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Novel Method of Phase & Frequency Extraction during Grid Abnormalities

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ABSTRACT

Due to the rapid growth in utilization of Distributed Power Generating Systems (DPGS) and its connection to the utility grid, an inevitable overcome capacity of DPGS during the short grid disturbances is needed. The synchronization unit which is the central part in the grid-side control strategies of converter, plays a big role in this difficulties. Auto-adjustable Synchronous-Reference-Frame Phase-Locked-Loop (ASRF-PLL) is a better choice for the purpose of synchronization over the conventional SRF-PLL. But by the inclusion of second order generalized integrator (SOGI), in the area of ASRF-PLL, provides a lot of advantage to the synchronizing unit. This paper proposes a combine approach of ASRF-PLL and SOGI for the achievement of better results. It is first illustrated how the positive and negative sequence extracted from unbalance supply in both 3-phase and 2-phase systems and further given a brief illustration of both ASRF-PLL and SOGI (QSG and FLL). Then the combine approach is described in MATLAB and experimentally verified by the use of LABVIEW-2010 with the inclusion NI USB-6341 (Data acquisition system). Advantages like frequency adaptions of entire system, estimation of positive and negative sequence fundamental component without use of butter-worth filter and frequency estimation is done without use of any extra frequency detection technique. Filtering delay also absent, though we are not using any filter.

KEYWORDS

Synchronization, FLL, SOGI-FLL, AGFLL, DSOGI-FLL, MATLAB/SIMULINK, LAB View

INTRODUCTION

Synchronization unit is indispensable for the operation of a large number of generating stations in unison. However inverter control of Distributed Power Generation Stations (DPGSs) require adequate information of power system network at PCC. Hence continuous and proper grid condition monitoring of phase and frequency are essential for the operation of inverter. The demand for energy, collectively with the growing interest in clean technologies leads to the development of power distribution systems using renewable energy [1]. For this it is needed a better controllability and reversible power flow capability for electrical power conversion system. For the connection of grid side converters to the power system network, synchronization unit needs the major concern. Grid-connected converters should be perfectly synchronized with the power system network, to support the grid service under unbalance and distorted condition.

Synchronous reference frame PLL (SRF-PLL) [2] has become a formal grid synchronization technique in three phase systems. But as per its response concerned, it deviates from its required response at the distorted grid voltage condition. This drawback overcame by using decoupled double synchronous reference frame PLL (DDSRF-PLL) [3]. In this method two synchronous reference frames and a decoupling network is used to isolate the effects of positive- and negative sequence voltage components. To overcome the drawback of SRF-PLL, Auto adjustable synchronous reference frame PLL (ASRF-PLL) is used [4][5]. Furthermore an interesting synchronization technique for variation frequency environment was discussed in [6]. In this technique three single-phase independent enhanced phase-locked loops (EPLL) are united with a positive-sequence calculator. And there is no need of any synchronous reference frame for the synchronization of distorted grid networks. Using frequency-locking instead the conventional phase-locking with similar methodology was confronted in [7]. In 2008 P. Rodríguez with his associate proposed a new method of synchronization called Multiple Second Order Generalized Integrators Frequency Locked Loop (MSOGI-

FLL)[8]. By automatic change in gain of FLL gives rise an optimum response for the extraction of phase [9]. This simultaneously solved many task like frequency adaption, band pass filtering, estimation of positive and negative sequence components of grid at fundamental as well as higher order harmonics. Except higher order harmonics, the rest tasks are already fulfilled by Dual Second Order Generalized Integrators Frequency Locked Loop (DSOGI-FLL) [7].

Adopted data does not have Simultaneity, due to Vα is achieved by advancing Vβ 90° [5],[6]. Though detecting time is about 5ms, it is hard to meat real-time request [10-11]. For solving the question the paper presented an improved method on detecting real part and imaginary part of voltage vector.

This paper proposes an efficient way of synchronization for grid connected converter using an enhanced frequency locked loop (FLL). This method is useful in estimation of the positive and negative sequence components of the fundamental frequency. The proposed FLL is called Auto-Adjustable Gain Frequency-Locked-Loop (AGFLL) due to its inherent gain-adjusting capability. A comparative study of proposed FLL with the existed SOGI-FLL with different gain is given. Finally the robustness of proposed algorithm was verified with Dual Second Order Generalized Integrator (DSOGI). All the results are investigated in MATLAB-SIMULINK and LAB View environment.

POSITIVE AND NEGATIVE SEQUENCE CALCULATION

Park's transformation is the essential choice for the transformation of three phase supply voltages ‘ V_{abc} ’ to rotating reference frame value ‘ V_{dq} ’(1).

$$\left[V_{dq0}\right] = [P] * [V_{abc}] \qquad (1)$$

$$\text{Where, } [P] = \frac{2}{3}\begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \cos\theta^* & \cos\left(\theta^* - 120^0\right) & \cos\left(\theta^* + 120^0\right) \\ -\sin\theta^* & -\sin\left(\theta^* - 120^0\right) & -\sin\left(\theta^* + 120^0\right) \end{bmatrix}$$

But if the three phases are not equally distributed and differ in magnitude, then the instantaneous positive and negative sequence components of fundamental voltages need to be calculated. Equation (2),(3) shows the positive and negative sequence components of fundamental voltage on both a-b-c and α-β frames of references respectively.

$$\begin{bmatrix} V_a^+ \\ V_b^+ \\ V_c^+ \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \lambda & \lambda^2 \\ \lambda^2 & 1 & \lambda \\ \lambda & \lambda^2 & 1 \end{bmatrix} * \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (2a)$$

$$\begin{bmatrix} V_a^- \\ V_b^- \\ V_c^- \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \lambda^2 & \lambda \\ \lambda & 1 & \lambda^2 \\ \lambda^2 & \lambda & 1 \end{bmatrix} * \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (2b)$$

$$\begin{bmatrix} V_\alpha{}^+ \\ V_\beta{}^+ \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & -q \\ q & 1 \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \qquad (3a)$$

$$\begin{bmatrix} V_\alpha{}^- \\ V_\beta{}^- \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & q \\ -q & 1 \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \qquad (3b)$$

Here phase advance operator $\lambda = 1\angle 120^0$ and phase delay operator $q = 1\angle -90^0$.

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Due to lesser computation in two phase system, the sequence component calculation in α-β frame of reference is the better choice. So we need to convert the voltage vector from three phase rotating reference frame (a-b-c) to two phase stationary reference frame (α-β) by the use of Clarke's transformation (4).

$$V_{\alpha\beta} = [T_{\alpha\beta}] \cdot V_{abc}; \qquad (4)$$

$$\text{Where } [T_{\alpha\beta}] = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}$$

The sequence split-up procedure is implemented in the two phase stationary αβ-frame of reference by introducing the phase- shift operator qthat represents a 90º phase lag . So quadrature signal generator is essential for positive sequence calculation.

STRUCTURE AND ANALYSIS OF AUTO-ADJUSTABLE SYNCHRONOUS REFERENCE FRAME (ASRF) PLL

Here in this section ASRF-PLL under three phase sinusoidal input is explained. And furthermore, with the help of butter-worth low pass filter the working and application is vividly illustrated.

Here as of (5), a three phase balanced supply is given.

$$\begin{aligned} V_a &= V_m \sin\theta \\ V_b &= V_m \sin(\theta - 120^0) \\ V_c &= V_m \sin(\theta + 120^0) \end{aligned} \qquad (5)$$

From (1) and (5),

$$V(d,q) = \begin{bmatrix} V_d \\ V_q \end{bmatrix} = V_m \begin{bmatrix} \mathrm{Sin}(\theta - \theta^*) \\ -\mathrm{Cos}(\theta - \theta^*) \end{bmatrix} \qquad (6)$$

Let the difference angle $\Delta\theta = \theta - \theta^*$ is big. But due to feedback, the angle θ is locked soon. Then, $\Delta\theta$ will be very smalland the Taylor approximation for the sine and cosine aroundzero is given by (7)[4]:

$$V(d,q) = \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \sqrt{\frac{3}{2}} V_m \begin{bmatrix} \Delta\theta \\ -1 \end{bmatrix} \qquad (7)$$

Normalized V_d with respect to V_q,

$$\frac{V_d}{V_q} = -\Delta\theta \qquad (8)$$

Equation (8) gives difference in angle as the controller input for our remaining controller action of PLL. Fig.1 shows the complete structure of ASRF-PLL.

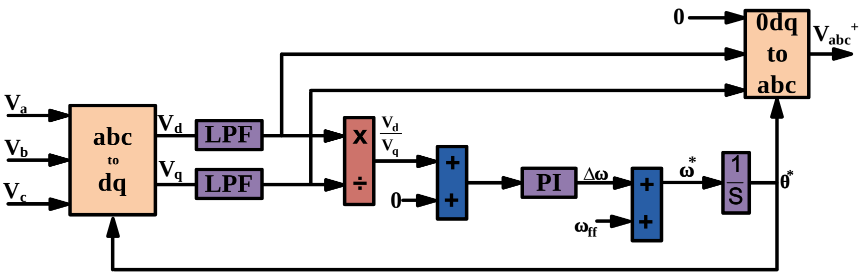

Fig 1:ASRF-PLL

Adopting this approach, PLL does not depend upon magnitude of voltage waveform.

Here the main aim is to make the phase deviation $-\Delta\theta = 0$. So by making $\frac{V_d}{V_q} = 0$, the required objective will be done as per (8). The division succeeds the controller, to be effective for any level of the input voltage magnitude.

The PLL control loop consists of a controller (C), which is useful to takes its error signal V_d/V_q and results the amount of pulsation $\Delta\omega$. This is necessary to add or subtract to a reference frequency ω_{ff} (feed forward frequency)to track the input voltage frequency $\omega_0 = 2\pi f_0$. The feed forward frequency $\omega_{ff} = \omega_0$ need to estimated [4]. Obviously ω_{ff} , which is the nominal value of frequency of the input supply, helps the process to improve the convergence. The result is the fundamental pulsation $\omega = 2\pi f$. So the positive sequence fundamental phase angle θ is obtained by integrating it. The phase will be locked, when the errors signal $V_d/V_q = 0$, that is $\omega = \omega_0$.

But for unbalanced and distorted three phase supply, there is a need for extraction of positive sequence fundamental components. Then only the PLL is valid for our requirement. This extraction of positive sequence fundamental components is done by the use of low pass butter-worth filter in both V_d and V_q. Only V_d is sufficient for our PLL control, but by applying the inverse Park transformation to V_q with the angle θ, the reconstruction of the positive-sequence fundamental supply voltage 'V_{abc}^{+}'is possible. The V_d component does not come forth in steady state. But by the use of it a softer dynamic state is possible, and also the rejection of homo-polar is done. [4]

SOGI BASED QUADRATURE SIGNAL GENERATION (QSG) AND FREQUENCY LOCKED LOOP (FLL)

As of (3), for getting the positive sequence voltage on α-β reference frame and transformation to d-q reference frame (9), the quadrature component of V_α and V_β must be estimated. In d-q axis, the direct voltage component on d-axis is real part and direct voltage component on q-axis is imaginary part of voltage vector.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \mathrm{Cos}\theta^* & \mathrm{Sin}\theta^* \\ -\mathrm{Sin}\theta^* & \mathrm{Cos}\theta^* \end{bmatrix} \begin{bmatrix} V_\alpha^+ \\ V_\beta^+ \end{bmatrix} \qquad (9)$$

Where $V_\alpha^+ = V_m \mathrm{Sin}\theta$

$V_\beta^+ = -V_m \mathrm{Cos}\theta$

Second order generalized integrator (SOGI) has some features, which not only fulfill the requirement of quadrature signal generator but also give the betterment in providing the frequency adaptive band-pass filtering. A small improvement of SOGI also has advantageous in estimating the frequency as in frequency locked loop shown in Fig.2 [7].

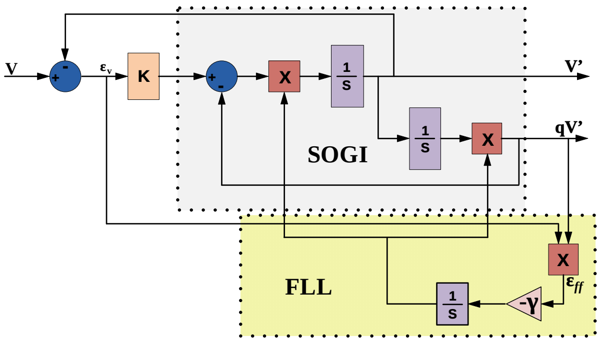

Fig 2: SOGI-QSG with Frequency Locked Loop(FLL)

As of fig.2, the close loop transfer function of V' (in-phase filtered voltage) and qV' (quadrature component of filtered voltage) to input signal V is given by (10).

$$D(s) = \frac{v'(s)}{v(s)} = \frac{k \cdot \omega' \cdot s}{s^2 + k \cdot \omega' \cdot s + \omega'^2} \qquad (10a)$$

$$Q(s) = \frac{qv'(s)}{v(s)} = \frac{k \cdot \omega'^2}{s^2 + k \cdot \omega' \cdot s + \omega'^2} \qquad (10b)$$

$$E(s) = \frac{\varepsilon_v}{v}(s) = \frac{s^2 + \omega'^2}{s^2 + k \cdot \omega' \cdot s + \omega'^2} \qquad (10c)$$

From (10), the transfer function is treated as a band-pass filter, whose band width varies according to the center frequency ω'. So by varying the SOGI resonance frequency ω', it is possible to vary the band-pass region. It is worthy to note that, from (10b) and (10c), a frequency locked loop was constructed by P. Rodriguez and his friends.

From the FLL block shown in fig.2

$$\varepsilon_f = qv' \cdot \varepsilon_v$$

But $$qv' = \frac{\omega' . v'}{s}$$

So we got,

$$\varepsilon_f = qv' \cdot \varepsilon_v = \frac{\omega' . v'}{s} \cdot \varepsilon_v \qquad (11a)$$

Again from figure we find

$$\omega' = -\frac{\varepsilon_f \cdot \gamma}{s} \qquad (11b)$$

Solving (11a) and (11b), the close loop equation of FLL block in fig.2 is presented in (12).

$$\omega' \left(1 + \frac{\omega' \cdot v' \cdot \varepsilon_v . \gamma \cdot}{s^2} \right) = 0 \qquad (12)$$

So FLL has also having an operating point of ‘zero’ (12). In order to prevent the value of frequency from zero, which is an undesired operating point, we put a select block (fig.3) of lower limit of frequency 250 rad/s. From fig.3 if the frequency extracted is less than 250 rad/s, the output frequency is 250 rad/s. Other-wise the extracted frequency of FLL shown as output.

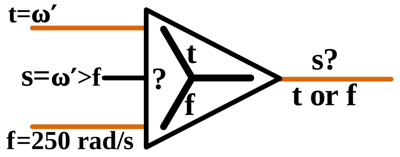

Fig 3: Select block in LABVIEW

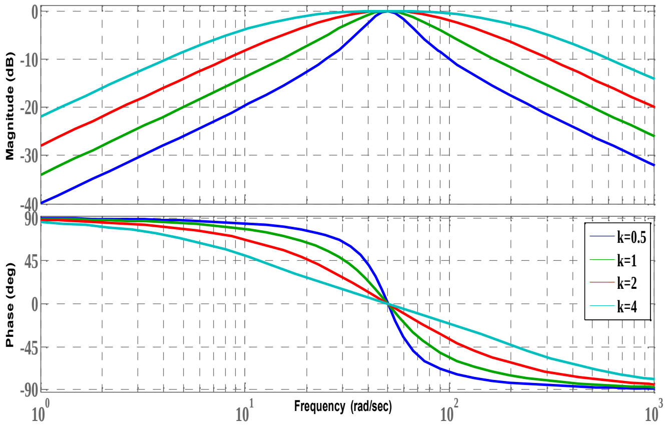

Fig 4:Bode plot of D(s) with centre frequency ω'=100*π

Fig.4 show the magnitude and phase response of D(s) with center frequency 100*π. And this figure is constructed with different types of gain (k=0.5, 1, 2, 4). These plots confirm that, for smaller value of k the response become more selective, but the stabilization time become longer.

The characteristics equation of (10) is

$$s^2 + k \cdot \omega' s + \omega'^2 = 0 \qquad (13)$$

But the second order generalized characteristics equation is shown in (14)

$$s^2 + 2 \cdot \xi \cdot \omega_n \cdot s + \omega_n{}^2 = 0 \qquad (14)$$

In order to tune the SOGI-QSG with proper value, we take the characteristic equation of (10).

Comparing (13) and (14),

$k = 2 \cdot \xi$

ξ = Damping ratio.

For better trade-off between overshoot and settling time, we keep ξ as $\frac{1}{\sqrt{2}}$. So finally we get $k = \sqrt{2}$.

COMBINE APPROACH OF SOGI AND ASRF

A dual-SOGI approach is necessary for extracting the positive sequence fundamental components in stationary reference frame (α-β). After mapping the three phase signal to two-phase stationary reference frame value, two separate SOGI required for extraction of quadrature components of each phase. Then by the help of positive sequence calculator (PSC) (3a), positive sequence fundamental components are calculated. As two individual SOGI is necessary for our sequence component calculation, this approach is called D-SOGI (dual-SOGI)[12]. As shown in fig.5, the required V_α^+ and V_β^+ from dual-SOGI approach, is given to ASRF block. Due to the band-pass adaptive filtering capacity of SOGI, the low pass filter for the extraction of fundamental component is not required. Simultaneously it makes the system frequency adaptive, due to the inherent capacity of frequency estimation. The difference lies in the region, where this filtering is done. In conventional ASRF approach, the filtering done in the d-q reference domain. Equation (15) represents the transfer function of LPF, maintaining the cut-off frequency $\omega_c = 2 \cdot \pi \cdot 13 \text{ rad/s}$ [4].

$$LPF(s) = \frac{\omega_c^2}{s^2 + \frac{\sqrt{2} \cdot \omega_c \cdot s}{\pi} + \omega_c^2} \qquad (15)$$

The complete structure is shown in Fig.6. As per our conviction, this combine approach needs to adopt the advantages of both SOGI-FLL and ASRF-PLL. Advantageous to conventional approach for positive sequence extraction and reconstruction of voltage, here no such butter-worth filters are needed. Delay also absent, due to the absent of filter.

Need of quadrature signal generation???

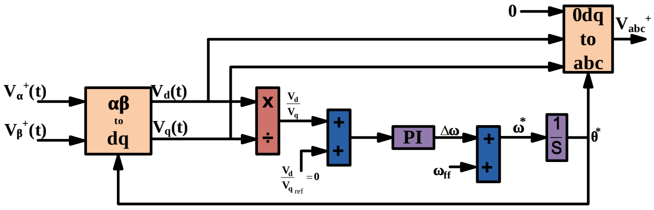

Fig 5:ASRF model applied to stationary rotating reference frame (S_tRF) without butter worth filter

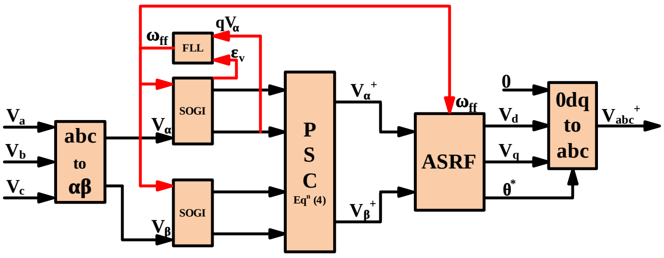

Fig 6: Combine approach of SOGI and ASRF

Here both voltage imbalance and distortion is taken in account. But due to the band-pass filtering and quadrature signal generation capability of SOGI, the requirement of butter-worth low pass filter is vanish. Furthermore, it gives adaptive filtering and frequency estimation.

EXPERIMENTAL TEST

NI USB-6341 is used for the generation and acquiring of signals. The signal was created in LABVIEW and by the interfacing of a 3-phase unbalance voltage source of Phase-A having 1pu∠0^0, phase-B having 0.85pu∠140^0 and phase-C of 1.15pu∠-100^0 was created. And all the phases distorted by characteristics harmonics of 5^{th} and 7^{th} order. Here the input fundamental frequency is 50Hz. Though NI USB-6341 can generate maximum two signals at a time, so by the use of Clarke's transformation (1), three phase voltages transformed to two phases. To show the change in frequency with better resolution, a step change in frequency of +10Hz is applied at time 0.2s.

Small periodic oscillation around nominal frequency is occurring due to the low value of sampling rate. So increase in sampling rate cause decrement of this oscillation.

Case-I

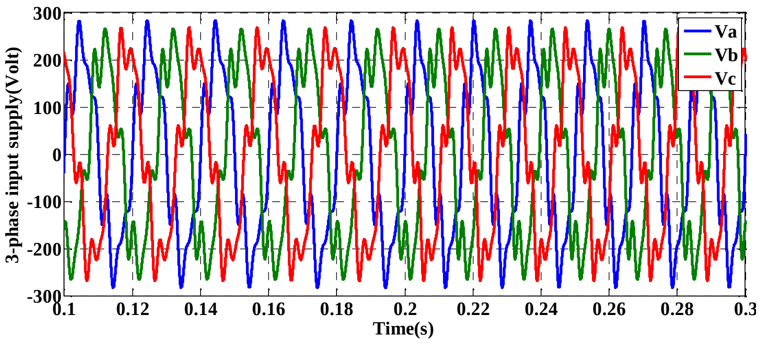

Fig 6(a): 3-phase input supply

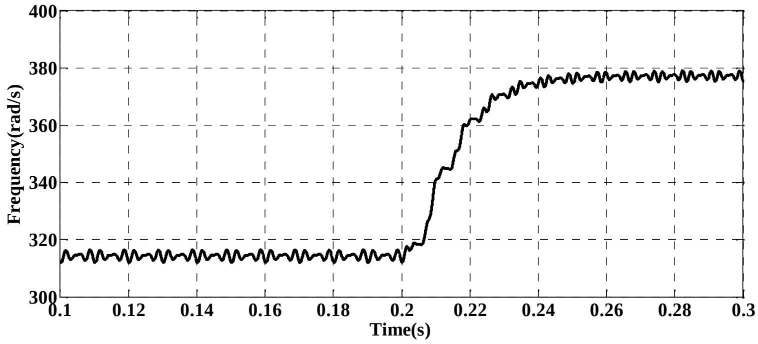

Fig 6(b): Frequency extracted by SOGI-FLL

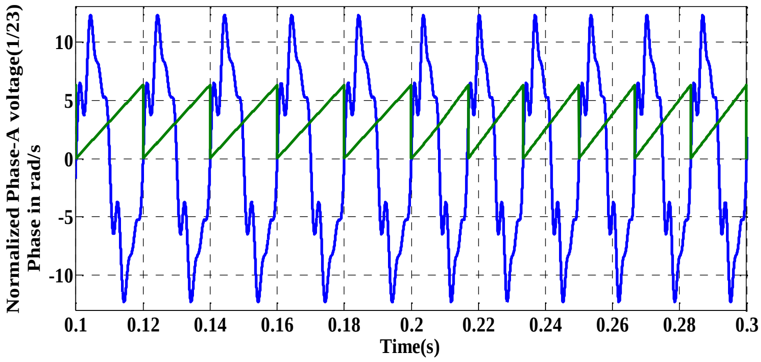

Fig 6(c): Distorted Phase-A and extracted phase of +ve sequence fundamental component

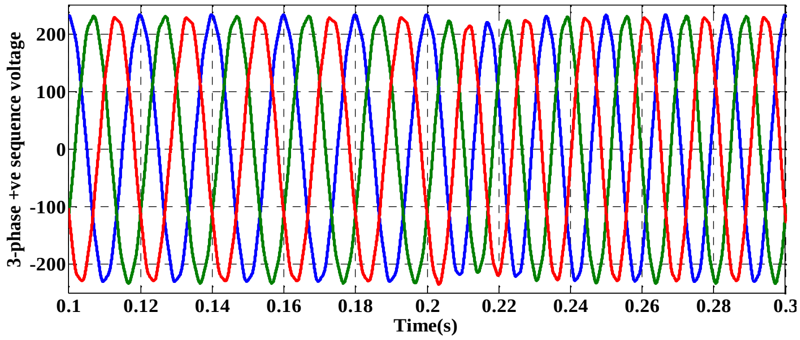

Fig 6(d): 3-phase positive sequence voltage extracted by ASRF PLL

Case II

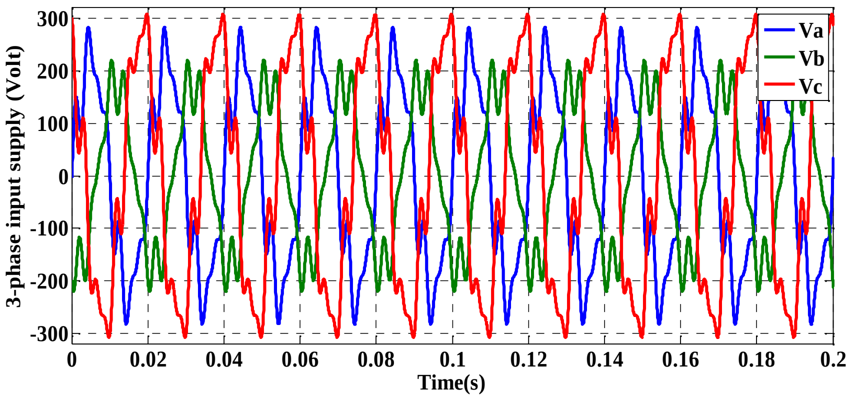

Fig 7(a): 3-phase input supply

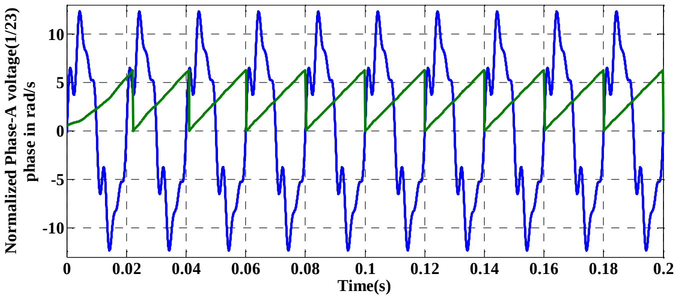

Fig 7(b): Distorted Phase-A and extracted phase of +ve sequence fundamental component

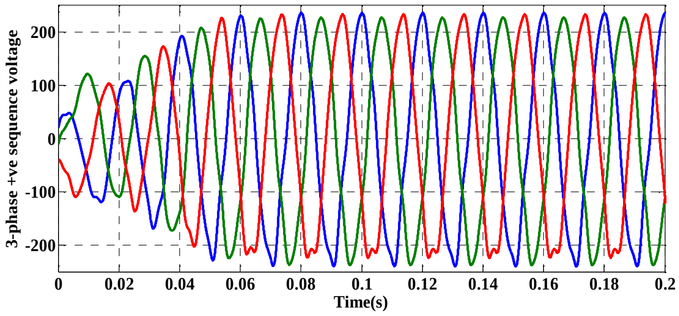

Fig 7(c): 3-phase positive sequence voltage extracted by ASRF PLL

As shown in fig 6(b), there is a small oscillation of frequency at steady state, around the centered frequencies (50Hz and 60Hz). Due to this, the extracted positive sequence fundamental component also having a very little distortion. This is happening due to the presence of harmonics of higher magnitude. For more better result, we can use a cross-feedback network i.e. multiple order SOGI (M-SOGI)[13]. So from the above simulation, Filter delay is absent, as we use a close loop system.

CONCLUSION

Inclusion of SOGI based QSG and FLL to ASRF PLL is a better idea to get the benefits of both. From the results it is experimentally verified that, for easy extraction of phase of the fundamental components in an abnormal voltage condition, this proposed model is a better choice. Advantages like frequency adaptions of entire system, estimation of positive and negative sequence fundamental component without use of butter-worth filter and frequency estimation is done without use of any extra frequency detection technique are occurred. Filtering delay also absent, as we are not using any filter. The little distortion remains in the extracted fundamental components can be eliminated by the use of cross-feedback network, i.e. multiple order SOGI(M-SOGI).

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