Impact of Current Transients on the Synchronization Stability Assessment of Grid-Feeding Converters

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***Abstract*— The synchronization instability in the presence of a fault is a main issue for the dynamic behavior and control of grid-feeding converters. In the literature, the synchronization stability assessment is carried out considering the dynamics of Phase-Locked Loops (PLL) but the transients of converter currents are neglected. The letter shows that such a simplification leads to inaccuracies and, thus, the current transients cannot be neglected. The letter proposes a model to reflect the effect of such current transients on the converter synchronization and using this model, a novel stability assessment method is obtained with high accuracy, whose features are duly discussed in the case study via a comparison with the EMT simulation results.**

***Index Terms*—Synchronization Stability, Grid-feeding Converter, Phase-Locked Loop, Current Transients.**

I. INTRODUCTION

THE majority of renewable sources are interfaced through 'grid-feeding/following' converters, which use a Phase-Locked Loop (PLL) for the synchronization and aims to inject the assigned power or current into the grid [1]. However, during a contingency, grid-feeding converters may lose synchronization with the grid and lead to power oscillations due to the PLL failure [2]. Different PLL implementations to counteract voltage sags have been tested in [3]. However, the full understanding of the synchronization stability of the grid-feeding converter is still an open question. Reference [4] provides an overview of the previous assessment of synchronization stability. Reference [5] proposes a steady-state analysis, which studies whether there is a stable operating point after the fault. Even though a stable operating point exists, the converter may still not approach this point during the fault and may lose synchronization. Taking into account PLL dynamics, reference [6] proposes a Quasi-Static Large-Signal analysis, [7] proposes an Equal Area Criterion and [8] proposes a phase portrait approach. According to the comparison amongst these methods [4], the Quasi-Static Large-Signal is more precise than other methods.

Since the dynamics of the current controller of the grid-feeding converter is much faster than the PLL mechanism, all methods outlined above neglect the current controller transients and make an assumption that the converter works on the constant current mode. Consequently, the model of the grid-feeding converter synchronization mechanism can be simplified to 2nd-order [6]. It is certainly true that, in some cases, the inductance of the filter is large and the time constant of the current controller is small. However, if these conditions are not satisfied, the transients of the current controller are significant and cannot be neglected. The grid-feeding converter although using current control, is still based on the voltage source converter, for which at the instant of the fault, its terminal voltage cannot step change but remains fixed until the next modulation of the PWM. In this circumstance, existing synchronization stability assessment methods are not accurate. Based on the Quasi-Static Large-Signal method, this letter at first proposes a model to highly reflect the converter synchronization transients and then using this model, can assess the converter synchronization stability.

II. GRID-FEEDING CONVERTER

The grid-feeding converter aims to control the output current i_d, i_q to track its reference i_d^*, i_q^* by actually varying the terminal voltage v_{cd}, v_{cq}. In order to track the reference current, the converter applies the current controller as follows:

$$\begin{cases} v_{cd}^* = K_{pc}(i_d^* - i_d) + K_{ic}\gamma_d - \omega_{pll} l_f i_q \\ v_{cq}^* = K_{pc}(i_q^* - i_q) + K_{ic}\gamma_q + \omega_{pll} l_f i_d \end{cases} \tag{1}$$

$$\begin{cases} \dfrac{d\gamma_d}{dt} = i_d^* - i_d \\ \dfrac{d\gamma_q}{dt} = i_q^* - i_q \end{cases} \tag{2}$$

where K_{pc}, K_{ic} are the PI controller parameters, ω_{pll} is the converter frequency, and l_f is the filter inductance.

Figure 1 shows the control structure of the grid-feeding converter, where a synchronous reference frame PLL (SRF-PLL), which is detailed in Fig. 2, is used to detect the phase at the point of the common coupling (PCC) for grid synchronization, where l_g is the transmission line impedance of the converter connecting to the grid. When the phase is locked ($v_q = 0$), the converter active and reactive current is decoupled.

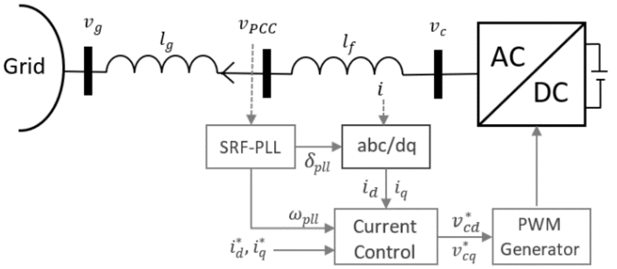


Fig. 1. Grid-Feeding Converter system structure

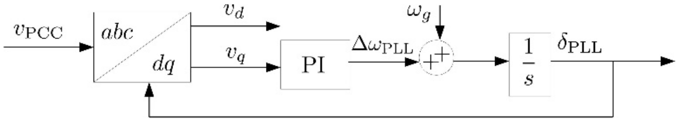


Fig. 2. SRF-PLL structure

III. CONVERTER SYNCHRONIZATION STABILITY ASSESSMENT

A stable synchronization of the grid-feeding converter ($\omega_{pll} = \omega_g$) relies on the convergence of the PLL. Typically, the assessment of the PLL stability only needs to consider the PCC fault voltage. However, the assessment of synchronization stability is different, in that it needs also to consider the state of the grid and the transmission line impedance. The line impedance has a negative effect on the synchronization stability, which will be discussed latter.

Referring to Fig. 1, the relationship between the PCC voltage and grid voltage is as follows:

$$\overrightarrow{v_{PCC}} = \overrightarrow{v_g} + \vec{\imath} * \mathrm{j}\omega_{pll} l_g \tag{3}$$

Assuming that the phase angle of the PCC bus voltage is the reference angle, the phase of the grid voltage is $-\delta_{pll}$. Then, using a dq-axis reference frame, (3) can be rewritten as follows:

$$v_q = V_g \sin(-\delta_{pll}) + \omega_{pll} l_g i_d \tag{4}$$

A successful synchronization ensures $v_q = 0$ after a contingency in the loop of Fig. 2. Note that due to the harmonics, v_q cannot be exactly zero in practice. However, this letter focuses on the fundamental frequency synchronization, and we thus assume that, thanks to the action of the PLL, v_q is null in steady state. The synchronization transients (3) can be divided into a grid-synchronization loop and a self-synchronization loop, where the grid-synchronization loop is the negative-feedback used to cancel positive-feedback effects from the self-synchronization loop so that overall v_q is regulated to zero. During a transient of the grid state change, e.g. a voltage sag, v_q changes resulting in a transient $\Delta\omega_{pll}$. Thus for example, if $\Delta\omega_{pll}$ is positive, δ_{pll} will continuously increase. In a "healthy" PLL, the increase in δ_{pll} can cancel the effect from the positive $\omega_{pll} l_g i_d$. However, if the phase δ_{pll} is over 90° while $\omega_{pll} l_g i_d$ has not been canceled, then a further increase in δ_{pll} leads to a $V_g \sin(-\delta_{pll})$ reduction, which can never cancel the effect from $\Delta\omega_{pll}$ thus resulting in the synchronization instability.

In the remainder of this section, we first outline the Quasi-Static Large-Signal analysis discussed in [6] as it serves as starting point for the proposed converter stability assessment, which is given in Section II.B.

A. *Quasi-Static Large-Signal analysis*

The assessment of the synchronization stability is to determine whether the phase δ_{pll} converges during the fault. The present assessment methods, Quasi-Static Large-Signal (QSLS) analysis, Equal Area Criterion and phase portrait assume that the current i_d, i_q remains fixed, i.e., $i_d = i_d^*$ in (4), during the transient of the synchronization. This is because the time constant of the current controller is much faster than that of the PLL. Therefore, only δ_{pll} and ω_{pll} are variables in (4), which leads to:

$$v_q = V_g \sin(-\delta_{pll}) + (\omega_g + \Delta\omega_{pll}) l_g i_d^* \tag{5}$$

Where $\Delta\omega_{pll} = \omega_{pll} - \omega_g$.

According to (5), the large-signal model of the PLL, considering converter connection to the grid through a transmission line, is given in Fig. 3, where the grid-synchronization is indicated by $V_g \sin(-\delta_{pll})$, and the self-synchronization is indicated by $(\omega_g + \Delta\omega_{pll}) l_g i_d^*$. Since the converter output angle is defined to be zero, then the phase error is $0 - \delta_{pll} = -\delta_{pll}$.

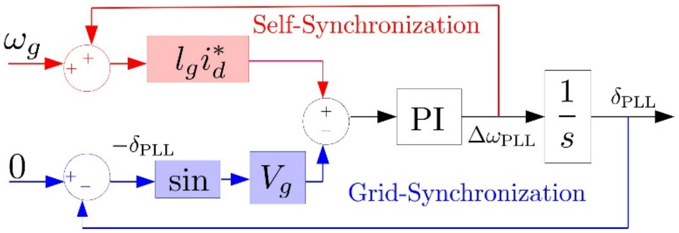


Fig. 3. Quasi-static large-signal model of the PLL [6]

In Fig. 3, the self-synchronization loop only contains the transient $\Delta\omega_{pll}$ movement. However, the grid-feeding converter is based on the voltage source converter (VSC), for which the terminal voltage v_{cd}, v_{cq} is changed only by the current controller (1,2). At the instant of the fault, the PWM of the converter does not change and the converter terminal voltage remains fixed. As a consequence, the current at this instant step increases.

Compared with the assumption of a fixed current in the previous methods, this transient current leads to a larger positive feedback introduced by the self-synchronization loop $\omega_{pll} l_g i_d$, which results in a larger δ_{pll} during the transient. In other words, the transient current has the potential to lead to synchronization instability, and this aspect cannot be assessed by previous analysis methods, e.g. Fig. 3.

B. *Proposed synchronization stability assessment*

In this section, we take in account the current transients and propose an improved method for synchronization stability assessment. Defining $\Delta i_d, \Delta i_q$ as the transient current change, i.e. $\Delta i_d = i_d^* - i_d$ and $\Delta i_q = i_q^* - i_q$ and substituting these into (4) gives:

$$\begin{aligned} v_q &= V_g \sin(-\delta_{pll}) + (\omega_g + \Delta\omega_{pll}) l_g (i_d^* + \Delta i_d) \\ &\approx V_g \sin(-\delta_{pll}) + (\omega_g + \Delta\omega_{pll}) l_g i_d^* + \omega_g l_g \Delta i_d \end{aligned} \tag{6}$$

The self-synchronization loop (6) now has two parts: one is the transient converter frequency effect, and the other is the transient current effect. At the instant of the fault, the converter terminal voltage has not been changed, and its value $v_{cd,0}, v_{cq,0}$ can be computed as:

$$v_{cd,0} = V_g \cos(-\delta_{pll,0}) + \omega_g (l_f + l_g) i_q^* \tag{7}$$

$$v_{cq,0} = \omega_g l_f i_d^* \tag{8}$$

where $\delta_{pll,0} = \sin^{-1}(\omega_g l_g i_d^*/V_{g,0})$ is the pre-fault phase.

Defining $\Delta v_{cd}, +\Delta v_{cq}$ as the converter terminal voltage change, then the relationship of the current to the converter terminal voltage is:

$$v_{cd,0} + \Delta v_{cd} = V_g \cos(-\delta_{pll}) + \omega_{pll}(l_f + l_g)(i_q^* + \Delta i_q) \quad (9)$$

$$v_{cq,0} + \Delta v_{cq} = V_g \sin(-\delta_{pll}) - \omega_{pll}(l_f + l_g)(i_d^* + \Delta i_d) \quad (10)$$

where the transient current change $\Delta i_d, \Delta i_q$ can be computed. Note, the current reference i_d^*, i_q^* maybe changed after the fault occurrence for the purpose of the fault ride through or reactive power compensation. Thus, the initial converter terminal voltage is computed $v_{cd,0}, v_{cq,0}$ in (7,8) via the current reference at pre-fault, while the transient converter terminal voltage $(v_{cd,0} + \Delta v_{cd}), (v_{cq,0} + \Delta v_{cq})$ in (9,10) should use the current reference during the fault.

Note, at the instant of the fault $t = 0^+$, i.e., V_g changes to $V_g + \Delta V_g$, but the converter cannot instantly respond so that it has an unchanged terminal voltage, phase and frequency, i.e., $\Delta v_{cd} = 0, \Delta v_{cq} = 0,\ \delta_{pll} = \delta_{pll,0},\ \omega_{pll} = \omega_g$. However, as the current is the consequence of the voltage difference between the converter and grid, its value at the transient is significantly changed and this change can be computed as follows:

$$\begin{cases} \Delta i_{d,0^+} = \dfrac{\Delta V_g \sin(-\delta_{pll,0})}{\omega_g (l_f + l_g)} \\ \Delta i_{q,0^+} = -\dfrac{\Delta V_g \cos(-\delta_{pll,0})}{\omega_g (l_f + l_g)} \end{cases} \quad (11)$$

Equations (11) indicates that the transient current depends on 1) the voltage change due to the fault, ΔV_g; 2) the initial converter operating point, $\delta_{pll,0}$; 3) the transmission line, l_g; 4) the filter inductance, l_f.

The changed current feeds back into the current controller (1)-(2), thus resulting in the change of the converter terminal voltage, as follows:

$$\Delta v_{cd} = K_{pc}\Delta i_d + \int K_{ic}\Delta i_d - \omega_{pll} l_f \Delta i_q \quad (12)$$

$$\Delta v_{cq} = K_{pc}\Delta i_q + \int K_{ic}\Delta i_q - \omega_{pll} l_f \Delta i_d \quad (13)$$

From (12) and (13), the decay of the current transient depends on the PI parameters of the current controller.

Equations (7)-(13) represent the effects of the current dynamics on synchronization stability. Substituting these into (6) gives the proposed model of the PLL, whose scheme is shown in Fig. 4.

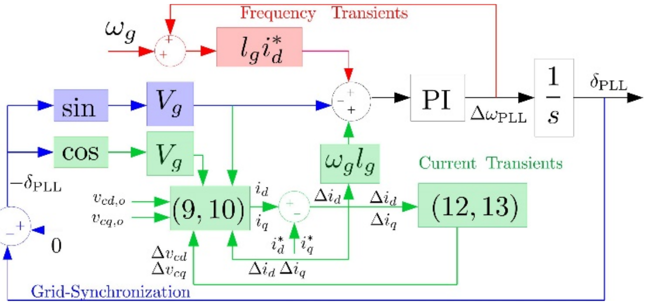


Fig. 4. Advanced synchronization stability assessment

IV. VALIDATION EXAMPLE

A real-time Electromagnetic Transients (EMT) simulation solved in Matlab/Simulink is used to validate the proposed synchronization stability assessment in comparison with the conventional QSLS methods. A 10 kV, 1 MW grid-feeding converter connected to a 50 Hz grid through an $l_g = 0.1\ H$ transmission line is discussed. The current limit in amplitude is 81.65 A. We consider maximizing the active power during the voltage sag, i.e. $i_d^* = 81.65\ A$; $i_q^* = 0\ A$. The PLL PI parameters are 0.022/0.392. The test examples include the following cases:

- Case 1: $l_f = 0.12\ H$, $K_{pc} = 1200$, $K_{pi} = 2433$; for which the current controller time constant is 0.1 ms.
- Case 2: $l_f = 0.12\ H, K_{pc} = 240, K_{pi} = 486.6$; for which the current controller time constant is 0.5 ms.
- Case 3: $l_f = 0.05\ H, K_{pc} = 500, K_{pi} = 2433$; for which the current controller time constant is 0.1 ms.
- Case 4: $l_f = 0.05\ H, K_{pc} = 100, K_{pi} = 486.6$; for which the current controller time constant is 0.5 ms.

The tests aim to assess the converter synchronization stability in response to a voltage sag. Table I records the minimum value of voltage sag for which the converter remains stable as obtained from the QSLS analysis, the proposed assessment method, and from EMT simulation.

From Table I, it appears that the QSLS method returns the same result in all cases, and its estimated values are much lower than the value obtained from EMT simulation. This is because the QSLS method neglects the current transient, while the other parameters remain identical as in Fig. 3 and in (5) for all cases.

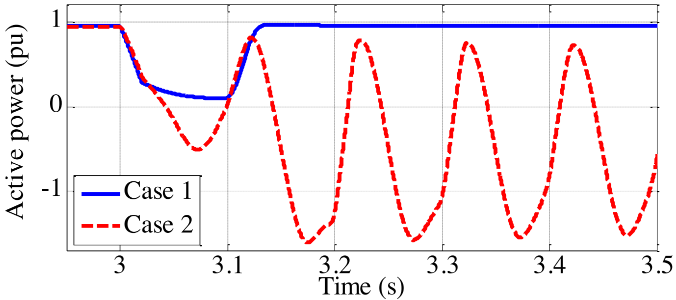
TABLE I
MINIMUM FAULT VOLTAGE (PU) FOR WHICH THE CONVERTER REMAINS STABLE AS COMPUTED BY THE DIFFERENT METHODS FOR THE DIFFERENT CASES. *THE HIGHER THE VALUE OF VOLTAGE, THE LOWER THE SYNCHRONIZATION STABILITY

Case	1	2	3	4
QSLS	0.341	0.341	0.341	0.341
Proposed	0.362	0.439	0.382	0.543
EMT	0.363	0.449	0.386	0.569

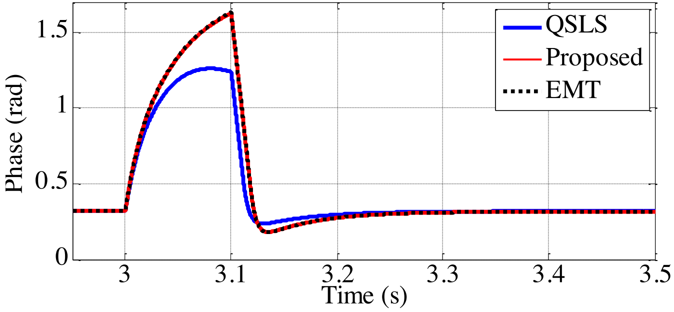
On the other hand, the proposed method considers current transients and, thus, shows a much higher accuracy. The values estimated with the proposed method approach those obtained from EMT simulation but are consistently slightly lower. This difference is due to the transients on the inductance, which slows down the process of the current back to the reference and resulting in a slightly larger phase. Comparing case 1 to case 2, or case 3 to case 4, the increase of the current controller time constant decreases the synchronization stability. Moreover, comparing case 1 to case 3, or case 2 to case 4, the reduction in the filter inductance worsens the synchronization stability. Note also that these circumstances further decrease the accuracy of the QSLS method.

In order to further verify the accuracy of the proposed model, we compared with QSLS and EMT in real-time simulation as results shown in Fig. 5 and Fig. 6, where the fault occurs at 3 s and is cleared at 3.1 s. When the grid voltage sags to 0.363 pu, the converter with case 1 parameters will be stable while that with case 2 parameters, which has a longer time constant, will be unstable. This can be seen in Fig. 5 (a) which shows that the active power output of the case 2 oscillates after the voltage sag. The rest of the figures in Fig. 5 shows the phase δ_{pll} transients obtained from the proposed method and QSLS method in comparison with the EMT result, where δ_{pll} is computed by the phase detected from the PLL minus the grid phase. It can be seen that in Fig. 5 (b) for case 1, both the proposed and QSLS methods effectively show a stable synchronization in response to the fault. However, the QSLS method gives a lower peak value compared to the EMT result, whereas the peak value can be accurately obtained by the proposed method. For case 2 as shown in Fig. 5 (c), only the proposed method can accurately reflect the loss of synchronization, which results in the continuous increase in the phase, leading to the power oscillation as shown in Fig. 5 (a). Since the QSLS neglects the current transients, its modelled phase transient for case 2, Fig. 5 (c) is identical to that in case 1, Fig. 5 (b), which cannot reflect the real phase transients and fails to precisely determine the synchronization stability.

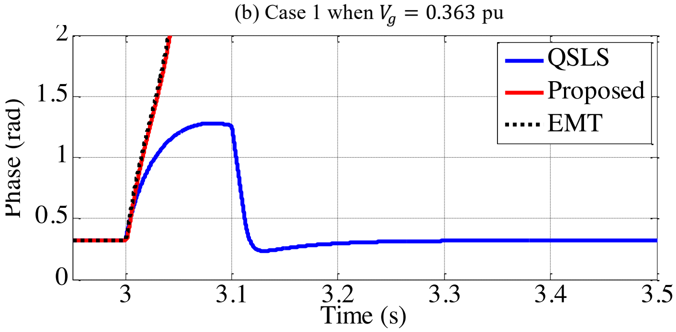
The current transients in the d-axis from the EMT simulation are shown in Fig. 6. The grid voltage only sags to 0.569 pu, which is the highest value in Table I representing to the minimum allowable voltage for all cases remaining stable. Case 1 with the larger filter inductance and faster current controller has the lowest current transients. This is the reason that the accuracy of the QSLS method in this case is higher than other cases as shown in Table I. The lower filter inductance and the slower current controller as indicated in (11) and (12,13) respectively lead to higher current transients, for which the peak current boosts the phase δ_{pll} as indicated in (6) and sometimes results in the instability as shown in Fig. 5.



(a) Active power comparison: case 1 vs. case 2 when $V_g = 0.363$ pu



(b) Case 1 when $V_g = 0.363$ pu



(c) Case 2 when $V_g = 0.363$ pu

Fig. 5. Result when V_g steps down to 0.363 pu at 3 s and recovered at 3.1 s.

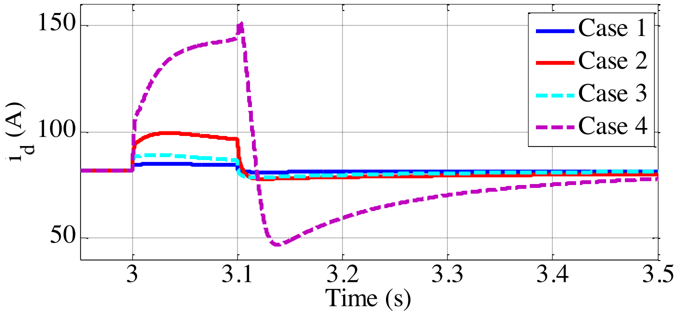


Fig. 6. d-axis current transient result when V_g steps down to 0.569 pu and recovered at 3.1 s.

V. CONCLUSIONS

This letter proposes a novel synchronization stability assessment method that considers converter current transients. The case study shows that neglecting such transients leads to inaccurate stability assessment as the computed stability range is larger than the actual one, especially for low values of the filter inductance and for relatively slow current transients. The proposed method proves to be more accurate and comparable to the results that can be obtained from a detailed EMT model.

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