Frequency-Adaptive Virtual Flux Estimation for Grid Synchronization under Unbalanced Conditions

Jon Are Suul*, Alvaro Luna**, Pedro Rodriguez**, Tore Undeland*

*Department of Electric Power Engineering
Norwegian University of Science and Technology, NTNU
Trondheim, Norway
jon.are.suul@elkraft.ntnu.no

**Department of Electrical Engineering,
Technical University of Catalonia, UPC
Terrassa, Spain
luna@ee.upc.edu

***Abstract*-This paper proposes a new and explicitly frequency-adaptive method for Virtual Flux estimation and voltage sensor-less grid synchronization under unbalanced conditions. The proposed system is based on using Second Order Generalized Integrators, arranged to simultaneously fulfill the purposes of frequency-adaptive band-pass filtering, integration and quadrature signal generation. This results in a simple and efficient structure for combined Virtual Flux estimation and separation into positive and negative sequence components. The properties of the proposed Virtual Flux model is analyzed theoretically, first as an integrator for implementing generic Virtual Flux estimation, and then with respect to sequence separation. The dynamic performance of the proposed estimation method is tested by simulations for the case of an unbalanced voltage drop in the grid and for a step in grid frequency. The simulations verify the performance to be as expected, with similar dynamics as synchronization based on voltage measurements.**

I. INTRODUCTION

As the use of power electronic converters in power systems is increasing, the three-phase Voltage Source Converter (VSC) is emerging as the main topology for a wide range of applications [1]. A large variety of strategies for control and grid synchronization of VSCs has therefore been suggested and analyzed in the scientific literature [2]-[4].

Operation of grid connected VSC's without AC-voltage sensors has been considered interesting for cost reduction, modularity and possible improvement of reliability [5], [6]. Another interesting aspect with voltage-sensor-less control algorithms is that estimation methods used to replace voltage measurements can also be used to estimate voltages that are not easily available for real-time measurements [7].

Voltage sensor-less operation has been investigated and implemented on basis of several different approaches for grid synchronization. The concept of "Virtual Flux," interpreting a voltage integral as a "grid flux," is a common and easily applicable method that has been utilized for synchronization of both traditional and sensor-less control systems [8]-[11]. The introduction of the term "Virtual Flux" and the first thorough analysis of application to voltage-sensor-less operation of VSCs was however presented by Malinowski in [12]- [14]. One of the main advantages of using this approach for sensor-less operation is that the values of flux or voltage behind an inductance can be easily estimated without depending on differentiation of the current.

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To avoid problems with drift and saturation of the Virtual Flux integral, many proposed implementations are based on simple filtering structures, although more advanced adaptive methods for correction of pure integrators have also been suggested [12], [15], [16]. Virtual Flux estimation based on simple filtering strategies will however be sensitive to grid frequency variations.

Even if the concept of Virtual Flux is becoming well established for control of VSCs, this is still a relatively new topic in the literature. Therefore, only a limited number of studies have until now considered operation of Virtual Flux-based control systems under unbalanced grid conditions [16]-[21]. Among them, only [16] has until now presented a generic Virtual Flux model designed specifically for separating positive and negative sequence flux components in the stationary reference frame.

Considering the drawbacks of existing Virtual Flux models with respect to frequency variations and operation under unbalanced conditions, this paper proposes a new method for Virtual Flux estimation that is inherently capable of handling these problems. The suggested method is based on utilizing the Second Order Generalized Integrator (SOGI) from [22], [23] as a combined frequency-adaptive band-pass filter, integrator and quadrature-signal generator. It will be shown in the paper how the result will be a general purpose frequency adaptive positive and negative sequence Virtual Flux model that can be used together with any control strategy for the converter. Verification and illustration of the proposed concept is provided by time-domain simulations.

II. VOLTAGE SENSOR-LESS GRID SYNCHRONIZATION BASED ON VIRTUAL FLUX

The flux Ψ calculated as the integral of the voltage V as given by (1) is the basic starting point of the Virtual Flux concept. For voltage-sensor-less operation, this voltage must be calculated from the switching states and the DC-link voltage of the converter [12]-[14], [16], [24].

$$\Psi = \int V \cdot dt + \Psi_0 \tag{1}$$

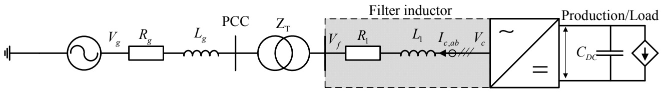

Fig. 1. Basic system under consideration

A. Ideal Virtual Flux Estimation for Grid Synchronization

An ideal model for Virtual Flux estimation in the circuit of Fig. 1 is shown in Fig. 2. The figure shows the principle of the Virtual Flux estimation, as the resistive voltage drop ($R_1 \cdot i_c$) is subtracted from the output voltage of the converter, while the inductive flux drop ($L_1 \cdot i_c$) is subtracted from the integrated voltage. To improve the Virtual Flux estimation, the converter voltage can also be compensated for the dead-time of the converter and the voltage drop of the semiconductor devices. The resulting calculation of Virtual Flux at the grid side of the filter inductor is then given by (2) [16].

$$\Psi_{f,\alpha\beta} = \int \left(v_{ref,\alpha\beta} \cdot \frac{1}{2} V_{DC} - V_{corr,\alpha\beta} - R_1 \cdot I_{c,\alpha\beta} \right) dt - L_1 \cdot I_{c,\alpha\beta} \quad (2)$$

Since the Virtual Flux is the integral of the voltage, its instantaneous phase angle γ_f is lagging the voltage by 90º for fundamental frequency signals. Therefore, the voltage phase angle θ_f can be easily estimated as given by (3). Since the integration of the Virtual Flux estimation has a filtering effect, the instantaneous phase angle for synchronization can usually be calculated directly from (3), but it can also be tracked by Phase Locked Loop [25].

$$\gamma_f = \arctan\left(\frac{\Psi_{f,\beta}}{\Psi_{f,\alpha}} \right) \qquad \theta_f = \gamma_f + 90° \quad (3)$$

B. State-of-the-Art for Virtual Flux Estimation

The simplest and most common approach for implementing the voltage integral of the Virtual Flux estimation, is to use a first order low-pass filter with a crossover frequency in the range around one decade below the fundamental frequency of the system [15], [16]. This will however result in significant amplitude attenuation and inaccurate phase estimation. Band-pass filters with more freedom to shape the frequency response have also been applied [10], [15]. Another simple method for Virtual Flux calculation was introduced by [16] and [26], based on two cascaded low-pass filters with crossover frequency equal to the fundamental frequency of the grid. With this implementation, a relatively fast transient response is achieved and the amplitude and phase characteristics are analytically corresponding to unity gain and 90º phase shift at the fundamental frequency.

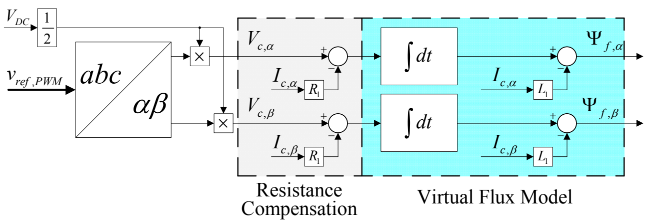

Fig. 2. Basic concept of an ideal model for Virtual Flux estimation

Despite of drawbacks with respect to accuracy and sensitivity to grid frequency variations, simple implementation still makes filter-based strategies for Virtual Flux estimation attractive compared to more advanced methods based on compensated or adaptive integration structures like the strategy discussed in [15].

C. Modified Per Unit Definition of Virtual Flux

Control systems are often analyzed and implemented in per unit values, due to the benefits of scalability and simple interpretation. Considering the Virtual Flux integral in (2), transformation into per unit values can be obtained by dividing by the base value of the flux, as given by (4), where V_b is the peak value of the rated phase voltage and ω_b is the nominal angular frequency of the system. The base value for the DC-link voltage is selected to be two times V_b. Neglecting the correction term, the per unit Virtual Flux model can then be expressed by (5).

$$\Psi_b = \frac{V_b}{\omega_b} \quad (4)$$

$$\psi_{f,\alpha\beta} = \omega_b \int \left(v_{ref,\alpha\beta} \cdot v_{DC} - r_1 \cdot i_{c,\alpha\beta} \right) dt - l_1 \cdot i_{c,\alpha\beta} \quad (5)$$

For grid connected converters, there is not necessarily a strong relation between the voltage and the frequency as for electrical machines, since their control is usually independent. At the same time, filter-based strategies for Virtual Flux estimation are not explicitly preserving the amplitude information, and are usually scaled to obtain unity amplitude at rated frequency. If deviations in frequency are considered, it can therefore be relevant to develop a Virtual Flux model that preserves the same per unit amplitude as the voltage instead of expressing the magnetic flux.

Such a modified Virtual Flux definition is here labeled by the letter χ as defined in (6). The resulting scaled Virtual Flux model can be easily obtained by multiplying the physical flux model with the per unit frequency of the system as given by (7).

$$\chi = \omega_{pu} \omega_b \int v \cdot dt \quad (6)$$

$$\chi_{f,\alpha\beta} = \omega_{pu} \omega_b \int \left(v_{ref,\alpha\beta} \cdot v_{DC} - r_1 \cdot i_{c,\alpha\beta} \right) dt - l_1 \cdot \omega_{pu} \cdot i_{c,\alpha\beta} \quad (7)$$

D. New Method For Virtual Flux Estimation

The Virtual Flux estimation suggested in this paper is based on the Second Order Generalized Integrator (SOGI) discussed in [22], [23]. The SOGI works as an explicitly frequency-adaptive integrator for sinusoidal signals, and can be configured as a frequency-adaptive band-pass filter by using a feedback from the output signal. The resulting structure is shown in Fig. 3 for a generic voltage v, where it is clearly seen that an estimate ω' of the fundamental frequency is an explicit input to the filter structure. The transfer function of the filter from the input variable v to the filtered variable v' is given by (8), and it can be seen that the frequency response can be shaped by selecting the gain k. In [22], it is shown that a value of k equal to $\sqrt{2}$ results in a good compromise between overshoot and stabilization time.

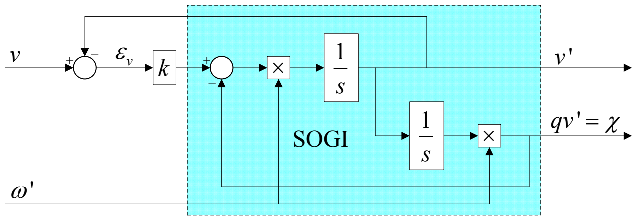

Fig. 3. Explicitly frequency adaptive second order band-pass filter based on a SOGI with the integral of the filtered value as secondary output representing the Virtual Flux

$$\frac{v'(s)}{v(s)} = \frac{k\cdot\omega'\cdot s}{s^2 + k\cdot\omega'\cdot s + \omega'^2} \tag{8}$$

Considering the block diagram of Fig. 3 it is clearly seen that the output qv' is the integral of the filtered output v', multiplied with the resonance frequency ω' as given by (9). From the previous discussion of Virtual Flux models, it should be clear that the SOGI-based filter will be suitable for implementing a simple and explicitly frequency adaptive Virtual Flux model that is scaled to the same amplitude as the grid voltage. For an ideal case without resistance, the estimation of the "flux" at the grid side of the filter terminals is given by (10), while (11) gives the expression if the per unit value of the "real" flux is desired as an output.

$$qv' = \omega' \int v' dt \tag{9}$$

$$\chi_f = \omega' \int v_c' \cdot dt - \omega_{pu}' \cdot l_1 \cdot i_c \tag{10}$$

$$\psi_f = \frac{1}{\omega_{pu}'}\omega' \int v_c' \cdot dt - l_1 \cdot i_c \tag{11}$$

The transfer function from the input signal v to the estimated Virtual Flux is easily found as a second-order low-pass filter given by (12). The total per unit Virtual Flux model for estimating the scaled "flux" at the grid side of the filter inductor L_1 is then given in the Laplace-domain by (13).

$$\chi(s) = qv'(s) = \frac{k\cdot\omega'^2}{s^2 + k\cdot\omega'\cdot s + \omega'^2} v(s) \tag{12}$$

$$\chi_{f,\alpha\beta}(s) = \frac{k\cdot\omega'^2}{s^2 + k\cdot\omega'\cdot s + \omega'^2}\cdot\left[v_{c,\alpha\beta}(s) - r_{L_1}\cdot i_{c,\alpha\beta}(s)\right] - \omega_{pu}'\cdot l_1 \cdot i_{c,\alpha\beta}(s) \tag{13}$$

It should be noted that the grid angular frequency ω' that must be provided to the proposed Virtual Flux model can be tracked by a traditional Phase Locked Loop (PLL), or by a Frequency Locked Loop (FLL) operating on the internal error signal ε_v and the output signals of the SOGI as discussed in [22], [23]. If can further be remarked that although Virtual Flux-based control systems are usually implemented for three-phase converters, the proposed Virtual Flux model is independent of the application and could also be used for single-phase systems.

III. Positive and Negative Sequence Separation in Stationary Frame for Unbalanced Conditions

For operation of converters under unbalanced conditions, detection of the positive sequence component of voltage or "flux" will be necessary. In [17]-[21] this has been obtained by different filtering techniques, or by using a Double Reference Frame PLL, applied on the estimated Virtual Flux variables. In [16] it was however shown how the sequence separation can be implemented in the stationary reference frame before carrying out the Virtual Flux estimation. The new approach for Virtual Flux estimation proposed in this paper will also utilize sequence separation in the stationary reference frame, based on the concept of Symmetrical Components in the time-domain.

The sequence separation algorithm is implemented in the two-phase stationary αβ-reference frame by introducing a phase-shift operator q that represents a 90º phase lag. Applying this strategy to the generic variable x, the calculation of positive and negative sequence components are given by (14) [23], [27].

$$\begin{bmatrix} x_\alpha^+ \\ x_\beta^+ \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & -q \\ q & 1 \end{bmatrix}\cdot\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \qquad \begin{bmatrix} x_\alpha^- \\ x_\beta^- \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & q \\ -q & 1 \end{bmatrix}\cdot\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \tag{14}$$

Implementation of the q-operator by using the SOGI as a frequency-adaptive quadrature-signal generator (SOGI-QSG) has been thoroughly analyzed for voltage based synchronization methods in [22], [23] and will also serve as basis for the further investigation in this paper.

IV. Frequency Adaptive Virtual Flux Model for Unbalanced Conditions

Considering the presented frequency-adaptive characteristics of the SOGI-based Virtual Flux estimation and quadrature signal generation, it is possible to suggest a new approach where frequency-adaptive filtering, Virtual Flux integration and sequence separation is merged into one operation. The basis for the proposed model will be the discussion in section II.D, considering the structure from Fig. 3 as general building block labeled as a SOGI-QSG. This building block is providing two filtered output variables where one is the in-phase filtered image of the input signal while the second output is the scaled integral of the first output, i.e., the in-quradrature version of the input signal.

A. Structure of the New Model for Virtual Flux Estimation

The starting point of the proposed Virtual Flux model is to consider the output qv' from the SOGI-QSG as a scaled Virtual Flux, χ, as defined by (6). The second set of signals needed for the sequence separation, which must be phase-shifted by 90º with respect to the Virtual Flux signals, are provided by inverting the sign of the in-phase output signal v'. In this way, positive and negative sequence components of the scaled Virtual Flux can be found by (14), utilizing a minimum number of integrators or filters.

A Virtual Flux model based on these simple considerations is shown in Fig. 4. As seen, both the Virtual Flux integral and the sequence separation are based on the same SOGI-QSG for each axis.

When the positive and negative sequence components of the Virtual Flux at the converter terminals is estimated in this way, the current induced fluxes have to be subtracted

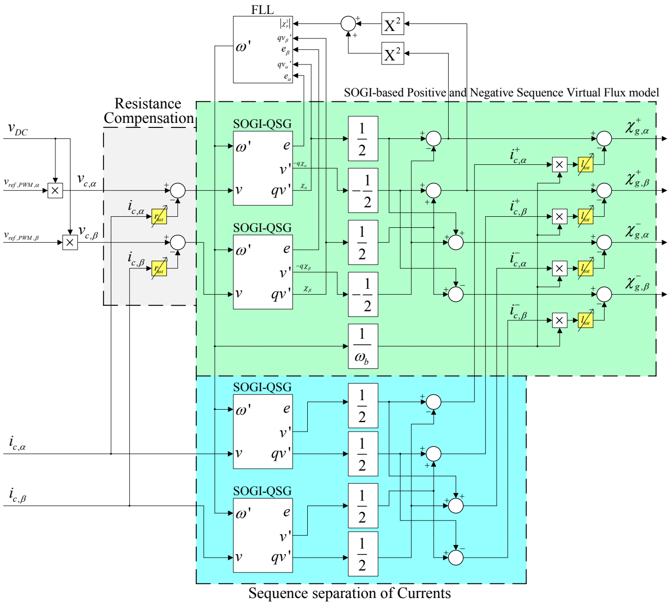

Fig. 4. Frequency Adaptive, Dual SOGI-based Virtual Flux model with Sequence Separation of fluxes and currents

separately for the positive and negative sequence. Therefore, sequence separation of the current measurements is needed as well, as shown in the figure. However, still only 4 filters are needed for the implementation, and there are no filters connected in cascade in the flux estimation. Therefore, this model is expected to have faster dynamic response than the strategy proposed in [16].

It can be seen from Fig. 4 that the presented model has the frequency as an explicit input for each operation. In this case, the FLL from [28] is used to track the system frequency. From the point of the Virtual Flux model, the source of the frequency information is however not important, and a PLL could also be used for the same purpose.

By using SOGI-QSGs for the implementation of the Virtual Flux estimation, the frequency scaled Virtual Flux definition presented in section II.C and equation (7) should be applied, or the sequence separated flux signals have to be divided by the per unit grid frequency as given by (11). In Fig. 4, the scaled Virtual Flux model is used, and it can be seen that the current measurements are multiplied with the per unit frequency before calculating the grid flux at the point of synchronization.

Since the "flux" estimation and the sequence separation is based on utilizing the two SOGI-QSGs in a similar way as presented for sequence separation of measured voltages in [22], [23] the proposed approach can be labeled as a Dual SOGI-based Virtual Flux (DSOGI-VF) model.

B. Properties of the Proposed Model

The properties of the SOGI-QSG as a Virtual Flux integrator have already been discussed in section II.D. It is however important to characterize the performance of the proposed approach for separating positive and negative sequence components. This can be investigated by studying the transfer function from the voltage reference input to the sequence separated flux components. In balanced conditions, the α- and β-components of the voltage have equal amplitude and the β-component is lagging the α-component by 90º in time. For the steady state frequency response, this phase displacement can be described as given by (15) [23].

$$v_{ref,\beta}(s) = -\frac{s}{\omega} v_{ref,\alpha}(s) \tag{15}$$

From Fig. 4, the positive sequence flux component can be described by (16). Substituting the expression from (15) into this equation results in (17), that can be further expanded, by using equation (8), into the full expression given by (18).

$$\chi_\alpha^+(s) = \frac{1}{2}\left(\chi_\alpha(s) - q\cdot\chi_\beta(s)\right) = \frac{1}{2}\left(\frac{\omega'}{s} v_\alpha{}'(s) + v_\beta{}'(s)\right) \tag{16}$$

$$\chi_\alpha^+(s) = \frac{1}{2}\left(\frac{\omega'}{s} v_\alpha{}'(s) - \frac{s}{\omega} v_\alpha{}'(s)\right) \tag{17}$$

$$\chi_\alpha^+(s) = \frac{1}{2}\left(\frac{k\cdot\omega'^2}{s^2 + k\cdot\omega'\cdot s + \omega'^2} - \frac{s}{\omega}\cdot\frac{k\cdot\omega'\cdot s}{s^2 + k\cdot\omega'\cdot s + \omega'^2}\right) v_{ref,\alpha}(s) \tag{18}$$

Analyzing only the steady state frequency response, the resulting transfer function from the α-axis voltage reference input to the α-component of the positive sequence Virtual Flux is given by (19).

$$\frac{\chi_\alpha^+(j\omega)}{v_{ref,\alpha}(j\omega)} = \frac{1}{2}\left(\frac{k\cdot\omega'\cdot(\omega'+\omega)}{\omega'^2 - \omega^2 + j\cdot k\cdot\omega'\cdot\omega}\right) \tag{19}$$

The frequency response of this transfer function can also be investigated for negative sequence frequency components by using negative values for the frequency ω when plotting the frequency response. A Bode-diagram showing the frequency response for both positive and negative frequency components is given in Fig. 5. This figure also shows the frequency response of the sequence separation strategy for voltages from [23]. As can be seen from the figure, the frequency response of the amplitude is exactly equal for the proposed DSOGI-VF model and for sequence separation of measured grid voltages. The differences can however be seen in the phase-response where the positive and negative sequence Virtual Flux components as expected are lagging the corresponding voltage components by 90º.

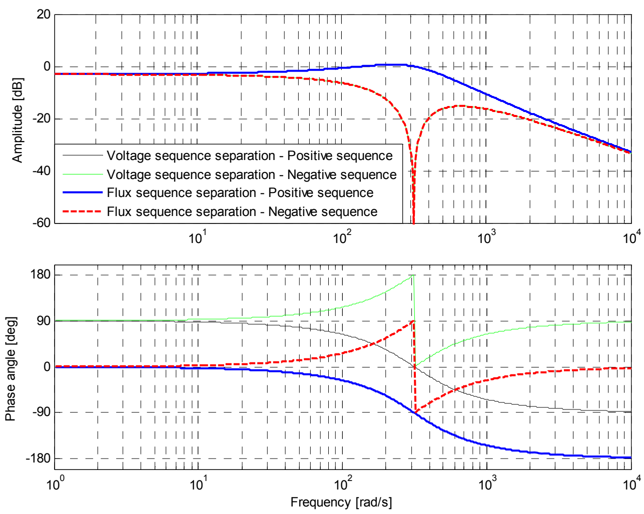

Fig. 5. Frequency response of strategy for separating positive and negative sequence components of voltage and Virtual Flux

Considering the results in Fig. 5, it is clear that the proposed method will fulfill its purpose of achieving both Virtual Flux estimation and sequence separation in steady state as long as the resonance frequency ω' is kept equal to the fundamental frequency of the grid.

V. Investigation of Proposed Concept by Simulation Studies

To investigate the dynamic performance of the proposed Virtual Flux model, a simulation study is carried out with the PSCAD/EMTDC simulation software. The simulation is based on an instantaneous average model, neglecting the switching operation, of a converter operating in a simple system similar to the one shown in Fig. 1.

A. Simulated System and Control Strategy

The simulation model is based on a vector oriented current control structure with Dual Frame PI-current controllers implemented in the positive and negative sequence reference frames as discussed in [29]. The phase angles for synchronization and transformation into the positive and negative sequence synchronously rotating reference frames are obtained by the proposed Virtual Flux model from Fig. 4 in the stationary reference frame.

The Dual Frame PI-controllers are used since this structure is well established and is inherently frequency adaptive if the real per unit frequency of the system is used to calculate the decoupling terms of the current controllers. The voltage feed-forward terms of the current controllers are not used as discussed in [16], although there are possible ways to substitute values obtained from voltage measurements by values derived from the Virtual Flux model [30].

For simplicity, only the positive sequence d-axis current reference is used to control the active power balance of the converter while all the other current references are set to zero. This simple approach results in balanced sinusoidal currents, also under unbalanced grid voltages.

The DC-link voltage is filtered by a frequency adaptive notch-filter, based on the same frequency adaptive structures as presented for the Virtual Flux model. This removes second harmonic oscillations during unbalanced conditions, so only the average DC-link voltage is used to control the power flow of the converter by a PI-controller giving the positive sequence d-axis current reference.

B. Operating Conditions and Simulated Cases

For all simulations, a constant active power of about 0.5 pu is being fed to the DC-link capacitance of the converter. The converter is connected to the grid through a filter inductor with 5% inductance and a transformer with a leakage inductance of 7 % and conduction losses of 0.5%. Under the initial operating conditions, the grid voltage at the high voltage side of the transformer is constant with 1.0 pu positive sequence component. A negative sequence component of 0.01 pu is also added to the voltage, to verify the capability for tracking low values of unbalance.

For these simulations, the Virtual Flux model is synchronized to the high voltage side of the transformer as discussed in [7]. The voltage at the same point is controlled directly by an ideal, controllable voltage source that can be used to impose disturbances to the system. By this simple approach, the estimated variables can be directly compared to values that are explicitly defined in the simulation model.

1. Transient Response to Unbalanced Voltage Sag

To test the transient response of the proposed strategy for Virtual Flux estimation and sequence separation, an unbalanced grid fault is imposed to the system at the high voltage side of the transformer. When the fault occurs, the positive sequence voltage is stepped down to 0.733 pu and the phase angle is shifted by 5º. At the same time the negative sequence component of the voltage is set to 0.210 pu while the phase angle is shifted by 50.4º. This corresponds to the influence from a distant single phase fault in the grid, and is the same fault as applied in [23].

The main results of the simulation are shown in Fig. 6, where the fault is applied at t=0.04 s while the system is

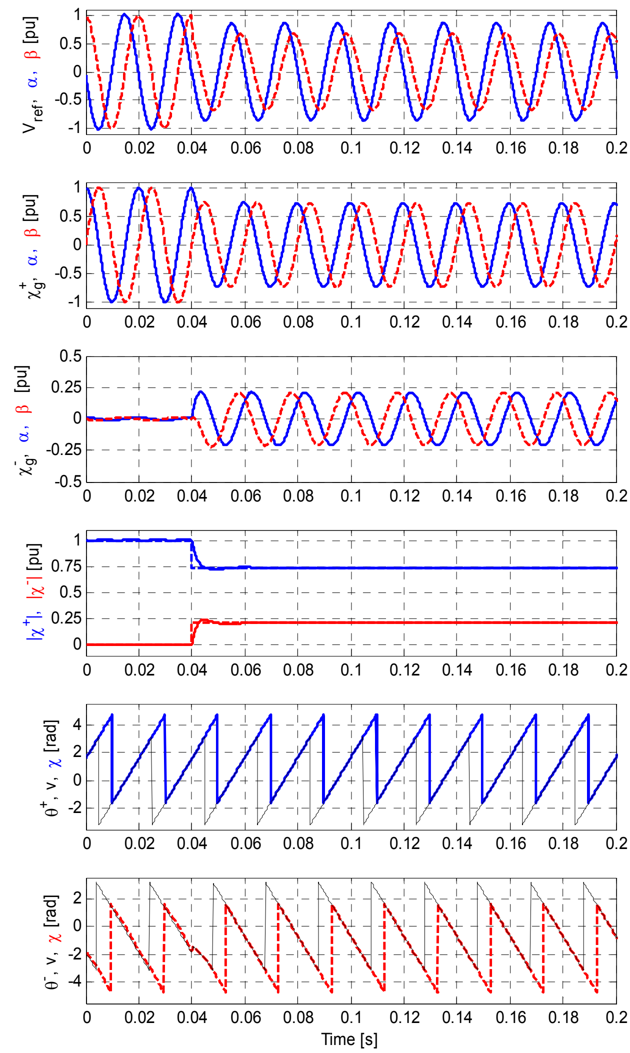

Fig. 6. Simulation results showing the response of the proposed Virtual Flux estimation when an unbalanced voltage sag occurs

operating under steady state conditions. From the figure, it can be seen how the voltage references for generation of PWM gate signals to the converter are becoming unbalanced when the fault occurs and the control system is continuing to inject balanced currents into the grid. The unbalanced voltage references are then integrated into Virtual Flux signals and separated into positive and negative sequence components by the proposed estimation strategy. The amplitudes of the positive and negative sequence flux components are calculated and compared to the amplitudes of the grid voltage imposed to the system. As can be seen in the fourth plot in the figure, the detection is relatively fast and accurate with about 5 ms rise-time and very little overshoot. The phase angles of the positive and negative sequence flux components are shown in the two lowest plots of the figure, phase shifted by 90º to correspond to the phase angle of the voltage components. The phase angles from the voltage measurements are shown with thin black lines in the figure, and it can be seen that the estimated values are corresponding very well. This verifies that the proposed Virtual Flux model with sequence separation performs as expected and does not introduce significant additional delays in the grid synchronization compared to strategies based on sequence separation of measured voltages.

2. *Transient Response to Changes in Frequency*

To demonstrate the frequency adaptivity of the proposed model by an extreme case, a step in frequency from 50Hz to 60Hz is imposed during the unbalanced conditions. Although not a realistic case, this situation is used to demonstrate how the proposed method is capable of responding to frequency changes in the grid and maintain its performance. The change in frequency is applied after the system has reached steady state in the unbalanced conditions, and the main results are shown in Fig. 7, where the time-axis is shifted so the frequency step occurs at t=0.04s.

Since the change of frequency is not introducing any change of voltage amplitude or power flow, the influence on the system is not well noticed in the plots of the αβ-components. However, in can be noticed that there is a disturbance in the amplitude of the estimated positive and negative sequence components. The estimated phase angles are also influenced, and the relative influence is larger in the negative sequence component since the amplitudes is smaller. The grid frequency estimated from the Virtual Flux model is shown in the last plot of Fig. 7, and here it can be seen that the Frequency Locked Loop used in these simulations is tracking the frequency within a time-period in the range of 100ms. When the frequency is correctly tracked by the FLL, so that the proposed Virtual Flux model is provided with the correct value of the grid frequency, the system reaches a new steady state condition where the disturbances in the estimation are eliminated. This verifies how the proposed system is inherently frequency adaptive. For realistic frequency variations in the grid, the response time of the frequency tracking is expected to have negligible influence on the performance.

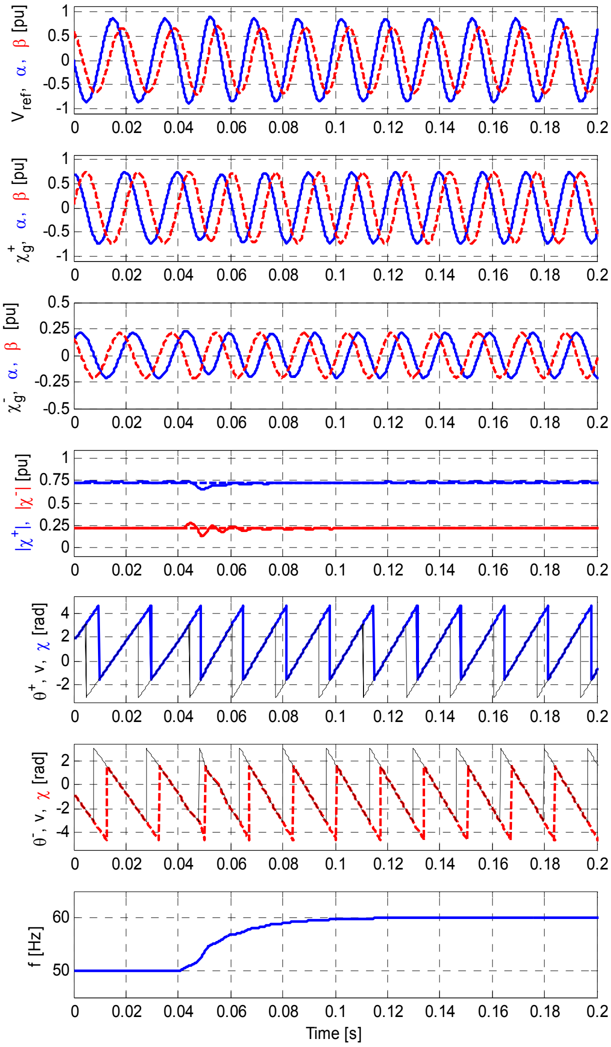

Fig. 7. Simulation results showing the response of the proposed Virtual Flux estimation when a large step in grid frequency occurs

VI. CONCLUSION

This paper has presented a new method for Virtual Flux estimation and voltage-sensor-less synchronization during unbalanced conditions. It has first been shown how a Second Order Generalized Integrator (SOGI) can be used as a basis for inherently frequency-adaptive Virtual Flux integration. Further on, this paper has presented a new configuration of a Dual SOGI-based Virtual Flux (DSOGI-VF) model where the functions of band-pass filtering, Virtual Flux integration and sequence separation are merged together in a simple implementation based on the SOGI as a basic building block. The resulting structure for Virtual Flux estimation overcomes the drawbacks of traditional Virtual Flux models with respect to frequency variations and operation under unbalanced conditions. The performance has been investigated by time-domain simulations, verifying that expected results are obtained with respect to steady-state and transient performance.

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