Transient Stability Analysis of Grid-Tied Converters Considering PLL's Nonlinearity

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Abstract—Transient instability events of grid-tied converters probably occur while riding through grid faults. During low-voltage ride through (LVRT) period, seeing from the converter terminal towards the grid, the Thévenin equivalent grid impedance becomes pretty significant, accordingly making the converter terminal voltage highly sensitive to the output current. Under such circumstances, it is challenging for the converter to resynchronize with the grid via a phase-locked loop (PLL). This paper develops a reduced-order nonlinear model to elaborate on the dynamic synchronization characteristic of the converters. By considering the impact of grid impedance and analysing spatial vector tracking relation, resynchronization principle of the converters during LVRT is revealed. Besides, the impacts of circuit parameters and controller parameters, including residual grid voltage, grid impedance, current references, and PLL parameters, on the transient stability of the converters are investigated. The results are verified by simulation and experimental results.

Index Terms—Grid fault, low voltage ride through, phase-locked loop, power converter, synchronization, transient stability.

I. INTRODUCTION

GRID-TIED power converters are playing increasingly important roles in power systems, along with the rapid development of renewable power generation in recent years. Three-phase voltage source converters (VSCs), as one of the most crucial components of renewable energy generation units, often offer quite different performance from the conventional synchronous generator units, such as outstanding rapidity and controllability, but limited fault ride through capability [1], [2]. Grid codes for renewable power generation, in which various facets of the operating characteristics of grid-tied renewable energy generation units are standardized, have been formulated by independent system operators in order to ensure the power system security and stability [2]–[4]. One of the grid codes, namely low-voltage ride through (LVRT) requirement, requires renewable energy generation units to remain connected to the

grid and also output a specific reactive current to support the residual grid voltage during LVRT period [2]–[4].

When a grid fault occurs, the Thévenin equivalent grid impedance generally becomes considerable [5], resulting in weak connection between VSCs and the power grid [5]–[7]. Consequently, the VSC terminal voltage is easily affected by the VSC output current. Conversely, the output current is also influenced by the terminal voltage since the current phase-angle is guided by the phase-locked loop (PLL) which is with the terminal voltage as the input. It has been reported that loss of synchronism (LOS) of the grid-tied VSCs probably happens during LVRT because of the dynamic interaction between the PLL and the terminal voltage [5]–[22]. Note that the LVRT requirements of the grid codes can no longer be satisfied once the LOS occurs.

During severe grid faults, i.e., under large disturbances, on one hand, initial states of the VSC systems will probably be random. On the other hand, state trajectories of the VSC systems often exhibit a large change magnitude. Therefore the nonlinearity in system components, especially PLL's nonlinearity, cannot be neglected in the stability assessment. In this regard, previous relevant small-signal stability studies of the VSCs [8]–[11] can not effectively address the transient stability issues.

The transient instability issues associated with the LOS have not drawn much attention. [12] and [13] made investigations on the presence of equilibrium points of the grid-tied VSCs during grid voltage sags, but dynamic synchronization characteristics were not taken into account. [14] and [15] also claimed that the transient stability of VSCs can be considered as the presence of post-fault equilibrium points. However, we found in [5]–[7] that there is an instability possibility for a grid-tied VSC due to improper initial states and poor dynamic performance in addition to the absence of equilibrium points.

To elaborate the instability issue in dynamic processes, [16]–[18] applied the concept of equal area criterion (EAC) to analyse the transient stability of VSCs during LVRT. Nevertheless, the results were conservative since the proportional unit of PLL was ignored in the EAC method. Lately, the research group of X. Wang made innovative studies on the synchronization of grid-tied VSCs using the concept of phase portrait [19]–[22], which have created a new perspective for the transient stability studies of grid-tied VSCs. Besides, it should be noted that Lyapunov's direct method was also employed to assess the transient stability of grid-tied VSCs in [23]–[26]. Although transient stability can be judged through Lyapunov's direct method, the impacts of circuit parameters and controller parameters on the transient stability margin can only be investigated in a case-by-case way through the method, rather

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than evaluated systematically.

According to the literature review, although the dynamic synchronization process of VSCs has been investigated in [14]–[22], resynchronization principle of the VSCs during LVRT considering the impact of grid impedance on the PLL detecting ability has not been completely clarified. Furthermore, the effects of circuit parameters and controller parameters on the transient stability have not been extensively investigated. As an expanded version of our conference paper [27], this paper is devoted to filling this gap. Specifically, a reduced-order nonlinear model is derived and validated in Section II. A comprehensive stability analysis is performed in Section III, where the resynchronization principle is analysed through the spatial vector tracking relation from the PLL point of view. Also, the impacts of circuit parameters and controller parameters on the transient stability margin is quantitatively investigated. Sections IV and V show the simulation and experimental results, respectively, and Section VI concludes this paper.

II. SYSTEM MODELING

A grid-tied VSC system is shown in Fig. 1. PLL is utilized to detect the phase-angle and frequency of the VSC terminal voltage u_{abc} , and the estimated phase-angle θ_{pll} is then used as the angle reference for the current control module. Fig. 1(b) depicts the dynamic interaction between the PLL and the VSC terminal voltage. The output of the PLL guides the phase-angle of the output current which makes the grid impedance produce a voltage drop ΔU . The grid impedance voltage drop ΔU makes the terminal voltage U no longer stiff and highly sensitive to the output current once the grid impedance becomes considerable rather than ignorable.

When a grid fault occurs, a Thévenin equivalent circuit can be built from the fault point of view [5]. [5] indicated that the Thévenin equivalent grid impedance would become considerable if the grid fault is severe. In other words, severe faults would lead to weak connection between the VSC and the infinite-bus grid in the Thévenin equivalent circuit, even though the pre-fault grid is not weak [5].

Prior to modeling the VSC system for the transient stability analysis, several assumptions are made as follows [5]–[7], [12], [13], [16]–[22]:

- 1) The DC-link voltage of the VSC is considered to be constant, due to the fact that the configured chopper circuit [not shown in Fig. 1(a)] can maintain the DC-link voltage during LVRT.
- 2) The VSC with the current-controlled vector control can be regarded as a controlled current source, considering that the current loop bandwidth with appropriate current controller parameters is much higher than the PLL bandwidth.
- 3) Transmission line electromagnetic transient behaviors are neglected because of the fast dynamics.
- 4) The power grid is represented by an infinite bus with lumped impedance, and grid frequency dynamics are also neglected. Particular attention of this study is focused on the PLL dynamics.

A commonly used synchronous reference frame PLL (SRF-

Fig. 1. Grid-tied VSC system. (a) PLL-based current control. (b) Illustration of the dynamic interaction between the PLL and the terminal voltage, where U and I are the phasors of u_{abc} and i_{abc} .

Fig. 2. (a) SRF-PLL diagram. (b) Steady-state relationship between the terminal voltage U and the two reference frames. (c) Dynamic relationship between the terminal voltage U and the two reference frames. (d) Reduced-order nonlinear system model.

PLL) is depicted in Fig. 2(a), where ω_0 denotes the nominal frequency. Fig. 2(b) and (c) show the relationship between the PLL d - q reference frame and the infinite-bus X - Y synchronous reference frame. In the steady state, direction of the terminal voltage vector U coincides with PLL's d -axis, whereas they have different directions during dynamic processes. The included angle between the two reference frames in Fig. 2(b) [or (c)] is denoted δ and it can be accordingly obtained that

$$d\delta/dt = \omega_{pll} - \omega_g \triangleq \Delta\omega \quad (1)$$

where ω_{pll} represents the PLL frequency and ω_g represents the grid frequency, and the difference between the two is defined as $\Delta\omega$. Furthermore, according to Fig. 2(a), PLL dynamics can be described as follows,

$$d\Delta\omega/dt = d(\omega_{pll} - \omega_g)/dt = d\omega_{pll}/dt = k_p du_q/dt + k_i u_q \quad (2)$$

where k_p and k_i are the PLL parameters and u_q is the q -axis

voltage of the terminal voltage $\mathbf{u}_{abc}$.

As shown in Fig. 2(b) or (c), transforming the grid voltage U_g from the X - Y reference frame into the PLL d - q reference frame gives rise to the d -axis and q -axis voltages of U_g as follows,

$$\begin{bmatrix} u_{gd} \\ u_{gq} \end{bmatrix} = \begin{bmatrix} \cos \delta & \sin \delta \\ -\sin \delta & \cos \delta \end{bmatrix} \begin{bmatrix} U_g \\ 0 \end{bmatrix}. \quad (3)$$

While neglecting the electromagnetic transient behaviors of the transmission lines, the mathematical relation between the VSC terminal voltage $\mathbf{u}_{dq}$ and output current $\mathbf{i}_{dq}$ can be expressed as follows,

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} u_{gd} \\ u_{gq} \end{bmatrix} + R_g \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_{pll} L_g \begin{bmatrix} -i_q \\ i_d \end{bmatrix} \quad (4)$$

where $\mathbf{u}_{dq}$ and $\mathbf{i}_{dq}$ are the counterparts of $\mathbf{u}_{abc}$ and $\mathbf{i}_{abc}$ transformed into the PLL d - q reference frame, respectively. Besides, R_g and L_g represent the resistive and inductive components of the lumped grid impedance. It is noted that the grid impedance is from the Thévenin equivalent circuit, therefore it would change with a transmission line ground fault [5], [28].

From (3) and (4), it can be further derived that

$$u_q = R_g i_q + \omega_{pll} L_g i_d - U_g \sin \delta \triangleq a - b \sin \delta. \quad (5)$$

From (5), it can be found that a is an offset term in u_q , which is introduced by the grid impedance voltage drop. Detailed expressions of a and b are as follows,

$$\begin{cases} a = R_g i_q + \omega_{pll} L_g i_d = Z_g I \sin(\theta_Z + \theta_I) \\ b = U_g \end{cases} \quad (6)$$

where Z_g denotes the grid impedance magnitude; I denotes the current amplitude; θ_I and θ_Z (impedance angle) are expressed as follows,

$$\mathbf{I} = I \angle (\theta_I + \delta), \theta_I = \arctan(i_q/i_d) \quad (7)$$

$$\mathbf{Z}_g = Z_g \angle \theta_Z, \theta_Z = \arctan(\omega_{pll} L_g / R_g). \quad (8)$$

The differential equations (1) and (2) combining the algebraic equation (5) constitute the reduced-order nonlinear system model, as shown in Fig. 2(d). In addition, value of the currents i_d and i_q in the model should be stated, in order to analyse the transient stability based on the model. Since the VSC system is regarded as a controlled current source, it can be considered that the output current $\mathbf{i}_{dq}$ is directly specified by the current references. Taking into account the unity power factor control, the pre-fault current references can be denoted as

$$\begin{aligned} i_{d_normal} &= i_{d0} \\ i_{q_normal} &= 0 \end{aligned} \quad (9)$$

where i_{d0} denotes the pre-fault steady-state active current, and

TABLE I
VSC MODEL PARAMETERS

Parameter	Per-unit value	Parameter	Per-unit value
L_g	0.08	Residual grid voltage	0.05 or 0.10
R_g	0.30	k_p (PLL)	100
L_c	0.15	k_i (PLL)	1000
R_c	0.005	k_p (current controller)	2
i_{d_normal}	1.0	k_i (current controller)	10
i_{q_normal}	0.0	Simulation step size	5×10^{-6} s
i_{d_fault}	0.0	i_{q_fault}	-1.0

Fig. 3. Validation of the reduced-order model by comparison with the detailed model, where the grid voltage dips to 0.10 p.u.

the VSC outputs zero reactive current under normal operating conditions. The output current during LVRT conditions is directly determined by the grid codes. For example, i_q^* is set to -1.0 p.u. if the PCC (point of common coupling) voltage dips larger than 50% [3] and i_d^* is often set to zero considering the output current capability, i.e.,

$$\begin{aligned} i_{d_fault} &= 0 \\ i_{q_fault} &= -1 \text{ p.u.} \end{aligned} \quad (10)$$

To demonstrate the adequacy of the developed reduced-order nonlinear model, the model is validated by comparing its time-domain responses with those of the detailed electromagnetic transient (EMT) model. Parameters of the detailed model are summarized in Table I.

Figs. 3 and 4 give the simulation results. In Fig. 3, the grid voltage dips from the nominal condition to 0.10 p.u. at 0.3 s, and the VSC output current quickly changes in the meantime according to the reference. Specifically, the reactive current instantaneously changes from 0 to -1 p.u., and the active current changes from i_{d0} to 0. Fig. 3 shows that the PLL is able to quickly resynchronize with the grid after the grid voltage sag.

Fig. 4. Validation of the reduced-order model by comparison with the detailed model, where the grid voltage dips to 0.05 p.u., making the VSC system become unstable.

In Fig. 4, a more severe grid voltage sag than that in Fig. 3 occurs, i.e., only 0.05 p.u. residual grid voltage. Simulation results in Fig. 4 indicate that the PLL is not able to resynchronize with the grid after the grid voltage sag. Hence, the VSC system becomes unstable.

From Figs. 3 and 4, it can also be observed that the time-domain responses of the reduced-order model and those of the detailed EMT model are highly consistent, therefore verifying the adequacy of the reduced-order model. Based on the reduced-order model, the transient stability analysis can be easily performed.

III. TRANSIENT STABILITY ANALYSIS

The reduced-order model is comprised of (1), (2), and (5). (1) and (2) describe the PLL dynamic nonlinear characteristic, whereas the zero-crossing point of (5), i.e., $u_q = 0$, determines the steady-state equilibrium point of the system. The transient stability of the system will be analysed from two points of views, which are the equilibrium point analysis and the dynamic characteristic analysis.

A. Steady-State Equilibrium Point Analysis

According to (5), the steady-state equilibrium point of the VSC system satisfies the condition that

$$u_q = a - b \sin \delta = 0. \quad (11)$$

Several examples of the equilibrium point are depicted in Fig. 5, where there are two types of zero-crossing points. The small-signal stability analysis is performed to distinguish between the unstable equilibrium points (UEPs) and the stable

Fig. 5. Illustration of equilibrium points. (a) Grid voltage U_g decreases. (b) Grid impedance magnitude Z_g increases.

equilibrium points (SEPs). The small-signal state variables $\tilde{\delta}$ and $\Delta \tilde{\omega}$ can be denoted as follows,

$$\begin{cases} \delta = \delta_0 + \tilde{\delta} \\ \Delta \omega = 0 + \Delta \tilde{\omega}. \end{cases} \quad (12)$$

Based on the nonlinear model consisting of (1), (2), and (5), and the equilibrium point in (12), the small-signal model can be derived, as shown in (13).

$$\begin{bmatrix} \dot{\tilde{\delta}} \\ \Delta \tilde{\omega} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{k_i U_g \cos \delta_0}{1 - k_p L_g i_d} - \frac{k_p U_g \cos \delta_0 - k_i L_g i_d}{1 - k_p L_g i_d} \end{bmatrix} \begin{bmatrix} \tilde{\delta} \\ \Delta \tilde{\omega} \end{bmatrix} \quad (13)$$

Considering that $1 - k_p L_g i_d > 0$ almost always holds true, to meet the small-signal stability criterion, the following conditions should be satisfied,

$$\cos \delta_0 > 0 \quad (14)$$

$$k_p U_g \cos \delta_0 > k_i L_g i_d. \quad (15)$$

(15) can further give rise to

$$\cos \delta_0 > k_i L_g i_d / (k_p U_g) \approx 0 \quad (16)$$

which is approximately equivalent to (14). Thus, (14) indicates the zone where SEPs are located, as shown in Fig. 5.

From Fig. 5(a), it can be observed that the curve amplitude b decreases along with the decrease of the grid voltage U_g (because $b = U_g$). In Fig. 5(b), the absolute value of the offset term $|a|$ increases along with the increase of the grid impedance magnitude Z_g .

If $|a|$ is larger than b , caused by a quite severe grid sag or a considerable post-fault grid impedance, there will be no equilibrium point. Then, it will be impossible to maintain the stability of the system whether PLL [29] or frequency-locked loop (FLL) [30], [31] is adopted. The critical equilibrium point corresponds to $|a| = b$.

From Fig. 5, it can also be found that the smaller the absolute offset term $|a|$, and the larger the residual grid voltage amplitude b , the higher the stability margin. Besides, (6) indicates that four variables associated with the output current and the grid impedance have impacts on the offset term. Specifically, both a large current amplitude I and a large grid impedance magnitude

Fig. 6. Illustration of the dynamic synchronization processes of a VSC subjected to a grid voltage sag at t_1 and grid voltage recovery at t_3 . Note that a_N and a_F denote the offset terms corresponding to the normal and fault operating conditions, respectively.

Z_g are able to facilitate a large offset term, which accordingly shrinks the stability margin.

When it comes to the relation between the offset term and θ_l or θ_z , (6) manifests that the relation is not linear. In particular, the offset term equals zero only if $\theta_l + \theta_z = 0$. In general, $\theta_l = -0.5\pi$ when $i_d = 0$ is set during LVRT. In this regard, the offset term equals zero only if $\theta_z = 0.5\pi$. Nonetheless, θ_z is random in actual grid fault scenarios, which is determined by actual fault points and short-circuit resistance.

B. Resynchronization Principle Analysis

Without taking into account the impact of the grid impedance on the PLL, grid synchronization principle as well as dynamic performance of PLLs have been extensively investigated in previous studies [29]. However, it is not enough to guarantee the transient stability of the VSC systems, especially for ones connected to the high-impedance weak grid. Here, from the perspective of spatial vector tracking relation, a resynchronization principle analysis of the VSCs during LVRT is conducted to clarify the stability principle associated with PLL's nonlinearity by considering the impact of the grid impedance.

In Fig. 2(d), the grid impedance introduces the offset term a into the input of the PLL. There is no doubt that the offset term makes the PLL no longer ideal since the input signal u_q is no longer a standard unbiased sinusoidal function related to δ . Therefore, it has effects on the synchronization performance of the PLL.

Fig. 6 illustrates an example of the dynamic synchronization process of a VSC subjected to a grid voltage sag and also a grid voltage recovery. When the grid voltage sag occurs at t_1 , the operating curve switches from the blue curve (Normal condition) to the orange curve (Fault condition), and the operating point steps from A to B . There are two steady-state equilibrium points, i.e., C and D , after the grid voltage sag. Note that point C is stable whereas D is unstable. Then, the

Fig. 7. (a) Spatial vector relation in the pre-fault steady state. (b) There are two steady-state equilibrium points after the grid voltage sag, i.e., U_{g1} (stable) and U_{g2} (unstable), where $\delta_1 + \delta_2 = -\pi$. (c) Spatial vector relation corresponding to the post-fault stable steady-state equilibrium point. (d) Dynamic synchronization process illustration.

operating point moves towards C because B is not a steady-state point, accompanied by a decelerating process of the PLL. The operating point crosses C at t_2 , thereafter the PLL frequency begins to increase due to u_q becomes positive. Finally, the operating point reaches the equilibrium point C due to the damping effects. It is supposed that δ would not exceed the UEP D in the accelerating process, otherwise the operating point will fall into the adjacent inversely regulating areas. When the grid fault is cleared at t_3 , similar dynamic synchronization process is performed.

Considering the impact of the grid impedance, resynchronization principle of the VSC is elaborated using spatial vector tracking relation. Fig. 7(a) shows the pre-fault steady-state spatial vector relation, where $\omega_g = \omega_{pll}$. Fig. 7(b) shows that there are two steady-state equilibrium points after the grid voltage sag. The grid impedance voltage drop ΔU is uniquely identified with respect to the d - q reference frame, provided that both grid voltage impedance Z_g and VSC output current

I are determined. The dashed circle denotes the grid voltage amplitude U_g , resulting in two intersections with the d -axis, hence corresponding to two grid voltage vectors, U_{g1} and U_{g2} . It has been known that only the equilibrium point corresponding to U_{g1} is stable.

Fig. 7(c) illustrates the post-fault steady-state vector relation, where $\omega_g = \omega_{pll}$. As shown in Fig. 7(d), the goal of the PLL is to track the determined voltage vector U , i.e., the post-fault steady-state terminal voltage vector, during the dynamic synchronization process. If the d -axis of the PLL reference frame surpasses the target vector U and the lead angle α is within the boundary, the PLL will decelerate. On the flip side, if the d -axis lags behind the target vector U and the lag angle is within the boundary, the PLL will accelerate.

It should be noted that the accelerating and decelerating areas are mismatched because of the offset term a in the PLL input signal u_q . Owing to the mismatched accelerating and decelerating areas, the lead angle α might become so large that it traverses the boundary and then falls into the adjacent inversely regulating areas. As a result, an additional round of tracking path is caused, which, unfortunately, leads to the accelerating and decelerating areas being further mismatched. Therefore, the tracking capability of the PLL is further deteriorated, and loss of synchronism (LOS) potentially occurs.

To sum up, the coordinate transformation (3) incorporates sinusoidal functions, hence introducing both periodicity and nonlinearity. The periodicity leads to the accelerating and decelerating areas being adjacent to each other. The nonlinearity causes the PLL dynamic performance inconsistency at different operating points. Given that the developed nonlinear model is second-order, it is feasible to elaborate the dynamic performance by using the concept of inertia and damping.

C. Damping Characteristic Analysis

Transform the developed nonlinear model into a typical form of motion equation as follows,

$$\begin{aligned} J_{eq} d\omega_{pll}/dt &= u_q - D_{eq} (\omega_{pll} - \omega_g) \\ d\delta/dt &= \Delta\omega \end{aligned} \quad (17)$$

where the equivalent inertia and damping coefficients are

$$\begin{aligned} J_{eq} &= (1 - k_p L_g i_d) / k_i \\ D_{eq} &= k_p U_g \cos \delta / k_i, k_i \neq 0. \end{aligned} \quad (18)$$

Actually, since $k_p L_g i_d \ll 1$, (18) can be further simplified as

$$\begin{aligned} J_{eq} &\approx 1/k_i \\ D_{eq} &= k_p U_g \cos \delta / k_i, k_i \neq 0. \end{aligned} \quad (19)$$

As shown in Fig. 6, the damping term plays an important role in weakening and gradually suppressing the oscillation during the dynamic synchronization process. If k_p equals zero, then D_{eq} will become zero, and it can be accordingly believed that the damping effect actually originates from the proportional unit of

Fig. 8. Change of D_{eq} with δ , where $D_{eq} > 0$ corresponds to positive damping zones whereas $D_{eq} < 0$ corresponds to negative zones.

the PLL. It should be noted that [16]–[18] employed the concept of equal area criterion to analyse the stability of grid-tied VSCs based on (17). Since the damping term was neglected, the results were relatively conservative.

According to (19), it can be found that a small k_p , a large k_i , and a small U_g are able to make the damping effect weak, therefore deteriorate the stability. Especially, the sign of the damping coefficient is directly decided by the PLL angle δ . Fig. 8 shows the relation between D_{eq} and δ . Once the operating point enters negative damping zones, loss of synchronism (LOS) is very likely to occur. In addition, (19) seemingly reveals that the grid impedance has no effect on the damping coefficient. However, it should be noted that grid impedance is able to produce impacts on the PLL angle δ , accordingly have impacts on the damping characteristics.

D. Inertia Characteristic Analysis

From (19), it can be found that the equivalent inertia coefficient J_{eq} is directly related to the integral coefficient k_i of the PLL. Specifically, J_{eq} is inversely proportional to k_i . Therefore, a large k_i is able to lead to a small J_{eq} , which, as a result, might cause potential oscillations with large amplitude. In other words, a large k_i is harmful to the stability of grid-tied VSC during LVRT.

IV. SIMULATION RESULTS

Simulations are conducted to verify the above results regarding the impacts of circuit parameters and controller parameters on the transient stability of VSCs. Simulations are performed based on a VSC switching-cycle average model with parameters given in Table I. On this basis, bandwidth of the PLL and the current loop can be calculated.

A. Different Grid Voltage Sags

Simulating three degrees of grid voltage sags, i.e., 85%, 90%, and 95%, the simulation results are shown in Fig. 9. It can be found that the VSC cannot resynchronize with the grid when the 95% grid voltage sag occurs. Actually, it is because that there is no equilibrium point after the grid voltage sag.

Besides, when the grid voltage dips 85% and 90%, it can be confirmed that there are indeed equilibrium points, and the system are stable in these two cases. It can also be found that a large residual grid voltage can not only help the present of post-fault equilibrium points, but also facilitate the damping effect for a fast convergence.

Fig. 9. Simulation results of 85%, 90%, and 95% grid voltage sags.

Fig. 10. Simulation results with different post-fault grid impedances, including $Z_g = 0.06 + 0.30j$, $0.08 + 0.30j$, $0.10 + 0.30j$, and $0.08 + 0.50j$.

To sum up, a large residual grid voltage after grid faults contributes to the enhancement of the transient stability.

B. Different Grid Impedance

Simulating four groups of grid impedance, i.e., $Z_g = 0.06 + 0.30j$, $0.08 + 0.30j$, $0.10 + 0.30j$, and $0.08 + 0.50j$ after the same 90% grid voltage sag with the same current reference $i_{d_fault} + ji_{q_fault} = 0.0 - 1.0j$, the simulation results are shown in Fig. 10. With the increase of the resistive component, it can be observed that the equilibrium point probably becomes absent, thus the system tends to become unstable after the fault.

Besides, Fig. 10 shows that the increase of the inductive component is also able to deteriorate the stability. Although the inductive component of the grid impedance has no effect on the existence of equilibrium points, it is able to affect the initial system state. Specifically, a larger inductive component of the grid impedance makes the initial system state move away

Fig. 11. Simulation results with different current references, including $0.0 - 1.0j$, $0.0 - 0.9j$, and $0.10 - 0.9j$.

from the post-fault equilibrium point, hence leading to a larger accelerating area, as shown in Fig. 6.

To sum up, the transient stability margin is reduced with the increase of grid impedance, either in the resistive or the inductive component. In other words, the weak connection between VSCs and the power grid is indeed harmful to the transient stability of VSCs.

C. Different Current References

Simulating three groups of current reference, i.e., $i_{d_fault} + ji_{q_fault} = 0.0 - 1.0j$, $0.0 - 0.9j$, and $0.10 - 0.9j$ after the same 90% grid voltage sag with the same post-fault grid impedance $0.1 + 0.3j$, the simulation results are shown in Fig. 11. For the first group of current reference, there exists a critical equilibrium point. The system becomes unstable because of overshoot. For the second group, although the stable equilibrium point is recreated by reducing the reactive current and thereby reducing the offset term in the q -axis voltage u_q , the system still becomes unstable due to the small stability margin. Furthermore, an additional active current is generated in the third group, which further reduces the offset term in u_q , and the system accordingly becomes stable.

To sum up, a small reactive current as well as a nonzero active current is conducive to improving the stability margin. It is because they can help to decrease the offset term in the q -axis voltage.

D. Different PLL Parameters

Figs. 12 and 13 show the impacts of PLL parameters on the transient stability. In Fig. 12, the system with $k_p = 80$ becomes unstable after the grid voltage sag, since a small proportional coefficient gives rise to a small damping coefficient [see (19)], therefore a poor damping effect. The stability is improved with the increase of the PLL proportional coefficient.

Fig. 12. Simulation results with different PLL proportional coefficients, including $k_p = 200$, 120, and 80, but the same integral coefficient $k_i = 1000$.

Fig. 13. Simulation results with different PLL integral proportional coefficients, including $k_i = 500$, 1000, and 1500, but the same proportional coefficient $k_p = 80$.

Fig. 13 shows that the stability is enhanced with the decrease of the PLL integral coefficient. Actually, it is because that a small integral coefficient yields a large damping coefficient. To sum up, the above results completely coincide with the findings from (19), i.e., both a large k_p and a small k_i during grid voltage sags, are able to make the damping effect strong and therefore improve the transient stability.

It should be noted that the above results are only valid under the condition of ignorable current control dynamics. Once the PLL bandwidth overlaps with the current control bandwidth, both PLL dynamics and current control dynamics should be taken into account while analysing the transient stability.

V. EXPERIMENTAL RESULTS

The stability analysis has also been verified in an actual three-phase 1.0 kW PWM converter system with a DSP digital control platform. The setup of the experimental system is shown in Fig. 14 with parameters given in Table II. Note that both the resistive and inductive components of the grid impedance are large enough to mimic quite weak connection between the VSC

Fig. 14. Experimental setup.

TABLE II
EXPERIMENTAL SYSTEM PARAMETERS

Capability	1 kW	
Nominal line-to-line voltage	170 V	
Grid resistance	3.5 Ω	0.121 p.u.
Grid inductance	20 mH	0.217 p.u.

and the grid.

From the viewpoint of enhancing the transient stability of grid-tied VSCs, regulating the current references and PLL parameters is a very easy way. For this purpose, two experimental cases are set to further verify: 1) the impact of current references and 2) the impact of PLL parameters on the transient stability of grid-tied VSCs.

A. Impact of Current References

The main attention of this case is focused on the active current reference, considering that there is almost no strict requirement on the active current output in most of the current LVRT codes. In Fig. 15(a), (b), and (c), the active current references are 0.0, 1.0, and 1.6 A, respectively, with the same reactive current reference of -5.1 A during the grid voltage sag from 170 V to 14.2 V. As shown in Fig. 15(a) or (b), the system is unstable with the active current of 0.0 A or 1.0 A, because there is no equilibrium point. Note that k_i is set to zero here, therefore the PLL frequencies undergo continuous oscillations instead of gradual deviations. In Fig. 15(c), the system is stable when the equilibrium point is recreated by a larger active current than that in Fig. 15(a) and (b).

B. Impact of PLL Parameters

The main attention of this case is focused on the PLL integral coefficient as an example. In Fig. 16(a), (b), and (c), the PLL integral coefficients are 2000, 1500, and 1000, respectively, with the same PLL proportional coefficient of 25 during the grid voltage sag. From Fig. 16, it is noticed that the stability is enhanced with the decrease of the PLL integral coefficient, due to the increase of the damping effect. The experimental results accordingly further verify the stability analysis.

Fig. 15. Experimental results with different active current references during a grid fault. (a) $i_{d_fault} = 0.0$ A. (b) $i_{d_fault} = 1.0$ A. (c) $i_{d_fault} = 1.6$ A.

Fig. 16. Experimental results with different PLL integral coefficients during a grid fault. (a) $k_i = 2000$. (b) $k_i = 1500$. (c) $k_i = 1000$.

VI. CONCLUSIONS

Loss of synchronism of the grid-tied VSCs probably occurs during severe grid voltage sags. This paper develops a reduced-order nonlinear model to describe the dynamic synchronization process of VSCs. Based on the model, it is clarified that the post-fault grid impedance voltage drop has a significant effect on the transient stability, since it introduces an offset term in the q -axis voltage (i.e., PLL input signal). By determining the target terminal voltage vector, the resynchronization principle is analysed from the PLL point of view, according to spatial vector tracking relation. Moreover, from the perspective of equilibrium points and dynamic characteristics, the impacts of grid parameters, current references, and PLL parameters on the transient stability are analysed and verified. The results of this study could be conducive to guiding the designs of current references and PLL parameters for efficiently addressing grid faults.

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