Improving synchronization stability of grid connected converters by virtual impedance

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Abstract
With the increasing penetration of inverter based distributed generation, recent grid codes do not permit the disconnection of converters as soon as fault happens. Considering the fact that electrical grids are not purely inductive, the grid connected converters face instability issues by fault occurrence. Converters applying Phase Lock Loop (PLL) are not able to synchronize with the weak grid during deep low voltage faults. This paper proposes a novel control strategy based on virtual impedance to maintain the synchronization of grid connected converters during heavy decrease of the grid voltage. Utilizing a virtual impedance and the measured current at the point of common coupling, the inverter can be virtually synchronized to a point which has a stronger connection. The virtual impedance can be a rough estimation of the line impedance or resistance from point of common coupling to the fault point. Furthermore, to avoid the need for impedance estimation, a simple technique is also proposed. Simulation results with MATLAB confirm the competence of the proposed method in improving the synchronization stability of the grid connected converters.

1 | INTRODUCTION

Deficit in fossil fuel energies and the environmental pollution caused by them is undoubtedly a global issue leading to the new trend toward renewable energy generation resources such as wind and solar. This new kind of power generation is called distributed generation and these energy resources are called distributed energy resources (DERs) [1]. Conventionally, grid operators did not allow the operation of distributed generators (DGs) in case of fault occurrences. Consequently, DGs had to be disconnected from the grid if there were any faults. However, in the recent years, with the considerable growth in the proportion of DGs contribution in supplying the energy in power systems, losing DGs during the faults may be critical and cause various problems for the power systems. Therefore, uninterruptable operation of DGs is demanded [2].

Some of the grid standards, such as E. ON of Germany, state that DGs should inject reactive current to the grid during low voltages. This capability of microgrids is called low voltage ride through (LVRT) [3]. Figure 1 represents the LVRT curve defined by German grid codes. As seen, the required reactive power is determined in accordance with the percentage of the voltage sag. For instance, if the voltage is <50%, the converter should dedicate all its capacity for reactive power generation.

LVRT control methods should be able to detect voltage variations and determine active and reactive power references as quickly as possible. They should also limit converter current to avoid overcurrent and regulate DC link voltage [4]. On top of that, controllers should work under different types of faults and system parameter variations. Several robust and computational methods such as neural and sliding mode control are proposed by researchers to improve LVRT capability of DGs [5, 6]. Some articles reviewed existing literatures about LVRT. In [7–11] different aspects of LVRT capability in photovoltaic and wind systems are reviewed.

A serious issue in achieving the LVRT capability of grid connected converters is the stability. Different types of instabilities such as small signal and large signal (transient) are modelled and analysed in the literatures [12]. There exist a great deal of researches on the small signal stability of the grid connected DGs [13]. In [14] it is concluded that the risk that the current
controller causes small signal instability would be higher as the bandwidth of PLL is larger. However, small signal analysis is only valid around the steady state operating point. Thus, recently much attention is also paid to the transient stability.

In [15], a 5th order nonlinear model is studied for voltage source converter (VSC) and it is deduced that transient stability of VSCs can be determined based on existence of system states inside or outside of the equilibrium point area. This paper also states that there is a discontinuity in the phase and amplitude of the output voltage of the converter by fault occurrence and removal. Another result of this model is that the system behaviour can be well described by DC link time scale dynamics. In [16] improvement of LVRT and transient stability is done by coordination between power system stabilizer (PSS) and static synchronous series capacitor (SSSC) controllers. In [17], based on a large signal model, a comparison is done between transient stability of four different grid forming controllers, namely the power synchronization control, the basic droop control, the droop control with low pass filters and the virtual synchronous generator. The first two methods are able to obtain a stable operation until there is an equilibrium point. Researchers in [18] studied the momentary cession capability of inverters and the undesirable effect of this capability on the transient stability is reported.

Many of energy resources are located in remote places. As a consequence, the large distance for energy transmission makes weak connections of DGs to the grid. Researchers’ results show that the weak connection has a negative influence on the system stability. It is also proved that in case of deep low voltage faults, PLL of converter controllers may lose resynchronization stability which is called loss of synchronism (LOS) [19]. However, LOS can also happen in other control structures not applying PLL [20]. As an example, synchronization instability can take place for droop controller when the current saturates [21].

During LVRT, terminal voltage of converters is sensitive and shows a lot of variations by the current injection. This gives rise to the converter difficulties with resynchronization by PLL. Various approaches exist for the synchronization stability analysis of the grid connected converters; steady state, quasi-static large signal, equal area criterion and phase portraits [19]. To overcome LOS, in [22] the equal area criterion method is applied. The method is based on altering the reference of active power during low voltage occurrence. In [23], the mechanism of the synchronization instability is studied by a simple method called voltage-vector-triangle graphic (VTG) not requiring much mathematical calculations. A criterion is also introduced in this article to assess the risk of instability during LVRT operation and a remedy is presented which requires the resistance to inductance ratio of the line.

A control strategy for improving the stability is applying virtual impedance in the control algorithm. An overview of virtual impedance based controllers for voltage and current source converters is presented in [24]. Shaping the output impedance of inverter is discussed in [25] and the concept of virtual impedance is applied to increase the stability of the system. The virtual impedance control for a desired power control of VSC at steady state is presented in [26]. Furthermore, to improve the transient performance of reactive power control an adaptive virtual impedance is introduced. Authors in [27] studied the small signal behaviour of wind turbines and made use of a virtual capacitance to resolve small signal instabilities by reducing the effect of high line impedance. The DFIG system impedance is extracted and an impedance reshaping controller based on a band pass filter and capacitor is introduced. The controller increases the phase margin of the DFIG system and consequently the small signal stability of system improves. However, an online grid impedance measurement is required to estimate the value of virtual capacitance and the transient stability of system is not discussed. In [28] a virtual impedance is employed to synchronize the control system of VSC to a stronger virtual point in the grid that the voltage is less influenced by the converter. A synchronous reference frame (SRF) PLL which uses both $d$ and $q$ axes is applied and impedance based compensation terms are added to it. The goal is to extend the steady state power transmission capacity in weak grids. The improvement of small signal stability range in a VSC HVDC is also analysed. To implement this approach a rough estimation of grid impedance is needed.

From the above mentioned references it can be deduced that several articles applied the concept of virtual impedance for increasing the stability of voltage source converters with the special attention to the small signal stability. To the best of our knowledge, the methods that deal with improving the synchronization stability of converters have not applied this technique. In this paper, the synchronization stability of the converters connected to the weak AC grids is studied. A novel control strategy based on the virtual impedance is proposed to synchronize the PLL with a stronger virtual point. If the virtual impedance is equal to the line impedance, this virtual point would be the fault point. In order to ensure the synchronization stability, the virtual impedance can also be equal to only the resistive part of the line impedance. However, in both cases, there is no need to obtain a precise estimation of the line impedance. Because the PLL only needs to be synchronized with a stronger point. Moreover, a simple method is proposed to eliminate the dependency of the proposed approach on impedance estimation. This novel approach employs the variations of PLL angular frequency for determining the virtual impedance. Hence, the synchronization stability even during deep low voltage cases is achieved without the need for impedance estimation.

The rest of this paper is organized as follows. Section 2 depicts the studied system together with the basic control strategy. The synchronization instability is further explained in Section 3. Section 4 elucidates the proposed method based on the virtual impedance. Simulation results are discussed in Section 5 and finally Section 6 deals with the conclusion.

2 | SYSTEM OVERVIEW

The structure of the studied system is illustrated in Figure 2. It is supposed that the inverter is connected to a constant DC link voltage which can be a wind turbine or a photovoltaic system. The DG is connected to the grid through a filter. The type of
FIGURE 1  LVRT curve for reactive power generation [3]

FIGURE 2  Structure of studied system with current reference extraction

filter here is selected to be LCL. This kind of filters took the place of L filters since LCL filters are able to make a smoother current from the output of voltage source converters [29]. $V_{PCC}$ is the voltage at the point of common coupling and $V_{fault}$ is the voltage at fault point. $Z (r + jωl)$ is the impedance of line from the point of common coupling to the fault point. In the proposed method if this value is known, the synchronization will be done with the fault point which will be further explained in the proposed method section. Also, $Z_{grid}$ is the impedance from the fault point to the main grid. The grid is supposed to be a weak resistive-inductive one with a low short circuit ratio (SCR) at the connection point. Since the probability of synchronization instability is higher for the weak grids. The synchronization instability phenomenon is fully explained in the next section.

Turning to the control system, the $V_{PCC}$ is measured and sent to the PLL. The applied phase locked loop is the common three phase synchronous reference frame (SRF-PLL) also known as the $dq$PLL which is the most widely used synchronization technique in the three phase power systems shown in Figure 3 [30]. Where $ω_c$ is the nominal angular frequency of the grid. References for active and reactive current in $dq$ reference frame are extracted as per grid codes. According to Figure 1, in normal grid operation the inverter generates only active power and no reactive power is injected to the grid. However, when the voltage is below 50%, all of the inverter capacity should be utilized for reactive power generation.

Extracted reference current are transferred to the stationary reference frame of $αβ$ applying the output phase of PLL ($θ_{PLL}$). The converter should be able to track the current reference signals. Thus, the current control loop shown in Figure 4 is employed. The measured currents are transferred to the $αβ$ reference frame and are subtracted from the reference signals. The difference enters a proportional resonant (PR) controller which has a good ability in tracking the sinusoidal signals [31]. Finally, the switching signals are generated by the space vector modulation.

By this way, the grid connected voltage source converter is able to inject the desired active and reactive power under the different conditions of the grid voltage. However, to achieve the LVRT capability the converter should be at first stable and synchronize with the grid. This issue is the main focus of this paper and is further discussed in the next section.

3 SYNCHRONIZATION INSTABILITY

The strength of connection between the PCC and the grid is defined by short circuit ratio (SCR) at PCC. A low SCR is due to the high grid impedance that causes the instability of the PLL or LOS. As it was mentioned previously, synchronization instability occurs in the weak grids during deep low voltage faults and PLL is not more able to remain synchronous with the grid. According to Figure 2 one can write:

$$V_{fault} = V_{PCC} - ZI \quad (1)$$

When the grid impedance is purely inductive ($0 + jωl$) and only reactive power is injected to the grid there will not be any instability. The Voltage diagram under this circumstance is shown in Figure 5. As it is seen the voltage at PCC ($V_{PCC}$) and the voltage at fault point ($V_{fault}$) are in the same direction. Thus, there is no need for active power exchange with the grid.

In another case, if the grid impedance contains also resistance ($r + jωl$), i.e. resistive-inductive grid, and only reactive power is
injected, there exist the risk of synchronization instability. Figure 6 demonstrates the voltage diagram. The grid voltage reduction is severe and the grid cannot provide the necessary active power. Hence, the converter that is exclusively injecting reactive power, on the basis of grid codes instructions (illustrated in Figure 1), is not able to remain synchronous. As a result, LVRT capability will not be attained anymore.

As a solution, active power should also be injected leading to the reduction of phase difference between \( V_{PCC} \) and \( V_{fault} \). In [23] a method is introduced that enhances the synchronization stability of the converter by selecting the ratio of active and reactive current references as:

\[
\frac{i_q}{i_d} = -\frac{\omega_l}{r} \tag{2}
\]

By choosing current references as Equation (2), \( V_{PCC} \) and \( V_{fault} \) will have a same direction. The voltage diagram is shown in Figure 7. By this strategy, in spite of grid code requirements all the inverter capacity is not used for reactive power generation. So the maximum voltage support for LVRT cannot be achieved. However, exchanging active power is essential to protect the stability of converter [19].

From the above mentioned discussions it can be concluded that the impedance that influences the synchronization stability of the converter is the impedance seen from PCC to the fault location. If the fault location is in a large distance from the PCC, the line impedance is higher and the risk of instability is more. However, in this paper a method based on virtual impedance is proposed to maintain the synchronization of the converter without being effected by different fault locations.

4 | PROPOSED METHOD

In this paper a novel method based on virtual impedance technique is proposed to enhance the synchronization stability of grid connected converters. A virtual impedance is employed in the PLL control loop during fault occurrence. Instead of synchronizing the PLL with the PCC, the synchronization is done with a virtual point that has a stronger connection. At first, it is assumed that the value of the line impedance is known and then the method is further extended to remove the need for impedance estimation.

As mentioned, initially it is presumed that the virtual impedance \( (Z_{virtual}) \) equals the line impedance \( (Z) \). If the input voltage of PLL is the virtual voltage drop \( (Z_{virtual} I) \), subtracted from \( V_{PCC} \) rather than \( V_{PCC} \), the synchronization will be done with the fault point which has a constant frequency and is not affected by the line impedance. One can write:

\[
Z_{virtual} = r_{virtual} + j\omega_{l_{virtual}} = Z = r + j\omega_l \tag{3}
\]

The input of PLL can be written as:

\[
V_{PCC} - Z_{virtual} I = V_{PCC} - ZI = V_{fault} \tag{4}
\]

Supposing that the virtual impedance is precisely the line impedance, the voltage diagram of the system can be drawn as Figure 8. Although references of active and reactive power are zero and \(-1 \) p.u. respectively \((I_d^* = 0, I_q^* = -1 \) p.u.), the active power will also be exchanged. The reason is that the PLL is synchronized with the \( V_{fault} \) and not the \( V_{PCC} \).

Applying the proposed strategy, the effect of the line impedance that is the main reason for the instability phenomenon can be compensated. It should be mentioned that inexact estimation of impedance will not affect the viability of the proposed method. As the converter will be synchronized with a stronger point and not necessarily the fault point.

To execute the proposed approach, current at PCC should also be measured since it is used as the input of PLL (see Equation (2)). To simplify the calculations, measured currents can be first transferred to \( dq \) reference frame. Only effective parameters in \( q \) axis voltage \( (V_q) \) can be added to the PCC voltage. As PLL uses only \( V_q \) for synchronization, according to
Equation (4) one can write the input of PLL as:

$$V_{\text{PCC}} - Z_{\text{virtual}}I = V_{\text{PCC}} - (r_{\text{virtual}} + j\omega l_{\text{virtual}})I$$

(5)

Transferring the voltage and current to $dq$ reference frame, PLL input in $q$ axis can be written as

$$V_{\text{PCC}q} - r_{\text{virtual}}I_q + \omega l_{\text{virtual}}I_d$$

(6)

where $V_{\text{PCC}q}$ is the $q$ axis of voltage at point of common coupling, $I_q$ and $I_d$ are $q$ and $d$ axis of injected current by the converter respectively.

The proposed PLL based on the virtual impedance is demonstrated in Figure 9. Applying the proposed strategy, the converter can effortlessly be synchronized with a virtual point and inject the desired active and reactive power even during severe low voltage faults.

Up to now, it was supposed that the line impedance ($r + j\omega l$) is known and the virtual impedance equals this estimated value. But if the virtual impedance is selected as only the resistive part ($Z_{\text{virtual}} = r$), the voltage diagram can be drawn as Figure 10. It is seen that the synchronization point is not $V_{\text{fault}}$ but a point in the same direction of $V_{\text{fault}}$. Therefore the synchronization can also be done only with knowing the resistive part of the line impedance. It should be noticed that same as the previous part, there is no need to have a precise estimation of the line resistance. Reducing the effect of resistance can certainly enhance the synchronization stability. Figure 11 shows the structure of proposed PLL applying only the resistive part of impedance estimation.

In the next step, to remove the reliance of the proposed method on the impedance estimation a simple strategy is proposed. Supposing the phase difference between $V_{\text{PCC}}$ and $V_{\text{fault}}$ to be $\delta$, one can write:

$$\omega_{\text{fault}} - \omega_{\text{PCC}} = \frac{\Delta \delta}{\Delta t}$$

(7)

where $\omega_{\text{fault}}$ and $\omega_{\text{PCC}}$ are the angular frequency at the fault point and PCC respectively. If $\delta$ variations (Equation (7)) equals zero, it means that the frequency at PCC is not changing and there is no synchronization instability. If the difference of $\omega_{\text{fault}}$ and $\omega_{\text{PCC}}$ passes through a PI controller, the PI output can be used as the virtual resistance. When the frequency at PCC ($\omega_{\text{PCC}}$) starts falling, the difference will be more and automatically a higher value for resistance enters the control loop. As the difference is less, the virtual resistance will decrease. Figure 12 demonstrates the proposed control method. $\omega_{\text{fault}}$ is considered to be the nominal grid angular frequency. The difference between $\omega_{\text{fault}}$ and output $\omega$ of the PLL determines the virtual resistance eliminating the requirement of line impedance estimation.

5 | SIMULATION RESULTS

To verify the validity of the proposed method, the system shown in Figure 2 is simulated in MATLAB/Simulink. Table 1 presents the studied system parameters. Table 2 displays as well the control parameters of the PLL and the PR controller in the current control loop.

At first, the conventional control algorithm, without virtual impedance, is employed to observe the stability of converter during low voltage faults. It is supposed that there is no fault in the grid and the voltage is at its rated value. The converter exploits all its capacity for active power injection to the grid and no reactive power is generated. It is supposed that a three-phase symmetrical fault occurs at 0.5 s and the voltage drops
TABLE 1 Parameters of studied network

| Symbol | Explanation                  | Value  |
|--------|------------------------------|--------|
| $S_b$  | Rated power                  | 7.35 kVA |
| $V_b$  | Nominal grid voltage (l-l, rms) | 400 V   |
| $F_0$  | Rated frequency              | 50 Hz  |
| $V_{DC}$ | DC link voltage             | 650 V  |
| $f_{sw}$ | Switching frequency          | 10 kHz |
| $L_{cf}$ | Filter Inductance of converter side | 5 mH   |
| $L_{gf}$ | Filter Inductance of grid side | 3 mH   |
| $C_f$  | Filter capacitor             | 2 $\mu$F |
| $l_g$  | Inductance of line           | 5 mH   |
| $r$    | Resistance of line           | 1 \(\Omega\) |

TABLE 2 Control parameters

| Symbol | Explanation                  | Value  |
|--------|------------------------------|--------|
| $K_p$  | Proportional gain of PLL     | 2      |
| $K_i$  | Integral gain of PLL         | 25     |
| $K_{pr}$ | Proportional gain of PR controller | 20   |
| $K_r$  | Resonant gain of PR controller | 10e3       |

...to 0.4 p.u. (the voltage amplitude changes from 326.6 to 130.6 V). Simulation results are exhibited in Figures 13 and 14. As it is seen, the converter can stay synchronized with the grid. As per the grid codes, the converter generates only reactive power to ensure that the converter has the maximum support of voltage for LVRT capability.

In another case, a more severe symmetrical three phase fault takes place and the grid voltage drops to 0.05 p.u. at 0.5 s. But in this case, the PLL cannot remain synchronized. The result is demonstrated in Figure 15. As it is evident, at 0.5 s the frequency at PCC starts falling and the converter fails to remain connected to the grid.

Now turning to the proposed method, instead of synchronizing the PLL with the PCC, the PLL is synchronized with a virtual point that has a stronger connection. Supposing to know the line impedance \((r + j\omega l_g)\) this virtual point will be the fault point. In a same condition as the previous case, at 0.5 s the voltage falls to 0.05 p.u. The virtual impedance is chosen to hold the line impedance value. The output frequency of PLL is shown in Figure 16. It is evident that the proposed control method can maintain the synchronization. The exchanged active and reactive powers are shown in Figure 17. It should be noticed that...
the active power is not zero in this case, about 340 W, and reactive power is about 930 Var.

To further investigate the infallibility of the proposed method, the virtual impedance is chosen to be only resistive and not equal to the resistive part of the line impedance. The output frequency of PLL is shown in Figure 18 when $Z_{\text{virtual}} = 0.6$ ohms (the line impedance is $1 + j1.57$). As it was expected the PLL can still stay synchronized.

To remove the need for impedance estimation the controller shown in Figure 12 is applied. The same fault occurs at 0.5 s and voltage drops to 0.05 p.u. To better observe the controller performance, the proposed controller starts working with a delay at 1 s after the output frequency fell. The line resistance is 1 ohm but the controller has no information of this value. Figure 19 illustrates the respective result. As it is demonstrated, the conventional controller cannot handle the fault and the frequency plunges. Conversely, the frequency reaches the desired level as the proposed technique operates.

To more examine the viability of the control strategy without impedance estimation, the line resistance is picked to be 4 ohms. The fault happens at 0.5 s and the proposed controller starts working as the previous case at 1 s. The PLL response is displayed in Figure 20. The proposed controller is able to maintain the converter synchronization.

Finally, to compare the proposed method with the existing remedy in [23] for synchronization stability, the same fault is studied (symmetrical three phase drop to 0.05 p.u.). This time to stabilize the converter when the fault happens, the reference currents follow Equation (2)

Applying this control strategy, when the fault is detected the active and reactive current references are $0.537$ and $-0.843$ p.u. respectively ($I_d^* = 0.537$, $I_q^* = -0.843$ p.u.) and the converter remains stable. The injected active power is 530 W and reactive power is 840 Var. In comparison with the proposed method, less reactive power is exchanged which may be considerable to obtain the LVRT capability.

6 Conclusion

In this paper, a novel method is proposed to enhance the stability of weak AC grid connected converters during deep low voltage faults. The method is based on applying a virtual impedance to synchronize the grid with a virtual stronger point. If the virtual impedance is selected to have the same value as the line impedance, the stronger point is where the fault happened. Alternatively, the virtual impedance can equal only the resistive part of impedance line. In this case, the synchronization point will be in the same direction as the fault point and can insure the stability. However, there is no need to estimate the line impedance accurately. Only a rough approximation for the virtual impedance can reduce the effect of line impedance and greatly enhance the converter synchronization stability. Furthermore, to deal with the reliance of the proposed method on line impedance a simple technique is proposed that automatically determines a proper value for the virtual impedance. Simulation results verified the effectiveness of the proposed approach. The current references are satisfactorily extracted and tracked without altering system control parameters. The synchronization stability is achieved even during severe low voltage faults with injecting a little active power.

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