A Comparative Study of Methods for Estimating Virtual Flux at the Point of Common Coupling in Grid Connected Voltage Source Converters With LCL Filter

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***Abstract*— Grid connected Voltage Source Converters (VSCs) with LCL filters usually have voltage measurements at the filter capacitors, while it can be important to control the active or reactive power injection at the grid-side of the LCL filter, for instance at a Point of Common Coupling (PCC). Synchronization to the PCC voltage can be obtained by Virtual Flux (VF) estimation, which can also allow for voltage sensor-less operation of VSCs. This paper is presenting a comparative evaluation of methods for estimating the VF at the PCC, considering a VSC connected to the grid through an LCL filter with a Proportional Resonant (PR) controller as the inner current control loop. The VF estimation is achieved by using frequency adaptive dual SOGI-QSGs (DSOGI-VF). The Frequency Locked Loop (FLL) is used in order to keep the positive and negative sequence (PNS) VF estimation inherently frequency adaptive. Three different methods are considered for obtaining the capacitor current needed for estimating the VF at the grid side of the LCL filter which are based on fully estimation by using the voltage sensor-less method, by estimating the capacitor current from the measured voltage or by using additional capacitor current sensors. The results have been compared and validated by simulation studies.**

Keywords—Virtual Flux Estimation, Voltage Source Converter, Proportional Resonant Current Controller, LCL-Filter.

I. INTRODUCTION

Grid connected inverters are the key components for interfacing Renewable Energy (RE) sources with the utility grid and to effectively produce high quality of power [1]-[3]. Inverters are connected to a grid through filters, and the current controller plays an important role in the tracking capability. LCL filters have outstanding harmonic suppression capability compared to L- and LC filters, but damping must be taken into account because the resonant peak could lead to instability. Early studies proved that grid voltage sensor-less control has a strong potential for maintaining normal operation of converter systems [4]-[6] while eliminating related sensors to reduce the cost and improve the modularity of the system. Virtual Flux (VF) estimation is one of the approaches that can achieve voltage sensor-less synchronization to the ac voltage. VF estimation is a simple and flexible approach which can be easily adapted to the system configuration, and the results are reliant and accurate as long as the filter parameters are known and stable. VF estimation can also be utilized to synchronize control systems to different remote points in the grid [7], [8]. Early contributions in this topic were made by Malinowski at el. in [9] where VF estimation was combined with Direct Power Control (VF-DPC). Consequently, a comparative study between voltage-based control and VF-based control for PWM rectifiers was presented in [10]. The work in [9] and [10] was compared in [11]. Antoniewicz also proposed an improved predictive direct power control algorithm based on VF estimation (VF-P-DPC) in [12].

In [13], Kulka presented the estimation of both positive and negative sequence (PNS) VF components in the stationary reference frame. The VF estimation and PNS separation were obtained separately, using two cascaded low pass filters with cut-off frequency identical to the grid frequency for obtaining the 90° phase shift utilized in the VF estimation and for the in-quadrature signal generation needed in PNS estimation. The author also include the drift compensation solution to achieve offset free VF estimation in the practical implementation in order to overcome the system sensitivity in case of grid frequency variations. A new method of VF estimation was presented in [14]-[16] where the transient response was improved by integrating the VF estimation and the PNS separation. The proposed synchronization method was made frequency-adaptive by using dual second order generalized integrators (DSOGI-VF).

Beyond the examples in [3], [8] and [17], it should be noted that previous studies have focused on the grid voltage sensor-less control based on VF estimation with L- and LC Filter. However, VF estimation can also be useful in case capacitor voltage measurements are available as discussed in [8], and this motivated the present study. In [3] a grid side voltage observer is designed to obtain the phase angle and amplitude needed to perform a voltage oriented control for the inverter, and the proportional integral (PI) current controller is adopted. On the other hand, only a PS-SRF current controller was applied in [17]. In this paper, a comparative study on VF estimation methods with the LCL filter and PR current controller is presented. Three different approaches of VF estimation will be studied. The work starts with an overview

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of grid synchronization based on VF estimation with LCL filter and PR current controller, continued by the three investigated methods of VF estimation. Furthermore, simulation results are discussed before concluding the paper with a discussion of obtained performances.

II. Grid Synchronization Based on VF Estimation with LCL Filter And PR Current Controller

The virtual flux (VF), Ψ can be obtained by integrating the converter output voltage, V_{con} [9]. The converter output voltage can be estimated from the pulse width modulation reference signal and the DC-link voltage. The virtual flux estimation can be done based on the synchronous *dq* frame or stationary *αβ* frame. Considering that the implementation is carried out in stationary reference frame, the flux is described in (1).

$$\Psi_{\alpha\beta}(t) = \int V_{con,\alpha\beta}\, dt + \Psi_0 = \int m_{ref,\alpha\beta} \left(\frac{V_{dc}}{2} \right) dt + \Psi_0 \qquad (1)$$

The positive and negative sequence calculation (PNSC) is needed to separate the voltage, virtual flux and current into positive and negative sequence components to suit with the application both balanced and unbalanced conditions [1], [15]. The 90° phase shifted signals needed for VF sequence separation is available from the in-quadrature and direct output signals qv' and v' from SOGI-QSGs. The transfer functions of the in-phase and in-quadrature outputs, v' and qv', with respect to the input v are given by (2) and (3) [1]. In this work, the value of $k=\sqrt{2}$ is used in all the simulations in order to ensure a compromise between the stabilization time and the overshoot [1], [14]-[16]. Since the direct output signal v' is equivalent to the derivative of VF, 90° phase lag of VF signals can be obtained by changing the sign. Thus, as an example, the per unit positive sequence VF components can be calculated by (4) and (5) [15], [16].

$$\frac{v'}{v}(s) = \frac{k\omega' s}{s^2 + k\omega' s + \omega'^2} \qquad (2)$$

$$\frac{qv'}{v}(s) = \frac{k\omega'^2}{s^2 + k\omega' s + \omega'^2} \qquad (3)$$

$$\chi_\alpha^+(s) = \frac{1}{2} qv'_\alpha(s) + \frac{1}{2} v'_\beta(s) \qquad (4)$$

$$\chi_\beta^+(s) = \frac{1}{2} qv'_\beta(s) - \frac{1}{2} v'_\alpha(s) \qquad (5)$$

The system parameters for the LCL filter design applied in this study are listed in Table I and the investigated system configuration is shown in Fig. 1. The design of the LCL filter is based on the 10kW nominal power. A passive damping resistor has been considered in the LCL filter design where a resistor has been placed in series with the capacitor. Taking into consideration the per phase model of LCL filter including a damping resistor, the transfer function of the filter is given in (6) [18]. In this paper, the PR current controller has been adopted. By using the PR current controller, the tracking capability of the current reference can be ensured. In term of the implementation wise, the computational burden is lower compared to the Proportional Integral (PI) controller in double synchronous reference frame. The PR current controller can be implemented either based on the ideal or non-ideal cases. However, only the non-ideal PR current controller is used in this work because using the ideal PR controller could leads to stability problems due to its infinite gain. The transfer function of the non-ideal PR current controller used in this work is given by (7) [1].

$$G_{f,d}(s) = \frac{C_f R_f s + 1}{L_2 C_f L_2 s^3 + C_f (L_1 + L_2) R_f s^2 + (L_1 + L_2) s} \qquad (6)$$

$$G_{PR}(s) = K_p + K_r \frac{2\omega_c s}{s^2 + 2\omega_c s + \omega_o^2} \qquad (7)$$

TABLE I. System Parameters

Parameters		
Abbreviation	***Nomenclature***	***Values***
P_n	Nominal Rated Power	10kW
V_{DC}	DC link Voltage	685V
V_g	Phase Grid Voltage	230V
f_g	Grid Frequency	50Hz
f_{sw}	Switching Frequency	10kHz
L_1	Inverter Side Inductor	0.00557H
L_2	Grid Side Inductor	0.00151H
L_T	Transformer Inductor	0.00254H
c_f	Capacitor Filter	39.8μF
r_d	Damping Resistor	1.81995Ω

III. Implementation Of VF Estimation With LCL Filter

A. Method 1: Voltage Sensor-less VF Estimation

This concept does not require any voltage sensors in the VF estimation. However, the current sensors have been used in the measurement of converter currents. The capacitor current, i_f will be obtained by fully estimation. The converter current, i_{con} is transformed into the stationary *αβ* frame and the grid current $i_{g,\alpha\beta}$ is obtained by subtracting the estimated capacitor current, i_f from the converter current. The resistive voltage drop in the primary filter inductor is attained by multiplying R_1 with the converter current, $i_{con,\alpha\beta}$ and this voltage drop will be subtracted from the converter output voltage. In order to estimate the capacitor voltage, V_f, the in-quadrature component of the converter current is multiplied with the inductance L_1 and added to the resistance-compensated converter output voltage. This corresponds to a quasi-stationary estimation of the inductive voltage drop across the filter inductor. The capacitor current, i_f can be directly estimated from the estimated V_f. The positive and negative sequence VF components at the capacitor, $\chi_{c,\alpha\beta+}$ and $\chi_{c,\alpha\beta-}$, will be obtained after subtraction of the induced PNS flux components in L_1 from the output of the DSOGI-VF estimation according to [14]-[16]. Thus, the estimation also depends on PNSC of the converter currents. The resistive drop in the grid side of the LCL-filter is calculated by multiplying R_2 with the integral of the PNS grid current components, ϑ_g.

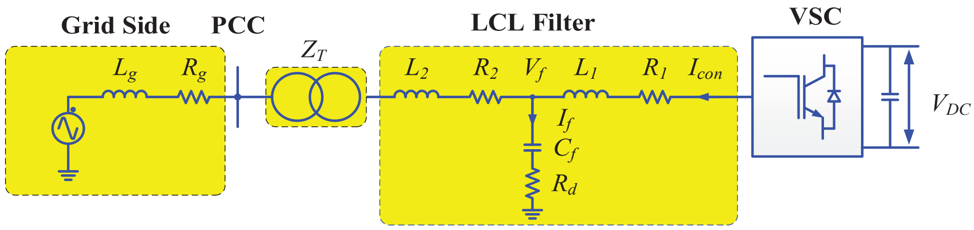

Fig. 1. Overview of investigated system configuration

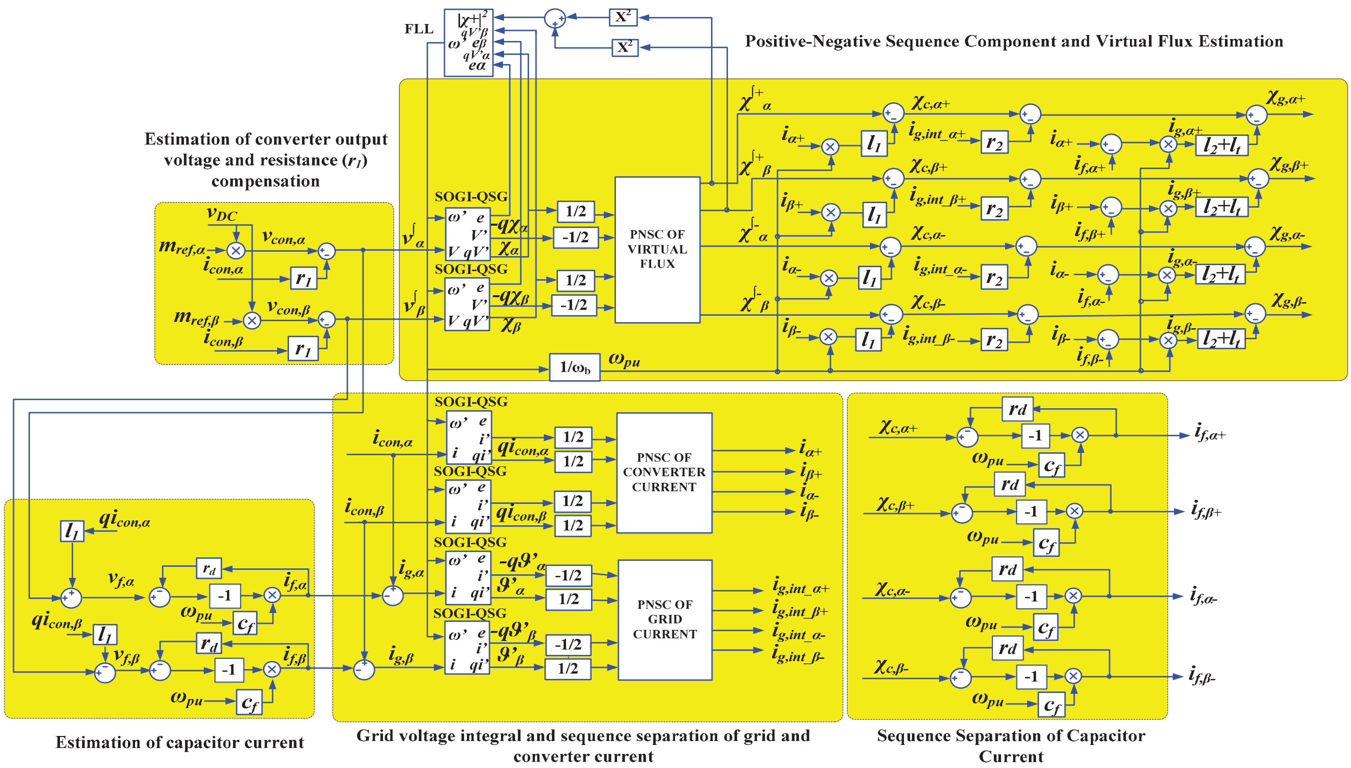

Fig. 2. VF estimation using voltage sensor-less method

The induced flux drop at the grid is considered by multiplying the PNS grid currents with added value of L_2 and L_T, where L_T is representing the transformer leakage inductance which is 5% of the base impedance value in this case. The structure of the voltage sensor-less VF estimation is shown in Fig. 2. By considering the per unit values, the resulting VF estimation in stationary reference frame can be expressed in (8), where the scaled virtual flux χ is the voltage integral multiplied with the per unit frequency of the system. Since $qv'=\chi$, the transfer function in (9) can be obtained. The output of the VF estimation can be used to calculate the current corresponding to a specific active and reactive power at the PCC. Other than that, the output of the positive sequence of the VF estimation will be used in the current reference calculation needed for the current controller. Since the current is controlled at the converter side, the current references needed for the PR current controller to regulate active and reactive power can be obtained by adding the capacitor current to the required current at PCC. In this case a good VF estimation is necessary because a good estimation will contribute to a perfect balanced sinusoidal current reference to the PR current controller. It is also important to make sure that the phase shifting of the SOGI is exactly 90° phase shifted because any phase displacements will contribute to the error between the voltage and current and also could leads to the error in reactive power measurement.

$$\chi^{\alpha\beta}(t)=\omega_{pu}\cdot\omega_b\int(m_{ref\alpha\beta}\cdot v_{DC}-(r_1\cdot i_{con,\alpha\beta}))dt-(l_1\cdot i_{con,\alpha\beta}(t)) \\ -(\vartheta_{g,\alpha\beta}(t)\cdot r_2)-[(l_2+l_t)\cdot(i_{con,\alpha\beta}(t)-i_{f,\alpha\beta}(t))] \tag{8}$$

$$\chi^{\alpha\beta}(s)=\left[\frac{k\omega'^2}{s^2+k\omega's+\omega'^2}\cdot v_{\alpha\beta}(s)-[(r_1\cdot i_{con,\alpha\beta}(s)]\right]- \\ [\omega_{pu}\cdot(l_1\cdot i_{con,\alpha\beta}(s))]-\left[\frac{k\omega'^2}{s^2+k\omega's+\omega'^2}\cdot i_{g,\alpha\beta}(s)\cdot r_2\right]- \\ [\omega_{pu}\cdot([l_2+l_t]\cdot[i_{con,\alpha\beta}(s)-i_{f,\alpha\beta}(s)])] \tag{9}$$

B. *Method 2: VF Estimation with voltage sensors at the filter capacitors*

In this method, the capacitor current is obtained by an estimation based on the measured capacitor voltage. Since the value of the capacitor voltage V_f is known, the capacitor current, i_f can be estimated directly from the measured capacitor voltage. However the method of estimating the capacitor current from the capacitor voltage is still as the same method shown in Fig. 2. Since one of the advantages of the utilization of VF estimation is to synchronize control system to different remote points in the grid, it is reasonable to have a sensor to measure the capacitor voltage, V_f. The presence of a voltage sensor also allows for checking the existence of voltage in the network and simplifies start-up of the converter. The active and reactive power at a remote point can still be controlled on basis of the VF estimation, as long as the LCL parameters, duty cycle and converter output current are known. As the same implementation as method 1, the converter output voltage alpha and beta components are calculated from the dc voltage multiplied with the pulse width modulation signal. The block diagram for the VF estimation based on the voltage sensor-less method shown in Fig. 2 is still valid, except for the capacitor current estimation where the block diagram is modified to Fig. 3. The resulting virtual flux estimation, χ in (8) and (9) are still valid for this method.

C. *Method 3: VF Estimation with capacitor current sensors*

In the case of method 3, the capacitor current, i_f is directly measured by using a current sensor. The estimation of the converter output voltage as well as the positive and negative sequence component of virtual flux estimation is similar to the method shown in Fig. 2. However, the block diagram of the capacitor current estimation is not necessary since the capacitor current is directly measured. Four sets of DSOGI-QSGs and PNSC blocks are considered in method 3 compared to only three sets required in method 1 and 2. By referring to Fig. 4, another set of DSOGI-QSG and PNSC is required to obtain the positive and negative sequence of capacitor currents. However, similar to method 1 and 2, the grid current is obtained by subtracting the capacitor current from the converter current, thus an integral of the grid current is necessary. As for the similar approach in section III. A and B, the expression in (9) is used to obtain the VF estimation output at the grid side.

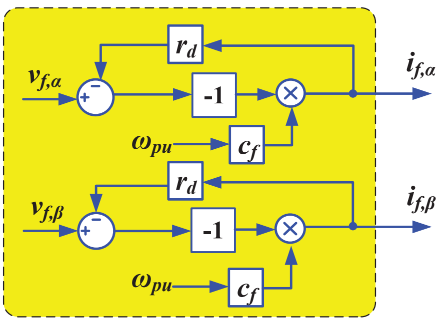

Fig. 3. Estimation of capacitor current for Method 2.

IV. Simulation Results of the VF Estimation

By considering the parameters listed in Table 1, the simulation has been carried out for all the three methods that have been proposed and the results are shown in Fig. 5 and Fig. 6 respectively. The K_p and K_r values used in this work are kept at 5.6 and 6000. The reference active power and reactive power is set to 10kW and 0kVar. The simulation results are expressed in per unit values. It is proven that by using all the three proposed methods, the system works as intended, and the converter current is forced to follow the reference current as shown in Fig. 5 (a). Transients occurring during the start-up are quickly attenuated and the system reaches its steady state at t = 0.15s. With proper tuning of the K_p and K_r as well as the effectiveness of using the DSOGI-VF, the system response is very fast and tracking of the current reference is almost immediate. In balanced condition, the alpha and beta components of positive sequence of converter current and virtual flux estimation should have the same amplitude and the beta component is expected to be lagging by 90° compared to alpha component as shown in Fig. 5 (b) and Fig. 5 (c). In Fig. 5 (b), the simulation results of the positive sequence of converter current are almost identical when considering the 1st and 2nd proposed method. However, when the 3rd method has been considered, the value of the positive sequence of converter currents are slightly lower compared to the results shown for the 1st and 2nd method. This is due to the ripple current occurred in the capacitor. Measuring the capacitor current directly will definitely degrade the results. The output of virtual flux estimation shown in Fig. 5 (c) will bring a significant impact of the overall system because without a good estimation, the tracking of the converter current will be affected since the current reference calculation is depending on the results of virtual flux estimation.

All the three methods produced a reasonable response for the virtual flux estimation. The active and reactive power at the point of common coupling is shown in Fig. 6 (a). Both active and reactive power matched with the reference setting values for the case of Method 1 and Method 2. However, as discussed earlier, the ripple current existing in the filter capacitor will deteriorate the performance of the system when method 3 is considered. It can be clearly seen by observing the waveform shown in Fig. 6 (a) when the active power for all the three methods are compared. The active power measurement considering method 3 is a little bit lower compared to the reference power. This is happening due to the distorted current waveform in the capacitor, hence giving an impact to the system. In real implementations, this condition cannot be compromised since the current in the capacitor has a lot of ripples and the capacitor current also has been considered in the current reference calculation. Thus, it is not recommended to directly measure the capacitor current because it will affect the active power control. To improve this situation, active damping could possibly considered. However, this alternative is out of scope of this work. The efficacy of using the PR current controller can be observed in Fig. 6 (b) where the zero steady state error has been achieved for all the three methods.

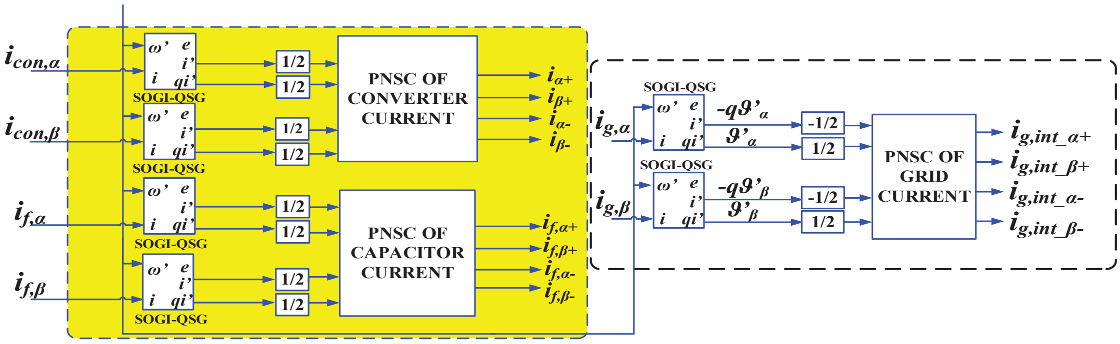

Fig. 4. Grid current integral and sequence separation of converter and capacitor current for Method 3

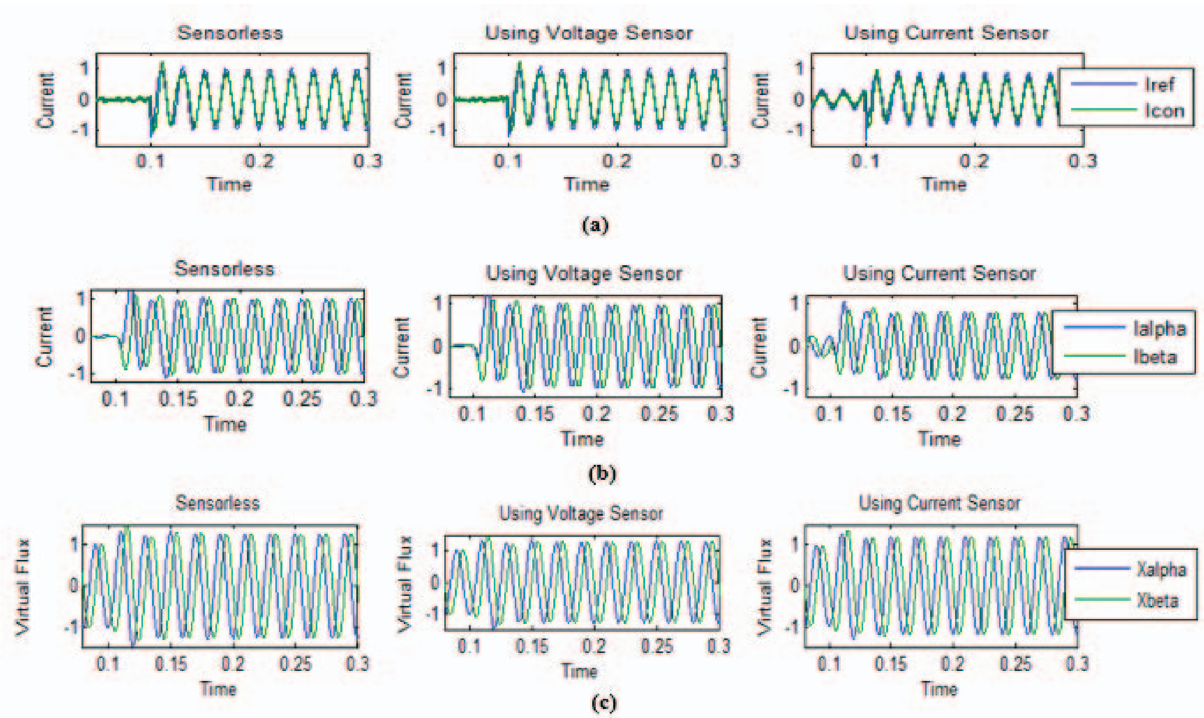

Fig. 5. Simulation Results (a) Reference Current and Converter Current. (b) Positive Sequence of Converter Current, and (c) Positive Sequence of Virtual Flux Estimation

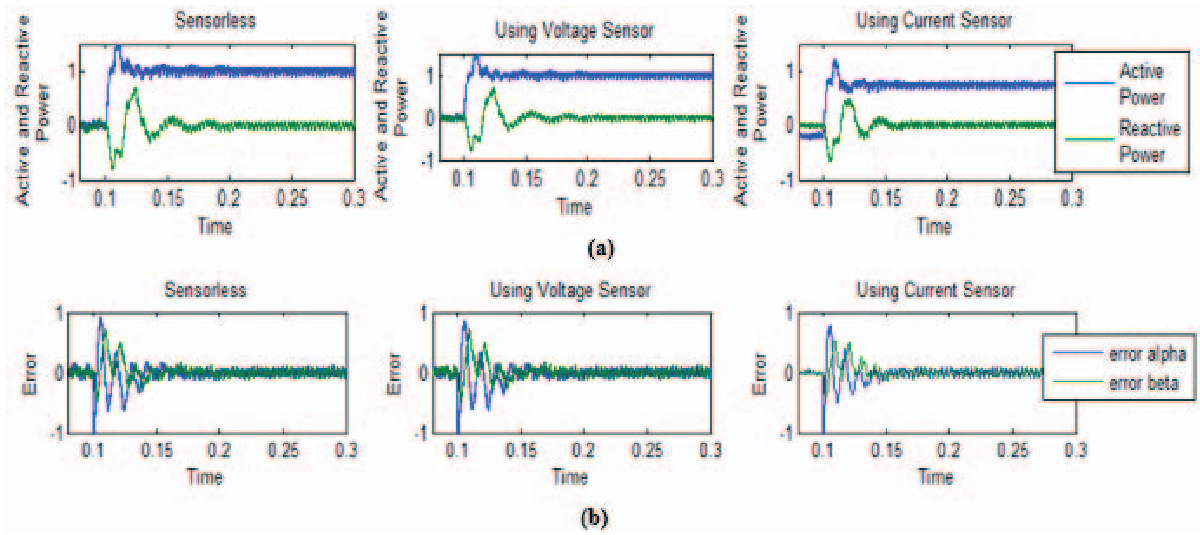

Fig. 6. Simulation results showing (a) Active and Reactive Power of the System, and (b) Steady State Error

If the practical implementation has been put into consideration, the VF estimation will definitely worked well in a balanced strong grid system. However when the system is connected to a weak grid, the VF estimation will not be affected by the weak grid condition because the VF estimation is just performing an estimation of the grid voltage condition and it can be done as long as all the parameters of the filter, dc voltage, measured current and pulse width modulation reference signal are available to perform an estimation. However, the accuracy of the VF estimation will depends on the stable filter parameters and a perfect measurement of the currents. One of the advantages of this system is that the parameters of the filter can be easily change online. Considering the weak grid condition, the value of the active power measurement may slightly lower compared to the active power reference due to the existence of capacitor and inductor in the filter and also a high value of grid impedance but the losses of power can be monitored online.

V. Conclusion

In this work, a comparative study of different implementations of VF estimation for grid connected inverters with LCL filter is presented. It is proven that the VF estimation based on either voltage sensor-less operation or capacitor voltage measurements provide a reliable output compared to estimations using capacitor current measurements. VF estimation based on voltage sensor-less operation can reduce cost, however for most practical implementations voltage sensors for measuring the capacitor voltage are essential to ensure safe and reliable operation. A highly dependent voltage measurement provides a stable output, thus contributing to a good estimation of virtual flux at the PCC. With a high consistency of VF estimation at PCC, detection of load imbalance is possible, thus leading to a good control of active and reactive power at a remote point. Placing a current sensor to directly measure the capacitor current is not a good choice in a real implementation since the ripple current in the capacitor will attenuate the current flowing in the capacitor and deteriorate the performance of the VF estimation.

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