Single-phase Grid-forming Inverters: A Review

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***Abstract*—Ever-increasing share of inverter-based resources (IBRs) has resulted in a significant reduction in system damping and inertia, posing significant stability and new performance challenges for electric power grids. To resolve these issues and provide reliable support to the existing power grid, advanced control schemes are already being researched and some are successfully implemented. Grid-forming (GFM) control methods are emerging to enhance grid-connected inverter stability and response to abnormal conditions. While research is more focused on three-phase converters, the ever-increasing contribution of single-phase IBRs calls for similar solutions to be developed for single-phase converters. In this paper, the state-of-the-art single-phase GFM techniques for IBRs are presented and the main challenges for successful implementation of them are highlighted.**

Keywords—Grid-forming (GFM) control, single-phase inverter, synchronverter

I. INTRODUCTION

Nowadays, to address climate concerns and energy demands, the penetration rate of renewable energy sources (RESs) into the power grids is rapidly increasing. Traditionally, the operation of power systems relies on the assumption that frequency stability is provided by synchronous generators (SGs) through their stored kinetic energy. Nevertheless, the majority of RESs, connected to power grids through inverters, do not possess frequency regulation capabilities, due to the lack of inertial capacity, stiff internal voltage and damping capability. These inverter-based resources (IBRs) are typically operated as current-controlled inverters, focused on extracting the maximum power available from the RESs. Consequently, increasing the RESs penetration results in the decline of the power system's inertia, posing certain challenges to its stability and reliability. Table I compares the total inertia constant (Heq) change for different regions from 1996 to 2016 [1]. The data reveals that Europe has faced the most inertia reduction by 20% during this period. As RESs share in electricity generation continues to increase, the potential for grid frequency, as well as voltage fluctuations, increases due to insufficient system inertia and voltage support.

Conventional IBRs, known as grid-following (GFL) inverters, follow the grid voltage and regulate the injected current into the grid, resembling a current source [2]. There are several limitations associated with GFL inverters, mainly the stability challenges in the presence of weak grids and faulty conditions, lack of inherent sharing of power and their adverse effects on system inertia. The flexible and fast control of inverters has been already utilized to emulate the characteristic of SGs to enable grid support capability and improve the power/frequency response. These include a wide range of solutions that are usually called grid-forming (GFM) control techniques and are mainly focused on three-phase IBRs.

The primary requirement for introducing frequency dependency into the operation of IBRs has paved the way for the emergence of droop-controlled converters [2]. Although the droop control strategies offer numerous advantages, their lack of inherent inertia emulation ability restricts their suitability for small-scale power systems. Hence, alternative and promising solutions have been proposed to mimic the transient behaviour of SGs as well as their steady-state behaviour by incorporating the swing equation, thereby enhancing the system's inertia. The strategies include the virtual synchronous generator (VSG) [3] and the synchronverter [4]. Alongside these strategies, a recent development in GFM control is the introduction of a novel approach called virtual oscillator control (VOC) [5]. The VOC operates like a weak nonlinear limit-cycle oscillator and shows great potential in enhancing system performance and stability.

Research has been mainly focused on three-phase IBRs, but the ever-increasing penetration of small distributed generation (DG) systems necessitates similar solutions for single-phase inverters. The literature on GFM has been reviewed in some papers [1], [2], [6]. These papers have primarily focused on three-phase inverters, so a review of single-phase control methods has been lacking. This paper aims to bridge this research gap by providing an in-depth analysis of the latest advancements in single-phase GFM, preparing useful resources for researchers who want to study single-phase GFM IBRs. The outline of this paper is structured according to Fig. 1.

II. CONTROL STRUCTURES

Fig. 1 summarizes the existing control strategies of single-phase GFM inverters, broadly grouped into the droop control, the synchronous machine-based control (SMBC) and the VOC [2].

TABLE I. COMPARISON OF EQUIVALENT INERTIA CONSTANT BETWEEN 1996 AND 2016 [1]

Continent	Africa	Asia	Europe	North America	South America
H_{eq} (1996)	4	4	4	4	3.5
H_{eq} (2016)	4.2	3.9	3.3	3.9	3.4

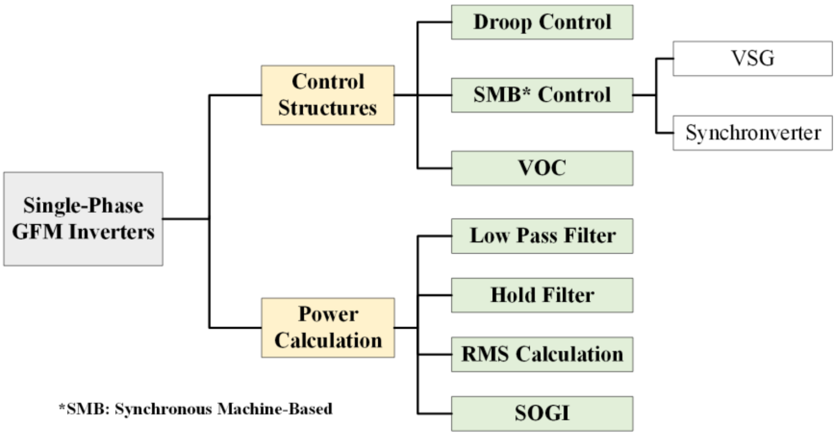

Fig. 1. Single-phase GFM control strategies and power calculation methods.

A. *Droop Control*

The droop control concept adjusts the output voltage and frequency of GMF inverters for synchronization, grid support and power-sharing purposes. The droop characteristics of the SG in steady-state are

$$\begin{cases} \Delta\omega = K_p\,(P_{ref} - P) \\ \Delta V = K_q\,(Q_{ref} - Q) \end{cases} \tag{1}$$

where $\Delta\omega$ and ΔV are the change of the angular frequency and output voltage, and P, Q, P_{ref} and Q_{ref} are the output active and reactive power and their setpoints, respectively. Also, K_p and K_q are power/frequency and reactive power/voltage droop coefficients, respectively. It is clear that for single-phase IBRs connected to distribution networks, there is a strong coupling between voltage and power and also between frequency and reactive power, which means that the simple equations of (1) may not be any more practical. Fig. 2 depicts the simple droop control block diagram for single-phase GFM inverters [7]. In this figure, V_n and ω_n are the nominal value of the amplitude output voltage and angular frequency, respectively. It is evident from the static equations comprising (1) that the droop control lacks inertia emulation capability. However, inertia support can be introduced to it by incorporating a low-pass filter (LPF) for eliminating the sampling ripple in power measurement [8].

B. *Synchronous Machine-Based Control*

The VSG and synchronverter are two well-known inertia emulation control strategies. The terms "VSG" and "synchronverter" are often used interchangeably, as they both refer to technologies that mimic the dynamic behaviour of the SG by emulating its model.

1) *VSG*

The idea of VSG can enable GFM inverters to provide voltage and inertia support to the grid. The core principles of the VSG method are rooted in the swing equation, which incorporates virtual inertia and damping factors. Based on this equation, (2) represents the mathematical model of the VSG, which includes both the inertia, J, and damping, D_p.

$$J\,\frac{d\,\omega}{dt} = \frac{P_{ref}}{\omega_n} - \frac{P}{\omega_n} + D_p\,(\omega_n - \omega) \tag{2}$$

Similarly, (3) is the dynamic model of the VSG's reactive power control (RPC) loop where K_i, v_g and v_{ref} are the reactive power-voltage inertia coefficient, the grid voltage and the voltage reference value, respectively.

$$K_i\,s\,v_{ref} = Q_{ref} - Q + \frac{1}{K_q}(v_g - v_{ref}) \tag{3}$$

Fig. 3 depicts the active power control (APC) and RPC block diagram of the VSG based on (2) and (3).

In [9] the dynamic behaviour of the single-phase VSG is investigated to enhance its performance. Also, In [10] a second fictitious phase signal is generated to build two synchronous d-q reference frames to extend the three-phase VSG to single-phase systems.

Single-stage power conversion is one of the attractive advantages of the impedance source networks making them suitable for renewable energy applications. Combining these impedance source inverters with the VSG can enhance the reliability and performance of the power systems. Hence, a quasi-impedance source inverter (q-ZSI) is proposed in [11], which can emulate the inertia behaviour of the SG.

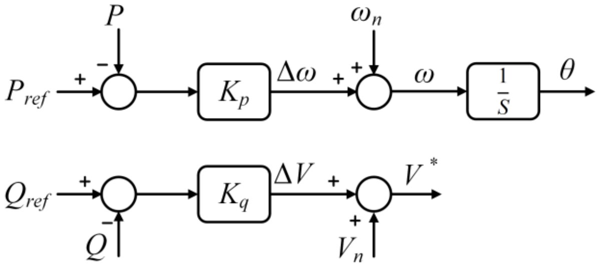

Fig. 2. Droop control block diagram.

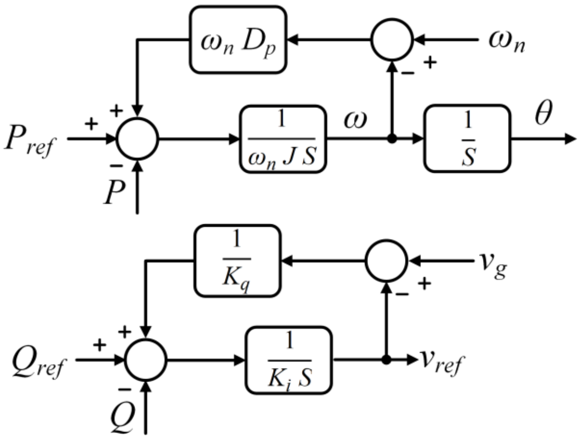

Fig. 3. APC and RPC of the VSG.

2) *Synchronverter*

The term "Synchronverter" refers to a power inverter technology that combines the functionalities of SGs and inverters. By incorporating essential properties such as self-synchronization, oscillation damping and rotor inertia, it ensures the stability of power systems [6]. The well-known dynamic model of the SG serves as the basis for the original synchronverter strategy, which is given in (4).

$$\begin{cases} \dfrac{d\omega}{dt} = \dfrac{1}{J}(T_m - T_e + D_p(\omega_n - \omega)) \\ T_e = M_f i_f \; i \; \sin\theta \\ e = M_f i_f \; \omega \sin\theta \\ Q = -M_f i_f \; \omega i \; \cos\theta \end{cases} \tag{4}$$

In (4), T_m and T_e are the input and electromagnetic torques, M_f is the mutual inductance between the windings of the stator and rotor, i_f is the excitation current, e is the induced electromotive force and i is the stator current. Based on this model, Fig. 4 demonstrates the control part block diagram of the synchronverter. The dynamic behaviour and parameter design of the single-phase synchronverter are investigated in [12]. The hold filter-based method is proposed in [13] to optimize the inertia. Furthermore, some improvements are introduced to the single-phase synchronverter to enhance their functionality in desired applications, such as PV systems [14].

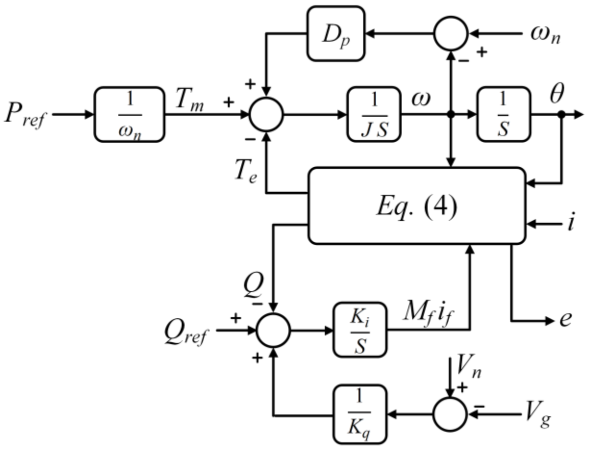

Fig. 4. Synchronverter control block diagram.

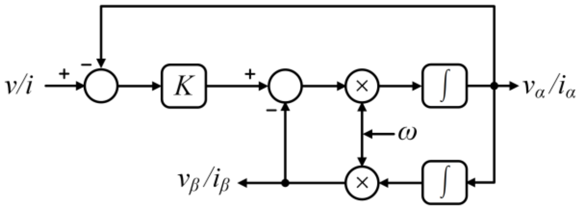

Fig. 5. SOGI block diagram.

C. *VOC*

The VOC is a non-linear control technique that leverages the intrinsic synchronization properties of a coupled oscillator network. By imitating the dynamic characteristics of a weakly nonlinear oscillator, the VOC converter can independently generate a sinusoidal voltage. From a small-signal perspective, the equivalency between droop control and the VOC is demonstrated in [15]. Additionally, due to its time-domain implementation, the VOC offers superior dynamic behaviour compared to the droop control technique. The Van-der-Pol oscillator serves as the basis for the commonly employed VOC techniques. In [16] a dispatchable VOC (dVOC) is proposed based on this oscillator for simultaneous active and reactive power regulation of single-phase islanded inverters. Despite its benefits, the exceptionally fast transient performance poses challenges in providing grid inertia support. Thus, additional improvements are necessary to successfully implement this technique in GFM inverters.

III. ACTIVE AND REACTIVE POWER CALCULATION

Contrary to three-phase systems, the power components of single-phase systems fluctuate at twice the fundamental frequency. Thus, several approaches have been proposed to eliminate the 2nd harmonic components of the active and reactive power. One straightforward approach is utilising a properly adjusted low pass filter (LPF) to eliminate these frequency components [12]. Another filter-based technique is using a hold filter to effectively remove the frequency components [13]. This technique provides the advantage of indirectly improving the system’s inertia [6]. In addition, a proposal has been made to utilize the RMS value of current and voltage for the calculation of single-phase power [14]. Nevertheless, the precise calculation of the true RMS value is achievable only for voltage and current waveforms that are purely sinusoidal. The inclusion of harmonics introduces inaccuracies in the calculation of average power [6].

The second-order generalized integrator (SOGI)-based method is widely employed for calculating single-phase average power due to its ability to effectively eliminate the double frequency component. As shown in Fig. 5, the single-phase voltage and current waveforms have been transformed into the stationary reference frame [7], [9]. The relation between the output and the input signals of the SOGI can be obtained from (5).

$$\begin{cases} \dfrac{v_\alpha}{v} = \dfrac{i_\alpha}{i} = \dfrac{k\,\omega s}{s^2 + k\,\omega s + \omega^2} \\ \dfrac{v_\beta}{v} = \dfrac{i_\beta}{i} = \dfrac{k\,\omega^2}{s^2 + k\,\omega s + \omega^2} \end{cases} \tag{5}$$

In (5) k is the damping factor and v_α, v_β, i_α and i_β are the transformed signal of voltage and current to the $\alpha\beta$ frame, respectively.

IV. CONCLUSION

With the ever-increasing penetration of small DG units, single-phase GFM inverters are increasingly required to support power systems and improve their reliability. This paper provides an overview of the control strategies for single-phase GFM inverters as well as the challenges around single-phase power calculation. Single-phase GMF is still underresearched and more research and development efforts are necessary to improve its functionality. Power calculation, over-current protection, self-synchronization capability and seamless transition between different operation modes are indeed challenges associated with single-phase GFM inverters that require further investigation and research.

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