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A detailed study on Transient Stability Enhancement of Grid-Forming Inverters

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Abstract

The integration of the weak grids along with the clean energy that comes from the natural resources requires stable interconnection of Voltage-Source Inverters (VSIs) with weak grids. During severe voltage sags, weak grid integrated VSIs may fail synchronization with the grid.These inverters' transient stability under severe grid disruptions is weak and significantly different from that of synchronous machines. To prevent the side band oscillations in the weak grids, the emerging inverters based on grid-forming are preferred over the grid following inverters in the weak grids. These inverters synchronise with the grid using a power-based synchronisation technique in order to prevent the instability brought on by a typical Phase Locked Loop in weak AC grids. This study presents a comprehensive review of the transient stability improvement of Grid-Forming VSIs.

Keywords: Voltage-Source Inverter, grid-forming, transient stability, Current Limitation Control, weak grid

1. Introduction

Conventional power systems use synchronous generators as interfaces for grid. When there is variation in frequency owing to mismatches in generation of power as well as demand, it automatically regulates the speediness according to the grid frequency. This property of the synchronous generators is called inertia [1], [2]. However, modern power systems lack this property because most of the renewable based power generations are combined with power-grid with the help of power-electronic interfaces. Nowadays, power electronic converters are widely used instead of the synchronous generators and hence the entire power system lack inertia and imposes challenges on stability and control [3].

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The power system stability is categorized as large signal and small signal stability. Since Voltage-Source Inverters (VSIs) are represented using small-signal linearization techniques, linear control theory may be used to analyse small signal stability. Numerous studies on the VSIs' small-signal stability have been conducted [4]-[9]. The large-signal stability investigation has only been the subject of a small number of studies. Transient (angle) stability and voltage stability are additional categories for the large-signal stability issues. References [10] through [16] concentrated on the examination of voltage stability under various fault circumstances. To simulate and handle the dynamic issues with the grid, a number of voltage-stiff control systems have been suggested, including Virtual Synchronous Machine (VSM), Synchronous Power Controller (SPC) and Power Synchronisation Control (PSC) [17]. Among them, PSC has the advantages of moving power in the middle of remote points of the grid and achieving better performance in weak grids [18].

The transient stability analysis of PLL and PSC based VSIs is studied further using large-signal disturbances by means of the phase portraits and equilibrium points [18] and [19]. The essential clearance angle has been discovered by the authors in order to simplify the power system design protection using phase portraits for PSC. In order to make up inertia loss as well as storage capacity, virtual synchronous machines are utilised to imitate the dynamic properties of conventional synchronous generators. Z. Shuai et al. [20] used Lyapunov's direct technique to evaluate Virtual Synchronous Generator’s (VSG) transient angle stability. The authors demonstrated that the control loop instability of the reactive power results in low internal voltage for the inverter during transient. Andres Tarraso et al., [21] to simulate the inertia, devised a synchronous power controller in synchronous generator to minimize power electronic converters cost. The increase in integrating the power grid with the energy sources that are renewable, makes the study in transient stability problems essential.

This study aims to present a complete review of transient steadiness improvement of Grid-Forming VSI mostly used in power generations from renewable sources. The different grid-synchronization methods are discussed in Section 2. The basics of Grid-Following and Grid-Forming inverters and the important control schemes are reviewed in Section 3. Then to identify the equilibrium points, static power transfer limitations are analyzed. Then the methods to improve transient stability as well as the control of Grid-Forming inverters present restrictions are conversed in Section 4 and the concluding statements are provided in Section 5.

2. Grid Synchronization

There are several grid-synchronization methods that may be used for the renewable energy integration in power electronics. Basically, methods to synchronize grid is categorized based on the converter operating modes as: 1) Voltage-based and 2) Power-based.

A. Voltage-based

This technique decides the PCC of the grid-integrated inverters by determining the frequency and the phase angle. The calculated phase angle in conjunction with direct power control or vector current control is regulated by the reactive and real system power flow. Due to the fact that they follow the grid voltage phase, this synchronisation technique is also known as the "Grid-Following Control" [22].

B. Power-based

By controlling the real power of the grid-integrated inverters, this approach directly reads PCC voltage phase angle. The synchronous machines' actual droop control of the power-frequency is utilised to synchronise the inverters with the grid. In contrast to inverters that follow the grid, voltage management is essential to follow the produced phase angle of PCC voltage. The term "Grid-Forming inverters" refers to these voltage controlled inverters [22].

These two alternative grid integration techniques have varied transient stability characteristics. It has been claimed that in weak AC grids, sideband oscillations might occur at the fundamental frequency due to voltage-based synchronisation techniques like PLL, which is typically seen in grid-following inverters [23]. In contrast, the employment of PSC with grid-forming inverters and other power-based grid synchronisation techniques can cause sideband oscillations in strong AC systems [24], and series compensated systems [25] equilibrium points determination becomes hard during the instable conditions. If there are no equilibrium points, the inverters will undoubtedly stop synchronising with the grid. The inverters may still disconnect from the power grid even if the equilibrium point remains after the disturbance [18], [19], and [26].

According to research, the PLL essentially converts grid-following inverters into second-order nonlinear swing equations, leading to a voltage-angle curve rather than the more typical power-angle curve for the transient stability study [18]. The Transient Stability (TS) increases for the first order nonlinear grid-forming inverter that experiences droop control [19]. However, the grid-forming inverters' transient stability may suffer as a result of the droop control in reactive power [27]. The restricted over current capability of power electronic converters, in contrast to synchronous generators, mandates the adoption of regulation in current limit, that puts still alternative restriction on the TS performance of grid-forming inverters [26].

3. Types of Inverters for Grid Integration

A. Grid-Following Inverters

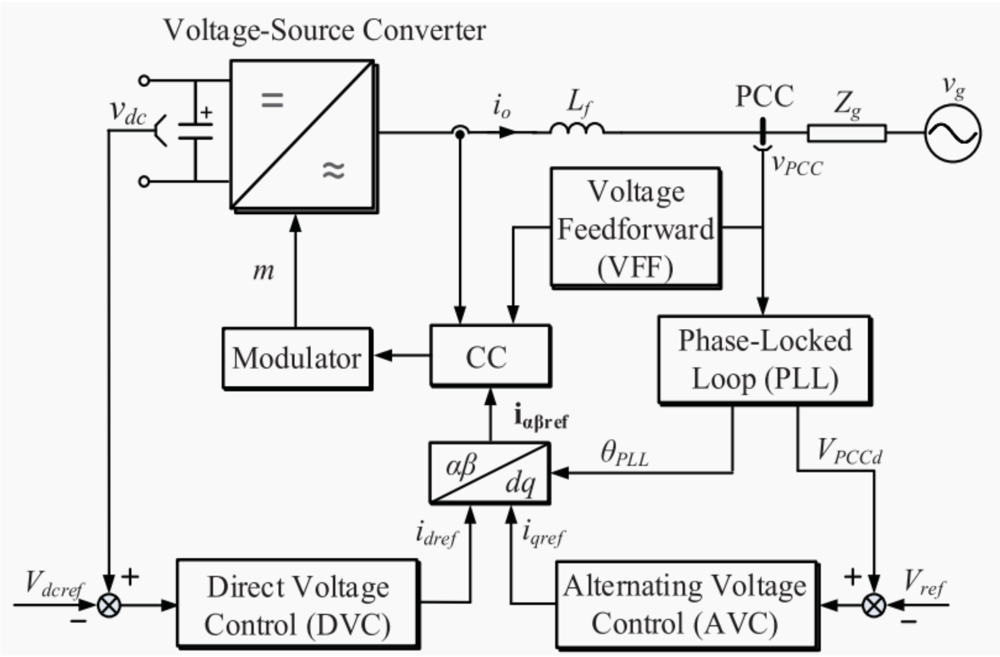


Figure 1. Schematic representation of a Grid-Following inverter [22]

Fig. 1 displays a grid- following voltage-source inverter using voltage-based synchronization method [22]. It acts as a controlled current source and follows any change in the voltage and frequency of the grid. Here the VCC technique is applied. The synchronization of the grid-following inverter depends heavily on the PLL. The PCC voltage vector is changed to the dq-reference and PI controller regulates the Q-axis voltage. Through a feedback control loop, PCC voltage phase is determined. The reference current i_{dref} and i_{qref} for controlling the reactive and real powers, respectively, are produced in outer loops using the Direct Voltage and Alternating Voltage Controls. Thus, the VCC can be done either by the αβ or dq-reference frame, depending on the current reference's magnitude and phase angle. To enhance the inverter's dynamic performance, the voltage feed forward control is additionally applied to current control output using a Low-Pass Filter (LPF).

B. Grid Forming Inverters

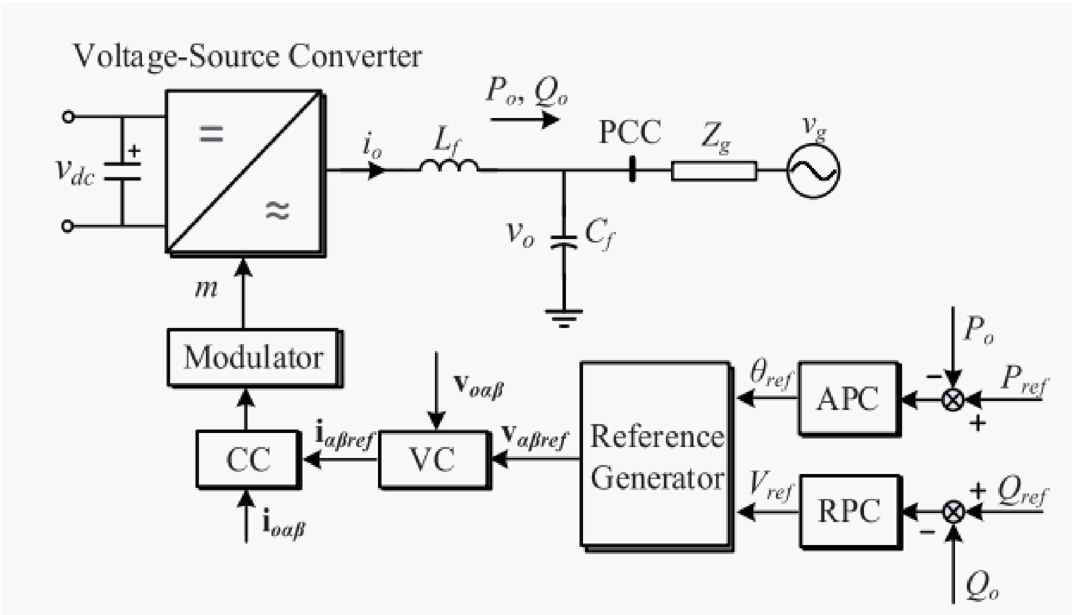
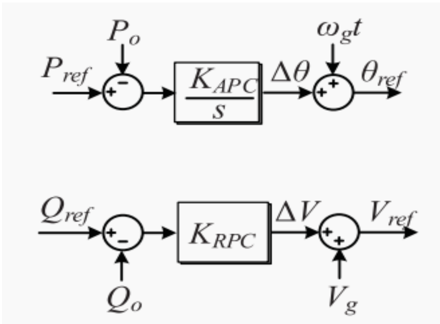


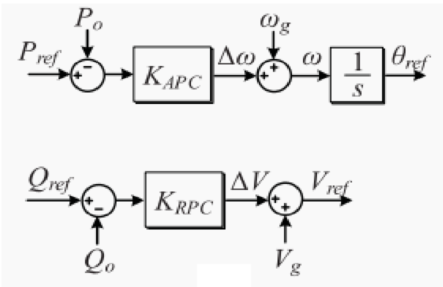
Figure 2. Schematic representation of a Grid-Forming inverter [22]

The schematic representation in fig.2 is based on Grid-Forming, employing the power-based synchronisation. To create the "phase angle and magnitude of the voltage reference",$V_{\alpha\beta ref}$, in this control technique, the reactive and active power outputs of the grid-forming inverter are controlled by the Active Power Control (APC) and Reactive Power Control (RPC). The inner Voltage Control (VC) loop controls the inverter's output voltage, and Current Control (CC) loop is added to this to restrict over current and filter (LC) resonance damping. The following techniques, as indicated in Fig. 3, can be used by grid-forming inverters to synchronise with the grid: Power Synchronisation Control (PSC), Droop control/ Virtual Synchronous Generator. There is no need for the PLL for grid-synchronization [28]. Unlike the Grid-Following inverter, a Grid-Forming inverter have controlled voltage source. Both PSC loop and fundamental droop control loop is categorised as first-order power controller loops because of their similarities. By incorporating the LPF into the fundamental droop-controller loop, which has been shown to be comparable to the fundamental VSG control

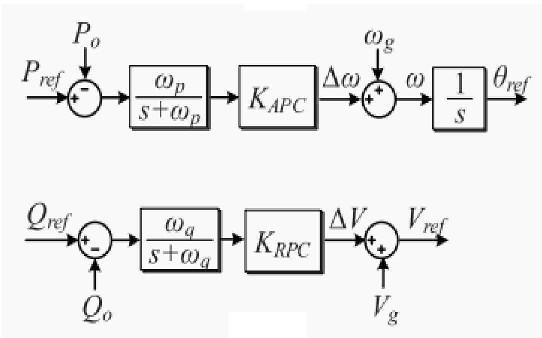
[29], the virtual inertia may be created. These control loops are categorised as second-order power-controller loops. A generic second-order power-controller model is utilized to characterise the changing aspects of the grid-forming inverters [27]. As a result, the PSC and basic droop controller is regarded as the specific instance of second-order power controls. Consequently, the grid-forming inverter's dynamics are crucial.



(a)



(b)



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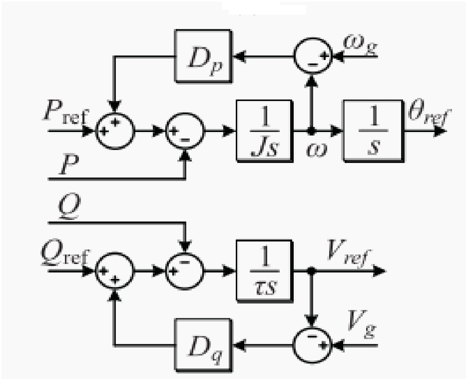

(d)

Figure 3. Characteristic control schemes for Grid-Forming inverter (a) PSC (b) Droop Control (c) Droop Control with LPF (d) VSG control [27]

4. Transient Stability in Grid –Forming Inverters

A. Limitation in power transfer

When inverter exceeds the maximum limit of static power transmission between the PCC and the grid, synchronisation instability will be inevitable under malfunctioning and weak grid situations. This restriction is a necessary stability requirement for equilibrium points existence in the power system and exists for both grid-following and grid-forming control architectures. The power transfer restriction guarantees a stable equilibrium point for the inverter's operation [30], [31]. The Grid-Following inverter's q-axis of the PCC voltage, utilised for synchronisation, is written as,

$$v_{pccq} = V_g \sin\left(\theta_g - \theta_{PLL}\right) + I_{PCC} Z_g \sin(\theta_I + \varphi_z) \tag{1}$$

The "φ_z" reresents grid impedance angle. For steady operation, PCC voltage q-axis is set zero by PLL. Only the first component in equation (1) can be regulated by the PLL, while the second term acts like negative feedback that destabilises PLL control. Therefore, the Phase Locked Loop is unable to regulate the voltage q-axis in low Short Circuit Ratio and high voltage sag leading to temporary instability of the inverter. The condition for stability can be obtained by equating v_{PCCq} = 0 in equation (1).

$$I_{PCC} < \frac{V_g}{\left|Z_g \sin(\theta_I + \varphi_z)\right|} \tag{2}$$

From equation (2), it is observed that for a specific grid voltage magnitude, “current injection angle”, and “grid impedance”, only a certain amount of I_{PCC} may be injected. The injection limit is simplified to the relationship within the grid reactance and the magnitude of the voltage for just genuine current injection ($\theta_I = 0$). However, in defective conditions when reactive current is frequently needed, the maximum amount of current that may be injected is limited by the rapport among the magnitude of voltage and grid resistance. The active-power output for grid-forming inverters may be computed as,

$$P_0 = \frac{3}{2}.\frac{V_0 V_g \sin\delta}{X_g} \tag{3}$$

The well-known power-angle curve, which is seen in Fig. 4, may be used to represent equation (3). The point ‘a’ is the stable equilibrium point and ‘b’ is the unstable equilibrium point, for power-angle curve. According to Fig. 4, the reference power (P_{ref}) must be less than or equal to maximum actual power (P_{max}) which may be transmitted from grid-forming inverter to the grid, to have an equilibrium point.

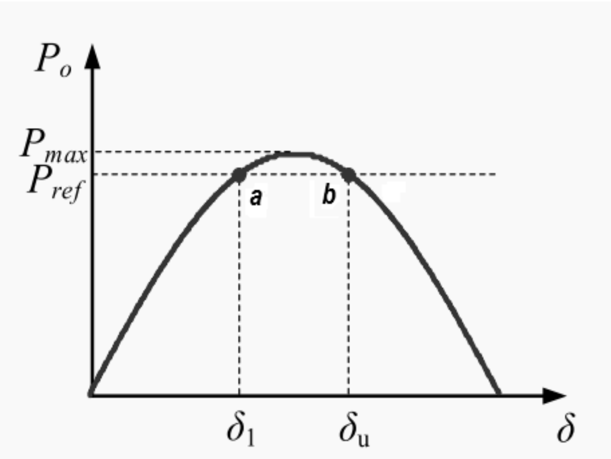

Figure 4. Power-angle curve

B. Transient Stability Enhancement Methods

Table 1. Methods for Improving Transient Stability in Grid Forming Inverters

Parameters varied	Research works
Real and reactive power references	Reducing the real power reference [20]
	Rising the reactive power reference [33]

	Control of real and reactive power [36]
Controller parameters or control loops	Mode- switching control [35]
	Minimizing acceleration and boosting deceleration [42]
	Employing machine learning methods [37]
Moment of Inertia and Parameters of Damping	Design coordination of the damping term and virtual inertia [24]
	Damping and gain scheduled inertia [34]
	Utilizing the virtual inertia to enhance the frequency dynamics [38]
	Different damping approaches to prevent steady-state changes [39]
	Transient damping to increase the damping ratio of the system [40]
	Transient damping through High Pass Filter [41]

The transient instability poses a serious danger to the power system's capacity to operate steadily and securely under significant load generating imbalances and grid blackouts. The difficulty of the power system to resume normal operation following a significant disruption is known as transient instability. Large disturbances can be caused by unexpected load increase or removal, switching activities, faults, transmission line or generator failure, etc. When a stable operating point is absent or when the synchronisation dynamics lack adequate damping required for the stable operating point, transient instability may develop in the grid-forming inverters during the failure. Generally speaking, there are three types of control techniques for improving the TS of grid-forming inverters. Table 1 summarizes the TS of grid-forming inverters.

C. Control Strategies for Current Limitation

In grid-forming, direct frequency and voltage control is possible, but limiting of fault ride through transient conditions is impossible. This is easily tackled by Conventional Synchronous Generators [44]. The inverters should be provided with over current precautions and it must be secured against severe faults such as short circuits, heavy load, line-tripping/reclosing, and voltage phase jumps. Hence current limitation control is essential during transients. Several control techniques have been developed which are summarized in Table 2.

Table 2. Strategies for Current Limitation Control in Grid-Forming Inverters

Proposal	References
Adjust outer reference power in fault	[17]
Virtual impedance and the droop controllers adaptive parameters	[26]
Switching to a grid-following mode	[28], [45]
Limiting the current by virtual resistance	[46]
By using virtual admittance, external power controls and current limitations are disabled	[47]
Improved droop control for limiting the current	[48]
Using voltage limits to limit current	[49]
Creating synchronization loop reference current	[50]
Using current reference saturation technique by computing critical clearing angle and time	[51]

5. Conclusion

This research has provided a thorough analysis of the Transient Stability (TS) of commonly used Grid-Forming inverters in weak AC grids. The limitations on static power transmission, various techniques for improving transient stability, and control schemes for current restriction are discussed. To preserve the TS of the grid-integrated converters, the grid code must be regularly updated as power-electronic inverters are used more often in power grids to produce electricity using the renewable sources.

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