Inter-Area Oscillation Damping with Type-5 Wind Power Plant

Preprint

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Inter-area Oscillation Damping with Type-5 Wind Power Plant

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***Abstract* – This paper investigates the potential of using brushless excitation (BLE) for not only riding through the fault but also to damp inter-area power oscillation with the help of a synchronous generator (SG) used in Type 5 Wind Power Plant (WPP). In BLE, an auxiliary synchronous generator (ASG) behaving like an exciter is coupled and driven by the rotor of the main SG. The BLE's field current's ASG is fed by two separate loops of the automatic voltage regulator (AVR) and power system stabilizer (PSS). The AVR system implements a control loop to regulate the generator terminal voltage, V_T. For the PSS, the kinetic energy of the wind turbine is utilized according to the estimated rotational speed of the synchronous generator shaft of the SG. It may mitigate the necessity of any curtailment of active power for damping. The effectiveness of the proposed control scheme is verified with a three-phase short circuit fault in a two-area power system.**

Keywords—Interarea oscillation, damping control, wind power plant, brushless, dynamic response, transient stability, PSCAD

I. INTRODUCTION

The energy sector has undergone a paradigm shift due to the widespread adoption of renewable energy generation (REG) in recent times. As per the latest available data, the global REG capacity witnessed a growth of 176 GW in 2019 [1], and by the end of 2020, the annual REG capacity had reached approximately 2800 GW[2]. Over the past few years, wind power, among the other renewable energy sources, has been the fastest-growing energy generation technology on both the land and sea. According to the Global Wind Energy Council (GWEC), more than 90 GW of new wind power was installed in 2020 [3]. The global new installed wind capacity expanded by 53% in 2020 (86.9 GW onshore and 6.1 GW offshore) compared to 2019 [3], bringing the total installed capacity to 743 GW.

However, inverter-based resources (IBRs) used in these WPP's differ significantly from the conventional synchronous generators. As the generation capacity of WPPs grows, transmission system operators (TSOs) are proposing auxiliary services to be provided by the WPPs in recent grid codes. These codes mandate that WPPs must comply with requirements such as voltage sag ride-through capabilities [4], frequency regulation [5], and active and reactive power regulation [6]. TSOs may require further contributions from WPPs in the future. Nevertheless, the high penetration of IBRs can lead to the following challenges in the Grid.

i) Reduction of inertia may raise stability and reliability issues.
ii) Degrading grid strength and short circuit current levels may cause stability and protection issues.
iii) Damping oscillations, providing resonance solutions, and riding through a fault without traditional synchronous generators can be challenging in IBR-dominated systems.

To address these challenges, implementing Type 5 wind turbines instead of commercial IBR-based wind turbines may be a viable solution.

Type 5 turbines consist of a typical wind turbine generator having a variable-speed drive train connected to a torque/speed converter coupled with a synchronous generator [7]. The torque/speed converter changes the variable speed of the rotor shaft to a constant output shaft speed. The synchronous generator can be designed appropriately for some specific desired speed (typically 6 or 4 poles) and voltage (typically medium voltage for higher capacities). This approach requires speed and torque control of the torque/speed converter along with the typical voltage regulator (AVR), synchronizing system, and generator protection system inherent with a grid-connected synchronous generator. Consequently, the utilization of Type 5 wind turbine generator (WTG) - a synchronous generator that operates without any power converters - can offer comparable features to traditional power plants, but adapted to the requirements of variable speed operation via a prime mover (wind rotor, in this case). Furthermore, Type-5 machine has an inherent ability to form the grid, also referred to as grid-forming control (GFM).

In recent years, research and practice investigations have been carried out on transient stability with high penetration of WPPs. Different fault ride-through (FRT) schemes are studied for IBR-based WPPs, such as adding a crowbar with dc link chopper [8], crowbar with battery [9], bridge type fault current limiter (FCL) [10] dynamic voltage restorer with FCL function [11]. As in frequency control, the first step in an additional POD controller for WPP is to copy the power system stabilizer (PSS) from the synchronous generators [12]. Proper tuning to adjust PSS parameters provided promising results [13]. The voltage of the point of interconnection (POI) of the WPP is chosen as input and a variation of power reference as output.

The conventional PSS scheme has been evaluated by inputs such as local and remote signals and voltage variation as output [14]. However, the limitations of IBRs with high voltage and current make the Type 5 WTG a better option to ride through the fault with regularly used excitation control available in the market. Auxiliary services like fault ride through (FRT) or supporting the grid to damp out the power oscillation (POD) can easily be incorporated on the Type 5 WTGs. The excitation system has to take responsibility for providing these services. The basic requirement for excitation systems is to provide and adjust the excitation current of generators to maintain the terminal voltage in the right levels. Over the years, different excitation systems have been applied for different stability purposes [15]. Commutators, slip rings, and brushes are mainly used in solid-state exciters. However, in recent times, the utilization of this solution has seen a significant decrease, mainly because brushes can produce significant resistive voltage drops and need periodical maintenance and replacement [16]. A more robust and modern solution to this problem is using BLE to provide field current without any voltage drop in brushes [17]. A BLE system is, essentially, an inside-out Auxiliary synchronous generator (ASG) that delivers its ac voltage to the rotor of the main synchronous generator (SG), and receives its excitation from the stator of that same generator. The ac voltage of the ASG is transformed to dc by a non-controlled rectifier, producing the main generator's excitation current.

This paper proposes a BLE scheme for Type 5 WPP to ensure the power system's resiliency during grid faults. For this, a generic model of Type 5 wind turbine has been developed that evaluates the systems impact on the grid side. The proposed excitation scheme is implemented into a simplified turbine model focusing on the power system dynamic studies, and the performance of the proposed field excitation scheme is accessed with a benchmark power system prone to power system oscillations. The study is conducted under the assumption of constant wind. The results show that the proposed control scheme improves the reliability and stability of the system.

II. Proposed Control Scheme for WPP

A. WPP System Model

The configuration of an aggregated WPP model used in this paper is depicted in Fig. 1. The WPP model consists of a wind turbine, drive train, hydrostatictorque converter, synchronous generator, and brushless exciter.

The power extracted by the turbine blade can be calculated using:

$$P_w = \frac{1}{2}.\rho.\pi.R^2.V_w{}^3.c_p(\lambda,\beta) \quad (1)$$

where P_w represents the extracted mechanical power from wind in Watts, R is the radius of turbine blade, β is the blade pitch angle in degrees, λ is the tip speed ratio determined by:

$$\lambda = \frac{\omega_t.R}{V_w} \quad (2)$$

where ω_t is the mechanical rotational speed of the turbine in rad/s. c_p and λ were interpolated using non-linear equations.

The maximum output power of the wind turbine is obtained by tracking the rotor speed to the optimum point λ_{opt} that yields the maximum aerodynamic efficiency. Therefore, the optimum wind turbine speed is given as:

$$\omega_{t,opt} = \frac{\lambda_{opt}.V_w}{R} \quad (3)$$

The machine's rotational speed ω_m, can be found from the gear ratio (GR) in the drive train,

$$\omega_{m,opt} = \omega_{t,opt}\,.GR \quad (4)$$

Therefore, the maximum power is obtained as:

$$P_{MPPT} = \frac{1}{2}.\rho.\pi.R^2.\left(\frac{\omega_{m,opt}.R}{\lambda_{opt}}\right)^3.c_{p,max} \quad (5)$$

Equation (5) can be rewritten as:

$$P_{MPPT} = K_g\omega_m^3 \quad (6)$$

where K_g is the coefficient of the MPPT curve.

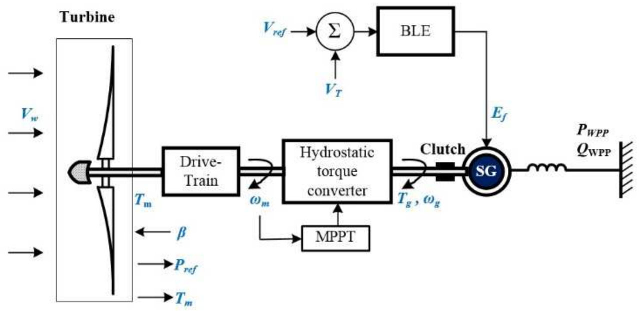

Fig. 1. WPP system model configuration.

The turbine end of the torque converter is connected to the impeller side, and the generator side is connected to the turbine. The torque is converted by the static reactor placed in the middle of the impeller and the turbine. The torque limiting features can be applied to this. The lock-up clutch is connected to the turbine and shaft of the synchronous generator.

The torque provided to the synchronous generator by the torque converter can be expressed as:

$$T_g = H(s).\left(\frac{P_{MPPT}(\omega_m{}^3,\ \beta)}{\omega_g}\right)^3 \quad (7)$$

where ω_g is the mechanical rotational speed of the SG in rad/s.

The simplified dynamics of the torque converter, *H(s)*, is represented by a second order transfer function.

B. The Brushless Excitor (BLE)

The excitation system for this paper is a combination of ASG and diode bridge rectifier coupled and driven by the same shaft as the main SG. The DC field current of the field winding of the ASG is supplied by the boost converter connected with two control loops. Here the boost converter is replaced by a dependent source to make the circuit simpler. The excitation of the ASG has two separate loops, one for maintaining the terminal voltage and another to replicate the PSS that has been added to the dependent voltage source.

The difference in the SG's terminal voltage, V_T, and the reference voltage, V_{Ref} controls the AVR loop. The difference is sent through a PI controller to get the ΔV.

The rotational speed of the main SG, ω_g, is fed to the washout filter to remove the steady-state component. The lead-lag compensator has compensated for the delay. The real power reference for the PSS, ΔP, is obtained by:

$$\Delta P = \omega_g \cdot \frac{sT_W}{1+sT_W} \cdot \frac{1+sT_1}{1+sT_2} \quad (8)$$

where T_w is the time constant of the washout filter. T_1 and T_2 are the lead and the lag time constant, respectively. In this case, we can say the design logic of PSS is same for conventional SG and Type 5 wind turbine.

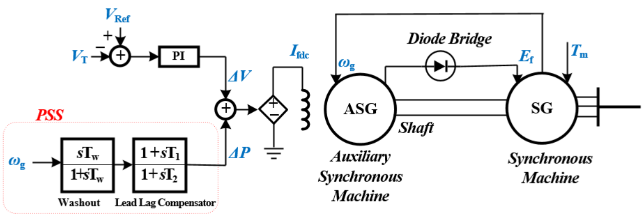

Fig. 2. Block diagram of the BLE

The ac voltage of the ASG is transformed to dc (E_f) by a non-controlled rectifier, this way producing the excitation current of the main generator. The output torque, T_m, from the torque converter is also fed to the main SG.

III. Case Studies

This study investigates the effectiveness of using a utility-scale WPP consisting of Type 5 WTGs to mitigate interarea oscillations in a two-area system with two 2-GW hydro generators. The system was simulated in PSCAD software, with a 170 MW Type 5 WPP with BLE connected between areas 1 and 2, as shown in Fig. 3. PSSs were not installed at the hydro generators. A three-phase to ground fault was introduced at area 1 for 0.15s. The objective of the study was to reduce power oscillations after fault clearance using WPP controllers and to evaluate the effectiveness of BLE in suppressing oscillations caused by the fault.

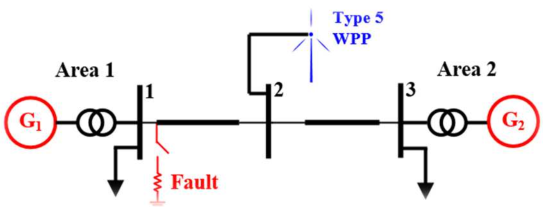

Fig. 3. Two-area system with the WPP plant in the middle of area 1 and 2.

Fig. 4 (a) depicts the active power output of areas 1 and 2, respectively. The frequency of oscillation is calculated as .3Hz for the interarea oscillation. From Fig. 4, it is observed that the oscillation is getting thoroughly damped within the 50s of the fault. Thus, we can conclude that both the controllers of BLE work efficiently to damp the inter-area oscillation.

Fig. 4 (b) illustrates the generators' reactive power output plots in areas 1 and 2. A fluctuation in reactive power output is noticed for both generators due to the fault. Both the reactive power output is again coming back to its initial position once the oscillation is over.

Fig. 4 (c) displays each area's frequency at the generator terminals. Unlike the power oscillations, the frequency oscillation is also getting damped efficiently for the proposed BLE scheme.

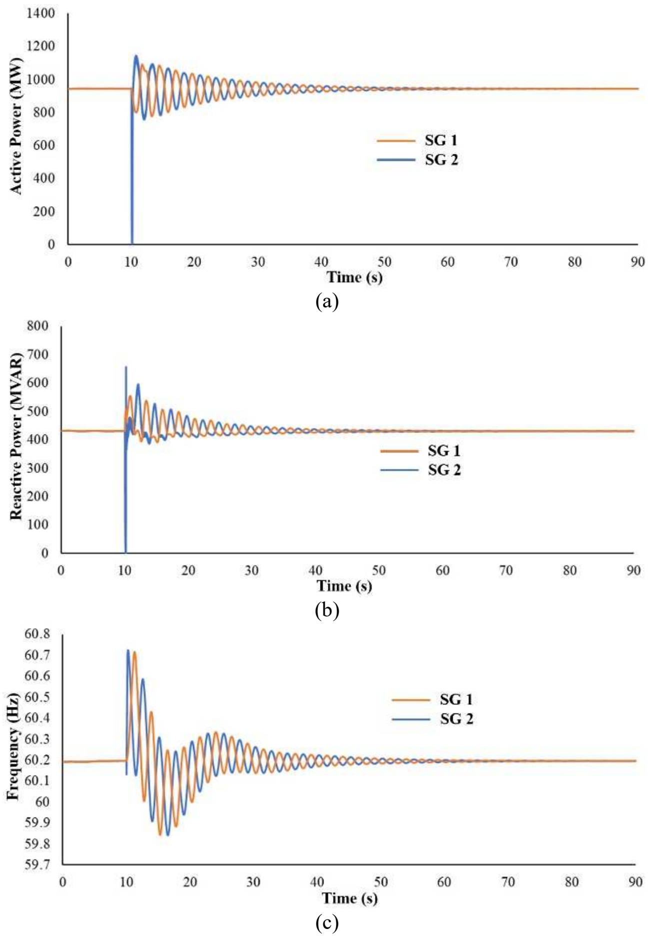

Fig. 4. Hydro generators output for area 1 and area 2 during fault and post fault condition. (a) active power output. (b) reactive power output. (c) frequency output.

The active power output in Fig. 5 (a), has provided the damping to the system without curtailing its power. The inertia of the wind turbine has been utilized to damp the oscillation. Hence, we can conclude the PSS scheme used in the BLE has provided efficient damping in this case.

The reactive power output in Fig. 5 (b), has also provided voltage stability to the system during fault and post-fault conditions. The reactive output of the proposed AVR in BLE excitation has successfully ridden through the fault without any disconnection.

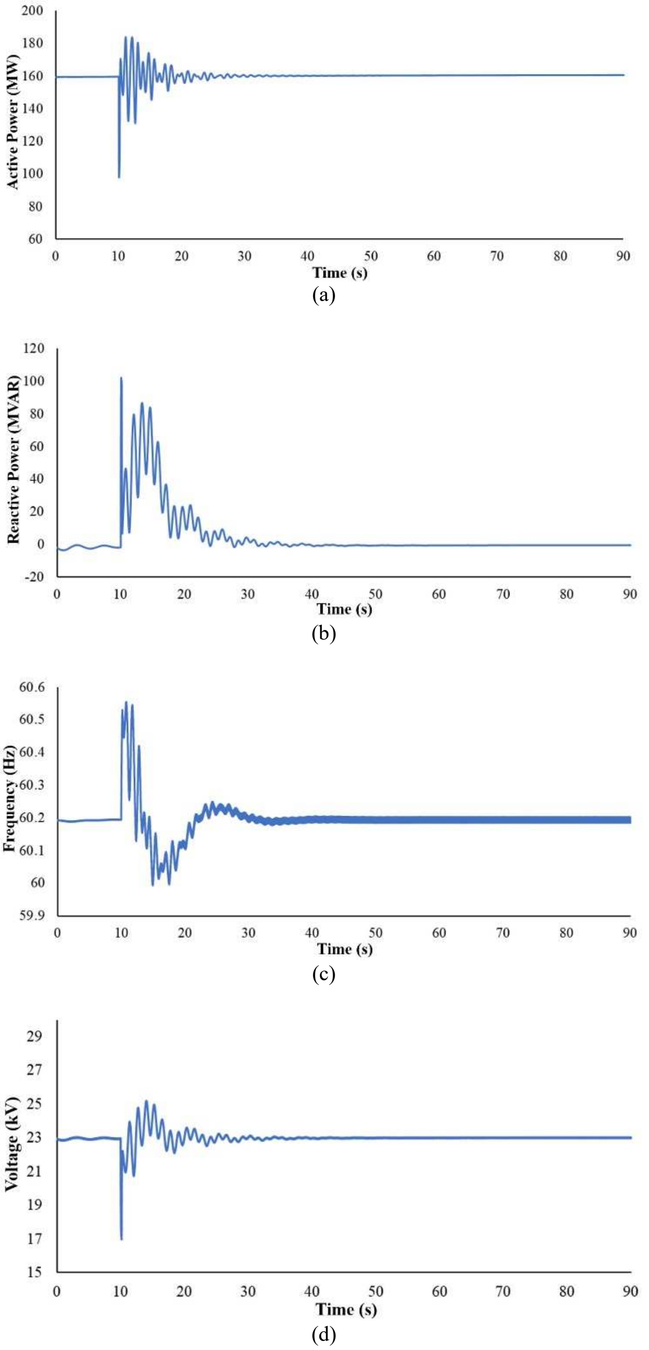

Fig. 5. Area 1 and area 2 SG output at the POC during fault and post-fault condition. (a) active power output. (b) reactive power output. (c) frequency, and (d) voltage.

The frequency at the POI is shown in Fig. 5 (c). It is also coming back to its initial position after the oscillation is over.

The voltage shown in Fig. 5 (d), also remained near to the nominal value 23 kV during and after the fault. It also stabilizes once the fault is over.

Thus, we can conclude that the proposed BLE exciter with AVR and PSS controller in a Type-5 WPP, having almost 10% of the hydro generator's capacity is efficiently damping inter area oscillations between two areas in this simple two-area system mode. In larger interconnected power system this ratio may be different.

IV. Conclusion

This paper analyzes the prospect of utilizing a utility-scale WPP of Type 5 wind turbines in inter-area low-frequency oscillation. Brief importance of using Type-5 WPP has been described at the beginning of this paper. A reliable and low-maintenance BLE scheme with two separate control schemes of AVR and PSS has also been investigated for riding through and damping out inter-area oscillation in this paper. The results show that the proposed control scheme improves the flexibility and stability of the system. A WPP with a capacity of nearly 10% of the hydro generators connected in both areas has successfully ridden through the fault and dampened the inter-area oscillation initiated by the fault in the system.

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References

[1] International Renewable Energy Agency, IRENA, "Renewable Capacity Statistics 2020," Abu Dhabi, Apr. 2020.

[2] International Renewable Energy Agency, IRENA, "Renewable Capacity Highlights 2021," Abu Dhabi, Mar. 2021.

[3] Global Wind Energy Council, GWEC "Global Wind Report 2021," Brussels, Nov. 2021.

[4] O. Gomis-Bellmunt, A. Junyent-FerrÉ, A. Sumper and J. Bergas-JanÉ, "Ride-Through Control of a Doubly Fed Induction Generator Under Unbalanced Voltage Sags," IEEE Trans. Ener. Conv., vol. 23, no. 4, pp. 1036–1045, Dec. 2008.

[5] A. Sumper, O. Gomis-Bellmunt, A. Sudria-Andreu, R. Villafafila-Robles and J. Rull-Duran, "Response of Fixed Speed Wind Turbines to System Frequency Disturbances," IEEE Trans. Power Syst., vol. 24, no. 1, pp. 181–192, Feb. 2009.

[6] O. Anaya-Lara, N. Jenkins, J. Ekanayake, P. Cartwright, M. Hughes, "Wind Energy Generation: Modeling and Control," John Wiley & Sons Ltd, 2009.

[7] V. Gevorgian, S. Shah, W. Yan and G. Henderson, "Grid-Forming Wind: Getting ready for prime time, with or without inverters," IEEE Elec. Mag., vol. 10, no. 1, pp. 52–64, Mar. 2022.

[8] K. E. Okedu, S. M. Muyeen, T. Rion, and T. Junji, "Wind farms fault ride through using DFIG with new protection scheme," IEEE Trans. Sustain. Energy, vol.3, no. 2, 242-254, Mar. 2012.

[9] C. Jin, and W. Peng, "Enhancement of low voltage ride-through capability for wind turbine driven DFIG with active crowbar and battery energy storage system," IEEE PES Gen. Meeting, Minneapolis, 2010, pp. 1-8.

[10] A. R. Fereidouni, V. Behrooz, and T. Hosseini, "The impact of solid state fault current limiter on power network with wind-turbine power generation," IEEE Trans. on Smart Grid, vol. 4, no. 2, pp. 1188-1196, June 2013.

[11] F. Jiang, C. Tu, Z. Shuai, M. Cheng, Z. Lan and F. Xiao, "Multilevel Cascaded-Type Dynamic Voltage Restorer With Fault Current-Limiting Function," IEEE Trans. Power Delivery, vol. 31, no. 3, pp. 1261-1269, June 2016.

[12] E. V. Larsen, and D. A. Swann, "Applying power system stabilizers part I: general concepts, " IEEE Trans. Power App. Syst., vol. 6, pp. 3017–3024, June 1981.
[13] J. L. Domínguez-García, O. Gomis-Bellmunt, F. Bianchi, and A. Sumper, "Power system stabilizer control for wind power to enhance power system stability," PHYSCON, 2011.
[14] M. Basu, V. R. Mahindara, J. Kim, and E. Muljadi, "Effect of high penetrated reactive power support based Inverter-Based-Resources on the power stability of microgrid distribution system during faults," Proc. IEEE Ind. Appl. Soc. Ann. Meeting, 2020, pp. 1–4.
[15] S. Nuzzo, M. Galea, C. Gerada and N. Brown, "Analysis, Modeling, and Design Considerations for the Excitation Systems of Synchronous Generators," IEEE Transactions on Industrial Electronics, vol. 65, no. 4, pp. 2996-3007, April 2018.
[16] T. L. Dillman, F. W. Keay, C. Raczkowsi, J. W. Skooglund, and W. H. South, "Brushless excitation," IEEE Spectr., vol. 9, no. 3, pp. 58–66, Mar. 1972.
[17] Z. Shushu, L. Chuang, N. Yinhang and T. Jie, "A Two-Stage Brushless Excitation Method for Hybrid Excitation Synchronous Generator," in IEEE Trans. on Magnetics, vol. 51, no. 6, pp. 1-11, June 2015.