# Synchronous Wind: Evaluating the Grid Impact of Inverterless Grid-Forming Wind Power Plants

## Preprint


Weihang Yan, Vahan Gevorgian, and Shahil Shah

*National Renewable Energy Laboratory*



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National Renewable Energy Laboratory
15013 Denver West Parkway
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# Synchronous Wind: Evaluating the Grid Impact of Inverterless Grid-Forming Wind Power Plants

Weihang Yan, Vahan Gevorgian, Shahil Shah
National Renewable Energy Laboratory (NREL)
Golden, CO. 80401, USA
{Weihang.Yan; Vahan.Gevorgian; Shahil.Shah}@nrel.gov

***Abstract*—Grid-forming (GFM) control of Type-3 and Type-4 wind turbine generators has attracted substantial attention in power systems research; however, the limited over-current capability of power electronics converters continues to deteriorate the grid strength of the evolving power systems. This paper develops the generic model of synchronous wind power generators, also known as Type-5 wind turbines, for power system integration studies. The Type-5 wind turbine interfaces with the electric grid through a synchronous generator; hence, its operation and consequent grid impacts are similar to a conventional power plant. Based on the developed model, a Type-5 wind power plant is integrated into the IEEE 14-bus test bed to evaluate its control and operation with a bulk power system. Finally, the stability properties of Type-5 wind turbine generators are compared with Type-3 wind turbines in GFM control mode through impedance characterization.**

***Index Terms*—Synchronous wind turbine generator, grid-forming control, grid strength, Type-5, stability.**

## I. Introduction

Wind power generation is one of the fastest-growing renewable energy technologies. Modern variable-speed wind turbines, known as Type-3 and Type-4 wind turbine generators, use partially or fully rated power electronics converters to achieve variable-speed operation and to meet the needs of both the turbine operation and the power system integration [1]. With increasing levels of renewable energy integration and with the replacement of synchronous generators (SGs), wind turbine generators are required to become energy sources that can provide reliability services to the electric grid, whereas traditionally this has been the responsibility of SGs. In this process, the grid-forming (GFM) control of Type-3 and Type-4 wind turbine generators has captivated the attention of power system engineers [2], [3].

Substantial evidence and results have demonstrated that GFM inverters are critical assets for maintaining power system stability as well as providing reliability services. For instance, a recent study in [4] confirmed the positive role of GFM inverters on enhancing power system voltage stability under weak grid condition. In [3] and [5], the authors also showed that GFM control can reduce the risk of subsynchronous resonance (SSR), which is prone to happen between Type-3 wind power plants and series-compensated lines. A landmark demonstration at the National Renewable Energy Laboratory (NREL) first showed that Type-3 wind turbines with GFM control can supply fundamental stability enhancement to bulk power systems, including primary frequency regulation, voltage support, and restabilization of the surrounding grid [6].

Despite the recent advancements in GFM control of Type-3 and Type-4 wind turbine generators, the limited over-current capability of power electronics converters fundamentally shifted the operation of power systems with continuously deteriorated grid strength. This issue can be mitigated by either oversizing the capacity of GFM inverters or with large-scale deployments of synchronous condensers (SCs), but both solutions are costly [1]. One solution for GFM wind turbine generators while maintaining grid strength has been around since the 1990s. It is known as synchronous wind power, or Type-5, a variable-speed wind turbine interfacing with the grid through a fixed-speed SG using either a hydrodynamic coupling between the SG's shaft and the gearbox (e.g., a German DeWind D8.2 2-MW wind turbine) or a hydrostatic torque reaction embedded in the turbine gearbox with torque limiting (e.g. the SyncWind powertrain concept used in Windflow wind turbines in New Zealand) [7]. Type-5 wind turbines use conventional, mass-produced, brushless SGs, reducing the manufacturing cost and the dependance on rare-earth materials. In fact, Type-5 wind power technology has been reliably providing approximately 10% of New Zealand's wind power at a 48-MW wind power plant since 2006. An additional 4-MW of these turbines have been installed in Scotland since 2013 [7], [8].

Type-5 wind turbine generators operate without power electronics converters; hence, their operation and consequent grid impacts are similar to conventional power plants [1]. The known impact of SGs on power system small-signal stability, transient stability, voltage stability, etc. also applies to Type-5 wind turbines [9]. Existing SG-based grid stabilization techniques, for instance, using power system stabilizers (PSS), are also applicable for Type-5 wind power plants. Additionally, each SG of a Type-5 wind turbine generator can be used as an SC during low or no wind condition, contributing short-

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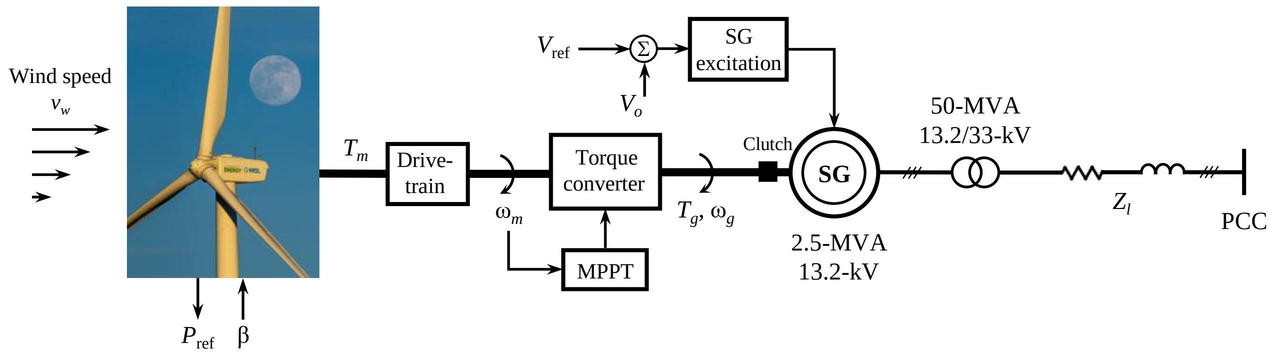


Fig. 1: Structural diagram of Type-5 wind turbine generator. *Photo by NREL*

circuit current capacity up to 5–7 times of the rated capacity [7], [8]. Nevertheless, there are still major differences that require comprehensive analysis between an SG-based Type-5 wind power plant and a conventional, large-scale power plant. First, the rotor of an SG is decoupled from the turbine's rotor shaft in Type-5 machines. This results in a significantly reduction of physical inertia and increases the risk of pole slipping in SGs during grid faults. Second, Type-5 wind turbine generators are designed to operate in maximum power point tracking mode; hence, auxiliary controls (managing the plant power curtailment) are needed to enable frequency and voltage regulations. On the other hand, the plant topology of a synchronous wind power plant, which is the combination of a number of small-scale SGs in multiple collection strings, is also different from a centralized power plant.

In this paper, we developed the generic model of Type-5 wind turbine generators to focus on the evaluation of the system impact at the grid side. A simplified torque converter is used to represent its second-order input-output characteristics. Additionally, the Type-5 turbine-based wind power plant is developed and integrated into the IEEE 14-bus test bed. It is clear to the industry that the GFM control of inverter-based wind turbines alone is not a sufficient measure to resolve many grid integration problems, such as the degradation of the system short-circuit ratio (SCR). This paper intends to recall the potential solutions and further provide insights on how Type-5 wind power plants can be used to enable high renewable energy penetration in the power grids.

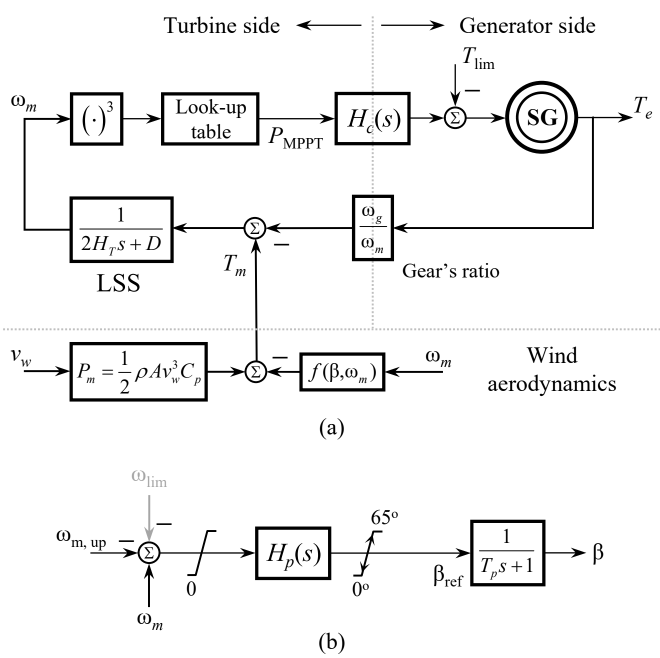


Fig. 2: Diagram of Type-5 wind turbine generator: (a) turbine system diagram, (b) turbine pitch controller.

## II. Modeling of Type-5 Wind Turbine Generators

Fig. 1 presents the structural diagram of the Type-5 wind turbine generator developed in this paper. The turbine mechanical side has no difference compared to Type-3 and Type-4 wind turbines. Instead of using back-to-back converters, Type-5 wind turbine generators use a (hydrodynamic or hydrostatic) torque converter to maintain the constant synchronous speed of the SG's high-speed shaft (HSS), whereas the turbine's rotor speed varies with respect to wind speed. Here, $T_m$ and $T_g$ are mechanical torques that drive the low-speed shaft (LSS) and the HSS, respectively. $\omega_m$ (operation range from 0.4-p.u. to 1.2-p.u.) is the turbine rotor speed of the LSS, and $\omega_g$ (near constant at 1-p.u.) is the synchronous speed of the SG's HSS. Ignoring power losses in the turbine's normal condition, the torque converter follows the power balance as:

$$T_m \omega_m = T_g \omega_g \tag{1}$$

The clutch of the HSS can be opened or closed to switch the SG between the generator mode and the SC mode. As in a conventional SG, the machine's excitation controls the terminal voltage of a Type-5 wind turbine generator and regulates its reactive power flow. $Z_l$ represents the impedance of the wind power plant collection feeder.

Fig. 2 gives the system diagram of the Type-5 wind turbine generator, where $H_T$ and $D$ denote the inertia constant and the mechanical damping of the turbine rotor, respectively. In this paper, an underdamped second-order transfer function with a steady-state gain of 1, $H_c(s)$, is used to represent the simplified torque converter model to highlight its oscillatory dynamics and response time [10]. Note that the developed

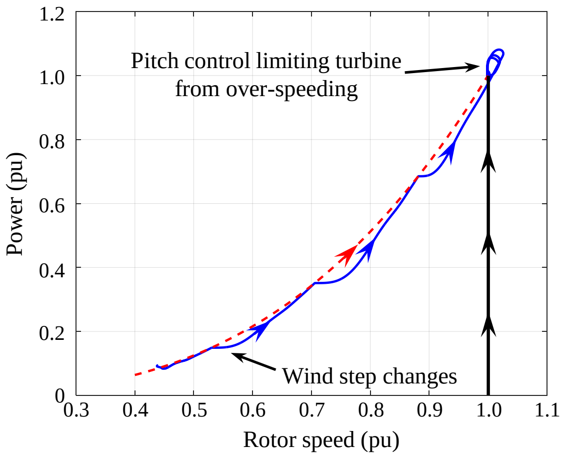


Fig. 3: Operation trajectory of the Type-5 wind turbine generator with step increases of wind speed. Red: theoretical MPPT trajectory. Blue: turbine rotor-power trajectory. Black: generator rotor-power trajectory.

model of a Type-5 wind turbine generator focuses on its impact on power system dynamic stability. A simplified transfer function is sufficient to capture the input-output characteristics of the torque converter with manufacture specifications [11].

To prevent the potential pole slipping in a Type-5 wind turbine generator due to severe grid faults, the auxiliary torque-limiting control, $T_{\text{lim}}$, is applied on the output of torque converter, $H_c(s)$, to limit the generator torque on the HSS. Alternatively, the torque-limiting control can be interpreted as DC choppers that are widely available in Type-3 and Type-4 turbines. As a result, the excessive power that cannot be converted due to grid faults can be dissipated as heat to prevent a SG from over-speeding. $T_e$ denotes the electrical torque of the SG. Fig. 2 (b) presents the diagram of the turbine's pitch controller, which prevents the LSS from over-speeding, where $H_p(s)$ is the pitch control compensator, and $T_p$ gives the time constant of the servo actuator. The auxiliary control reference, $\omega_{\text{lim}}$, is for the torque-limiting control, and it is optional for the pitch controller, depending on the turbine's manufactures.

Fig. 3 demonstrates the operation trajectory of a Type-5 wind turbine generator with step increases of wind speed. It further explains the variable-speed operation at the turbine side, and the constant synchronous speed operation at the generator side for a Type-5 wind turbine generator. The circular operation trajectory at the turbine's full power is because of the pitch control delay.

## III. Control and Operation Validation of Type-5 Wind Turbine Generators

### A. Single Turbine Operation

To evaluate the control and operation of Type-5 wind turbine generators, a 2.5-MVA/13.2-kV turbine model is developed in PSCAD. The turbine aerodynamics are modeled based on GE's report on wind turbine modeling for power system studies in [12]. The pitch control loop of the developed Type-5 turbine model serves the same functionality as Type-3 and Type-4 wind turbines, and it is calibrated against the field measurements of the GE 1.5-MW wind turbine generator at the Flatirons Campus of NREL [13]. Table 1 and 2 tabulate the detailed system and control parameters of the developed Type-5 turbine model.

TABLE I: Circuit Parameters in PSCAD Simulation

| Parameter | Value |
|---|---|
| SG rated power | 2.5 MVA |
| SG rated L-L voltage | 13.2 kV |
| Rated voltage of collection feeder (L-L) | 33 kV |
| Turbine cut-in wind speed | 3 m/s |
| Turbine cut-out wind speed | 25 m/s |
| Turbine inertia constant | 3 s |
| Generator inertia constant | 1 s |
| Turbine and generator damping | 0 pu |
| Time constant of pitch servo | 0.3 s |
| Generator synchronous speed | $120\pi$ rad/s |
| SCR at PCC | 4 |

TABLE II: Converter Control Parameters

| Controller | Parameter |
|---|---|
| Pitch controller | $H_p(s) = 31.29 + 41.32/s$ |
| Torque converter | $H_c(s) = 1/(0.05s^2 + 0.2s + 1)$ |
| Excitor gain | $K_a = 100$ pu |
| Excitor time constant | $T_a = 0.02$ s |

Fig. 4 shows the system responses of the Type-5 wind turbine generator when the wind speed is step increased from 6 to 16-m/s with a step size of 2-m/s. As one of the GFM wind technologies, Type-5 wind turbine generators behave as voltage sources in power systems; hence, the active and reactive power are coupled. The rotor speed of the LSS varies with respect to wind speed. Meanwhile, the speed of the SG's HSS also slightly varies but remains close to 1-p.u. The pitch control of the Type-5 wind turbines, as in Type-3 and Type-4, ensures that the turbine speed does not exceed 1.0-p.u.

### B. Operation of Type-5 Wind Power Plant

In this section, a 3-string Type-5 wind power plant model is developed. Each turbine string has 5 wind generators in series (with each separated by 300-m). The collection cables are assumed to be 1-km, 5-km, and 9-km from the substation. Fig. 5 shows the power and frequency responses of the Type-5 wind power plant after a 100-ms zero voltage fault was applied at string 1 (1-km from the substation). Note that the torque-limiting control is disabled in this case. As a result, the short-term imbalance between the mechanical and electrical torques of the SG leads to power and frequency swings. In fact, Type-5 wind turbine generators are more vulnerable to pole slipping without torque-limiting control, which further leads to a loss of synchronism (LoS) due to the reduced generator inertia. Fig. 5 also shows the intra-plant oscillation mode among multiple wind turbine generators, where phase shifts are observed in turbines' frequency oscillations (between string 1 and string 3). In this case, the oscillation mode is well damped. Enabling the PSS is also an option to prevent inter-turbine oscillations and to maintain the stability of a Type-5 wind power plant.

Fig. 6 gives the frequency response of the Type-5 wind power plant when the torque-limiting control is considered.

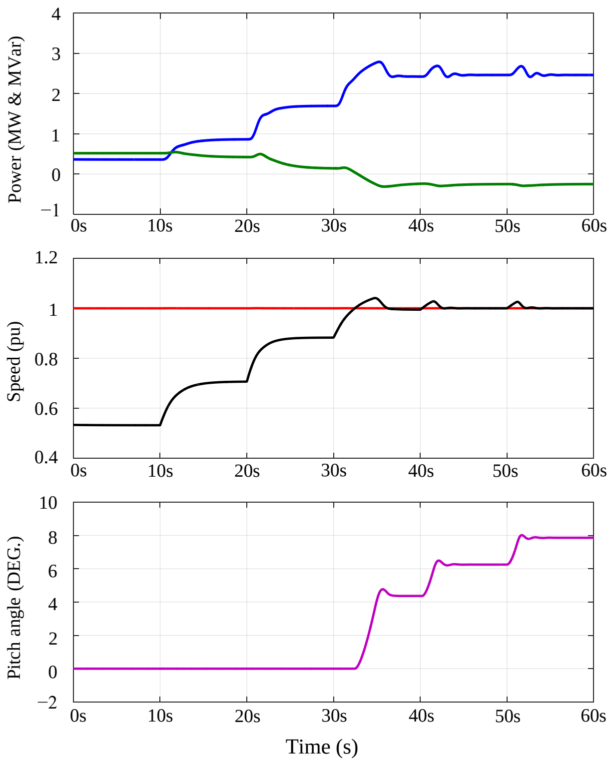


Fig. 4: System responses of the Type-5 wind turbine generator with step increases of wind speed. Blue: active power. Green: reactive power. Red: generator rotor speed. Black: turbine rotor speed. Purple: pitch angel.

In this case, the torque limiter is set to enable when the frequency of the SG exceeds the predefined threshold; hence, the torque limiter can dissipate the mechanical power that cannot be converted through the SG due to voltage faults, which further prevents the SG from over-speeding or LoS. Here, we consider a worst-case scenario for the Type-5 wind power plant, where a zero-voltage fault is applied. In fact, the rating of the torque limiter can be adjusted according to the low-voltage ride-through requirements of wind power plants.

### C. Type-5 Power Plant Reliability Services

This section integrates the Type-5 wind power plant into the IEEE 14-bus test bed. The capacity of the wind power plant is increased to 150-MW, such that the instantaneous wind penetration level of the studied system reaches 42%. Fig. 7 presents the frequency trajectories and the power responses of the Type-5 wind power plant with and without adding the frequency controller. Compared to Type-3 (or Type-4) wind turbines, Type-5 machines inherently can provide inertial response to power systems, reducing the rate-of-change-of-frequency and the frequency nadir; however, the inertial response from Type-5 wind power plants is limited because of the reduced generator inertia (decoupling the turbine rotor shaft from the generator shaft). Similar to Type-3 (or Type-4) wind turbines, additional frequency controllers are needed to fully use the kinetic energy in the turbine rotor and the power curtailment for power system frequency regulation.

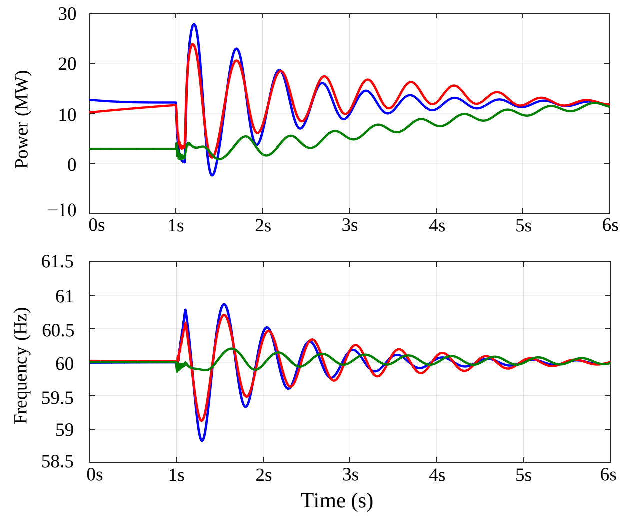


Fig. 5: Power and frequency oscillation of the Type-5 wind power plant without torque-limiting control. Blue: turbine string 1. Red: turbine string 2. Green: turbine string 3.

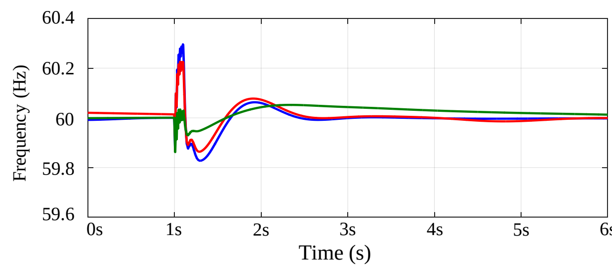


Fig. 6: Frequency of the Type-5 wind power plant with torque-limiting control. Blue: turbine string 1. Red: turbine string 2. Green: turbine string 3.

On the other hand, the SG-based Type-5 wind power plant can provide a significantly higher value of the short-circuit current, which improves the SCR at the point of common coupling (PCC) of the wind power plant. In the IEEE 14-bus case study, the SCR at the PCC of the wind power plant increases from 7.8 to 11.3, when the 150-MW Type-4 wind power plant is switched to Type-5.

## IV. Stability Impact of Type-5 Wind Power Plants

Impedance-based methods have proven effective for the stability analysis of modern power systems. Previous research of impedance modeling in [3] and [5] has pinpointed the reason why the risk of SSR between wind power plants with Type-3 wind turbines and series-compensated transmission lines is low when the wind turbines are operated in GFM mode, instead of the standard grid-following (GFL) mode. This paper, as shown in Fig. 8, further compares the impedance responses of the Type-5 wind turbine generator with Type-3 wind turbines. Note that the impedance amplitude of the Type-5 wind turbine generator is transformed into a 0.69-kV voltage level for fair comparison.

The phase response of the positive-sequence impedance for the Type-3 GFL wind turbine, as indicated in blue, crosses +90° at subsynchronous frequencies. This confirms the negative resistance behavior (negative damping) at subsynchronous

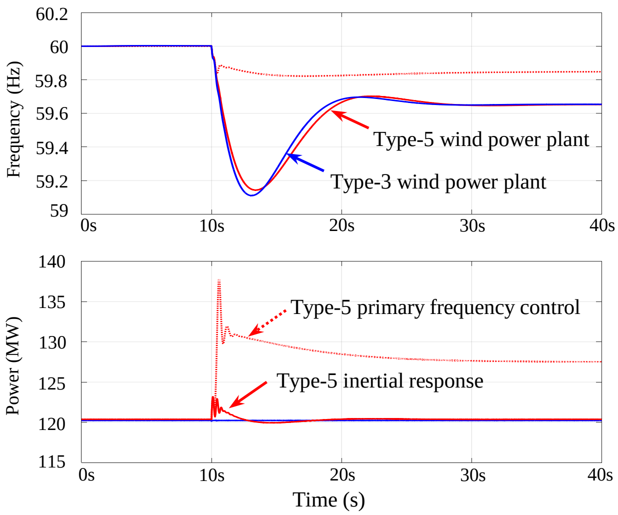


Fig. 7: Power system frequency and power responses of wind power plants. Blue: Type-3. Solid red: Type-5 without frequency controller. Dashed red: Type-5 with frequency controller.

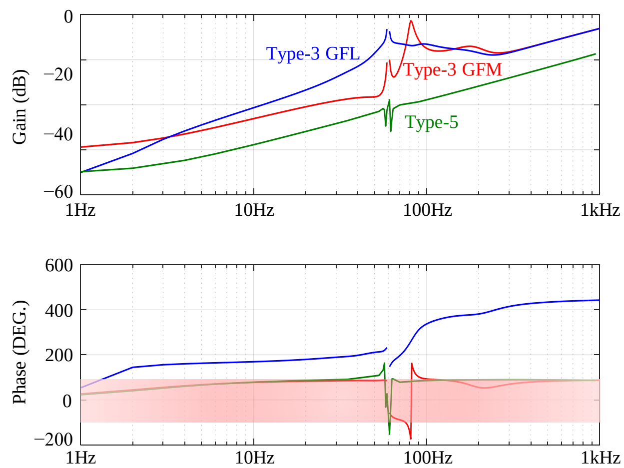


Fig. 8: Impedance characterization of Type-3 and Type-5 wind turbine generator. Blue: Type-3 GFL wind turbine. Red: Type-3 GFM wind turbine. Green: Type-5 wind turbine.

frequencies, which potentially leads to SSR instability when a GFL wind power plant is within the proximity of a series-compensated transmission line. The impedance characteristics of Type-3 GFM wind turbines do not exhibit negative resistance at subsynchronous frequencies, in which the phase response of the GFM wind turbine (red) varies from 26° to 87° and reduces the risk of SSR problems.

Contrary to the impedance characterization of Type-3 wind turbines, which involves complex controls, the impedance response of a Type-5 wind turbine generator is dominated by the SG's winding inductance. Turbine torque control and excitation only modify the impedance response of a Type-5 turbine around the fundamental frequency; hence, the stability properties of Type-5 wind turbine generators are easy to interpret. Similar to Type-3 and Type-4 wind turbines in GFM mode, a Type-5 wind turbine generator has less risk of high-frequency resonance; however, Type-5 wind turbine generators can still suffer from SSR instability as the phase response of the Type-5 turbine crosses +90° near 30-Hz.

## V. Conclusion

This paper developed the generic model of synchronous wind turbine generators for power system integration studies. Compared to GFM inverters, Type-5 wind power plants can improve the grid strength of the PCC by contributing a higher capacity of the short-circuit current. Finally, the stability properties of Type-5 wind turbines are compared with GFM wind turbines.

Given the simplified torque converter model used, the developed generic Type-5 turbine model has limited capability to analyze the mechanical interactions between the turbine mechanical side and the generator side. Future research will integrate a detailed torque converter model to comprehensively analyze the dynamic behavior of Type-5 wind turbines.

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