. Primary frequency control of each energy source can be guaranteed in AC MGs in order to integrate other energy sources. This paper proposes a micro-hydro frequency control scheme, combining the control of a reduced dump load and the nozzle flow control of Pelton turbines operating in isolated from electricity grid. Some researchs have reported the integration of dump load and flow control methods, but they did not reduce the dump load value and adjust the nozzle flow linearly to the power value demanded by users, causing the inefficient use of water. Simulation results were obtained in Matlab®/Simulink® using models obtained from previous research and proven by means of experimental studies. The simulation of the proposed scheme shows that instantaneous frequency variation is about 2 % even for perturbations magnitude up to 12 %. The validation result shows a 60 % reduction in overshoot and settling time of frequency temporal behaviour operating the micro-hydro autonomously.

Key words. Microgrids (MGs), frequency control, isolated micro-hydropower operation, dump-load control.

1. Introduction

According to [1], a MG is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. MGs are being used mainly to increase resilience and reliability of electrical grids, to integrate the addition of distributed renewable energy sources like wind, solar photovoltaic (PV) or micro-hydropower generation, to provide electricity in isolated areas not served by centralized electrical networks, and to reduce greenhouse gases emissions.

More than 130 million people around the world are served by MGs and a 67 percent of these are by autonomous micro-hydro power plants (AMHPP) [2]. Since most MGs generating sources lack the inertia used by large synchronous generators, an efficient primary frequency control is needed to reduce the impact of imbalances of electricity generation and demand, especially in AMHPP. Micro-hydropower is one of the most cost-effective renewable energy technologies to be considered for rural electrification in developing countries. When AMHPP works isolated from centralized electrical grid, and as a unique source of energy, it is said to operate autonomously [3, 4]. They require a good control system to keep frequency and voltage outputs constant in spite of changing user loads [3]. Frequency stability is the most critical issue in isolated power systems due to their low rotational inertia [5, 6]. Hence, maintaining frequency within a certain range is indeed a challenge [7, 8]. Fig. 1 shows a typical behaviour of a Cuban's AMHPP without frequency regulation.

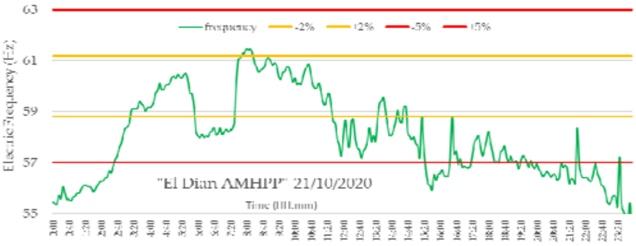

Fig. 1. Typical behaviour of the frequency of a micro-hydropower without automatic regulation.

The electrical frequency generated in this AMHPP oscillates outside the allowable variation range of ±1 % (± 0.6 Hz) according to the Cuban standard of Cuba National Electric System (NES) NC62-04 [9]. The standard applies to the power generation of the entire national territory, including grid connected or isolated. Due to the size of grids, the energy demands of a large power electrical system represent a small percentage value in comparison to a low-power autonomous system, such as the AMHPP. They should not have the same technical requirement regarding their dynamic and quality behaviour [10].

Good electrical energy quality must be guaranteed through maintaining an uninterrupted power at rated electrical voltage and frequency (60 Hz) for directly powering loads. Hence, voltage is regulated by controlling the generator excitation and the frequency by eliminating the imbalances between instantaneous generation and load demand. In the latter case, controlling water flow through the action of a water regulating device on the hydraulic turbine can be achieved using a DC servomotor [11]. However, this solution cannot ensure good performances when the load variation is large, which can lead to instability and others negative effect of hydraulic transients [12], like water hammer.

Classical speed governor is widely used in hydropower control. However, due to the less dynamic response of AMHPP and relatively high costs, the speed governors are less preferred in AMHPP [13]. In Cuba, conventional speed governor is not used due to prohibitively high cost according to [14]; therefore, frequency is controlled by resistive load [15] called dump load. On the other hand, dump load control is proved to be cost effective only when there is a hot water requirement [16] because it dumped a lot of electricity and water. Therefore, the reduction of a dump load value is needed as much as possible [13] making the use of water more efficient.

An alternative to speed governors could be the combination of a reduced amount of dump load with flow DC servomotor for nozzle control. It guarantees frequency control in nominal limits giving better dynamical response than flow control alone at lower cost. Also, by adjusting a nozzle setting in Pelton turbines could improve overall energy efficiency from the point of view of water uses.

This paper is organized as follows. Section 2 describes the frequency control review of the state of the art of frequency control methods used in AMHPP. In Section 3 a combined flow-reduced dump load procedure (proposed methodology). In addition, a plant case study of load disturbances behaviour in AMHPP is discussed in Section 4. Simulations results are analysed and discussed in Section 5 for the plant study cases. Finally, Section 6 outlines the main conclusions of this paper.

2. State of the art review

Several approaches are reported in the specialized literature to keep hydropower plants operating at their nominal values. Some works consider the use of mechanical energy storage systems through flywheels [17], interconnected systems [18], storage of electrical energy [19] and use of MGs [20, 21]. Other papers consider the use of asynchronous generators [22] and isolated micro-grids [23]. Some of these solutions do not include autonomous systems; therefore, they are not taken into consideration in the scheme proposed in this work. In the most general case, the AC MGs integrate the energy supply from several sources, in which the equality of frequencies, voltages, and phases is mandatory for synchronization.

From the operation of AMHPP point of view with the Pelton turbines, two ways of frequency control are known: manipulating the flow of water entering the turbine or adjusting the generator load [24]. The first method seeks to adjust the operating point of the turbine, regulating the nozzle flow. The 95% of Cuban AMHPP operate with Pelton turbines of TP-15 and TP-16 models. These turbines have limited frequency regulation capabilities due to the high costs of commercial speed governors. Moreover, to avoid problems of transient pressure in the gate, a large value of the setting time of the turbine nozzle is commonly used [25].

The second method, based on the use of a resistive dump load, ensures that the turbine works at a fixed operating point, the maximum power, balancing the load that represents the demand of the users with a second resistive load connected in parallel [26]. This method of regulation has a simpler design and good performance against impulse and sustained disturbances. However, in classic designs, the nominal power of the secondary load is chosen 30 % higher than the nominal power [16]. In this case, it is shown that it is profitable only when hot water is required for different uses [19]. Some research suggests matching the dump load power to the plant nominal power [27], but at a high cost [28] and low efficient energy source use. Other authors [16] propose the reduction of the secondary load to 50% of the nominal power through the adjustment of the turbine flow in fixed amounts of 30% and 50%. In previous investigations [4], a dump load regulator was designed, with a dump load nominal value of 30%, obtaining good control performance only when is acting sustained disturbances of small amplitude.

In [29], by means of a mixed electronic regulator, a reduction of the dump load to 10% of the generator nominal power is proposed. According to the authors, empirical rules are used, a demand load study is not carried out and nor are evaluated the most frequent types of disturbances. On the other hand, in [19], [27], a mixed regulation scheme is proposed for flow control by means of on-off valves that instantly increase or decrease the turbine inlet flow by default values of 30% or 50%. In these works, the frequency is maintained according to the parameters designed for sustained disturbances of 2.4% of the nominal power. In [30], a mixed load-flow regulator is proposed, combining a PI regulator for the dump load control and a fuzzy algorithm to control the nozzle flow, refeeding the frequency measurement. The firmware and hardware based on a micro controller is designed in [30], but it is not intended to minimize the dump load, does not refer to compliance with the regulations regarding the permitted frequency variations and the design of the control algorithms. These elements indicate that the design of [30] is not oriented to the efficient use of water.

Through previous papers review, it seems that combination of flow and reduced dump load is an intuitive way to use the hydro energy source more efficiently and guarantee the required frequency in nominal values. In this form of operation, it is necessary to adjust the turbine operating point. Load demand fluctuations are compensated thanks to the speed of dump load control, and immediately through flow control, to adjust the operating point of the turbine to the power demanded.

With this new method, the system could operate in a regime close to demand instead of operating at maximum power. As a result, energy would be supplied according to quality standards and the water would be used more efficiently by reducing the power of the dump load. The dump load rate would be based on the desired quality requirements of the electric power system (NC62-04 in Cuba), and not on the percent of nominal power installed, which would bring economic benefits by equipment savings and increasing the water efficient use.

3. Combined flow-reduced dump load method.

The installed power (P_e) of a hydropower station is determined by equation (1). The operating point at which the turbine operates depends on the values of design hydraulic head (H_d), flow, through the turbine (Q_d) and turbine efficiency at the nominal point of operation (η_T). It can be adjusted by linearly changing the Pelton nozzle setting, which will vary the turbine intake flow and efficiency, considering that the hydraulic head remains constant.

$$P_e = \rho \cdot g \cdot Q_d \cdot H_d \cdot \eta_T \qquad [W] \tag{1}$$

The flow to the turbine inlet is adjusted to the desired value by means of a servomotor that moves the turbine's nozzle stem a distance Δl, in a limited range $[0 \le \Delta l \le 21\ mm]$, depending on the value of the frequency measured at the generator terminals.

The turbine operating point is defined by the amount of load demanded (electricity) by the users (P_u). In addition, the dump load control consists of balancing the increase or decrease of user demanded power through the dump load (P_l). This point implies that the adjusting of the turbine operating point is defined by equation (2):

$$\Delta P_e = \Delta P_u + \Delta P_{l\_max}\,, \tag{2}$$

and the decision to adjust the operating point based on the power demanded, represented by $f(P_u)$, depends on function (3).

$$f(P_u) = \begin{cases} No\ Adjust \rightarrow if & |\Delta P_u| \le |\Delta P_{l\_max}| \\ Adjust \quad \rightarrow if & |\Delta P_u| > |\Delta P_{l\_max}| \end{cases} \tag{3}$$

The magnitude of the adjustment and the minimum value of the dump load installed power depend on the desired behavior of the combined scheme. In this case, it is designed to obtain a maximum steady-state error (e_{ss}) of ±1 % (±0.6 *Hz*), a settling time (t_s) less than 60 *s*, and a maximum overshoot (m_p) of the error of ±1.5 *Hz*, in accordance with the Cuban standard NC62-04.

To adjust the operating point of the turbine, through the combined flow-reduced dump load control, the regulation scheme shown in Fig. 2 is proposed [31].

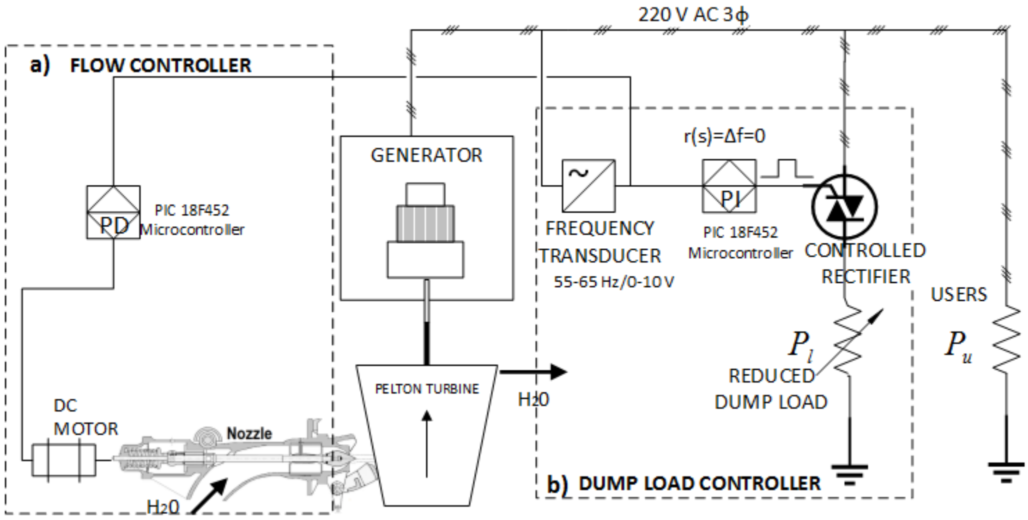

Fig. 2. Proposed combined regulation scheme for AMHPP frequency control.

The scheme consists of two control loops: Flow control (Fig. 2.*a*), and dump load control (Fig. 2.*b*). The first one adjusts turbine operation point only when dump load control cannot compensate frequency deviation. The dump load control loop keeps the generator power constant only in a limited range of a dump load value, adjusting the power consumed in the resistive dump load, by the controlled three-phase rectifier bridge. The modular value of the change in the dump load is equal to the demanded power change but in the opposite direction. This is only possible when the user load demand amplitude in less or equal than dump load installed.

PID controllers have been widely used in hydropower frequency control [32-36]. About 95% of the control loops in industry are PID controllers and fundamentally, most of them PI [37]. They are also common, making them easy to design and implement this in microcontroller application.

A PI algorithm is used to dump load control; another PD algorithm to flow control. A PI algorithm is selected to make cero a steady state error of frequency; thus, a PD algorithm anticipates an inverse response due to non-minimum phase characteristics of turbine [24]. These control algorithms were suggested in [38] for chemical process control with non-minimum phase behaviour. A combined control action can produce desired temporal response of electric frequency in accordance with [9].

As flow control temporal response is precise but slower, a user load demands can be compensated rapidly by a reduced dump load. Next, slowly, it must be adjusted linearly the Pelton nozzle setting in accordance to the demanded load magnitude. A well-designed combined flow-dump load control can guarantee a required temporal response.

4. Simulations cases

According to the load studies carried out by the authors, impulse load disturbances are associated with electrical equipment that by its nature demands high electrical consumption in a short time interval, e.g., electric arc welding or motor starting in the existing mini-factories. Most of a load of household appliances and lighting are considered sustained loads and as such are modelled in this research. The magnitudes of the disturbances are designed from the analysis of the behaviour of the loads, obtained from previous studies [4]. Therefore, the analysis of the electric frequency temporal response is relevant for the following cases:

- When the duration of impulse load disturbances varies between 2 and 3 seconds. To make sure a capacity of reject impulsive loads.
- When the power required by users does not exceed the dump load nominal value $\left|\Delta P_u\right| \le \left|\Delta P_{l\ max}\right|$. To test the capacities of dump load control alone.
- When the power required by users exceeds the dump load nominal value $\left|\Delta P_u\right| > \left|\Delta P_{l\ max}\right|$. To test the capacities of combined control in most general case.
- When the amplitude of the sustained disturbances is much bigger than dump load amplitude. To test the capacities of combined control in a limit special case.

Table I shows the types (Impulsive (I) and Sustained (S)), magnitudes and times at which the simulated disturbances are acting.

Table I. -Types and magnitudes of simulated disturbances

Cases	Type	Amplitude (kW)	Duration (s)	P_u/P_T (%)	$\Delta P_{l\ max}$ (kW)
Case 1	I	5	2	11	±3
Case 2	I	5	3	11	±3
Case 3	S	3/6	-	6.6/ 13.3	±3
Case 4	S	3/7	-	6.6 / 15.5	±3

According to the loads types that are usually present in these isolated power generation systems, a dynamic behavior in the case of impulse type disturbances of great amplitude and short duration is simulated (Table 3 cases 1 and 2). As well as of the sustained type of small amplitude in relation to the generator power, case 3. The dynamic behavior is also simulated in the event of sustained disturbances of up to 15.5 %, case 4.

5. Results and discussion

A. Results for impulsive loads. Cases 1 and 2

Fig. 3 shows the temporal response to the separately dump load and flow control, and in Fig. 4 the behaviour of the frequency of the combined flow-dump load control. In Cases 1 and 2, with the magnitudes of the impulse type disturbance of up to 11 % of the nominal power, dump load control alone stabilizes the frequency in 3 seconds. It could be considered instantaneous compared with the 60 s of the flow controls (Fig. 3).

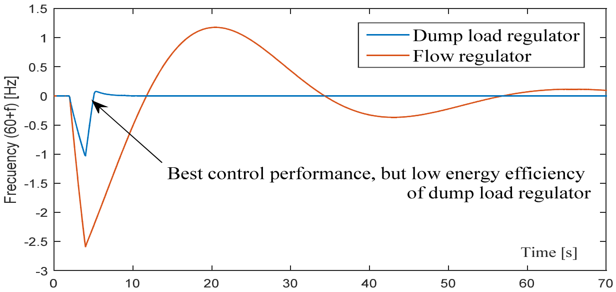

Fig. 3. Response to 11 % impulse load. Independent flow and dump load regulators.

Dump load control is suitable only when there is a hot water demands. In this hypothetical case, the dump load nominal value of 100 % of generator value is required, implying inefficient water use. When user's load demand is greater than 11%, the frequency variations are greater than 1 Hz, so they would be outside the norm considered.

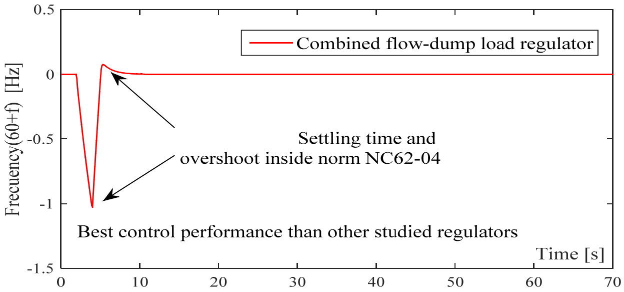

Fig. 4. Response to 11 % impulse load. Combined flow-dump load regulator.

As shown in the previous figures, the dump load control has a dominant effect for Cases 1 and 2. However, from the point of view of the rational use of energy, the efficiency of the combined control action could be increased, as the value of the dump load installed decreases.

B. Results for sustained loads. Case 3 and Case 4

For sustained disturbances up to 10%, the frequency behaves within the limits allowed only for combined flow-dump load regulation, as shown in Fig. 5. Flow control alone converges to its desired frequency value, but, very slow and with variations greater than those admitted in the NC62-04 standard. Similarly, dump load control by itself, not compensates the disturbances whose magnitude is greater than ±3kW, this conclusion is derived from (2). Fig. 5 shows that the settling time is smaller than 25 s and the maximum overshoot is minor than 1.8 Hz (3 %) only by means of combined flow-dump load controller. This behaviour confirms the possibility of to give better dynamic response of flow control, through the combination of flow and reduced dump load control schemes. At the same time, they can increase the energy efficiency, ensuring frequency temporary response inside technical standards.

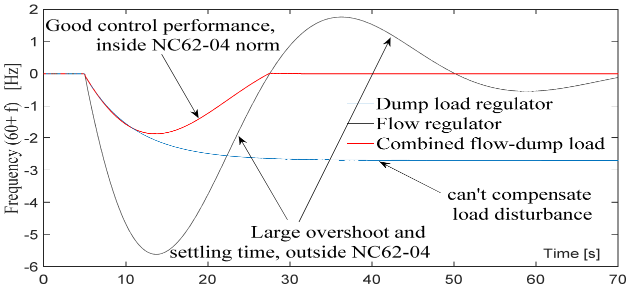

Fig. 5. Frequency behaviour of all regulator with sustained load disturbances of 10%.

When the load disturbance amplitude is up to 12 %, considered excessively large limit, but possible in Cuban isolated power systems, the settling time remains. However, the overshoot increases by 5 % equivalent to 3Hz, which is outside the established norm, as Fig. 6 shows.

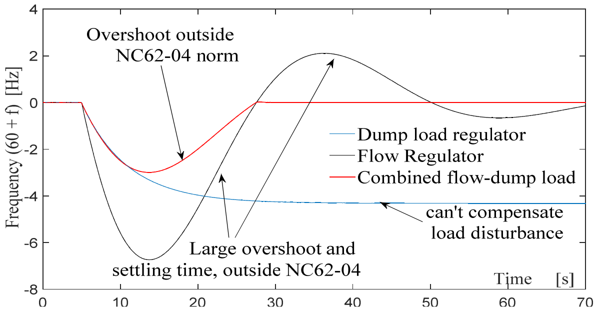

Fig. 6. Frequency behaviour of all regulators with sustained load disturbances of 12 %.

Combined flow-dump load control scheme is best solution than others, as showed Cases 1 to 4. Nevertheless, is necessary to reduce a dump load value to guarantee water savings and therefore energy source efficiency [31].

6. Conclusion

The simulation results have shown that frequency variation in AMHPP with the limits states of NC62-04 norm is guaranteed, if proposed combined flow-reduced dump load control scheme is used. Instantaneous frequency variation is about 2 % even for perturbations magnitude up to 12 %. The NC62-04 standard, which considers connected and isolated power plants on equal terms, could be modified to allow possible frequency variations in AMHPP by up to 2 % without deteriorating control requirements. In addition, it is possible to increase energy efficiency in the AMHPP by reducing the value of the resistive dump load by up to 7.5 kW in a case study. A user load demand study plays a necessary role in the dump load reduction and controllers design.

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Nomenclature

g	Acceleration due to gravity=9.81	m/s^2
H_d	Turbine design head	m
P_e	Electric Power	kW
P_l	Installed dump load value	kW
ΔP_{l_max}	Maximum value of installed dump load	kW
P_{max}	Instantaneous maximum generator power	kW
P_{min}	Instantaneous minimum generator power	kW
P_T	Generator nominal power	kW
Q_d	Design Flow	m^3/s
ρ	Density of water	kg/m^3
η_T	Turbine efficiency	%

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