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An adaptive neuro-fuzzy inertia controller for variable-speed wind turbines

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ABSTRACT

A Variable-Speed Wind Turbine (VSWT) can serve as a good reservoir of Kinetic Energy (KE) for few seconds owing to wide operating rotor speed. Based on this fact, several approaches have been proposed to introduce synthetic inertial response in VSWT. Usually, this is accomplished by introducing an additional control loop at the outer most level of the control hierarchy. However, several key issues including the selection of control parameters and the effects of wind speed variations on the synthetic inertial support are not addressed. As a result, the KE reserve is severely under utilized. To address these concerns, in this work, a simple approach is proposed to control parameter selection which ensures the optimal use of available KE reserve. Further, to tackle the variable KE reserve, a comprehensive inertia controller using intelligent learning paradigm is designed. The proposed inertia controller can adapt to wind speed variations while providing optimum inertial response. Efficacy of the proposed approach is evaluated over the entire operating range of the VSWT. For further evaluation, wind speed data from NREL western wind integration is utilized. The results indicate that the proposed system is quite effective and can maintain an adequate performance over the entire operating range.

1. Introduction

During the last two decades, the wind energy generation has grown by almost 20% per year and it is expected to continue at its present rate [1]. Grid integration studies indicate that, in economically dispatched system, new wind energy installation results in either replacement or de-loading of the Conventional Power Plants (CPP) [2,3]. This situation is rather challenging for utility operators as, traditionally, Wind Farms (WF) do not take part into any ancillary services [4–8].

In the event of any generation and demand mismatch, the grid inertia plays a major role in maintaining the frequency stability [9]. The inertia, in essence, is the ability to reflect the change in the generator torque with change in the grid frequency. When it comes to inertia, there is a fundamental difference between the synchronous generator and the VSWT. In VSWT, the rotor speed is closely controlled as per prevailing wind speed to track the maximum power point. The rotor speed is therefore decoupled from the grid frequency. Hence, the VSWT are unable to provide any inertial support [10,11].

The grid integration studies show that, with increased share of wind energy in the generation mix, the grid inertia will be reduced [2,3]. In this scenario, the under-frequency events (loss of major generating units or transmission lines) are, arguably, the biggest challenge for the utility operators. To address this issue, utility operators are already in process to include ancillary support from WF as a grid code requirement [4–8]. Nevertheless, the studies indicate the presence of significant amount of Stored Kinetic Energy (SKE) in the installed wind capacity even at low wind speeds [12], which can be tapped for the purpose of the inertial support with a proper control strategy.

The inertial response is an inherent characteristic of the conventional synchronous generator; to mimic similar response in the VSWT, it is necessary to establish the link between the grid frequency and the generator torque. Earlier research revealed that, unlike VSWT, fixed speed WT can respond to frequency deviations and hence can provide some inertial response [11]. It was found that it is possible to enable a similar link, and hence emulate the inertial response in the VSWT [11,13]. The main idea is to modify the generator torque or the active power reference (based on the

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control hierarchy) as per grid frequency deviations. Based on this concept, several inertia emulation approaches have been reported [14–30]. Most of the approaches can be broadly classified into either *Governor-Inertia* [14–25] or *Step Over-Production (SOP)* [26–30]. The Governor-Inertia is in essence a PD controller, which modifies the generator torque or active power reference (based on control hierarchy) as per grid frequency deviations. On the other hand, in the SOP approach, the active power reference is increased above its MPPT requirements for a short duration (usually for few seconds). The magnitude and the duration of temporary power increase (power boost) is either pre-determined or it is some function of grid frequency [26].

It is pertinent to note that while emulating inertial response the released kinetic energy, subsequently, has to be absorbed in order to go back to the pre-disturbance operating point. Usually, to regain the released the kinetic energy more energy is required to make up for the losses incurred during energy release [28,30]. In other words, the over-production period (wherein SKE is released by deceleration) is inevitably followed by the under-production period (wherein SKE is regained by acceleration). From the grid point of view, the end of the additional power support is equivalent to loss of generation. If the synthetic inertial support is not properly designed, transfer from deceleration to acceleration may cause another frequency disturbance. In governor-inertia approach, this process is natural and it is determined by the control parameters and the grid frequency behavior. However, in the SOP approach, usually the under-production has to be designed to accommodate the effects of WT acceleration.

Earlier inertia emulation approaches [16–19] were more concentrated on demonstrating the ability of the VSWT to provide the inertial support. A slightly different approach was proposed in Ref. [22], in this approach, a transient change in slip is introduced inside the inner control loop. A shaping function is used to inject the temporary change in slip reference to enable the release of kinetic energy. However, the effects of shaping function on the inertial response were not evaluated and no clear guidelines were provided for its selection. The need to control the effects of energy regain (acceleration) by VSWT after the inertial support was emphasized in Ref. [19]. Since then several approaches have been proposed to tackle this issue. For example, smooth change of active power reference (or torque reference, based on control hierarchy) [30]. Another approach suggested ending the support of individual WT at different time in a wind farm [27]. However, there are several key issues, which are usually not addressed, e.g., the co-ordination of the inertial support duration within a wind farm and its effects on the aggregate inertial response.

The major challenge in the inertia emulation is the variable speed operation of the VSWT. The Stored-Kinetic Energy (SKE), in the WT blades and the other rotating masses, is directly proportional to the rotor speed (which is tightly controlled as per prevailing wind speed). Hence, the SKE reserve will vary with the wind speed [26,30]. The other challenge is posed by the operating limits of the VSWT. Since the rotor speed falls with the release of SKE, care should be taken that it does not fall beyond its minimum-operating limit (especially in low and medium wind speed regions). Moreover, the additional power injected should be limited as per the generator and convertors' maximum current carrying capacity (in high wind speed regions). However, most of the approach to inertia emulation [16–29] do not address these issues.

Usually, it is a general practice to assume that the mechanical input is constant while assessing the inertial support in the CPP. However, the same cannot be extended to the VSWT as the inertial support lasts for several seconds and, within this duration, it is not plausible to assume constant wind. Therefore, it is essential to accommodate these variations within the inertial support scheme. In particular, it is more challenging to address the inter-support wind variations while designing the under-production (acceleration) period. Most of the inertia emulation approaches [14–30] are designed considering constant wind input for the duration of the inertial support and neglect inter-support wind variations.

The main objective of this work is to exploit the variable speed operation for the benefit of inertia emulation while addressing aforementioned issues, which have not been considered so far. The main contribution of this work is twofold: First, for a given wind speed, inertia emulation is approached as an optimization problem in order to maximize the use of the available kinetic energy reserve while limiting the effects of post-support disturbances. Second, a neuro-fuzzy adaptive inertia controller is proposed which can adapt to the wind speed to provide optimal inertial response at all possible wind speeds.

The remainder of this paper is organized as follows. Section two provides the details of WT and micro-grid model used in this study along with the conventional inertia controller. Section three presents the proposed approach to adaptive inertia emulation. Simulation results are presented in section four and section five contains the conclusions.

2. System model

The VSWT's ability to provide inertial support is well established. Usually, to emulate inertial response, a temporary change in active power or generator torque (based on the control hierarchy) is required to trigger the fall in WT rotor speed and, subsequently, to bring it back as per MPPT requirements. The required change in the active power or generator torque is achieved through additional synthetic inertia control loop at the outer most level of the active power control hierarchy. The main challenge of the inertial emulation is to design a synthetic inertia control that can adapt to a variable KE reserve.

For the purpose of this work, the VSWT model and test micro-grid used are based on earlier studies [26–30]; to facilitate easier comparison among inertial emulation approaches. The details of both are provided, very briefly, in this section. The conventional approach (Governor-Inertia or PD) to inertia emulation is also included.

2.1. Wind turbine model

The VSWT model used in this study is based on GE 3.6 MW WT [33,34]. The WT uses a Doubly Fed Induction Generator (DFIG). The control of active and reactive power is achieved through field-oriented control on back-to-back connected converter link in the rotor circuit of DFIG. The active power control loop of the WT is shown in Fig. 1 and the controller details are provided in the Appendix. All the variables are in *p.u.* on the basis of rated power of the WT.

The MPPT characteristic of the WT is approximated by setting the reference speed for the rotor speed control, ω_{mppt} according to the following equation for the active power below 0.75 pu. For the higher values of active power, ω_{mppt} is saturated to 1.2 *p.u.* [33].

$$\omega_{mppt} = -0.67P_{meas}^2 + 1.41P_{meas} + 0.51 \quad (1)$$

More details about the WT model can be found in Ref. [33]. Note that since the control loop for inertia emulation is located at the outermost level of the active power control hierarchy, the proposed