An Integrated Control System for Frequency and Voltage Support via Type-3 Wind Turbines equipped with Energy Storage System

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An Integrated Control System for Frequency and Voltage Support via Type-3 Wind Turbines equipped with Energy Storage System

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***Abstract*—Generation from Wind Turbines has a minimal impact on the environment compared to traditional energy sources. Renewables can effectively tackle the problems which arise with fossil fuel usage. The most considerable disadvantage of the Renewable Energy Sources (RES), and also Wind Turbines, is that, since they are inverter-based they cannot inherently support system's frequency. Thus, when their penetration is increased, the systems stability and reliability are endangered. Moreover, nowadays RES are mostly rewarded only for providing Active Power to the grid; thus, they did not participate in voltage regulation. This situation can risk the voltage stability of the system with high renewable penetration. The contribution of this paper, is an integrated control system which is capable of providing frequency and voltage support to the grid, while operating the Wind Turbine at its optimal point, by utilizing an Energy Storage System. The design and the simulation of this system was performed in real-time with RTDS.**

***Index Terms*—Renewable Energy Sources, Ancillary Services, Wind Turbines, DFIG, Real-Time Simulations, RTDS.**

I. Introduction

Renewable sources and especially wind energy is going to hold a key role in the future of power generation. This leads to the need of researching the impact that wind penetration is going to have to the existing utility grid and finding ways to make the transition to a RES-based generation system feasible by ensuring grids stability.

The most important parameters of the grid that define its stability are frequency and voltage. The substitution of traditional Synchronous Generators (SGs) with power electronic interfaced RES drives to several problems that need to be addressed for a smooth and secure transition.

As it is known, Synchronous Generators, inherently associate load balance at the system with frequency. This assumption is not valid for RES which, as they are interfaced with the existing utility grid with power electronics. This situation, in a future scenario with high wind penetration, is going to make frequency volatile. Except frequency, rate of change of frequency (RoCoF) is another important index that needs to be taken into responsibility. During the previous years, when generation was provided mostly by SGs with inherent inertia, RoCoF had minor significance, since the inertia as mentioned above inherently limited this rate of change when power imbalance occurred. Yet, in a future system with high RES penetration, due to decreased systems inertia, RoCoF values will increase, which endangers the stable operation of the system. Synchronous Generators, due to their inherent mechanical limitations are stressed from high RoCoF values and protection devices can be triggered [1]. It can be perceived that all those reasons become a major drawback when it comes to high levels of RES penetration.

Regarding Voltage stability, Synchronous Generators, which in the existing system are responsible for providing power to the grid, are equipped with control systems that modify their excitation in order to match their output voltage to the desired one. Those systems are widely known as Automatic Voltage Regulators (AVR). During the past years, most RES power generation units such as WTs, were operated under Unity Power Factor (UPF). This means that they did not provide reactive power to the grid since active power production is the one that was rewarded by the Transmission System Operators (TSOs). As the level of RES penetration increases, more and more TSOs are going to require from WTs operators to be capable of providing reactive power support to the grid, to ensure stable operation [3].

The operations needed, beyond generation and transmission, in order to maintain grid stability and security are widely known as Ancillary Services. Traditionally, RES did not provide the grids voltage and frequency stabilization ancillary services to the grid.

Currently there are different proposals in literature regarding inertial response and primary frequency control [3,4,5]. The drawback of all those techniques that are used in order to provide frequency support to the grid, is that they operate WT in a lower point than their maximum; thus power generation is not optimal. Moreover, those strategies involve rotor dynamics which makes WT's response to the disturbances slower [3].

There are also different control strategies in literature regarding WT participation in grids voltage regulation [6,7]. The drawback of all those control strategies is that they focus on providing reactive power from a specific WT component,

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regardless the operational scenario (sub and super-synchronous operation). This may lead to power electronic converter overload which can damage the equipment.

Finally, all the aforementioned controllers act separately and manage to cure only one disturbance, frequency or voltage respectively. In a real system those disturbances may happen simultaneously. This means that those controllers are not able to guarantee the stable operation of the grid.

In this paper, an integrated control strategy is proposed, which is capable of providing simultaneously inertial response, primary frequency control and voltage support to the grid. To achieve this, VSC's feature of separately controlling Active and Reactive Power is utilized. To achieve constant optimal operation, an ESS is integrated in DFIG's existing topology.

II. Type-3 Wind Turbine with ESS

A. Topology

In order to tackle the aforementioned challenges, current DFIG control strategies have, this thesis proposes a modified topology. Specifically, a new connection of an Energy Storage System (ESS) with the DC Link is proposed. The interface between the ESS and the DC Link is achieved with the utilization of a Bidirectional DC-DC Converter. A bidirectional topology is proposed, so ESS can be involved both in under-frequency and over-frequency situations and provide frequency support to the grid.

With this improved proposed topology and the appropriate control system, it is possible to operate the WT in its optimal power output all the time. When frequency support is needed, instead of providing this extra power reserve from turbines shaft, ESS is activated with the proper control of the interface Bidirectional DC-DC converter and injects the needed extra power.

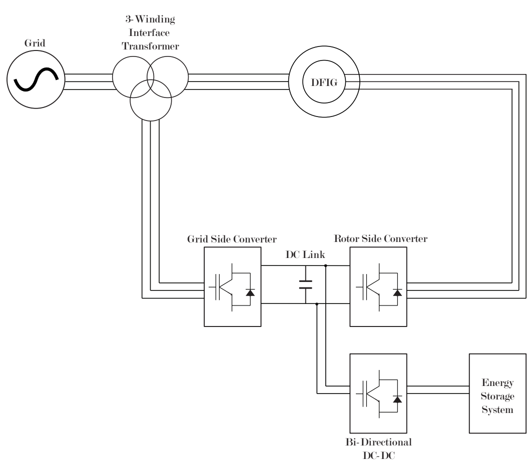

Fig. 1: Modified DFIG Topology.

B. ESS and Half - Bridge Bidirectional DC-DC Converter

There are different types of bi-directional DC-DC Converters which can be divided into two categories based on the galvanic isolation between input and output. Those main categories are:

- Non-Isolated Bidirectional DC-DC Converters.
- Isolated Bidirectional DC-DC Converters.

Isolated Bidirectional DC-DC Converters require a high frequency transformer between the two conversion stages. This feature makes that specific type of converters less attractive for this specific application, since the converter with the ESS need to be installed in a limited space. Non isolated DC- DC Converters on the other hand are more compact, which is critical for this type of application, and provide higher efficiency. Between the non isolated DC-DC converter topologies, Half Bridge Bidirectional DC-DC Converter is the most common one for this kind of applications due to its simple structure and reliability. Half-bridge DC-DC converter consists of two switches which are operated separately and not in a complementary fashion like VSC. A saw-tooth carrier waveform one is used for the pulse width modulation control of this converter [2]. The aforementioned waveform is scaled from zero to one, and it is compared with the desired duty cycle, which provides the desired power output.

III. Integrated Control for Frequency and Voltage Support

A. Inertial Response and Primary Frequency Control proposed approach

The control strategy for inertial response and primary frequency control block diagram can be seen in the following figure:

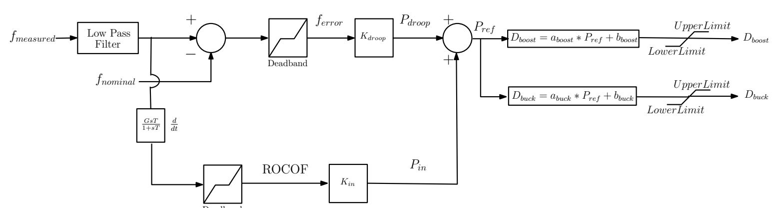

Fig. 2: ESS control for Frequency Support.

This control strategy can be expressed mathematically with Equation (1):

$$P_{ref} = (f_{measured} - f_{nominal}) * K_{droop} + \frac{df}{dt} * K_{in} \quad (1)$$

The first part, which acts as synthetic inertial response, is a fixed droop control which is adjusting P_{in} value in terms of RoCoF. Thus, controller output tries to restrict the rate of frequency deviation [3].

The second part, which acts as a primary frequency controller, is a droop controller which changes P_{droop} value according to frequency deviation (Δf) between measured and nominal frequency. This control output enhances frequency nadir (or peak) [3]. In contrast with current strategies, this approach allows WT to permanently operate at its maximum power point and does not alternate WT's shaft speed. All the extra power needed to mitigate frequency deviation, which is calculated by the controller (P_{ref}) is provided by the ESS that is paired with the DC Link of the "Back to Back" converter setup of DFIG. The active power set-point is translated to the necessary Duty Cycle for each switch of the Bidirectional DC-DC Converter; thus, the desired power is provided at DC Link and the Grid Side Converter (GSC). This happens due to the fact that, GSC control uses d-axis current component in order to maintain DC Link voltage stable. As explained before, in order to do so, total active power at the DC Bus has to be zero. Thus, power injected (or absorbed) from the ESS at the DC Link via the converter is also injected to the grid.

B. Primary Frequency Control for Grid Code Compliance

Previous control might be capable of supporting system's needs but TSOs require from the generating units a specific response pattern during frequency disturbances.

Active Power regulation is divided into Automatic Frequency Response, where the active power is automatically adjusted by governors and Manual Control where the power output is changed based on the demanded by the TSO set point values.

In Europe, Requirements for Generators (RfG) define three types of automatic frequency response [8], [9]:

- Frequency Sensitivity Mode (FSM)
- Limited Frequency Sensitivity Mode for Over-frequencies (LFSM-O)
- Limited Frequency Sensitivity Mode for Under-frequencies (LFSM-U)

Those active power control modes details, specified in German Grid Code [10] are shown in Table I:

TABLE I: Frequency sensitivity modes defined by German Grid Code.

Mode	Description
FSM	0.2 Hz Deadband, 6% droop, 2% of WT capacity
LFSM-U	49.8 Threshold, 2% droop
LFSM-O	50.2 Threshold, 5% droop

A comparison between LFSM-O,LFSM-U and FSM modes is shown in Figure 3:

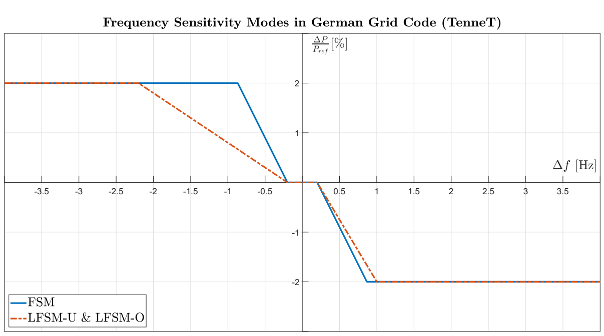

Fig. 3: Frequency Sensitivity Modes.

A control system for the WT and ESS, in order to comply with the LFSM-O and LFSM-U operation modes is depicted in Figure 4:

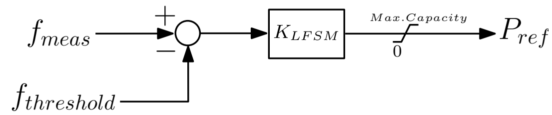

Fig. 4: ESS Control Strategy for Grid Code Compliance (LFSM-U and LFSM-O).

The mathematical formulation of this controller is shown in Equation (2):

$$P_{ref} = (f_{meas} - f_{threshold}) * K_{LFSM} \tag{2}$$

Where,

$$K_{LFSM} = \begin{cases} -0.02, & f_{meas} < 49.8Hz \\ 0, & 49.8Hz < f_{meas} < 50.2Hz \\ -0.05, & f_{meas} > 50.2Hz \end{cases}$$

A control system for the WT and ESS, in order to comply with the FSM operation modes is depicted in Figure 5:

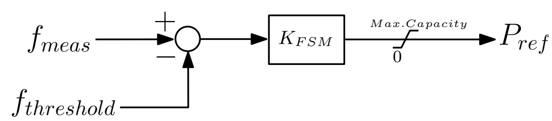

Fig. 5: ESS Control Strategy for Grid Code Compliance (FSM).

The mathematical formulation of this controller is shown in Equation (3):

$$P_{ref} = (f_{meas} - f_{threshold}) * K_{FSM} \tag{3}$$

$$K_{FSM} = \begin{cases} -0.06, & f_{meas} < 49.8Hz \\ 0, & 49.8Hz < f_{meas} < 50.2Hz \\ 0.06, & f_{meas} > 50.2Hz \end{cases}$$

With those control systems, the proposed WT topology is capable of complying with the RfG defined specifically by the German Grid Code.

C. Voltage Support proposed approach

DFIG "Back to Back" VSC converter topology, allows active and reactive power separate control with the help of Park transformation. This fact provides the capability of controlling active and reactive power output separately in order to regulate the grid's frequency and voltage [4,8].

Due to the fact that "Back to Back" converters are partially rated and need to be as small as possible to reduce overall system's cost, it is understood that during high slip values, those converters are not able to participate in voltage regulation.

On the other hand, if slip is close to zero, then GSC is capable of providing reactive power at its full range, which is a feature of DFIG that can be exploited in order to create a flexible control scheme which can always provide the desired reactive power to the grid and utilized all its equipments (stator and power electronic converter topologies).

To begin with, the voltage at the Point of Common Coupling (PCC) is measured and compared with a reference value, which is the limit for steady-state operation defined by each TSO's grid code. This error is used as an input of a PI Controller, which provides as an output a current reference i_{ref}. The block diagram of the aforementioned scheme is shown in Figure 6:

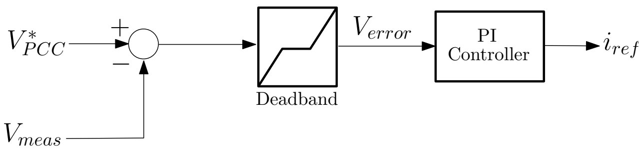

Fig. 6: Reference current calculation for Voltage Support.

The mathematical formulation of this control scheme is demonstrated in Equation (4):

$$i_{ref} = (V^*_{PCC} - V_{meas})(K_p + \frac{K_i}{s}) \quad (4)$$

After that, current state of operation needs to be determined. For this reason, turbine speed ω_{ref} is measured and compared with the synchronous speed ω_{sync} in order to calculate the slip. It is decided that GSC has to be able to provide (or absorb) a portion of reactive power to (or from) the grid. Thus, a deadband has to be utilized. This deadband defines the amount of reactive power that is held as a reserve from GSC. After passing slip through the deadband, this value is compared with zero in order to define which component is going to provide voltage support in case of a disturbance. So, current reference calculated from previous control scheme (Figure 6) depending on slip, is provided to the DFIG's converters.

The control strategy is depicted in Figure 7.

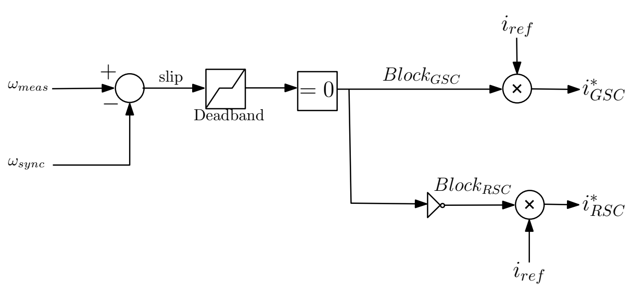

Fig. 7: Converter participation control logic.

The aforementioned control system is capable of providing voltage support to the grid in each case of operation (sub, synchronous and super-synchronous) by smartly utilizing the converters according to the slip; thus according to their loading and protect them from overcharging. It has to be noted that the system is enabled only when voltage is breaching the allowed operational limits defined by the grid code and maintain it between them. In order to bring the voltage back to its nominal value, TSOs have to proceed to further actions.

IV. Simulation and Results

In this section, frequency and voltage behaviour for different operational scenarios is going to be demonstrated, and the impact of the proposed topology and control system is explained. For all the following simulations, IEEE 14-Bus System was used as a benchmark, since it is suitable for frequency and voltage stability studies. Wind Turbines are connected at Bus 2, substituting synchronous generator on this bus (15% of total generation). Results were obtained by real-time simulations with the help of RTDS.

A. Grid Code Compliance

This section examines the behavior of the controller when WTs are operated under Frequency Sensitive Mode.

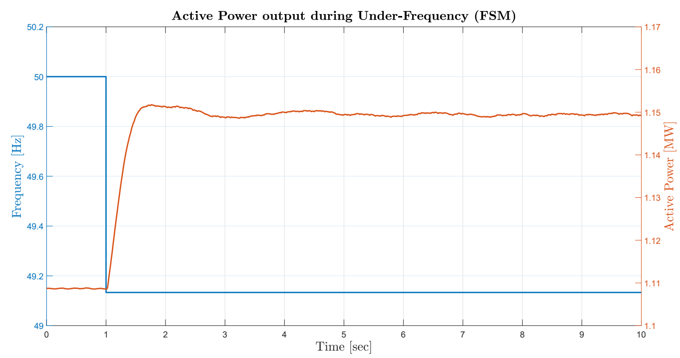

Fig. 8: Wind Turbine response during under-frequency event (FSM operation, 0.87 Hz disturbance).

It is clear that immediately after the disturbance, active power injection at the PCC is modified, according to the frequency deviation. This is happening since ESS is providing frequency support to the grid according to the controller. The proposed system is capable of complying with the Frequency Sensitive Mode, as stated in Germany's grid code. The same applies also for Limited Sensitive Frequency Modes.

B. Integrated Control for Frequency and Voltage support

In order to investigate the controller's response, a simultaneous active and reactive power step load increase is considered. Specifically, a 10MW + 50MVAr load increase occurs at Bus 2. Moreover, the Wind Penetration is considered as 15% (in terms of Active Power).

1) Voltage Support by DFIG's stator:: For this operational scenario, generator speed is considered as 1.2 p.u.; thus generator is operated at super-synchronous speed and rotor provides slip power (in this case 0.2 p.u.) to the grid via the "Back to Back" converter configuration. As a results, reactive power support is provided, when needed, by DFIG's stator with the help of the GSC. With such an operation, overloading power electronic converters is avoided, since stator can be transiently overloaded and provide extra reactive power reserve [10].

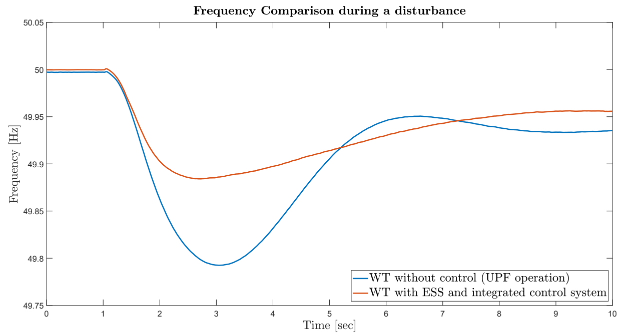

Fig. 9: Frequency Comparison (super-synchronous speed)

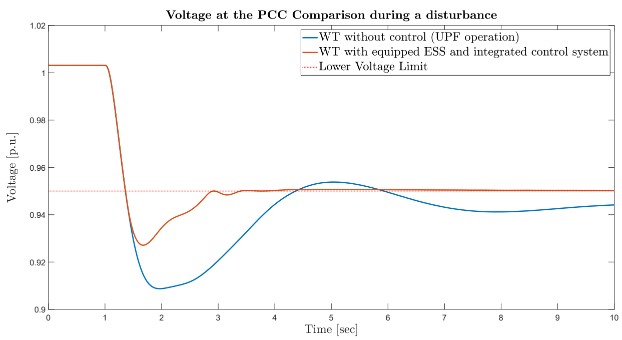

Fig. 10: Voltage Comparison (Support provided by DFIG's Stator.

2) *Voltage Support by GSC:* For this case generator speed is considered at 0.9p.u., so controller will provide reactive power, when needed, from the non fully-utilized GSC. Frequency and Voltage results for DFIG Unity Power Factor operation compared to those with the proposed controller implemented are shown in the following figures. Frequency nadir and RoCoF are significantly reduced. Furthermore, regarding primary frequency control capability, it is clear that the settling point of the frequency is within the allowed limits (50 ± 0.05 Hz). Moreover, voltage is supported as soon as it falls under the lower limit.

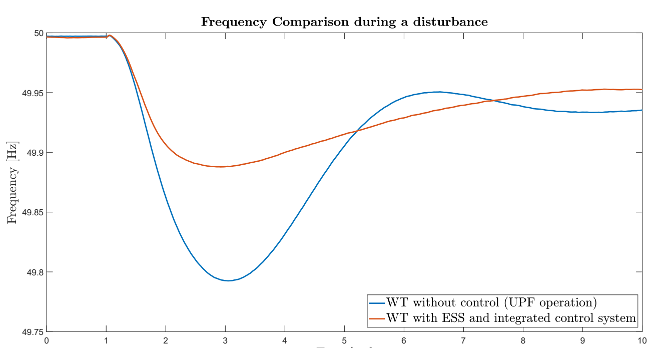

Fig. 11: Frequency Comparison with the proposed control (sub-synchronous speed).

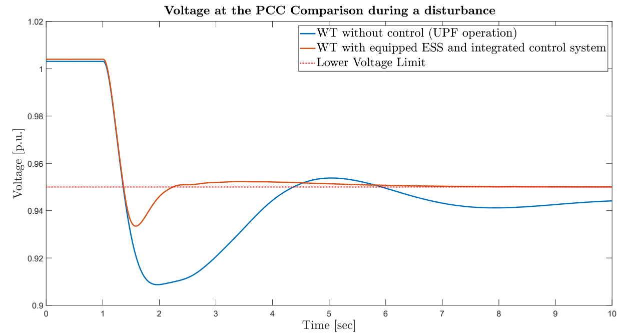

Fig. 12: Voltage Comparison (Support provided by GSC).

V. Conclusions

The proposed topology allows WT to constantly operate at its maximum power point, which is beneficial for both Wind Farm operators and TSOs. The controller is capable of mitigating disturbances by reducing both frequency fluctuation and RoCoF. Moreover, it is also helpful regarding the grid's voltage stability. It is shown that the traditional integration approach of RES, operated under Unity Power Factor, causes voltage fluctuations that breach the limits, dictated by the grid code. The proposed control strategy is capable of mitigating those voltage fluctuations and maintain the voltage between the voltage limits. It also has to be mentioned, that this support happens in a way, that secures DFIG's equipment.

Acknowledgments

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