Flexible Reference Frame Orientation of Virtual Flux-based Dual Frame Current Controllers for Operation in Weak Grids

Jon Are Suul, Tore Undeland, Fellow IEEE

Abstract — This paper discusses voltage sensor-less grid synchronization and control of three-phase Voltage Source Converters under unbalanced conditions. First, it will be shown how the concept of “Virtual Flux” can be used for grid synchronization in unbalanced conditions. For this purpose, a method for separate estimation of positive and negative sequence Virtual Flux components will be reviewed and analyzed in combination with Dual Frame Current Controllers for separate control of Positive and Negative Sequence current components. Then, it will be shown how the presented approach allows for flexibility in choosing the point of grid synchronization for the Virtual Flux estimation, and that this flexibility can be utilized to improve the operation and stability of the converter in power systems with high impedance. Simulation results are presented to show the influence on the dynamic response and on the limits for stable operation of the converter when different points of reference frame orientation are selected.

Index Terms— Current Control, Grid Synchronization, Voltage Source Converter, Unbalanced Grid, Sensor-less Control, Stability limit, Virtual Flux,

I. INTRODUCTION

The three-phase Pulse Width Modulated (PWM) voltage source converter (VSC) is becoming a standard solution for many different applications related to electrical drives and grid connected power conversion systems in a wide power range [1]. Because of the growing interest in utilization of VSCs for numerous applications, a large variety of control structures and methods for synchronization to the grid voltage have been developed and presented in the literature [2]-[5]. It has also for long time been known that unbalanced grid voltages will deteriorate the operation of the converter and possibly lead to damages if measures to handle unbalanced conditions are not taken during the design of the control system [6], [7]. Many different methods for synchronization to unbalanced grids and control of positive and negative sequence currents have therefore been investigated and discussed in the recent literature, as for instance described in [8], [9] and [10]-[12] respectively.

Another issue of recent interest with respect to control of VSCs is techniques for voltage-sensor-less operation as presented in [5], [13]-[17]. Among these studies, [15]-[17] apply the concept of “Virtual Flux,” as known from [18]-[20], for voltage sensor-less control of VSC’s by estimating a grid “Flux” that can be considered in analogy to the flux of an electrical machine. However, few investigations of voltage sensor-less control for operation under unbalanced conditions have been presented in the scientific literature, although some relevant approaches to this issue are found in [21]-[26]. Of these studies, [22]-[26] are based on the concept of Virtual Flux, but only [25] and [26] have presented methods for Virtual Flux-based grid synchronization especially designed for estimating positive and negative sequence Flux components. In [25], the proposed strategy for positive and negative sequence Virtual Flux estimation was experimentally verified in combination with Dual Frame current controllers for control of positive and negative sequence currents. However, the presented concept was not exhaustively analysed from the theoretical point of view.

This paper will start from the control system and the Positive and Negative Sequence Virtual Flux (PNS-VF) estimation proposed in [25], and will further analyze the performance with respect to Sequence Separation, Current Control, grid synchronization, and stability under weak grid conditions characterized by high grid impedance. From this starting point, it will be shown how it is possible to utilize the Virtual Flux estimation to select the point of synchronization to the grid and by that the point of reference frame orientation for the vector oriented current control. The presented results will show that this flexibility in choosing the reference frame orientation can be utilized to influence the performance of the converter and extend the limits for stable operation in a power system with high impedances.

II. SYSTEM DESCRIPTION

The following subsections will present the investigated control system based on [25], and will show analytical results illustrating the characteristics of the presented control strategy and the Virtual Flux estimation method.

A. Control system overview

An overview of the control system under investigation is shown in Fig. 1. As can be seen from the figure, the control is based on Dual Frame Current Controllers (DF-CC) implemented in the Positive and Negative Sequence Synchronous Reference Frames (PNS-SRFs) [11]. In this case, the voltage feed-forward terms usually included in Dual Frame PI-controllers are not used, although it would be possible to estimate these values from the corresponding PNS-VF components.

For simplicity, the only outer loop controller included in this investigation is a PI-controller for the DC-link voltage.
This control loop is giving the positive sequence active current reference value \( I_{\text{ref}}^q \) and a 100Hz notch filter is included in the DC-link voltage measurement to remove the voltage oscillations that can be caused by the unbalanced operation. Thus, only average power is controlled in closed loop, and the converter will operate with balanced three-phase currents unless non-zero current references are specified for the negative sequence current components.

The angular positions of the Positive and Negative Sequence Components (PNSC) of the grid voltage are obtained from the estimated Virtual Flux components, and are used to transform the output voltage references generated by the current controller back to the stationary reference frame. The DF-CC structure as shown in Fig. 1 is however independent of the synchronization method.

**B. Sequence separation**

For implementing Current Control and Virtual Flux estimation based on PNSCs, a strategy for sequence separation of three-phase signals in the time-domain is needed as discussed in [11], [27]-[31]. For strategies based on Delayed Signal Cancellation or filter-based approaches in the stationary reference frame, the individual PNSCs can be calculated according to (1), where \( q \) is a phase shifting operator corresponding to a 90° time delay of the input signal.

\[
\begin{bmatrix}
    x_a' \\
    x_b' \\
    x_c'
\end{bmatrix} = \begin{bmatrix}
    1 & 1 & -q \\
    2 & q & 1 \\
    1 & -q & 1
\end{bmatrix}
\begin{bmatrix}
    x_a \\
    x_b \\
    x_c
\end{bmatrix}
\]

(1)

In this paper a simplified implementation of (1) is adopted by using 2nd order low-pass filters with crossover frequency equal to the grid angular frequency \( \omega_0 \) for generating the required phase delay [25]. The phase shifting operator in (1) is then replaced by the transfer function of the low-pass filter as given by (2). It should be noted that the same sequence separation method can be used for both current and voltage measurements, and in this paper it will also be used in the Virtual Flux estimation.

\[
q = \frac{2 \cdot \omega_0^2}{s + \omega_0}
\]

(2)

To study the performance of this Sequence Separation strategy, the frequency response from a generic input signal to the estimated positive or negative sequence components should be analyzed. A simple approach for such investigations can be achieved by considering that fundamental frequency \( \alpha \)- and \( \beta \)-components will have equal amplitude under balanced conditions and that the \( \beta \)-component is lagging the \( \alpha \)-component by 90° in time as described by (3).

\[
x_{\beta}(j\omega) = -j \cdot x_{\alpha}(j\omega)
\]

(3)

Considering that the phase shifting operator \( q \) from (1) is implemented by a 2nd order low-pass filter, the corresponding steady state transfer function is given by (2). Combining equations (1), (2) and, (3) it can be found that the Positive Sequence component of the generic variable \( x \) can be represented by (4). A similar expression can also be derived for the negative sequence component.

\[
x_{\alpha}(j\omega) = \frac{1}{2} \left[ 1 + j \cdot \frac{2 \cdot \omega_0^2}{j \omega + \omega_0} \right] \cdot x_{\alpha}(j\omega)
\]

(4)

The resulting frequency responses for the estimation of Positive and Negative Sequence components are then given by (5) and (6) respectively and plotted in Fig. 2 a) and b). The frequency responses are plotted for both positive and negative sequence frequencies to verify the response to both positive and negative sequence signals.

\[
x_{\alpha}^*(j\omega) = \frac{\omega_0^2 - \omega^2 + j \cdot 2 \omega_0 (\omega + \omega_0)}{2 (\omega_0^2 - \omega^2 + j \cdot 2 \omega_0 \cdot \omega)} \cdot x_{\alpha}(j\omega)
\]

(5)

\[
x_{\beta}^*(j\omega) = \frac{\omega_0^2 - \omega^2 + j \cdot 2 \omega_0 (\omega - \omega_0)}{2 (\omega_0^2 - \omega^2 + j \cdot 2 \omega_0 \cdot \omega)} \cdot x_{\alpha}(j\omega)
\]

(6)

From Fig. 2 a), it can be seen that fundamental frequency Positive Sequence signals will pass through the Sequence Separation with unity gain and 0 phase shift. It is also clearly
seen that the influence of fundamental frequency Negative Sequence components will be effectively eliminated in the estimated Positive Sequence output signal. This is easily verified by specifying the angular frequency ω to be equal to -ω₀ in (5). The same verification of the characteristics with respect to estimation of negative sequence components can be found by considering (6) and Fig. 2 b).

An important observation that can be made from (4) and from Fig. 2 is related to the amplitude and phase response at high frequencies. Since 2nd order low-pass filter are used for generating the 90º phase shift, the amplitude of the phase shifted signal will be attenuated for high frequencies. Therefore, the influence from the phase shifted signal on the estimated positive and negative sequence signals will be negligible at high frequencies, and the transfer function will be reduced to a gain of 0.5. This clearly seen in Fig. 2, where the amplitudes of estimated Positive and Negative Sequence components are settling at -6dB with zero phase shift at high frequencies.

C. Current Controller design

In control system designed for operation only under balanced conditions, decoupled PI-controllers in the dq-SRF can usually be designed according to the simple open loop transfer function given in (7). This assumes that decoupling terms are included in the current control structure, as shown in Fig. 1, to compensate for rotational induced voltages, and that the switching frequency is relatively high. The parameters Kᵢ and Tᵢ of the PI-current controller can then be selected according to conventional control theory, for instance by using the Modulus Optimum method as given by (8) [32].

\[
\frac{1}{1+T_{\text{delay}}\cdot s} \frac{1}{1+T_{\text{filter}}\cdot s} \frac{1}{r/(1+T_{\text{inductor}}\cdot s)} \text{Model of inductor}
\]

(7)

\[
T_i = T_{\text{filter}} = \frac{r.T_{\text{inductor}}}{2.T_{\text{inductor}}}
\]

(8)

In the case of DF-CCs, the influence of current sequence separation must be taken into account when selecting the controller parameters. Usually, this requires a significant bandwidth reduction to maintain an acceptable stability margin of the current controllers. With the particular sequence separation method from section II B, the presented analysis has however shown that the high frequency response is reduced to a gain of 0.5. As long as the bandwidth of the current controller is kept significantly higher than the fundamental frequency of the grid, this sequence separation method should therefore have limited influence on the operation of the current controller, and mainly introduce a gain of 0.5 in the feedback. This reduction in the loop gain can easily be compensated by multiplying the gain of the PI-controllers from (8) by 2.

To investigate the validity of such a simplified approach, the frequency response of the DF-CCs should be investigated together with the frequency response of the sequence separation method. However, the corresponding transfer function can not be calculated straightforwardly since the sequence separation is implemented in the stationary αβ-reference frame while the Current Controllers are implemented in the PNS-SRFs. Thus, reference frame transformations as discussed in [33]-[35] will be necessary to analytically investigate the frequency response. Since transformation of the Sequence Separation strategy from (1) into the PNS-SRFs is cumbersome, a simplified approach is followed here by rather transforming the Synchronous Reference Frame PI-controllers into the stationary reference frame.

It is well known from [33] that transformation of dq-SRF PI-controllers into the stationary reference frame basically results in a Proportional-Resonant controller as given in (9).

\[
h_{\text{pR}}(s) = K_p + \frac{1}{s^2 + \omega_0^2}
\]

(9)

Disregarding the cross-coupling terms in the dq-frame, the filter inductor has the same transfer function in the stationary frame, and the delay approximation shown in (7), is anyway most accurately described in the stationary reference frame. Introducing the PR-controller from (9) with an extra gain factor of 2 into the open loop transfer function for the current control, and combining with the sequence separation from (5) and (6), results in the steady state transfer functions of (10) and (11) for positive and negative sequence Current Control respectively. Although these transfer functions do not express a control strategy that would be relevant for implementation, they give illustrative information about the performance of the control structure from Fig. 1, and are corresponding frequency responses are plotted in Fig. 3 a) and b) respectively.
The curves in Fig. 3 are representing a case with 0.05 pu filter inductor and 0.001 pu resistive losses within the current control loop. The plots are shown in linear scale for both positive and negative values of frequency, to better illustrate the influence of the sequence separation and the Synchronous Reference Frame current control. Both Fig. 3 a) and b) show 3 sets of curves, where the blue curve shows the frequency response of a dq-PI-controller in its Synchronous Reference Frame. As expected, these curves show infinite gain at zero frequency, corresponding to dc-signals in the positive and negative sequence reference frame respectively. The red curves represent the frequency response of a conventional PR-controller implemented in the stationary reference frame, showing resonant peaks at both positive and negative values of the fundamental frequency \( \omega_0 \).

The dashed black curves in Fig. 3 a) and b) show the frequency response of the transfer functions in (10) and (11) respectively. These curves verify how the Positive Sequence estimation introduces zero gain for Negative Sequence components and vice versa, so that (10) is only controlling Positive Sequence components while (11) is only controlling Negative Sequence components. It should also be noted from the figures, that the frequency response of (10) and (11) is converging towards the characteristics of the system without the Sequence Separation strategy for both positive and negative sequence frequency components above the fundamental grid angular frequency \( \omega_0 \). This is as expected from (4), considering that the gain of 2 is introduced in the transfer functions. Thus, the presented assumptions regarding the tuning can be realistic as long as the crossover frequency of the Current Controllers is kept significantly above the fundamental grid frequency. Plotting the transfer functions from (10) and (11) for higher frequencies also verifies that the crossover frequency and the phase margins will not be significantly influenced by the Sequence Separation as long as the crossover frequency is kept above \(-1000 \) rad/s.

D. Virtual Flux Estimation and Grid Synchronization

The Virtual Flux estimation method used for grid synchronization in Fig. 1 is shown in Fig. 4. The estimation is based on the voltage references for the PWM operation, the measured DC-link voltage and the current measurements as described in [25], [36]. First the voltage reference signals are expressed in the stationary \( \alpha \beta \)-reference frame and normalized.
to per unit voltages by multiplying with the per unit DC-link voltage. Then, the resistive voltage drop included in the model is subtracted. Compensation for on-state voltage drop of the converter switches and dead-time correction can also be easily included in the estimation [25]. The resulting signals are then separated into PNSCs by using the same sequence separation method as analyzed in section II B. The sequence separated signals are then used for estimating the PNS-VF components.

The general estimation of the Virtual Flux $\psi_g$ at the desired point of synchronization to the grid can be expressed by (12).

$$\psi_g = \int (v_r - r_{ox} \cdot i_r) dt - l_{ox} \cdot i_r$$  \hspace{1cm} (12)

An ideal integration according to (12), as understood from the basic concept of Virtual Flux discussed in [16], [18], [20], can however not be used for practical implementations due to problems with drift and saturation of the estimated values. In this paper, second order low-pass filters as given by (2) are therefore used to estimate the Virtual Flux values as suggested in [25], [37]. This is the same transfer function as used for the sequence separation, and will emulate integration by resulting in 90° phase shift and unity gain for fundamental frequency signals. The transfer functions from the converter voltage reference to the estimated PNS-VF components can then be found by multiplying the transfer function of (2) with (5) and (6) respectively. The corresponding frequency responses are plotted in Fig. 5 a) and b), and verify that unity gain and 90° phase shift is achieved for the estimated frequency response of estimated Positive Sequence Virtual Flux

![Frequency response of estimated Positive Sequence Virtual Flux](image)

a) Estimation of Positive Sequence Virtual Flux

![Frequency response of estimated Negative Sequence Virtual Flux](image)

b) Estimation of Negative Sequence Virtual Flux

**Fig. 5 Frequency response of PNS VF estimation**

components. It is also clearly seen from the figures that the Negative Sequence Components are eliminated in the estimation of the Positive Sequence Virtual Flux, and vice versa.

With the PNS-VF signals estimated in the stationary reference frame, the flux angles can easily be calculated by the inverse tangens of the $\alpha\beta$-components. If necessary, a Phase Locked Loop (PLL) can be used to track the phase angles [38], but usually this will not be necessary because the virtual flux model will filter high frequency ripple. The angular position of the grid voltage components can be easily estimated from the flux angles by adding 90° in the direction of rotation, and the resulting angle can be used to transform the PNSCs into the corresponding SRFs.

E. Point of synchronization

For operation of converters with voltage sensors, the point of synchronization to the grid is determined by the location of the voltage sensors. Usually the sensors will be located at the grid side terminals of the filter inductors, and this will then be the point of synchronization. Since the parameters of the filter inductor are usually known, implementations of voltage sensor-less control systems are traditionally based on the same point of synchronization.

By studying Fig. 4, the expression in (12) and the simple grid structure in Fig. 1, it can be understood that the point where the Virtual Flux is estimated, and by that the point of synchronization, can be easily changed by changing the parameter values of $r_{ox}$ and $l_{ox}$. By knowing or assuming values for the total per unit resistance and inductance in the feeding grid of Fig. 1, it is therefore possible to move the point of synchronization towards the equivalent voltage source shown in the figure. The value of the PI-controller parameters and the decoupling terms shown in Fig. 1 must then be updated as implied by the results presented in [39] and discussed for balanced conditions in [40]. As will be shown by the simulation results presented in the next section, this freedom to chose the point of synchronization can be utilized to influence the characteristics and the stability of the converter control system in case of weak grids with high total impedance.

It should be noted that LCL-filters or other capacitances in the grid will complicate the Virtual Flux estimation. However, by estimating or measuring the capacitor current, the capacitive influence can be included in the Virtual Flux estimation as for instance shown in [41].

Another interesting point to note from Fig. 4 is that the Positive and Negative Sequence Virtual Flux components are estimated independently from the PNS Voltage components. This allows for another type of flexibility in the Virtual Flux estimation that could be used to select different points of synchronization for control of positive and Negative Sequence current components. This is a feature that could be further investigated with respect to relevant control objectives.

III. SIMULATION STUDIES

To investigate how the point of synchronization, determined by the parameters of the Virtual Flux estimation,
will influence the operation of the converter, the system shown in Fig. 1 has been simulated in PSCAD/EMTDC. For these simulations, the converter has been rated at 2.26 MVA at 690 V_{\text{RMS}} and has been operated as a generator with 1 MW of power fed to the DC-link. Filter inductors of 0.05 pu inductance are assumed, and the system is connected to a weak AC power system with a total resistance of 0.05 pu and inductance of 0.45 pu referred to the converter KVA rating. The voltage source feeding the system is specified to have a magnitude of 0.9 pu positive sequence with a superimposed 0.1 pu negative sequence.

As a starting point, four different strategies for grid synchronization are simulated to illustrate the limits for the possible range of reference frame orientations:

- **Reference case**: synchronization based on sequence separation of voltage measurements at the filter terminals.
- Synchronization to the Positive and Negative Sequence Virtual Flux estimated at the filter terminals.
- Synchronization to the estimated Positive and Negative Sequence Virtual Flux components of the equivalent voltage source of the grid by including the total grid impedance in the Virtual Flux model.
- **Theoretical reference case**: synchronization by sequence separation of the voltages at the equivalent source of the grid in the simulation model.

In the cases where voltage measurements are used, synchronization to the positive and negative sequence components are obtained by using the same method as discussed in section II.B and separate PLL’s on each sequence component. It should also be noted that operation based on remote measurements will not be realistic for practical implementation, but is presented here as an illustrative case of simulation, since similar operation can be achieved by Virtual Flux estimation.

### A. Dynamic Response with different Reference Frame Orientations

To compare the dynamic response following a perturbation, the simulation model has been exposed to a step in the reference value for the positive sequence reactive current, $i_{q,\text{ref}}$ when synchronizing to the grid by different strategies. Some of the obtained results are shown in Fig. 6, where the two upper plots are showing the resulting response in the positive sequence reactive current. As can be seen, the system based on voltage measurements or Virtual Flux estimation synchronized to the filter terminals have a quite similar, smooth, response with the Virtual Flux-based control resulting in less overshoot.

For synchronization to the equivalent voltage of the grid, the current-controllers are re-tuned according to the discussion in section II.C. Also in this case the currents show almost the same response when comparing synchronization by voltage measurements and by Virtual Flux estimation. The current responses are however more oscillatory than when synchronizing to the filter terminals. This is mainly because the system attempts to quickly control the current through a large inductance, causing more interaction between the PNS-CCCs. Even if the current response for the different cases can be improved by making more detailed studies for selecting the controller parameters, it is remarkable that the current response is almost the same when the control is based on estimation of a remote “Flux” as when based on an ideal measurement of the corresponding voltage. Although there can be many complicating factors in practical systems, like LCL-filters, cable capacitances in the system etc, this shows the capability of the investigated method for Virtual Flux estimation to provide reliable synchronization for voltage sensor-less operation under unbalanced conditions.

Considering the DC-link voltage that is plotted in the lowest part of Fig. 6, it can also be observed that the smallest disturbance in the power balance occurs when the converter is synchronized to the remote source voltage. This is mainly because the system in this case is synchronized to a stiff voltage, so there is less indirect perturbation of the operation of the control system caused by the response in local grid voltage when the flow of reactive power is changed. In addition to the lower overshoot, there is also a faster tracking of the reference value for the DC-link voltage when the control system is synchronized to the equivalent grid voltage source. This indicates that the point of synchronization will have an influence on the loadability limits and power handling capability of the converter in the case of large grid impedance.

### B. Stability Limits for Steady State Operation

To investigate the stability limits of the converter with different strategies for grid synchronization, trial-and-error simulations have been carried out, where the power input to the DC-link was slowly increased until the DC-link voltage control reached instability. In addition to the 4 cases already listed in the beginning of section III, the system was also simulated for synchronization to the following two points in the feeding grid: $a)$ The high voltage side of the connection transformer, corresponding to Point of Common Coupling
(PCC) in Fig. 1, b) The inductance mid-point of the line, corresponding to the point where the inductance towards the converter is equal to the inductance towards the grid source. All these cases were simulated for synchronization based on voltage measurements and based on PNS-VF estimation.

The stability limits resulting from this series of simulations are presented in Fig. 7. In this figure the results from synchronization based on voltage measurements are presented with blue bars in the left side, while the results obtained with synchronization based on PNS-VF estimation are presented with red bars in the right side. The x-axis is scaled according to the “electrical distance” from the grid voltage source, given by the ratio between the inductance from the ideal source to the point of synchronization and the total inductance. As seen from the figure, the stability limit is increased as the point of synchronization is moved towards the grid equivalent source. This is partly because the system will be synchronized to a more stable voltage when the point of synchronization is moved towards the ideal Thévenin-equivalent voltage source of the grid. Since only \( \frac{L_{id}}{L_{ref}} \) is controlled, the power handling capability of the converter is also inherently increased by moving the reference frame orientation towards the grid source, since this will imply that the converter will supply the reactive power consumed by the inductance between the converter and the point of synchronization. This was partly discussed for balanced conditions in [40], and the influence of the reference frame orientation will be similar also under unbalanced conditions.

Considering the results in Fig. 7, it is seen that synchronization to the mid-point of the line results in a stability limit of almost 2.0 pu power. This corresponds to the theoretical maximum transfer capability between two voltage sources of 1.0 pu voltage through an inductive line with 0.5 pu inductance. It can also be observed from the figure that the power transfer capability is not increasing much by moving the reference frame orientation from the mid-point of the line to the grid voltage source. For the case of Virtual Flux-based control, the stability limit is actually lower when synchronized to the grid than when synchronized to the mid-point of the line. This is because the voltage at the converter terminals will increase when the converter attempts to control the current to be in phase with the grid voltage source, and the converter is therefore forced into over-modulation that deteriorates the Virtual Flux estimation. The grey bars plotted in the figure for the case of synchronization to the grid voltage, are obtained with the DC-link voltage increased to 1.5 pu, and by that more power can be transferred through the line before the converter is reaching over-modulation. The control based on voltage measurements is in this case having higher stability limits since the voltages measured at the ideal source are not influenced by the over-modulation.

IV. CONCLUSION

This paper has analysed a control system for voltage sensor-less operation of Voltage Source Converters (VSCs), based on Dual Frame Current Controllers (DF-CCs) in combination with Positive and Negative Sequence Virtual Flux (PNS-VF) estimation for synchronization to unbalanced grids. The characteristics of the Sequence Separation method, the tuning of the Current Control loops and the characteristics of the PNS-VF estimation have first been analyzed. It has then been shown how the Virtual Flux estimation can be utilized to synchronize the control system to different remote points in the grid, while still achieving satisfactory dynamic response. Finally, it is shown that the described flexibility in selecting the point of synchronization by the Virtual Flux estimation can be utilized to extend the limits for stable operation of the converter. In general, the presented results show that the power transfer capability of a converter in generator mode can be increased by moving the point of reference frame orientation towards the grid source, as long as the converter does not reach over-modulation.

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