Impact of Virtual Flux Reference Frame Orientation on Voltage Source Inverters in Weak Grids

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Abstract—This paper investigates how different approaches to grid synchronization and reference frame orientation can improve the control performance of a voltage source inverter operating in a weak grid. It is first shown how voltage-sensor-less operation based on Virtual Flux allows for flexibility in how to choose the reference frame orientation of the control system. The different possible orientations are then explained, and the potential improvement in stability and performance of the control system is discussed. If is further explained how the choice of reference frame orientation can be used to select a point in the grid seen from the converter, where reactive power flow or power factor can be explicitly controlled. The dynamic response and stability limits of an inverter operating in a weak grid have been investigated by simulations for verifying and illustrating the influence of different reference frame orientations.

Index Terms—Grid Synchronization, Stability, Virtual Flux, Voltage Source Converter

I. INTRODUCTION

For renewable energy systems and electrical conversion systems that require reversible power flow or a high degree of controllability, the three-phase voltage source converter (VSC) is becoming a standard modular solution with a wide range of possible applications [1] [2]. Therefore, much attention has been focused on control system design for this converter topology, and a wide range of possible control methods have been proposed [3], [4]. Most of these control strategies have been extensively presented in the scientific literature and analyzed with respect to performance and digital implementation. However, there has been limited attention on the possible interaction between the inner control loops of the converter and the power system impedance in case of weak grids.

For traditional cascaded control systems, only a few published studies are considering the overall stability of the converter control system together with both the details of the inner control loops and the influence of large grid impedances. The available literature includes investigations of the performance of Proportional-Resonant current controllers in the presence of LCL-filter for a range of grid impedances as presented in [5]. Also the influence of large grid impedance values on hysteresis current controllers has been studied in [6]. Robustness and stability properties of PI-current controllers and state-feedback current controllers in the synchronously rotating reference frame have further been investigated in [7]. However, these studies are focused on the current controllers, and do not fully take into account the influence of the synchronization method, the DC-link voltage controller or other outer control loops.

A more elaborated topic in the recent literature is voltage-sensor-less control of voltage source converters. Several possible control strategies for such sensor-less operation have thus been developed during the last years [3], [8], [9]. Although most of the proposed control schemes fall into the categories of either Voltage Oriented Control (VOC) or Direct Power Control (DPC), the concept of Virtual Flux as presented in [8], [10] seems to be established as a common basis for many different voltage-sensor-less control schemes.

In an attempt to introduce new concepts for analysis and control of converters operating in weak grids, this paper presents an investigation of how a Virtual Flux model can be utilized to improve the control performance and stability in case of high line impedances. This will be obtained by moving the orientation of the synchronous reference frame, and by that the point of synchronization, into the grid as seen from the converter. The possible improvement in the dynamic response and stability of a control system based on this new approach will be shown by simulations. Results based on grid synchronization by a Phase Locked Loop (PLL) as discussed in [11], [12] will also be presented as a basis for comparison.

II. VIRTUAL FLUX CONCEPT AND CHOICE OF REFERENCE FRAME ORIENTATION

As a technical background for the investigations, the concept of Virtual Flux will first be reviewed and discussed with respect to its implementation. The orientation of the synchronously rotating reference frame used in the control of a converter will also be discussed from a conceptual and theoretical point of view.

A. Background of the Virtual Flux concept

The concept of Virtual Flux is based on the voltage-time integral as given by (1), where it can be clearly seen that the flux \( \Psi \) is defined as the integral of a voltage \( V \).

\[
\Psi = \int V dt + \Psi_0 \tag{1}
\]

This definition corresponds to the magnetic flux of an electrical machine, and the voltage-time integral has therefore been used for a long time in electrical motor drives, and has also been presented for general analysis of voltage source inverters and PWM rectifiers [13], [14]. Later, the understanding of the voltage integral as a “flux” in case of a voltage source converter connected to the grid have been further developed and analyzed for control purposes, where the grid has been considered as a “virtual electric machine” [10], [15]-[18]. It was also quickly realized that the concept of converter or grid...
“flux” could be utilized for applying the Direct Torque Control (DTC) method for AC machines to line converters [19].

The terminology and the concept of “Virtual Flux,” with respect to voltage-sensor-less control of VSC’s, seems to have settled in the literature after the work of Malinowski [8], [20]. This work discussed both the concepts of Virtual Flux Oriented Control (VFOC) by using vector control principles and Virtual Flux-based Direct Power Control (VF-DPC). Later, also a concept for Virtual Flux based Direct Power Control using Space Vector Modulation (DPC-SVM) have been presented for obtaining DPC with constant switching frequency [21]. For the following discussion, the term Virtual Flux will only be used when considering a voltage-sensor-less control system, and for simplicity the investigations will be limited to vector oriented current control strategies implemented in a synchronously rotating reference frame.

B. Virtual Flux Model and Implementation

For voltage-sensor-less control, the starting point of the Virtual Flux calculation will be the converter voltage \( \mathbf{V}_c \), as shown in Fig. 1. Considering the calculations to be implemented in the two-axis stationary \( a\beta\) reference frame, the general expression for the converter flux \( \psi_c \) is given by (2).

\[
\psi_c = \int V_{c,a} \, dt + \psi_{c,0} \tag{2}
\]

For a PWM-based control system, the converter voltage \( V_c \) can be calculated from the DC-link voltage and the modulation signals or voltage references \( V_{ref} \) used for generating the gate signals. To improve the accuracy of the estimation, the voltage reference can be compensated for the influence of the dead-time of the converter and the average resistive voltage drop in the switches before calculating the integral [22].

It is well known that a pure integrator as in (1) and (2) can not be used in practical implementations since this will cause drift and saturation of the estimated Virtual Flux values. Several methods have therefore been proposed in the literature to avoid this problem, but in this paper, a simple method based on utilization of a second order low-pass filter as proposed in [22] and [23] will be applied. Considering implementation with per unit variables and assuming constant grid frequency and constant DC-link voltage, the resulting Virtual Flux model expressed in the Laplace-domain is given by (3).

\[
\psi_c(s) = \psi_{ref}(s) \cdot v_{dc} \cdot \frac{2 \cdot \omega_0}{s + \omega_0} \tag{3}
\]

In this equation, the symbols for flux and voltage are the same as in (1) and (2), although lower-case letters are used to indicate per unit variables. The angular frequency of the grid is given by \( \omega_0 \). By using a second order low-pass filter with the corner frequency given by the grid frequency, the resulting output signal will be phase shifted by 90° and the amplitude will be equal to half the input signal. The low-pass filter must therefore have a gain of 2, to maintain the amplitude equal to that of the input signal [22]. The frequency response of the proposed Virtual Flux model is shown in Fig. 2, where it can be clearly seen that unity gain and 90° of phase shift is achieved for fundamental frequency signals in a 50 Hz system.

It can be noted that the applied Virtual Flux model will be robust against drift towards infinity, but there will still be a gain of 2 for DC-offset from the input signals. Such DC-offset can be eliminated separately by simple strategies, for instance by subtracting the average value of the AC signal from the output [22].

C. Traditional Choice of Reference Frame Orientation

For converters with voltage sensors, the synchronization to the grid is usually obtained with a PLL or another phase tracking technique based on the voltage measurements [11]. The location of voltage measurements will then fix the point of synchronization and the orientation of the synchronously rotating reference frame used for vector oriented control systems. The point of synchronization is therefore usually fixed to the grid side terminals of the filter inductor, to keep a short distance between the converter and the sensor. The voltage at this point can also be used as basis for implementing algorithms for damping LC-oscillations in case of an LCL-filter [24].

If the purpose of implementing a Virtual Flux model is mainly to replace the voltage sensors by an estimation routine, the natural choice will be to use the same orientation of the Virtual Flux model as for a system with a PLL. Then the system will be oriented with respect to the “flux” at the grid side of the filter inductor \( L_f \). This is also a convenient choice, since the value of the filter inductor is usually known, and because the estimate of the flux at this point can be used for purposes of voltage sensor-less active damping in case of LCL-filter [25].

Neglecting possible correction terms and the resistance of the filter inductance, the estimate of the flux \( \psi_f \) at the grid side terminals of the filter inductor can be calculated as given by (4) [8], [12], [25].

\[
\psi_f = \psi_c - L_c \cdot i_c \tag{4}
\]

\[
\gamma_f = \arctan \left( \frac{\psi_f}{\psi_f} \right) \quad \theta_f = \gamma_f + 90^\circ \tag{5}
\]

In this equation, the per unit filter inductance is given by \( L_f \) and the converter current is given by \( i_c \). The angle \( \gamma_f \) of the flux vector at the filter terminals can further be calculated directly as given by (5), although it could also

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**Fig. 1. Simple system model of voltage source converter connected to a grid, with a power generation system interfaced to the DC-link**

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**Fig. 2. Frequency response of applied Virtual Flux model**

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**Table:**

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**Equation:**

\[
\psi_c = \int V_{c,a} \, dt + \psi_{c,0} \tag{2}
\]
be tracked by a Phase Locked Loop (PLL). The equation also shows how the angular position $\theta$ of the voltage at the same point can be easily estimated by adding 90º, so that the orientation of the reference frame is the same as for a system based on voltage measurements.

D. Reference Frame Orientation in a Weak Grid

In the case of weak grid conditions, the grid synchronization and control of a Voltage Source Inverter is put under additional challenges. From the perspective of power system stability investigations or converter control system design, a weak grid can be understood as a power system where; the impedance is high so that the Short Circuit Ratio (SCR) at the connection point of the converter is low, and/or the total inertia of the system is low so that significant frequency deviations can be expected [26]. In this paper, only the case of low SCR with high impedance as seen from the terminals of the converter will be investigated.

Considering the simple structure shown in Fig. 1 and assuming voltage-sensor-less operation based on the Virtual Flux concept, allows for looking at grid synchronization from an untraditional point of view. Since the synchronization is obtained from the Virtual Flux estimation, it can be understood that the point of synchronization is not any more determined by practical considerations regarding the location of physical sensors. In theory, any point along the radial line of Fig. 1 could thus be selected as the point of synchronization and used for orientation of a synchronously rotating reference frame.

Following the proposed line of reasoning, the orientation of the reference frame could be chosen freely according to the required objectives of control, as long as the corresponding values of the grid parameters are available. The range of possible points of orientation is also indicated by the arrows in Fig. 1 and further illustrated with a vector diagram shown in Fig. 3.

The phase angles shown in the vector diagram of Fig. 3 will depend on the active and reactive power flow in the system. In the simple radial structure from Fig. 1, the amplitude and phase of the grid voltage $V_g$ will however be constant and independent of the operation of the converter. This will also be the case if a power system can be represented by a Thévenin equivalent model. If the Thévenin impedance of the system is known, it will thus be possible to synchronize a Virtual Flux model directly to the equivalent grid voltage source of the system. This will correspond to a case where a converter is synchronized to a strong grid with a stiff voltage source.

It is also implicit to the presented considerations that the closer to the equivalent grid voltage source the point of synchronization is chosen, the less it will be influenced by the operation of the converter itself. It can further be understood that choosing a strong and stable point in the grid as the point of reference frame orientation can have the potential to increase the range of stable operation, as will be investigated in the last part of this paper.

Another important aspect related to the choice of reference frame orientation is that the point of synchronization is determining the point where control of active and reactive power is inherently decoupled. As indicated in [27], the reference frame orientation is therefore giving the point in the grid where the power factor is inherently controlled and kept at unity when the reactive current reference is zero. The same considerations can also be made for voltage control by reactive current, but it should be noted that the concept of voltage control will be less relevant as the point of synchronization is moved towards the Thévenin equivalent voltage source. The different possibilities for reference frame orientation will require corresponding knowledge about the grid impedance, but the required accuracy will depend on the objectives of control.

E. Overview of Synchronization by Virtual Flux Model

An overview of the total Virtual Flux model used in this paper is given in Fig. 4. The arrows on the resistance and inductance terms indicate how the point of synchronization can be easily changed by changing the corresponding values of the grid parameters. The resulting Virtual Flux calculation is also shown with ideal integration in (6), and it can be seen directly from the figure how the angular position of the grid voltage is found in the same way as given by (5).

$$\psi^\theta = \int \left( \psi^\theta_{ref} \cdot V_{DC} - r \cdot i^\theta \right) \, dt = \int \left( \psi^\theta_{ref} \cdot V_{DC} - r \cdot i^\theta \right) \, dt = \int \left( \psi^\theta_{ref} \cdot V_{DC} - r \cdot i^\theta \right) \, dt$$  (6)
III. CONTROL SYSTEM AND SIMULATION MODEL

This section provides a short description of the vector control structure used as basis for the investigations. The section further includes a description of the PLL for comparison to the results of the presented Virtual Flux model. The strategy for tuning the current controllers of the vector oriented control system is also discussed.

A. Simulation Model Overview

To investigate the influence of different reference frame orientations, the simple system from Fig. 1 have been simulated with the PSCAD/EMTDC software. An overview of the simulation model consisting of the simple grid equivalent, a transformer, the converter and its control system is shown in Fig. 5. It should be noted that the simulation model is based on an instantaneous average model of the PWM operation [28]. This is a common technique for reducing the simulation time, but in this case another main motivation is to be able to easily compare details of dynamics in the simulation results without the visual disturbance of the switching ripple in the currents.

As Fig. 5 shows, the control system is based on PI current controllers implemented in the synchronously rotating reference frame [29]. The control system is synchronized by either the Virtual Flux model as shown in the figure, or by a PLL based on voltage measurements, and the d-axis of the synchronously rotating reference frame is oriented after the voltage vector at the point of synchronization. The reference value for the d-axis current controller is thus given by a PI-controller operating on the DC-link voltage to control the power flow of the system.

B. Phase Locked Loop

The basic block diagram of the PLL used as reference for comparison to the Virtual Flux-based synchronization is shown in Fig. 6. This is a standard Synchronous Reference Frame PLL with filtering introduced in the d- and q-axis voltage components and phase angle calculation by an inverse tangens function [30], [31]. The PLL is tuned according to a simple strategy based on the Symmetrical Optimum as discussed in [31]. The time constants \( T_f \) of the low pass filters are intended for attenuation of switching noise, and are set to 1 ms, and the integral time constant \( T_i \) of the PI-controller is set to 10 ms, leading to a gain \( K_i \) of about 50. The resulting PLL will have a fast and well damped response in case of a strong grid and is therefore used as a reference case for the further investigations, although a slower tuning with a correspondingly slower response can improve the robustness in case of weak grid conditions.

C. Design of the Current Controllers

For a control system based on grid voltage synchronization by a PLL, the decoupled current controllers in Fig. 5 are usually designed to control the current in the filter inductors. The tuning of the controllers are then adapted to the values of the inductance and resistance in these inductors. This is also the normal approach in case of sensor-less control based on Virtual Flux [8], [12]. The basic equations for the current in the filter inductor expressed in the synchronous reference frame as given by (7) is then the starting point for design of the current controller [12], [29].

\[
\begin{align*}
\frac{d i_d}{dt} &= -r_d i_d + \omega_m l_q i_q - v_d^f + v_p^f \\
\frac{d i_q}{dt} &= -r_q i_q - \omega_m l_d i_d - v_q^f + v_p^f
\end{align*}
\]

To decouple the system, and to make the control independent of the grid voltage, feed-forward terms \( v_p^f \) as given in (8) are also included in the control structure as shown in Fig. 5. The decoupling term for cancelling the current induced cross-coupling of the equations is independent of the synchronization strategy and will be the same for both implementations based on voltage measurements and for the case of implementation based on a Virtual Flux model. Voltage feed-forward terms can however not be applied straightforward in case of Virtual Flux-based control. Although it is possible to derive an estimate of the voltage at the filter terminals from the Virtual Flux, this will require differentiation and thus introduce additional noise in the system. A suitable approximation can therefore be to use the Virtual Flux components in the Synchronous Reference Frame directly for the feed-forward as shown by the approximations in (8) [12].

\[
\begin{align*}
v_p^f &= v_d^f - \omega_m l_q i_q \\
v_p^f &= v_q^f - \omega_m l_d i_d
\end{align*}
\]

The discussion presented in this paper, and the results shown in [27] are however implying how different orientations of the reference frame and correspondingly different tuning of the current controllers can be relevant. The design of the parameters for the PI current controllers should therefore be studied in a general way where the resistance and inductance within the current control loop can be whatever values included in the Virtual Flux model.
The tuning of the current controllers can be most easily investigated by considering the open loop transfer function of the current control loop as given by (9). Here, \( T_{RL} \) is the time constant of the inductance, while \( r \) is the per unit resistance between the converter and the point of synchronization. The time constant, \( T_{sum} \), is representing a first order approximation to the PWM operation and all the small time delays of the system. For this equation, it is assumed that the output of the PI-controller is decoupled from the DC-link voltage before being used as reference signals for the PWM operation.

\[
h_{rc}(s) = K_p \frac{1 + T_p \cdot s}{T_p \cdot s} \frac{1}{1 + T_{sum} \cdot s} \frac{1}{r \cdot (1 + T_{RL} \cdot s)}
\]  

(9)

Using conventional control theory, the parameters \( K_p \) and \( T_p \) of the current controller can be tuned according to the Modulus Optimum method as given by (10) [29].

\[
T_p = T_{RL} \quad K_p = \frac{r \cdot T_{RL}}{2 \cdot T_{sum}}
\]  

(10)

By considering (9) and (10) together with Fig. 1 or Fig. 5, it can be seen that the suitable parameters for the PI-current controllers will depend on the point of synchronization and by that the orientation of the synchronous reference frame. It should also be noticed that the de-coupling terms in the current controller structure must be selected according to the inductance included in the Virtual Flux model, as investigated from a different perspective in [27].

Since the tuning of the current controller according to (10) is based on pole cancellation, the resulting dynamic response will be determined by the delay in the system as approximated by the time constant \( T_{sum} \). Because the main objective of this paper is to study the influence of the reference frame orientation without considering the detailed influence of nonlinearities in a switching converter, continuous time control without significant delays or sampling effects in the current control loop is assumed. The only delay included in the tuning of the controllers is therefore the influence of the switching frequency that is assumed to be 5 kHz.

The resulting response to a step in reactive current reference is shown in Fig. 7, when the converter and control system from Fig. 5 is connected to a strong grid. This result is shown to serve as a reference for how the performance of the converter is influenced by the large impedance in case of a weak grid.

IV. SIMULATION STUDY UNDER WEAK GRID CONDITIONS

As a starting point for investigating the influence of the synchronization strategy, the system is simulated for operation in a weak grid with half of rated power as production on the DC-link. The filter inductance in the model is 5\%, with about 0\% resistance, referred to the converter rating. A step-up transformer with the same kVA rating as the converter, a leakage inductance of 7\% and resistance of 2\%, is connecting the system to a weak grid with additional 3\% resistance and 38\% inductance.

Four different grid synchronization strategies are simulated, intended to illustrate the limits for the possible range of reference frame orientations:

- **Reference case**: synchronization by a PLL based on voltage measurements at the filter terminals.
- **Synchronization to the flux at the filter terminal by a Virtual Flux model including only the filter inductor**
- **Synchronization to the equivalent voltage source of the grid by including the total grid impedance in the Virtual Flux model**
- **Theoretical reference case**: synchronization by PLL directly to the stiff voltage source of the grid model

The last case is of course purely theoretical, but is included to illustrate an ideal case where the system is synchronized to a stiff voltage source even if the impedance seen from the converter terminals is large.

It can be noted that the simulations with synchronization to the equivalent grid voltage source are carried out with voltage feed-forward terms as given by (8). For the simulations with synchronization to the filter terminals, the feed-forward terms are however reducing the damping of the control system, resulting in a negative influence on the system stability, and they are therefore omitted in the control system.

A. Response to Step in Reactive Current Reference

Results from simulations with a step in reactive current reference from 0 to -0.5 pu are shown in Fig. 8. The response in reactive, q-axis, current is shown for the two cases of reference frame orientation at the filter inductor terminals in the upper plot. The case with the PLL shows a significant overshoot and an oscillatory response that is significantly different from the response in Fig. 7. The slow and oscillatory response is mainly caused by the interaction between the large grid impedance and the phase angle detection of the PLL. Although this influence can be reduced by designing a slower PLL, this problem can not be completely eliminated as long as the control system is synchronized to the voltage at a point that is highly influenced by the operation of the converter.

The results with the Virtual Flux model synchronized to the filter terminals are showing a much more damped response without pronounced oscillations, but the response is still significantly slower than expected from the results in Fig. 7 and it takes a relatively long time before the reference value is perfectly tracked.

The second plot in Fig. 8 show results from the two cases with the equivalent grid voltage source as the point of reference frame orientation. It can be seen that both the
case of the Virtual Flux model and the theoretical case with synchronization directly to the grid voltage source in the simulation model results in a fast and accurate response similar to what was expected from the discussion of Fig. 7. This shows how the change of reference frame orientation can be used to significantly reduce the interaction between the converter control system and the grid impedance. The influence on the DC-link voltage of the converter is shown for all the simulated cases in the lower plot of Fig. 8. From the curves it can be observed how the cases with synchronization to the filter terminals are leading to a larger disturbance in the DC-link voltage than the cases where the system is synchronized to the stiff grid voltage source. It should however be noticed that in the case of orientation to the filter inductor terminals, there are two main causes for the influence on the DC-link voltage. One is that when the reactive current is changed, this also influences the voltage at the filter terminals, and when this voltage changes, the active current must also be changed to maintain the power balance. Therefore, the DC-link voltage will be perturbed to make the d-axis current reference adapt to the change of voltage. The other issue in this case is that the weak grid makes the instantaneous phase angle at the filter terminals to change significantly when the operation point of the converter is changing, and this result in a dynamic response of the synchronization method.

The amplitudes of the measured voltage or the estimated Virtual Flux are compared for the 4 different cases. By considering the results before the step in the reactive current reference occurs. The reactive power flow at different points in the grid with the different synchronization strategies is shown in Fig. 10, using the same line-style convention for the 4 different cases. By considering the results before the step in the reactive current reference occurs, the influence of the reference frame orientation on the flow of reactive power can be easily analyzed. It is for instance seen that in case of synchronization to the filter inductor terminals, the reactive power flow at that point is zero, while the grid voltage source is delivering reactive power to cover the reactive power consumption of the inductive line. Since the reactive power consumption of the filter inductor is small, the reactive power flow in the converter is also negligible. When the equivalent grid voltage source is selected as the point of synchronization, it is however seen that the converter is delivering reactive power to the line while the reactive power exchange with the equivalent grid voltage source is zero. These results illustrate in a simple way how the choice of reference frame orientation for a Virtual Flux model can be used to select a point in the grid where the power factor or flow of reactive power can be explicitly controlled.

B. Stability Limits

Simulations have also been carried out to investigate the influence of the reference frame orientation on the
stability limits of the converter control system under weak grid conditions. For simplicity, the approach has been based on simple trial and error simulations where the power injected to the DC-link has been increased in small steps until instability or uncontrolled operation is reached. For all the simulations, the reactive current reference has been set to zero, so that unity power factor is kept at the point of synchronization. The main results are shown in Fig. 11, where the highest power injection that results in stable steady state operation is given for synchronization at different points in the grid. Results are shown for synchronization by a PLL and by the Virtual Flux model.

From the results in Fig. 11, it can be seen that the stability limits is almost equal for synchronization based on a PLL or the Virtual Flux model. In case of synchronization to the grid equivalent source, the case with the PLL shows to be more stable, and this is mainly because the converter in this case is running into over-modulation that influences the Virtual Flux model. It can however be noted that the dynamics of the control system is influenced by the synchronization technique when the system is close to the stability limit, in a similar way as discussed for the results presented in section IV.A.

The most noticeable and important result from Fig. 11 is however that the maximum power injection before reaching the limit of stable operation is increasing as the point of synchronization is moved away from the converter terminals and towards the voltage source in the simulation model. The results for synchronization to the Point of Common Coupling (PCC) from Fig. 5 are added to illustrate this trend, and the presented results can serve as another verification of how the point of reference frame orientation can be used to influence the stability and the dynamic response of the converter.

As a point of reference, it can also be useful to refer to the traditional power flow equation for an inductive line as given by (11), where $p$ is the active power, $I_{\text{tot}}$ is the total inductance and $\delta$ is the power angle between the converter voltage $v_c$ and the equivalent source grid voltage $v_g$ [26]. Assuming unity voltages, neglecting the resistive losses and using the total inductance in the system of 0.5 pu, the maximum transferable power from idealized steady state considerations should in this case be in the range of 2.0 pu. It can be noted that the results in Fig. 11 show that the when the synchronous reference frame is oriented at the grid voltage source, the converter control system is capable of stable operation for powers quite close to this theoretical stability limit.

$$p = \frac{v_c \cdot v_g}{I_{\text{tot}}} \sin \delta$$

(C) Practical Considerations and Future Work

The results presented in this paper are mainly of idealized and conceptual nature, and are presented with focus on the concept of changing the reference frame orientation of a converter control system in a weak grid. For further investigations, a more rigorous theoretical approach should be followed for the stability investigations. There will also be many practical considerations that have to be made before applying such a concept to a converter in a real application. Among such practical challenges, it will be important to investigate the proposed concept in case of a realistic LCL-filter as interface between the converter and the grid. It must then be studied how to obtain an accurate reference frame orientation independent of the influence of the shunt capacitors. Further on, it will be relevant to investigate how the presented approach can be combined with strategies for damping oscillations in the LCL-filter in similar ways as discussed in [12], [24], [25], [32].

It can also be noted that the concept of synchronizing to the equivalent grid voltage source as discussed in this paper is mainly of theoretical interest. In practical applications, the total equivalent grid impedance can change significantly and there might be other controllable units in the grid that can interfere with the concept discussed in this paper. A more realistic approach can however be to include well known parts of the power system into a Virtual Flux model, for orienting the converter control system to a specific, well defined, point in the grid. The basic structure from Fig. 5, with a filter and a transformer, is for instance the common configuration of wind turbines or other medium-sized generation systems. For such applications it can be relevant to use a Virtual Flux model for synchronization to the grid side of the transformer, to achieve easy fulfillment of requirements for control of power factor or reactive power while at the same time improving the stability properties of the converter control system. This might be one of the most realistic applications of the theoretical considerations presented in this paper.

V. Conclusion

This paper presents a new approach for reference frame orientation and synchronization of grid connected voltage source converters. Starting from the traditional choice of synchronizing to the grid voltage at the terminals of the filter inductor, it is shown how voltage-sensor-less operation based on the Virtual Flux concept can be used to freely choose the point of orientation for the control system. By synchronizing to a flux or voltage vector at a strong and stable point in the grid, the converter control system can become more stable and this can improve the operation in weak grids with high impedance seen from the converter. Simulations results have been presented to discuss the influence of the point of reference frame orientation on the dynamic response.
and the limits for stable operation of a converter. It has also been shown how the choice of reference frame orientation determines the point where control of active and reactive power is explicitly decoupled. As long as the corresponding grid parameters are known, the investigated Virtual Flux approach can thus be used to freely select a point where the power factor or the flow of reactive power can be explicitly controlled.

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REFERENCES


