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A network control system for hydro plants to counteract the non-synchronous generation integration

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ABSTRACT

Sweden, a country with abundant hydro power, has expectations to include more wind power into its electrical system. Currently, in order to improve the frequency response requirements of its electrical system, the country is considering upgrading its hydro-governors. This effort is part of maintaining the system frequency and reaction within their limits following any disturbance events. To partially compensate for increased frequency fluctuations due to an increased share of renewables on its system, the frequency response of hydro-governors should be improved. This paper proposes an innovative network control system, through a supplementary control, for the improvement of the hydro-governor's action. This supplementary control allows having more flexibility over the control action and improves the primary frequency control, and thereby the overall system frequency response. The proposed supplementary control, based on an evolutionary game theory strategy, uses remote measurements and a hierarchical dynamic adjustment of the control. Additionally, in order to guarantee an optimal response, a Simulated Annealing Algorithm (SAA) is combined with the supplementary control. This paper illustrates the analysis and design of the proposed methodology, and is tested on two power systems models: (i) an aggregated model that represents the frequency response of Sweden, Norway and Finland, and (ii) The Nordic 32 test system.

1. Introduction

Concerns about global warming have motivated governmental agencies the world over to employ more friendly environmental policies. The current European energy goals, set for 2030 and 2050, to enhance green power are a driving factor in the development and integration of more renewable resources into the grid [1]. Consequently, technical challenges in the power generation system have emerged due to the rapid development and integration of renewable power [2].

The renewable power interconnection has been possible due to the use of high-power electronics converters as a control interface of the power to be supplied to the grid. One of the challenges of the large integration of Renewable Energy Sources (RES) is the inertia reduction in the system which has resulted in a larger deviation from the nominal system frequency under a disturbance [3]. Thus, additional controller options are needed in the frequency process restoration [4].

One of the aspects that needs consideration is the maintenance of the frequency stability boundaries in the system [5], and adequate response in order to avoid undesirable events like outages or blackouts [6]. Potentially, hydro-dominated systems can counteract the lack of inertia by improving the hydro-governors involved.

The hydro turbine governor is a system that regulates the inlet water into a turbine, which in turn rotates the generator to produce electricity. In order to maintain a required generated frequency at the reference value (50 or 60 Hz), the turbine speed of rotation must be kept constant [7,8]. The turbine governor receives information on the current rotational speed of the turbine and adjusts the water flow to maintain the speed at the correct level [9,10].

The Nordic power system is mainly a hydro dominated system and frequency control is predominately performed by hydropower plants.

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Many of the governors currently in use in Sweden are of an older generation and purely mechanical design. While effective, these suffer from mechanical wear due to ageing. As these units reach the end of their working life, replacement is essential. At the present moment in time, the replacement of choice is a Proportional-Integral-Derivative (*PID*) controller adapted to function as the governor for a turbine [11,12].

A faster response of the governor in reacting and returning the system frequency closer to its nominal values when subjected to a disturbance is desired.

Several proposals have been studied in order to enhanced the hydro-governors response. A hydro governing system based on fuzzy logic is presented in [13], where it is compared to a *PID* governor showing an improvement in the settling time and the overshoot. Another fuzzy proposal is compared to slide mode control for the performance improvement of a hydro governing system in [14].

In [15], a fuzzy $PI + D$ control structure is designed showing the possibility of including the derivative term as an extra signal involved in the hydro-governor control.

Authors in [16], proposed a robust control based on a high gain observer as an adjustable parameter for obtaining an adequate dynamic response under disturbances. A decentralized control signal for hydro governors has been designed using H_∞ control in [17], showing the speed of response during different disturbances.

By using a feedback linear approach, the authors in [18], aimed to design a governor to deal with the transient stability and to damp the oscillations in the system. The authors in [19], present a robust control design for hydro-governors based on additional inner states feedback signals and it is compared to traditional *PI* and *PID* architectures.

Analytical controllers such as the ones proposed in [16,19] might require a new design in case of a necessary modification in the system. In contrast, fuzzy approaches such as [13,15], could adapt themselves under a larger operation range.

In [20], an isolated system which includes a hydro governor and a wind turbine generation system is studied; the influence of both generations on the frequency under load changes is shown. A frequency control design framework for hydro power is proposed in [21], for counteracting the influence of the wind integration and reducing the frequency deviation.

In [22], the primary frequency control of hydro-dominated power system which integrates wind power is studied. It is focused on the pitch control and the frequency support from the turbine. A similar approach is given in [23], where a control method is developed to enhance the frequency capability including energy storage.

As a partial improvement for the integration of large renewable integration, several authors have proposed the application of the so-called virtual inertia. Authors in [24] added the derivative control in multi-area power systems.

Another example in the literature using the virtual inertia is given in [25]. It uses a similar approach to [24] with the application of control layers. Additionally a dynamic security constraint assessment is proposed by the power generation changes versus the droop coefficients.

In [26], a synchronous generation emulation for VSC stations is presented. Current and droop controllers are improved for achieving the frequency regulation under several scenarios.

In this context, a virtual inertia emulation is presented in [27], where linearized models are used for the frequency response modeling. Moreover, a maximum power tracking point method is applied to reduce the frequency fluctuations and operate under real wind conditions.

Another contribution perspective [28], where there is a generation mix also, presents the fusion of droop control and a pitch control, for improving the system frequency and reducing the need for reserves. A distributed Model Predictive Control is proposed in [29] for the frequency improvement including the coordination optimization strategy between the aggregated hydro-dominated systems and the wind power plant.

At the same time, the transformation of the power systems into a Cyber-Physical Systems (CPSs), where remote measurements and control interactions are combined, have brought opportunities to propose new control architectures for solving common goals in the systems [30,31].

CPSs have been used widely in several power systems applications such as distributed automatic generation control [32], microgrids management [33], microgrids secondary/primary control [34], distributed Power System Stabilizers (PSS) [35], adaptive power flow control [36], distributed power injection in low-inertia power systems [37], distributed dispatch [38], and distributed active power control [39].

Under the framework of CPS and Multi-Agent System (MAS), several protocols have been deployed. Depending on the application, MAS can be classified or used as: decision making, commitment-based, coalition-forming, negotiation, and resource allocation [40]. Distributive controllers intended to cooperate to reach or improve certain common goal such as the frequency response improvement is the motivation of this document. Consensus or leader-follower protocols have shown to be a potential tool for the frequency control regulation (secondary control) in power systems reaching a distributive convergence to the nominal frequency [41].

Another MAS protocol is Replicator Dynamics (RDs) which belongs to the Evolutionary Game Theory (EGT). RDs is inspired by natural selection and uses simple population dynamics that show how individuals or populations change their strategy over time based on payoff functions [42]. RDs have been used in several MAS applications with successful results [38,43].

RDs protocol has the property of maximizing the social welfare for group actions and plants. In the case of the governors, RD not only looks for the best response of one individual, but for the group as well, obtaining the equilibrium where all the derivative actions reach the best group action. Additionally, having an initial optimal value obtained from the SAA guarantees an optimal response.

As a remedial action in the primary frequency control performance due to the increasing non-synchronous generation and response enhancement, this paper proposes a control network paradigm using remote and local information in the hydro-governors through a supplementary signal. Our proposal aims to do a dynamic control distribution, in each of the *N*-systems conformed by the hydro-governors involved, and optimize the frequency response in the system. For the latest, the optimal frequency response, it applies a novel procedure based on an evolutionary game theory, i.e., the RD, acting as a centralized controller [44,38]. The design constraints are studied including the population game strategy. The applied method is compared to the Simulated Annealing Algorithm (SAA) for obtaining the optimal local controllers in the system.

The paper is organized as follows: in Section 2 the theoretical preliminaries of graph theory and RDs are presented. Then Section 3 briefly presents notation and the application to the stated problem. In Section 4, the power system preliminaries, the frequency power response, and the modeling of the system are introduced. Section 5 presents the control architecture, the measurement and the performance metrics, and the proposed RD function. Section 6 presents the simulation results considering the two systems, the aggregated model and the Nordic 32 test system. In the latter, a gradual inclusion of non-synchronous generation is included in order to observe the impact on the system frequency control, and the improvement by the presented method is shown. Finally, the conclusions and future work are given.