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Frequency regulation for large load variations on micro-hydro power plants with real-time implementation

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ABSTRACT

Micro-hydro power plants (MHPP) are usually built on mountains to provide electricity for rural communities. However, most of them are isolated from the national grid; thus, they require good control system to ensure the stability of both MHPP frequency and voltage outputs in spite of varying users load. This paper treats a new approach for frequency regulation of a MHPP against large load variations. For our simulation studies, a MHPP model is constructed from the mains physical equations that describe the nonlinear behavior of the plant. A self-tuning fuzzy proportional–integral (PI) controller, in which the controller gains are adjusted in real-time using a fuzzy logic inference system, is proposed. To demonstrate the effectiveness of the proposed controller, practical results under different loading conditions are presented. Those results show overall a good correlation between the computer simulation and the field-testing data.

1. Introduction

Since our environment suffers from gas emission, the use of clean and renewable energy sources is one of the best solutions that would help limiting the global warming effect [1]. Scientists are widely interested in modeling and control of renewable energy plants as the number of published papers on the subject do not cease increasing since the last decade, especially those related to hydro and micro-hydro power plants [2–8].

In a suitable location micro-hydro power is one of the most cost-effective and reliable renewable energy technologies. It has several advantages over solar and wind power, with a high level of predictability. It is a long-lasting and robust technology and systems can readily last for more than 50 years. Micro-hydro power system is one of the most environmentally benign energy conversion options available. Unlike large-scale hydro power, it does not attempt to interfere significantly with river flows.

Micro-hydro power plants (MHPP) are usually built on mountains to provide electricity for rural communities. However, they are mostly isolated from national electric grid. In addition, variations of the consumed power on the load side cause deviations between the produced and the consumed power, which causes variations of both MHPP frequency and voltage outputs. Thus, MHPP that work in isolated mode require the synthesis of good and price moderate control system to ensure the stability of both MHPP frequency and voltage in spite of changing users load. This latter would be considered as a disturbance to the system and might be called load disturbance.

A control system of a MHPP must keep the rotational speed of the turbine generator unit stable around its nominal value for any connected load and prevailing conditions in the water conduit. However, MHPP is a nonlinear and non-stationary multivariable system whose characteristics vary significantly with the unpredictable load on it. This presents a difficulty to design efficient and reliable controllers. Generally, two main control strategies could be used to automatically control the rotational speed of the generator shaft, and thus the frequency of the voltage waveform. The turbine speed can remain constant either by acting on the gate opening position (mechanical regulation of the turbine water flow) or by using an electronic load controller (ELC). First, actuating the gate opening position aims to produce just the necessary power according to the connected load [2]. However, this speed governor has to be slow in order to avoid the water hammer effect, and so, it takes a significant time to stabilize the turbine speed when a load disturbance occurs. It becomes insufficient in case of large load variations [9]. Moreover, the cost of such governor is often dearer than the cost of the generator [3]. Second, the accepted alternative to the speed governor is the ELC which maintains the speed of the set by adjusting an electrical ballast load connected to the generator terminals through a power electronic system [1,3]. In this case, the water flow is kept constant and hence the water regulating device can

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Nomenclature

F_r	is the MHPP frequency (Hz)
f_r	is the MHPP frequency (pu)
Q_t	is the water flow ($m^3\,s^{-1}$)
q_t	is the water flow (pu)
H_e	is the effective falling height (m)
h_t	is the falling height (pu)
P_t	is the turbine power (w)
p_t	is the turbine power (pu)
P_e	is the load (w)
p_e	is the load (pu)
g	is the gravity acceleration ($m\,s^{-2}$)
ρ	is the water's density ($kg\,m^{-3}$)
k_t	and Ta are constants that characterize the plant
Rt	is the ray of the turbine (m)
S_n	is the nominal power (VA)
$J\Delta$	combines moment of inertia of both the generator and the turbine
C_t	is the mechanical torque (N m)
Ω_t	is the angular velocity of the generator ($rad\,s^{-1}$)
C_e	is the resistant torque (N m)
Ω_{tn}	is the nominal speed of the turbine ($rad\,s^{-1}$)
V_t	is the turbine's drive speed
V_1	is the water's speed in the contact of the jet with the buckets
V_2	is the water's speed when it comes out from buckets
m	is the report of V_1 and V_2
β	is the angle between $\vec{V}_1$ and $\vec{V}_2$
n_t	is the turbine speed (pu)
Q_{tn}	is the nominal water flow ($m^3\,s^{-1}$)
V_{1n}	is the nominal speed of the jet ($m\,s^{-1}$)
P_{tn}	is the nominal turbine power (w)
P_d	is the electrical power dissipated on the ballast load (w)

be dispensed with. Typically the cost of the ELC is about one tenth that of the speed governor and so the economic advantage of the ELC is twofold, as a result of the lower capital cost of the governor and of the turbine.

The ELC uses power electronic equipments; hence, the frequency stabilizing time is very short, especially for small load variations. However, for large load variations, the stabilizing time and even the performances depend on the used controller. The first part of this paper treats this specific point, where it will be proven through simulation and practical results that linear controllers with fixed gains could lead to the instability of autonomous MHPP even with the use of an ELC as actuator.

Through simulations and practical tests it has been shown that the use of ELC governor with PI controller guaranties good regulation results for specific load variations. It means that PI controller guaranties good regulation results only when the occurred load variation is equal to the value of the load variation that the PI controller was designed to work with (no matter if it is small or large load variations). But, when the occurred load variation is smoothly different, the PI controller does not guaranties good regulation results anymore. This point is very important, because, in the literature, most of the papers present linear controllers for MHPP only for small load disturbance, while those controllers will certainly not be able to work properly for large load disturbances. Moreover, most of the proposed hydropower models are linear. However, such linear models are valid only for small signal performance study (load disturbance < ±10%), and are inadequate for large variations in power output (>±25% rated load) [8].

The main goal of this paper is to propose a controller that would guarantee good MHPP frequency regulation for all range of load variations, small and even for large ones. We do not propose voltage controller because we threat isolated MHPP that uses permanent magnet alternators, where the voltage is linearly varying with the frequency. The MHPP is a MIMO nonlinear system. Yet, to take into account the nonlinear behavior of MHPP towards the load variations, we propose two approaches. First, for our simulation investigations, the MHPP should be presented by a nonlinear model. Second, to guarantee a good frequency regulation of MHPP, we think that PI controller's gains should vary according to the load variations. This would keep good system performances for all range of load variations, even for large ones.

On the other hand, fuzzy logic has been widely used in the literature for its ability to model and control nonlinear system based on linguistic information given by expert [10–13]. To improve performances of nonlinear systems, several approaches combining classical controllers and fuzzy logic have been presented. Among them, the self-tuning fuzzy PI controller allows improving the dynamical performances since its gains are adjusted on-line using fuzzy logic system [14–18]. In this paper, a self-tuning fuzzy PI controller for MHPP frequency regulation is proposed in order to make the ELC control strategy more efficient against large load disturbances.

The dynamic MHPP model for simulation investigations is briefly introduced in Section 2. Practical validation of the used MHPP model and identification of two parameters that characterize the plant are presented in Section 3. Regulation study of the ELC control strategy using a PI controller is introduced in Section 4. In Section 5, Design methodology of the self-tuning fuzzy PI controller is described. Lastly, both simulation and practical results are provided to valid the new control design considerations.

2. Micro-hydro power plant design model

Most papers present controllers based on MHPP transfer function models. In [1], the authors present a modern approach based on the construction of a mathematical model of the plant and on its numerical simulation. A simulation study of the model is also considered. The followings are the main equations that were used to build the MHPP model presented in [1].

The turbine power is given by [19]:

$$P_t = \rho g Q_t H_e \quad (1)$$

Pelton turbines are used for high water fall and low water flow. On a generating unit that uses Pelton turbine, Eq. (1) becomes: [19]

$$P_t = \rho Q_t V_t (V_1 - V_t)(1 + m \cdot \cos\beta) \quad (2)$$

In this paper, capital letters represent the variables with their (SI) units and the minuscule ones represent the variables with per units. Using per units, the expression (2) becomes:

$$p_t = \rho(1 + m\cos\beta)\frac{q_t Q_{tn} R_t \Omega_{tn} n_t}{P_{tn}}(v_1 V_{1n} - R_t \Omega_{tn} n_t) \quad (3)$$

The water's velocity at the penstock's output varies only with the falling height and it is given by:

$$v_1 = \sqrt{h_t} \quad (4)$$