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An Overview of Grid-Forming Control for Wind Turbine Converters

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***Abstract*—As the penetration level of renewable energy increases, the integration of large-scale wind power plants (WPPs) into the the utility grid may pose a series of challenges in terms of voltage, frequency, and synchronization stability. One potential solution is applying grid forming (GFM) control to wind turbine converters (WTCs) to maintain voltage and frequency in power systems, emulating synchronous machine (SM) dynamics, provided that there are sufficient energy buffers. Over the past few years, several control algorithms have already been developed for the GFM operation of WTCs. This article investigates the state-of-the-art in the field of GFM control for WTCs, where the principle of each control algorithm is discussed in detail, and corresponding characteristics are summarized. Comparisons are given in tables, which leads to the conclusion and the suggestion for the future research.**

***Index Terms*—Wind power plants (WPPs), wind turbine converters (WTCs), grid-forming (GFM) control.**

I. Introduction

Nowadays, increasing efforts have been devoted into using sustainable energy sources for the electric power generation. Among all the renewable electricity generation technologies, wind power generation has already become a mainstream, and the integration of large-scale offshore wind power plants (OWPPs) is increasingly gaining more attention, especially in Europe. As shown in Fig. 1, at the end of 2030, new offshore wind installations in Europe are expected to reach almost 14.5 GW [1]. With a large-scale wind energy integrated into the grid, ensuring system stability is becoming a challenge.

One major problem that arises from a high penetration level of electronic-based wind generation is the reduction of overall system inertia, since there will be less synchronous machines (SMs) in the system to contribute to the inertia response. Thus, the rate of change of frequency (RoCoF) will increase in the case of transient events like a large load variation or a loss of generation, which may in turn trigger cascading disconnections [2]. Apart from this, under grid disturbances, inadequate power management limits the fault-ride-through capability and then increases the risk of voltage collapse [3]. Regarding the transient stability, less margins are available when conventional SMs are replaced by electronic-based sources [3]. Facing those integration challenges, conventional grid-following (GFL) control methods applied to wind turbine converters (WTCs) can be insufficient to ensure a reliable integration of large-scale WPPs. Currently, a shifting from conventional GFL to GFM control has being taken as a potential solution to deal with aforementioned challenges, since GFM converters can be taken as controllable voltage sources with coupling impedance, which shares more similarities with conventional SMs [4]. Moreover, in the case that WPPs are disconnected from the main grid, GFM converters may work with energy storage systems to maintain WPP voltage and frequency, avoiding a complete collapse and being prepared for the reconnection. Another benefit of applying GFM control to WTCs is the possibility of being used for early stages of system restoration after the black out, with the condition that

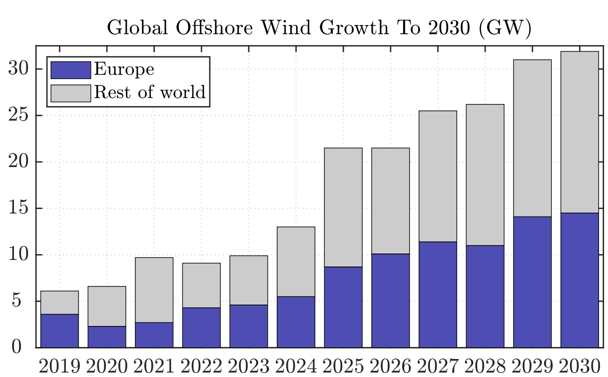

Fig. 1 Global offshore wind growth to 2030 [1].

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there is sufficient energy buffer that can be provided by either the energy storage or wind turbines.

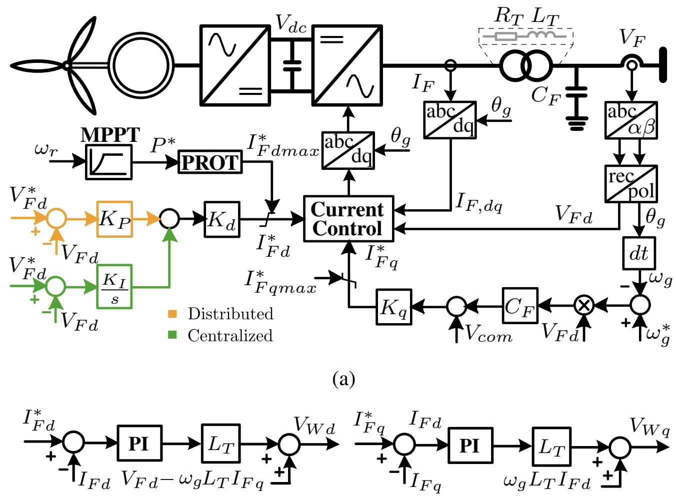
Regarding the GFM operation of WTCs, extensive investigations have been conducted in the literature. For instance, in [5], the distributed voltage and frequency control (DVFC) method has been proposed, where the voltage- and frequency-control were realized by a combination of both distributed and centralized regulators. Further improvements have been made in [6] and [7] for the expansion of fault-ride-through capability and the reduction of harmonics in WPP voltage. In addition, the fixed reference frame control (FRFC) was first proposed in [8] and [9] to make GFM characteristics available for WTCs, where a centralized global positioning system (GPS) is used to ensure a stable and constant WPP frequency. Moreover, voltage injection control (VIC) was applied in [10] for the mitigation of transient overvoltages during a sudden islanding operation. In addtion to those methods based on centralized control frame, distributed PLL-based control (DPLLBC) has been proposed in [11]. DPLLBC approach is less dependent upon the robustness of communication links, this control algorithm has been further advanced in [12] with additional frequency-support control. Another distributed approach proposed in [13] is the two-sequential-loops-based control (TSLBC) method which includes the mitigation of oscillations among GFM WTCs. Furthermore, as one of the most widely used GFM control methods with the direct emulation of SM dynamics, virtual synchronous generator (VSG) advantages in providing inertia responses [14]–[16], and this GFM control concept has been applied to both type-III and type-VI WTCs for a better integration of wind in various applications [17]–[25].

This article aims to conduct an overview of existing GFM control applied to WTCs. The rest of this article is organized as follows: In Section II, existing GFM control algorithms applied to WTCs are presented. A comparison of those control algorithms is presented in Section III, and the potential requirements for future GFM WTCs are given in Section IV. Finally, the suggestion for future work and the conclusion are given in Section V.

II. GFM Control Algorithms for WTCs

A. Distributed Voltage and Frequency Control

The DVFC algorithm was initially applied in [5] to let WTCs control WPP AC grid independently. In this algorithm, dc-link voltage of each generation unit is assumed to be well regulated by the generator-side converter. Thus, control algorithms can be freely applied to the grid-side converter for controlling WPP AC grid. The corresponding control scheme is shown in Fig. 2(a). Assuming that the leakage impedance $(R_T + j\omega_F L_T)$ of medium voltage transformers is dominant when compared with cables and the transformer magnetizing impedance, conventional vector current controllers are implemented in inner loops with decouping terms like Fig. 2(b). The regulation of WPP terminal voltage is then achieved by adjusting the d-axis current of each WTC, where distributed



(a)

(b)

Fig. 2 The scheme of DVFC. (a) Overall control scheme (PROT represents the protection, rec represents the rectangular coordinate, and pol represents the polar coordinate). (b) Current control loops.

proportional gain K_P as well as centralized integral regulator K_I/s are both implemented, the corresponding output is multiplied by the wind turbine power contribution factor K_d for the predefined active power sharing. Under normal operation conditions, voltage loops will be designed to stay saturated, and d-axis current references will be determined by adjusting the corresponding limitation according to individual WTC's power set point. However, in the case of an islanding operation, distributed and centralized voltage control loops will work together to regulate the voltage without reaching current limitations. In addition, the WPP terminal voltage vector angle is calculated for the synchronization of all WTCs, and the measured angular frequency is utilized for the direct calculation of reactive current references. Similar to the active power dispatching applied in voltage loops, the reactive current contribution factor K_q is used in frequency loops for the predefined reactive current sharing as well. For the purpose of protection and fault ride through, protection strategies demonstrated in [5] is used to dynamically set the limitations of d-axis and q-axis currents.

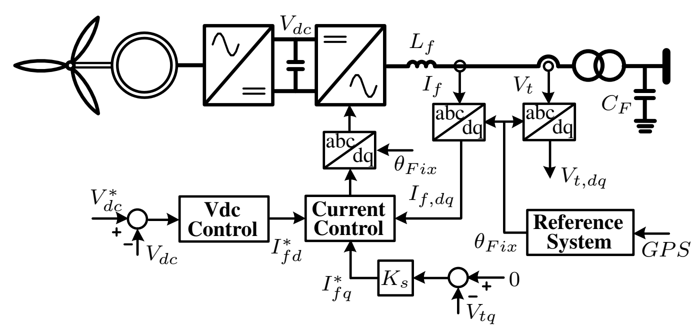


Fig. 3 The scheme of FRFC.

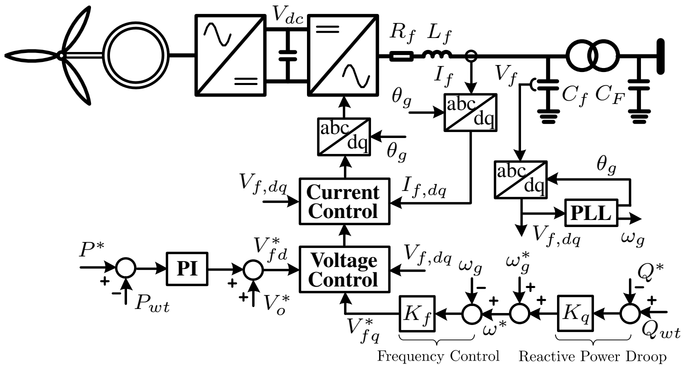


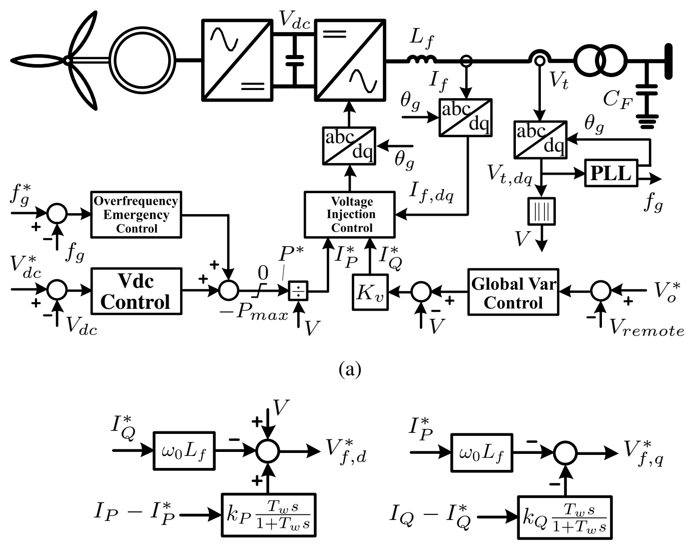
Fig. 4 The scheme of DPLLBC.

B. Fixed Reference Frame Control

In order to handle instability issues in operating weak WPP AC grids with conventional synchronization technologies, i.e., using the phase-locked loop (PLL), FRFC concept was initially proposed in [8] as an alternative solution which can be easily applied to both type-III and type-VI wind energy conversion systems [9]. By replacing commonly used distributed PLLs with the centralized reference system (e.g., GPS signals), the phase angle and the frequency for the control of each WTC can be accurately coordinated, and preservation of conventional WTC control blocks can be largely attained. As indicated in Fig. 3, reactive current sharing is achieved by the traditional droop controller, while traditional dc-link voltage and inner current control loops are preserved without additional modifications.

C. Distributed PLL-Based Control

Fig. 4 shows the overall scheme of the DPLLBC solution proposed in [11], where all the control loops are arranged in a conventional cascaded frame. This method uses conventional PI controllers as inner current regulators for a fast current response together with a easy implementation of current limitations during transient events. Each WTC is equipped with a LC filter, and the voltage on filter's terminal is measured and regulated for controlling WPP voltage. As indicated in Fig. 4, the active power transmitted by converters is adjusted by the conventional PI controller to follow the set points (e.g., obtained from maximum power point tracking curves), and the reactive-frequency droop controller is applied as well to share reactive currents among WTCs by modifying the individual frequency reference. Additionally, distributed frequency control loops which use frequency error to adjust q-axis voltage V_{fq} is embedded following the PLL synchronization principle, i.e., driving q-axis voltage V_{fq} to zero. It worth noting that the frequency regulator K_f in Fig. 4 differs from the contribution factor K_q of DVFC, even though they appears in similar control loops, the former is mainly designed to synchronize the voltage angle of each WTC by reducing q-axis voltage V_{fq}, and the latter is set according to WT capacities for an appropriate reactive current sharing.



(a)

(b)

Fig. 5 The scheme of VIC. (a) Overall control structure. (b) Inner voltage injection control loops.

D. Voltage Injection Control

Different from other GFM control solutions developed for WTCs, the VIC strategy was initially proposed in [10] to tackle transient overvoltage issues in the case of a sudden islanding operation. One distinct feature of VIC is that conventional inner PI current regulators are replaced by high-pass washout filters, as shown in Fig. 5(b). By doing this, adequate damping for transient processes can be carefully designed without integration functions, and the current regulator windup which results in the overvoltage can be avoided since voltage references are directly generated without integrating current errors. WTCs can be then controlled to behave more like voltage sources when WPPs are disconnected from the main grid. Moreover, reactive power controller with droop characteristics, conventional DC-link voltage regulator and over-frequency emergency control can be applied in outer loops respectively, as shown in Fig. 5(a), a detailed description can be found in [10], [26]

E. Two-Sequential-Loops-Based Control

In the aforementioned GFM control algorithms for WTCs, either synchronous (dq) frame voltages or currents of each WTC are independently regulated to control the grid voltage and adjust power flows among GFM WTCs. However, in the case of many parallel-connected GFM units, the risk of interaction-triggered oscillations may increase, especially when individual converter's terminal voltage responses to power-flow changes with different transients. Considering the risk of interactions among WTCs, voltage angle and amplitude at each converter's terminal have been selected as the variables to be controlled and coordinated in [13], and the classical power-angle control is applied with an additional frequency PI regulator to construct the outer control layers of TSLBC,

TABLE I: A general comparison of GFM control for WTCs

GFM control methods	Grid integration in the study	Initial voltage build-up	Synchronization method	Interaction mitigation	Inertia emulation	Controller complexity
DVFC	DR-HVDC	WTCs	Centralized calculation	No	No	Complex
FRFC	DR-HVDC	External grid	GPS signals	No	No	Simple
DPLLBC	DR-HVDC	WTCs	Distributed PLL	No	No	Simple
VIC	VSC-HVDC	Not addressed	Distributed PLL	No	No	Complex
TSLBC	DR-HVDC	Not addressed	Distributed PLL	Yes	No	Simple
VSG-Basd (for type-III)	LCC-HVDC HVAC	Not addressed	Switching equation	No	Yes	Simple
VSG-Basd (for type-VI)	HVAC	Not addressed	Switching equation	No	Yes	Simple

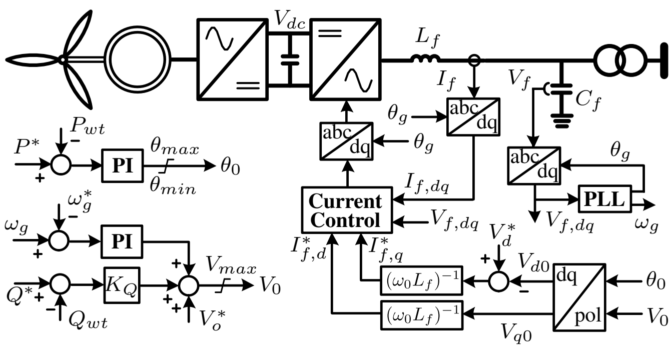


Fig. 6 The scheme of TSLBC.

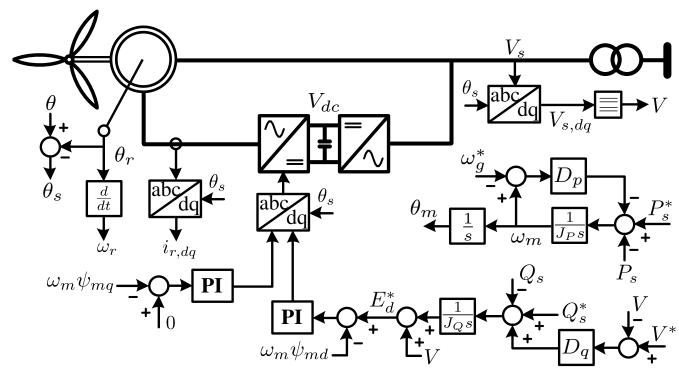


Fig. 7 The scheme of VSG-based control for type-III WTCs.

as indicated in Fig. 6. Since terminal voltage magnitude is synchronously corrected by utilizing the same frequency deviation, more stable operations with less risk of oscillations can be anticipated. In the inner control loops, conventional vector current regulators are applied, and the references can be calculated based on the steady-state analysis in [13].

F. VSG-Based Control

1) For Type-III WTCs: A simplified diagram of VSG-based control for type-3 WTCs is indicated in Fig. 7 [22], [23]. When the concept of VSG is applied to type-III WTCs, the control of grid-side converter can remain the same, which means the normally used vector control can be still used for the grid-side converter. Regarding the control for generator-side converter, the swing equation will be applied to regulate both phase angle of terminal voltages and transmitted active power. By adjusting the inertia coefficient J_P and damping factor D_P, desired inertia responses and damping effect can be attained. The voltage amplitude reference is calculated through the feedback control of stator reactive power, where a voltage droop control is also included to generate the reactive power reference. Compared with the traditional GFL control for type-III WTCs, the VSG-based GFM control is able to provide improved stability, especially in the case of weak grids [18]–[20], [22], [23].

2) For Type-VI WTCs: In the case that the VSG control is applied to type-VI WTCs, generator-side converter is re-

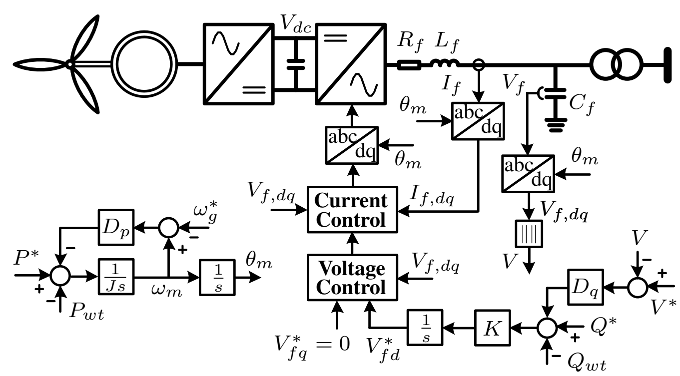


Fig. 8 The scheme of VSG-based control for type-VI WTCs.

sponsible for regulating the DC-link voltage, and the grid-side converter actively controls the phase angle and amplitude of terminal voltages. As shown in Fig. 8, similar to the VSG-based control for type-III WTCs, swing equation is used for both phase angle and active power control, and reactive power feedback control together with voltage droop control are used for generating the voltage amplitude reference. Different for the type-III wind generation system, the generator is fully decoupled form the grid in type-VI system. Thus, for GFM control, LC filter is installed, and inner voltage control loops is applied to regulate terminal voltages.

III. Comparison of GFM Control for WTCs

A general comparison of aforementioned GFM control algorithms is presented in TABLE I, where the initial voltage build-up, the grid integration, the synchronization, the mitigation of interactions, the inertia emulation and the controller complexity are included. Regarding the initial voltage built up, DVFC and DPLLBC approaches are able to provide effective solutions which only use WTCs and the DC-link energy, while FRFC still needs the help of external grid or additional energy storage systems. Compared with centralized synchronization technologies used in DVFC and FRFC methods, the distributed PLL used in DPLLBC, VIC and TSLBC does not rely on communication links and is easy to be implemented. However, when the distributed PLL is applied, special attention need to be paid to the stability in the case of weak grids. On the other hand, VSG-based control is able provide improved stability in the case of weak grids and involves the emulation of inertia for frequency support, which is an advantage in interconnecting with the grid with a high renewable penetration level [27], [28]. Furthermore, the risk of interactions among parallel GFM WTCs has only been considered in TSLBC.

IV. Potential requirements for Future GFM WTCs

With less conventional power plants in the system, large-scale WPPs play an important role in maintaining system stability and contributing to the system restoration. Considering the ongoing structural changes, potential requirements for future GFM WTCs can be listed as follows [29]:

- Build and maintain the AC voltage, where voltage amplitude and phase angle are actively controlled;
- Actively utilize reserves to support frequency and voltage in the case of transient events;
- Contribute to the overall inertia of power systems with a high penetration level of electronic-based generation;
- Actively mitigate oscillations and harmonic resonances;
- Enable islanding operations after a disconnection;
- Enable black start for early stages of system restoration.

V. Conclusion

This article reviews the research on GFM control applied to WTCs firstly, where comparisons have been conducted in terms of the initial voltage build-up, the grid integration, the synchronization, the mitigation of interactions, the inertia emulation and the controller complexity. Subsequently, for the improvement of existing GFM control for WTCs, potential requirements for future GFM WTCs are presented. Base on the review, the suggestion for the future work are summarized from authors' point of view as follows:

1) Interactions in the form of low-frequency oscillations or harmonic resonances are likely to be more complex when GFM WTCs are applied in the system. The risk of such interactions among GFM WTCs and other sources (e.g., GFL units and SMs) cloud be studied.
2) GFM WTCs will attempt to adjust the output active power automatically according to the instantaneous frequency deviation. The resulting power ripples can be passed to turbine side when the DC-link capacitance is not large enough. Thus, the assessment of those power ripples on generators and wind turbines could be included in the future work.
3) In the case of a large frequency event, the frequency-support characteristics of GFM WTCs will slow down the wind turbine speed. The worst case would be that the event happens when the wind speed is low, and the wind turbine may be tripped because of the low rotation speed. To avoid the unnecessary tripping of wind turbines, the soft switching between GFM and GFL modes or the adaptive GFM control algorithm could be investigated in the future work.
4) To provide grid-support functions or even black-start services, the energy buffer provided by wind turbine itself may not be sufficient, considering the inherent variability of the wind speed. Thus, additional energy storage may be required, either distributed or aggregated storage systems. The coordination control of GFM WTCs and energy storage systems could be investigated in the future work.
5) In order to have a better understanding of GFM WTCs' contribution to the overall inertia, adequate inertia assessment approaches could be studied in the future work, where available wind power, energy buffers form the storage and applied WTCs control algorithms could be simultaneously included.

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