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Synthetic inertia control based on fuzzy adaptive differential evolution

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ABSTRACT

The transformation of the traditional transmission power systems due to the current rise of non-synchronous generation on it presents new engineering challenges. One of the challenges is the degradation of the inertial response due to the large penetration of high power converters used for the interconnection of renewables energy sources. The addition of a supplementary synthetic inertia control loop can contribute to the improvement of the inertial response. This paper proposes the application of a novel Fuzzy Adaptive Differential Evolution (FADE) algorithm for the tuning of a fuzzy controller for the improvement of the synthetic inertia control in power systems. The method is validated with two test power systems: (i) an aggregated power system and its purpose is to understand the controller-system behavior, and (ii) a two-area test power system where one of the synchronous machine has been replaced by a full aggregated model of a Wind Turbine Generator (WTG), whereby different limits in the tuning process can be analyzed. Results demonstrate the evolution of the membership functions and the inertial response enhancement in the respective test cases. Moreover, the appropriate tuning of the controller shows that it is possible to substantially reduce the instantaneous frequency deviation.

1. Introduction

To reduce the pollution and produce clean electricity, many countries' national environmental policies have targeted to achieve a large percentage integration of non-synchronous generation into the grid [1]. However, the challenge of integrating renewables into the overall power delivery has generated a common question: what is the impact of such integration on the power system stability [2]? During the last decade, significant research studies and proposals have been addressed to that question by several Transmission System Operators (TSO) [3], manufacturers [4], research energy centres [5], and governmental associations around the world [6].

Since the transmission grid is the central artery that delivers power from generation plants to million of users, it is important to understand the impact of the large-scale integration of the non-synchronous generation on the power systems dynamics behavior [7]. The development of the full scale converters has made possible the renewable energy sources interconnection as well as the High Voltage Direct Current (HVDC) transmission capability. The full converters have enhanced the power exchange over long distances achieving a high penetration level of renewables [8].

However, the large-scale integration of renewables creates different challenges such as the provision of an uninterrupted supply and the stability impact on the system. Different dynamic effects have been observed and studied based on the decoupling effect produced by the power electronic interface. The main phenomena studies regarding the stability are mainly the small signal stability [9], the transient stability [10], the coherency [11], and the frequency response [12]. This latter aspect, is the requirement of maintaining the frequency stability within the respective boundaries of the system [13].

In order to maintain these limits, the frequency control should act in a manner such that the balance between generation and load is always met. The frequency response in power systems can be divided into different time frames:

– Initially, an inherent action named as inertial frequency response is present, which takes energy from the rotating masses to oppose a frequency deviation from the scheduled frequency [14].

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– In the next stage, the automatic governing systems are activated to keep the frequency deviation to an acceptable level (primary control).
– Finally, the secondary control action is performed which restores the used reserves and the system frequency to its nominal value.

Non-synchronous generation (a non-inertial generation) is unable to contribute to the frequency response, unless an extra supplementary control - the so-called synthetic inertia [15], hidden [16] or virtual inertia [17] - is added. This supplementary control is able to contribute to the inertial response by injecting additional power obtained from dynamics of the wind power.

To overcome this problem, many control techniques have been adopted in the synthetic inertia control loop. The fixed (P/I/D) proportional/integral/derivative control combinations have been adopted in the synthetic inertia control loop [18]. By applying a slight change in the inverter electrical power set-point, the kinetic energy from the wind dynamics is released [19]. This control action reduces the frequency dip and the rate of change of frequency (RoCoF) [20]. Nevertheless, this extra power can only be extracted for up-to 10 s [21].

In recent times, soft computing methods such as neural networks, fuzzy logic, genetic algorithm, and swarm intelligence controllers are replacing the conventional techniques [22,23]. These techniques have been successfully applied to different power systems applications such as microgrids [24], Power System Stabilisers [25], HVDC [26], FACTSs [27], etc.

Fuzzy systems can be embedded in Hardware in the Loop (HIL) platforms in order to emulate real-time systems and understand the performance of the controllers with the respective plants [28]. A successful application of fuzzy systems in real systems environments is shown in [29], where the permanent magnet motor response is improved through fuzzy logic, in a micro wind system. Possible options to implement fuzzy inference systems in transmission level rely on the use of fully dedicated laboratories [30,31], however this implementation is out of the scope of this paper.

Differential Evolution (DE) is a newer branch of evolutionary algorithms like Parallel Simulated Annealing (PSA) and genetic algorithms [32]. DE is a very effective combinatorial optimization method that has been applied in diverse automatic control areas [33], power systems [34], and power electronics [35]. The increasing use of the bio-inspired algorithms in control tuning is based on their individual population (possible solutions), and the convergence to a value closer to the optimal solution in the final generation [36].

Some of the DE applications in power systems are in topics such as voltage stability assessment [37], automatic generation control (AGC) [38], induction generation [39], PSS tuning [34,40], voltage power (source) converters [41], optimal power flow [42], electricity forecast [43], etc.

DE has been proposed as a control methodology for fuzzy logic tuning inference system parameters for non-linear process control in [44]. The FADE algorithm adapts the fuzzy logic controller parameters while obtaining the information of the system to be controlled.

This innovative technique is applied in this paper for the improvement of the synthetic inertial control response of power systems under penetration of non-synchronous generation. The application of the DE looks for an adequate diminution of the Instantaneous Frequency Deviation (IFD or nadir) through the improvement of the fuzzy control parameters respecting the electrical and/or mechanical constraints. Moreover, since typical synthetic inertia approaches rely on user-experience tuning and, only a few approaches have shown the possibility of optimizing the active power injection [45], a further study is required and, therefore, is the motivation of this document.

The tuning of the Fuzzy Logic Controller (FLC) is developed based on an on-line co-simulation script-Simulink training system. Two test power systems are proposed in order to observe the frequency response under non-synchronous generation inclusion. The first test system represents an aggregated power system and the ideal supplementary inertia control. The second test system, is the two-area system where one of the synchronous machines has been replaced by a full aggregated wind power system. Both test systems are completely developed for frequency studies in Simulink. The results show the IFD and frequency response improvement thought the controllers evolution process.

The paper is organized as follows: In Section 2, the research motivation regarding the frequency and inertial response is presented. Also, the definition of non-synchronous generation and its relation with the synthetic inertia are introduced. In Section 3, the theoretical fundamentals of the Fuzzy Adaptive Differential Evolution (FADE) control method are presented. Section 4 presents the architecture of the two test power systems and their modeling. Section 5 presents the simulation results considering the two control scenarios; the ideal one with minimal constraints, and the second one incorporating the full aggregated wind turbine. Finally, the conclusions and future work are given.

2. Frequency response

The frequency control in a power system after a large disturbance is performed in different stages and time frames, namely inertia frequency, Frequency Containment Reserve (FCR) (primary control) and Frequency Restoration Reserves (FRR) (secondary control).

Inertial response is inherent in the system due to rotating mass of machines synchronously-connected providing counter response within seconds to oppose the frequency deviation following a loss of generation or a load event [46].

In a synchronous system, in the case of losing a generating unit, the frequency drops because of the imbalance between generation and load. The system frequency response is reflected in the power system instantaneously. During the first period, the inertial response of the spinning machines in the entire system, reacts by releasing or storing kinetic energy tending to reduce the frequency deviation. System inertia is defined as the total amount of kinetic energy stored in all rotating masses.

The inertial constant of an individual generator can be interpreted as the time that generator can provide full output power from its stored kinetic energy, taking values between 2 and 9 s.

Beyond the inertial response, the frequency is first stabilized and then restored to the nominal frequency by the FCR (governor action) and secondary controllers, respectively. The FCR acts as a proportional controller avoiding large frequency deviations; however, a steady state error still remains in the frequency response. The response of this control is given in seconds (< 30 s). FRR returns the frequency back to its nominal value and also restores the reserves; its deployed time frame is given in minutes.

Fig. 1 shows the dynamic response of the system frequency after disconnection of one generator. In the figure, the Maximum Instantaneous Frequency Deviation (IFD) (in cyan) and the post-disturbance Steady-State Frequency Deviation (SSFD) (in purple[1]) are also indicated.

2.1. Non-synchronous generation and synthetic inertia

In this paper, non-synchronous generation is defined as when the power is supplied or absorbed through power electronic converters (DC-AC) to/from the grid system. For wind power turbines applications, Voltage Source Converters (VSC) have been employed to represent Full Rated Converters (FRC), Doubly-Fed Induction Generator (DFIG), and High Voltage Direct Current (HVDC) and Multi-terminal HVDC connection [11]. The non-synchronous generation allows controlling active

[1] For interpretation of color in Figs. 1, 4, 6, and 13–15, the reader is referred to the web version of this article.