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Optimal use of kinetic energy for the inertial support from variable speed wind turbines

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ABSTRACT

The use of kinetic energy, stored in the rotational masses of Variable Speed Wind Turbines (VSWT), for inertial support is well established. The idea is to employ the fast control response of the VSWT to inject additional power for the short duration following the disturbance. However, the variable speed operation of the VSWT poses a great challenge in successfully designing an appropriate control approach, applicable for wide operating ranges, capable of minimizing the effects of energy regain by the Wind Turbine (WT) after the support period. To address this issue, this paper proposes a modified inertia-emulation scheme, based on Step Over-Production (SOP) approach. Further, to enable optimum energy transfer and to handle the problem of variable Stored Kinetic Energy (SKE), the shaping parameters of the proposed scheme are optimized using the Particle Swarm Optimization (PSO) algorithm. The results show that the proposed approach can limit the fall of frequency while reducing post disturbances across the entire operating range of the WT. In addition, the quantitative analysis reveals that the proposed method can easily satisfy the stringent grid code requirements for the inertia emulation and provides a better alternative to the conventional inertia control architectures.

1. Introduction

With the increased share of power generation from Wind Turbines (WT) and the consequent reduction in system inertia [1], under frequency events emerge as one of the biggest challenges for transmission operators [2–8]. The first few seconds after a major frequency disturbance are very crucial in the frequency restoration process. During this period, the system inertia plays a major role in maintaining the supply-demand balance [1,9,10]. The inertia, in essence, is a result of an ability to reflect the grid frequency deviation in generator torque, which is an intrinsic quality of synchronous generators employed in conventional units [9–11]. However, the Variable Speed Wind Turbines (VSWT), which share the major portion of the installed wind capacity, do not provide any inertia; resulting in a grid that is more susceptible to disturbances.

The lack of inertia in VSWT can be attributed to the fact that the stator/rotor of the generator (depending on the configuration, i.e., Type 3 or Type 4 [12]) is not directly connected to the grid; rather, it is connected through power electronic converters to enable variable speed operation. In VSWT, usually, vector or field oriented control is employed along with the fast acting power electronic converters to independently control active and reactive powers [13]. The active power or the generator torque (based on the control hierarchy) is controlled precisely to track the Maximum Power Point (MPP) with change in wind speed. This control arrangement compensates for any changes in the torque due to frequency deviations and maintains it at a constant value determined by MPP. For this reason, VSWT are unable to provide any change in electromagnetic torque, and consequently in rotor speed, with variations in grid frequency and, therefore, no inertial response is observed [1,10,14].

The research carried out by Mullane and O'Malley [10] suggested that the rotor current controller can have significant effect on the inertial response of the Induction Machine (IM) based VSWT. It was observed that if the bandwidth of the current controller is reduced, influence of the grid frequency on the generator torque is increased, which has a positive impact on the inertial response of the IM [10,15]. However, a larger bandwidth for the current controller is essential for accurate control of the generator torque and, hence, for the Maximum Power Point Tracking (MPPT).

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Nevertheless, the study laid the ground for inclusion of synthetic inertial response in the VSWT. Based on these findings, a modified control architecture was proposed in Ref. [16]; wherein an external signal was injected in the generator control loop as a disturbance to modify the torque reference and to enable the deceleration of the generator to release the Stored Kinetic Energy (SKE). Almost all of the current inertial emulating architectures are based on these earlier findings and rely on the modification of the generator torque (or the active power, based on the control hierarchy) reference for short duration, to emulate the inertial response.

The external signal, used to modify the generator torque (or the active power) reference, can be a function of the grid frequency or a pre-determined value. Based on the external signal employed to emulate the inertia, mainly two different approaches can be identified among the proposed approaches so far: Governor-Inertia Controller [11,17–30] and Step over Production (SOP) approach [31–36]. The Governor-Inertia is in essence a Proportional-Derivative (PD) controller with grid frequency as an input. In the SOP, the active power reference of the WT is increased for a pre-determined duration to balance the supply demand mismatch. After the inertial support period, the active power reference is reduced below its optimum value to regain the kinetic energy. The magnitude and the duration of the injected power can be adjusted to achieve the desired inertial response. The major challenge, here, is the fine-tuning of the magnitude and duration of this action to improve the inertial response.

The focus of this article is to improve the performance of the SOP approach, as it allows much more flexibility in implementation. In addition, the inertial response can easily be shaped as per the prevailing requirements. In the literature, various versions of the SOP approach are reported [31–36]. The differences are mainly based on the selection of the shaping parameters and the way the released kinetic energy is regained.

In Ref. [31], a dedicated under-production (acceleration) period for regaining the released energy for SOP approach was proposed. The shaping parameters of the SOP for the deceleration period are selected following the Hydro Quebec's earlier inertial support requirements for VSWT [8,37]. The main idea is to have an under-production period determined based on the equal area criterion, i.e., the amount of energy absorbed during acceleration (to return back to the pre-disturbance operating point) is the same as that injected during deceleration. However, under some operating conditions, the energy transfer involved is not exactly neutral; usually, more energy is required to recuperate the losses incurred during the over-production (deceleration) period. Based on this fact, to recuperate the kinetic energy, an acceleration period with deeper under-production level and slightly longer duration compared to that of the deceleration period was proposed in Ref. [32]. However, a proposed larger fall in the active power for acceleration may cause additional frequency disturbance. It is, therefore, advisable to distribute the energy regain over a longer period.

Another approach based on a distributed recovery strategy to recover the kinetic energy was suggested in Ref. [33]. This approach, instead of relying on the effect of the acceleration period, relies on an aggregating effect of the wind farm, i.e., the support from an individual WT ends at different incremental times. This tends to avoid the sudden drop in the injected power. In Ref. [34], a strategy based on the constant acceleration power (difference of WT mechanical power and generator active power output) was used for the acceleration period. The main drawback of this approach is the prolonged acceleration time, which delays the restoration of the WT to its pre-disturbance state.

A common drawback of all the aforementioned approaches is that they have a sudden drop in the active power reference during transition from deceleration to acceleration period, which is highly undesirable. To minimize the effects of this changeover from deceleration to acceleration, transition along a slope was suggested in Ref. [35]; though the effect of this additional shaping parameter was not evaluated.

The large variations in the SOP approach to emulate the inertia stems from the fact that it is difficult to maintain the balance of kinetic energy transfer with the grid during the inertia emulation process while balancing all the objectives. It is logical to inject as much SKE as possible to the grid after the disturbance. However, the higher the released kinetic energy, the more amount of energy will be required to regain the pre-disturbance operating speed [36]. If the energy regain during acceleration is not controlled properly, it may cause another frequency disturbance.

The other challenge is the variable mode of operation. Unlike the synchronous generators, the rotor speed of the VSWT is decided by the prevailing wind conditions. As a consequence of variable rotor speed, the amount of SKE is also variable. The variable SKE is a major influencing factor in the design and implementation of the inertia emulation scheme. This fact is not considered in most of the recently proposed approaches. Usually, the parameters are selected on trial-and-error basis [11,17–36]. The selection criteria for the shaping parameters are not set to optimally extract SKE, but to have a single set of parameters that can be used for all wind speeds. The main drawback of this approach is that the selection of the shaping parameters is dictated by the operating and design limits imposed on the WT, e.g., minimum rotor speed (at low wind speeds), maximum current carrying capacity of the converters and the generator (at high wind speeds). The selection made on this basis will always have a sub-optimal performance for almost the entire operating region of the WT.

It is possible to use SKE optimally if a link between the operating point and the shaping parameters is established. The main objective of this work is to establish such link with the objective of improving the performance of the inertia control architecture. For this purpose, a new approach based on the SOP is proposed. A simple function is designed to enable the aforementioned link between the parameters and the operating conditions. The proposed function is optimized using the Particle Swarm Optimization (PSO) algorithm to enable the optimum extraction of the SKE. In addition, a simple framework is suggested to control the inertial response as per Transmission System Operator (TSO)'s specification.

The paper is organized as follows; Section 2 presents the WT model and a brief description of two well-known inertia emulation architectures. The effects of operating points on the SKE are also covered. In Section 3, the proposed inertia emulation architecture is explained in detail. The micro-grid used for the test purposes is given Section 4. The performance evaluation of the architectures using simulation results is covered in Section 5. A framework to regulate the inertial response is proposed in Sections 6 and 7 presents the conclusions.

2. Inertial response

In this section the VSWT model used for the study is presented very briefly, along with the Governor-Inertia and the SOP inertia emulation schemes. In addition, the effect of the operating point on the releasable amount of SKE is evaluated.

2.1. Wind turbine model

In this work, the variable speed wind turbine based on GE 3.6 MW WT is considered [38,39]. The WT is of Type 3 [12], i.e., VSWT with Doubly Fed Induction Generator (DFIG). The stator of