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Grid-voltage Synchronization Algorithms Based on Different Phase-Locked Loop for Power converter under Balanced and Unbalanced conditions

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Abstract : In this article different types of Phased locked loop technique are studied and after comparing all circuits we found that the Voltage Reforming Synchronous Reference Frame PLL (VRSRF-PLL) shows better and quicker performance than the other PLL techniques. The control design depends on quick and exact tracking of phase angle of grid voltage. The task of PLL is crucial condition, since grid connected system is to operate the power system under grid fault conditions. The main objective of the PLL is to extract positive and negative fundamental voltage in a precise manner during distorted grid conditions. There are many PLL techniques introduced in the past decades. Some of the techniques only give good results in normal grid voltage, and some techniques give good results in both normal and abnormal grid voltage conditions. This paper deals with performance and investigation of different grid interactive PLL techniques in the unbalanced supply voltage conditions.

Keywords: Grid Synchronisation, Band pass filter, Low pass filter, Phase locked loop (PLL), total harmonic distortion, PI regulator.

I. INTRODUCTION

The phase angle of the utility voltage is critical part of information for the operation of most apparatus such as: controlled ac $\leftrightarrow$ dc converter, static VAR compensator, cyclo-converters, active harmonics filters and other energy storage systems coupled with the electric utility[1].This information may be used synchronize the turning on\off of power devices, calculate and control the flow of active\reactive power or transform the feedback variables to a reference frame suitable for control purposes. The angle information is typically extracted using some form of phase locked loop(PLL)[2].Besides utility interface application ,PLL methods are also used in motor control to estimate the electrical angular speed of rotor[3-5].The power generated from Renewable source i.e solar and wind is injected into the grid through power electronics converter. Control circuit of power electronic converter needs information about the fundamental angular velocity (ω) of the grid voltage for the synchronization with the grid.

For the purpose of the fundamental angular frequency Synchronous Reference Frame (SRF-PLL) [6] is generally works under balanced grid voltages condition , but in case of unbalanced grid voltages SRF-PLL does not give accurate results [7]. In [8], the design and implementation of SRF-PLL using micro-controller is discussed. Advanced PLL techniques like Double Synchronous Reference Frame PLL (DSRF-PLL) and Decoupled Double Synchronous Reference Frame PLL (DDSRF-PLL) [9], uses two rotating synchronous reference frames, whose angular velocity is constant but rotates in opposite direction with respect to each other and then a decoupling network is used for the determination of the fundamental angular frequency of the grid voltages. In [10], an improvement of DDSRF-PLL is done to reduce the overshoot by combining the DDSRF-PLL and dual second order generalized integrator. In [11], a Voltage Reforming Synchronous Reference Frame PLL (VRSRF-PLL) technique is introduced, which consist of a voltage reforming block which converts the magnitude unbalanced grid voltage into a balanced grid voltage. In [12-17], an improvement of VRSRF-PLL is done so that it can work under grid voltage with harmonics and unbalance in magnitude and angle. In [8], SRF-PLL and DDSRF-PLL are discussed and their performances are compared under abnormal grid conditions.

In this paper investigated the effect of abnormal grid voltage on different PLLs are discussed. It examines the various PLL,DSRF-PLL, DDSRF-PLL and VRSRF-PLL techniques with its merits and demerits in it.

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II.WORKING PRINCIPLE OF CONVENTIONAL PLL TECHNIQUES

The basic structure of Synchronous Reference Frame PLL(SRF-PLL) is shown in Fig. 1. In this angular frequency detection circuit at first, by the use of Park's transformation the three-phase voltage vector is transformed from the abc-natural rotating reference frame to the dq- synchronous reference frame as shown in equation(1).

$$v_{sa} = V_m \cos(\theta),\ v_{sb} = V_m \cos\left(\theta - \frac{2\pi}{3}\right),\ v_{sc} = V_m \cos\left(\theta + \frac{2\pi}{3}\right)$$

In alpha-beta reference frame:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix}$$

$$v_\alpha = V_m \cos(\theta),\ v_\beta = V_m \sin(\theta)$$

In dq-reference frame

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = \begin{bmatrix} \cos(\theta^*) & \sin(\theta^*) \\ -\sin(\theta^*) & \cos(\theta^*) \end{bmatrix} \cdot \begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} \quad (1)$$

$$v_{sd} = V_m \cos(\theta - \theta^*),\ v_{sq} = V_m \sin(\theta - \theta^*)$$

$$\text{if } \theta^* = \theta,\ v_{sd} = V_m,\ v_{sq} = 0,\ \theta - \theta^* = \Delta\theta$$

θ^* is the output response, shown in figure 1. At steady state control action is taken such a way $\Delta\theta$ should be zero.

$$v_{sd} = V_m \cos\Delta\theta,\ v_{sq} = V_m \sin\Delta\theta$$

A feedback loop is used to regulate the q component to zero by controlling the angular velocity of the dq synchronous reference frame. The voltage vector amplitude is given by the d component and the output of feedback loop gives the angular velocity of the grid as shown in Fig.1. When a balanced fault occurs, the $dq-$PLL is operating well and can track the phase angle. However, when an unbalanced fault occurs, then the $dq-$PLL fails to track accurately the phase angle because V_d does not perfectly match with the positive sequence voltage V^p due to the oscillation which appears because of the existence of the negative sequence voltage V^n under unbalanced disturbances [1].

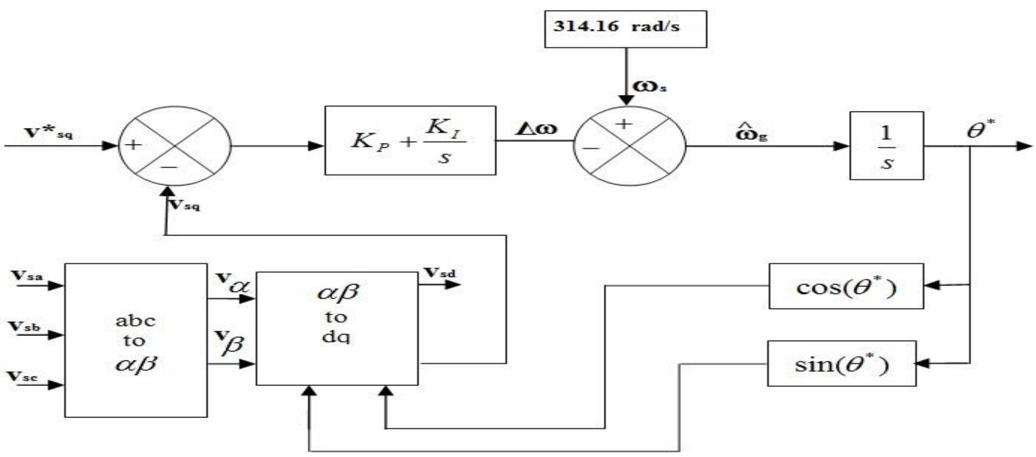

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Fig.1.General structure of the SRF-PLL

III.PERFORMANCE OF PLL TECHNIQUE IN UNBALANCED GRID VOLTAGE

The input phase voltage space vector of the grid supply voltage can be written as

$$\vec{v}_i = \frac{2}{3}\left(v_a + v_b e^{j\frac{2\pi}{3}} + v_c e^{-j\frac{2\pi}{3}}\right) \quad (2)$$

In the case of a balanced and sinusoidal supply voltage, $\vec{v}_i$ makes a circular trajectory because the magnitude of $\vec{v}_i$ and angular velocity are constant. When the grid voltages are unbalanced then it consists of a positive sequence component vector and a negative sequence component vector as in equation (3)

$$\vec{v}_i = \vec{v}_p + \vec{v}_n$$
$$\vec{v}_i = V_p e^{j\omega_i t} + V_n e^{-j\omega_i t - \theta_n} \quad (3)$$

where, ω_i is the angular frequency; $\vec{v}_p$ is the positive sequence component whose peak value is V_p and the initial phase angle is assumed zero; $\vec{v}_n$ is the negative sequence component whose peak value is V_n and θ_n is the initial phase angle of the unbalanced grid voltage.Space vectors $\vec{v}_p$ rotates in anti-clockwise direction with angular velocity ω_i and $\vec{v}_n^*$ rotates in clockwise direction with angular velocity ω_i as shown in Fig.2..Due to the presence of negative sequence component vector in the grid voltages, $\vec{v}_i$ makes an elliptical trajectory because the magnitude of $\vec{v}_i$ and angular velocity is not constant with time.

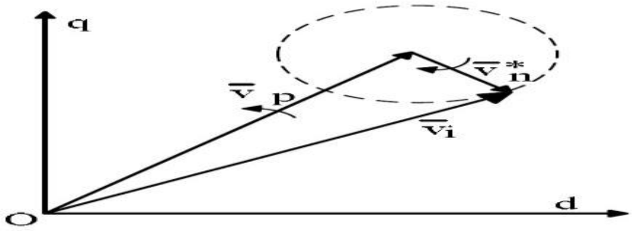

Fig. 2. Space vector representation of the unbalanced grid phase voltagez

Different PLL Techniques

In normal grid condition, SRF-PLL [6] behaves with quite high bandwidth fast and accurate performance. In harmonics distortion and imbalance condition, it fails in accuracy. In last decades many researchers investigated in improving the conventional PLL as follows,

B. Double Synchronous Reference Frame (DSRF) PLL

The unbalanced voltage vector, consisting of positive and negative sequence components is expressed on a “double synchronous reference frame” (DSRF). An improved three phase PLL technique [10] based on using, positive and negative synchronous speed. The handling of this technique permits in decoupling the effect of negative sequence component by the SRF rotating with positive angular speed that makes possible grid synchronization in unbalanced conditions.

C. Decoupled Double Synchronous Reference Frame PLL (DDSRF-PLL)

In this PLL technique two rotating reference frames: one for the positive sequence component (dq^p) rotating in the anticlockwise direction whose initial phase angle is θ' and another one for the negative sequence component (dq^n) rotating in the clockwise direction whose initial phase angle is $-\theta'$ are used for the detection of the angular frequency accurately in the case of the unbalanced grid voltages. Both reference frames are rotating with an angular velocity of ω_i .When the unbalanced grid voltages are transformed from abc reference frame to $\alpha\beta$ reference frame then it also

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consists two sub-vectors positive sequence vector $\vec{v}^{p}_{(\alpha\beta)}$ and negative sequence vector $\vec{v}^{n}_{(\alpha\beta)}$ as expressed in equation (4)

$$\vec{v}_{in}(\alpha\beta) = \begin{bmatrix} \vec{v}_{\alpha} \\ \vec{v}_{\beta} \end{bmatrix} = \vec{v}^{p}_{(\alpha\beta)} + \vec{v}^{n}_{(\alpha\beta)} \tag{4}$$

$$\vec{v}_{in(\alpha\beta)} = V_p \begin{bmatrix} \cos(\omega_i t + \phi_p) \\ \sin(\omega_i t + \phi_p) \end{bmatrix} + V_n \begin{bmatrix} \cos(-\omega_i t + \phi_n) \\ \sin(-\omega_i t + \phi_n) \end{bmatrix} \tag{5}$$

V_p is the peak value and ϕ_p is the initial phase angle of positive sequence of the input voltages; V_n is the peak value and ϕ_n is the initial phase angle of negative sequence of the input voltage and θ' is the phase angle which is the output of PLL. Then, if PLL is detecting the phase angle θ' accurately then it could be assumed that θ' is approximately equal to $\omega_i t$. The voltage vectors $\vec{v}^{p}_{(dq)}$ and $\vec{v}^{n}_{(dq)}$ after the transformation from $\alpha\beta$ stationary reference frame to the dq^{p} and dq^{n} rotating reference frames can be expressed as follows:

$$\vec{v}^{p}_{(dq)} = \begin{bmatrix} \vec{v}^{p}_{d} \\ \vec{v}^{p}_{q} \end{bmatrix} = \left[T^{p}_{dq}\right]\vec{v}_{in(\alpha\beta)}$$

$$\vec{v}_{(dq)} = \begin{bmatrix} \vec{v}^{p}_{d} \\ \vec{v}^{p}_{q} \end{bmatrix} = V_p \begin{bmatrix} \cos(\phi_p) \\ \sin(\phi_p) \end{bmatrix} + V_n \cos(\phi_n) \begin{bmatrix} \cos(2\omega_i t) \\ -\sin(2\omega_i t) \end{bmatrix} + V_n \sin(\phi_n) \begin{bmatrix} \sin(2\omega_i t) \\ \cos(2\omega_i t) \end{bmatrix} + V_n \sin(\phi_n) \begin{bmatrix} \sin(2\omega_i t) \\ \cos(2\omega_i t) \end{bmatrix} \tag{6}$$

$$\vec{v}^{n}_{(dq)} = \begin{bmatrix} \vec{v}^{n}_{d} \\ \vec{v}^{n}_{q} \end{bmatrix} = \left[T^{n}_{dq}\right] v_{in(\alpha\beta)}$$

$$\vec{v}^{n}_{(dq)} = \begin{bmatrix} \vec{v}^{n}_{d} \\ v^{n}_{q} \end{bmatrix} = V_n \begin{bmatrix} \cos(\phi_n) \\ \sin(\phi_n) \end{bmatrix} + V_p \cos(\phi_p) \begin{bmatrix} \cos(2\omega_i t) \\ \sin(2\omega_i t) \end{bmatrix} + V_p \sin(\phi_p) \begin{bmatrix} -\sin(2\omega_i t) \\ \cos(2\omega_i t) \end{bmatrix} \tag{7}$$

Where,

$$\left[T^{p}_{dq}\right] = \left[T^{n}_{dq}\right]^{T} = \begin{bmatrix} \cos(\theta') & \sin(\theta') \\ -\sin(\theta') & \cos(\theta') \end{bmatrix}$$

As can be seen from (6) and (7), the magnitude of the low harmonic components in the dq^{p} axis depends on the average value of the signal in the dq^{n} axis, and the magnitude of the low harmonic components in the dq^{n} axis depends on the mean value of the signal in the dq^{p} axis.

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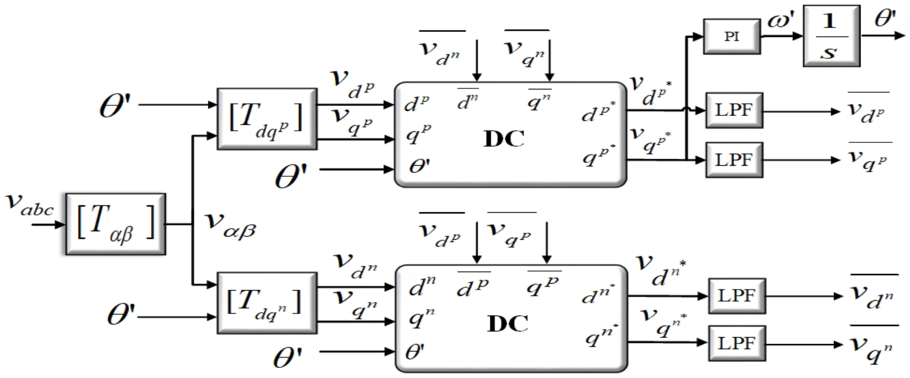

Fig. 3. Block diagram of the DDSRF-PLL

For the elimination of low order harmonics from the dq^p and dq^n axis a decoupling network is used for the elimination of the oscillations from both reference frames.
The equations of the decoupling network is

$$\vec{v}_d^{p*} = v_d^p - \cos(2\omega_i t)\vec{v}_d^n - \sin(2\omega_i t)\vec{v}_q^n \quad (8)$$

$$\vec{v}_q^{p*} = v_q^p - \cos(2\omega_i t)\vec{v}_q^n + \sin(2\omega_i t)\vec{v}_d^n \quad (9)$$

$$\vec{v}_d^{n*} = v_d^n - \cos(2\omega_i t)\vec{v}_d^p + \sin(2\omega_i t)\vec{v}_q^p \quad (10)$$

$$\vec{v}_q^{n*} = v_q^n - \cos(2\omega_i t)\vec{v}_q^p - \sin(2\omega_i t)\vec{v}_d^p \quad (11)$$

Fig.3 shows the basic scheme of the DDSRF-PLL technique. After the decoupling network the signal v_q^{p*} can be used as the input to the $dq - PLL$ for the detection of the fundamental angular frequency without any error.

D. Voltage Reforming Synchronous Reference Frame PLL (V RSRF -PLL)

The basic structure of the Voltage Reforming Synchronous Reference Frame PLL (VRSRF-PLL) technique [16] as shown in Fig.4. It consists of two blocks, first one is the voltage reforming block and the second one is the conventional $dq - PLL$ block. Input signals of the voltage reforming block are v_a, v_b and v_c ;which are the grid voltages with magnitude unbalance and v_a^*, v_b^* and v_c^* are the output of the voltage reforming block which are balanced signals with same magnitude after signal reforming.

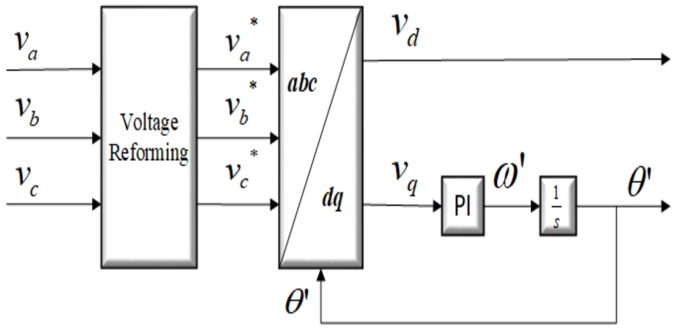

Fig. 6. Block diagram of the vrsrf – PLL

The grid voltages with magnitude unbalance can be expressed as equation (12), v_a, v_b and v_c

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} V_a\cos(\theta_a) \\ V_b\cos(\theta_{b)} \\ V_c\cos(\theta_c) \end{bmatrix} \quad (12)$$

where V_a, V_b, V_c are the amplitudes and $\theta_a, \theta_b, \theta_c$ are the phase angles of the grid voltages v_a, v_b and v_c respectively.

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Two coefficients k_2 and k_3, are defined which satisfy the relation in equation (13).

By the use of k_2 and k_3, a new voltage sequence $(v_a, k_2 v_b, k_3 v_c)$ could be derived in equation(14). Hence, by the calculation of k_2 and k_3 a new reformed balanced set of voltages could be created without disturbing the grid phase angle information.

$$V_a = k_2 \times V_b = k_3 \times V_c \qquad (13)$$

$$\begin{bmatrix} v_a \\ k_2 v_b \\ k_3 v_c \end{bmatrix} = \begin{bmatrix} V_a \cos(\theta_a) \\ k_2 V_b \cos(\theta_b) \\ k_3 V_c \cos(\theta_{c)} \end{bmatrix} = \begin{bmatrix} V_a \cos(\theta_a) \\ V_b \cos(\theta_{b)} \\ V_c \cos(\theta_c) \end{bmatrix} \qquad (14)$$

$$v_a + k_2 v_b + k_3 v_c = 0 \qquad (15)$$

For the calculation of k_2 and k_3, any one of the phase voltage is taken as the reference signal, here v_a is taken as the reference signal. At first the value of k_3 is calculated by identifying the zero-crossing instants of phase voltage v_b. At the zero crossing instant of phase voltage v_b, equation(15) becomes (16) at this instant. Then by using the instantaneous values of v_a and v_c the value of the coefficient k_3 could be exactly calculated in equation (17)

$$v_a \mid v_{b=0} + k_3 \times v_c \mid v_{b=0} = 0 \qquad (16)$$

$$k_3 = -\frac{v_a \mid v_{b=0}}{v_c \mid v_{b=0}} \qquad (17)$$

The reformed phase voltage v_c^* can be calculated as

$$v_c^* = \left(-\frac{v_a \mid v_{b=0}}{v_c \mid v_{b=0}} \right) v_c = k_3 v_c \cos(\theta_c) = V_a \cos(\theta_c) \qquad (18)$$

Now two phases become equal in magnitude and the phase v_b reformed signal v_b^* can be generated by the use of equation (15).

$$v_b^* = -v_a - v_c^* \qquad (19)$$

Now all the reformed phase voltages have the same magnitude which is the same as that of the magnitude of the reference signal. Hence, in this case, the conventional dq gives accurate results because the input signals to the $dq-PLL$ are balanced one.

IV.SIMULATION RESULTS

The performance comparison of different PLL techniques three grid voltage conditions: a balanced grid voltage, a magnitude unbalanced grid voltages and both magnitude and phase unbalanced grid voltages are used for the investigation of each PLL at this three grid voltage conditions. MATLAB/ Simulink software is used for the simulation purpose. The KP and KI parameters of the PI controllers for different PLL techniques are given in Table I. The selection of KP and KI is based on the small signal analysis [17] of each PLL.

TABLE:I
PI CONTROLLER PARAMETERS FOR DIFFERENT PLL'S

Sl.no	Name of different PLL	K_P	K_I
1	SRF-PLL	13.657	30342.8
2	DSRF-PLL	13.657	30342.8
3	DDSRF-PLL	13.657	30342.8
4	VSRF-PLL	13.657	30342.8

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In the simulation, initially grid voltages are balanced and its RMS value of phase voltage is 230V and its fundamental frequency is 50Hz. The sampling frequency is 5KHz. At 0:5sec magnitude unbalance is introduced in the grid voltages, the voltage of phase B to neutral is decreased by 20% of the initial voltage and the voltage of phase C to neutral is increased by 10% of the initial voltage. At 0:1sec phase unbalanced is introduced in the grid voltage i.e magnitude and phase unbalance both are present in the grid voltage, the phase angle between phase A and phase B is increased by 20% of the initial phase angle and the phase angle between phase A and phase C is decreased by 10% of the initial phase angle.

In this way three grid voltage conditions: a balanced grid voltages (0.00-0.05sec), a magnitude unbalanced grid voltages(0.05-0.10sec) and both magnitude and phase unbalanced grid voltages (0.10-0.15sec)are created in MATLAB/Simulink software for the comparison of different PLL techniques under these grid voltage conditions as shown in Fig.5-10.

It can be observed from the simulation waveform that, when the grid voltages are balanced then all five PLL's give accurate results of $\theta^{'}$ and $\omega^{'}$. When the grid voltages change from balanced to magnitude unbalanced voltages at 0:05sec then only three PLL techniques :DSRF-PLL, DDSRF-PLL and VRSRF-PLL give accurate results of $\theta^{'}$ and $\omega^{'}$. When both magnitude and phase unbalanced present in the grid voltages then only DDSRF-PLL give accurate results of $\theta^{'}$ and $\omega^{'}$.SRF-PLL does not give accurate results due to an unbalanced grid.

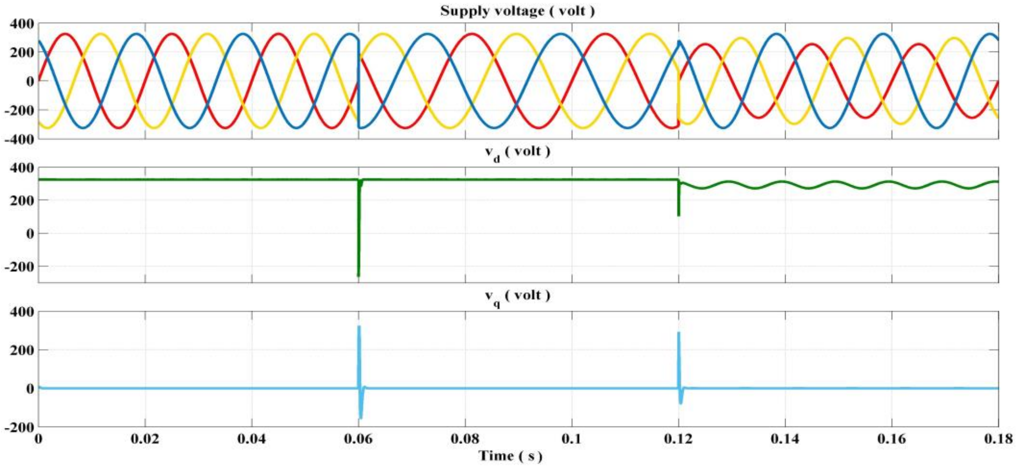

Fig.5: (a) Waveform of three-phase supply voltages v_{abc} which is balanced for the duration t = (0.00-0.06)s with frequency = 50Hz, for the duration t = (0.06-0.12)s, frequency = 40Hz and for the duration t = (0.12-0.18)s magnitude unbalance occur with frequency = 50Hz; (b) d-axis component of the supply voltage v_d ; (c) q-axis component of the supply voltage v_q .

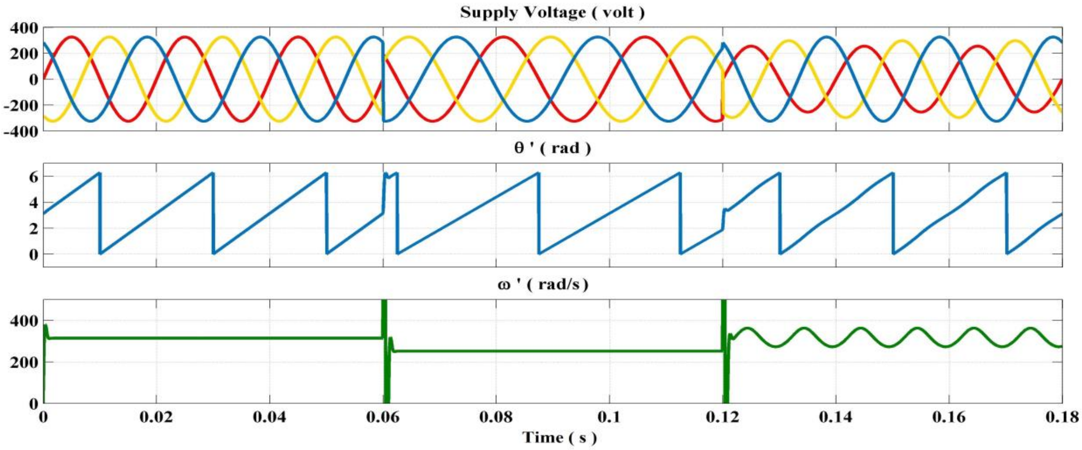

Fig. 6: Performance of synchronous reference frame PLL, (a) grid voltage (v_{abc}); (b) angular velocity the grid voltage ($\theta^{'}$); (c) angular frequency of the grid voltage ($\omega^{'}$)

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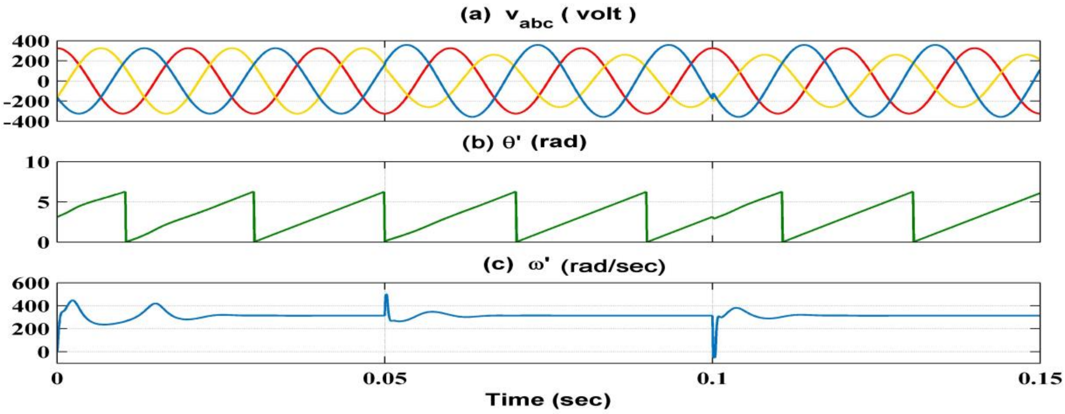

Fig.7: Performance of decouple double synchronous reference frame PLL, (a) grid voltage (v_{abc}); (b) angular velocity of the grid voltage ($\theta^{'}$); (c) angular frequency of the grid voltage ($\omega^{'}$)

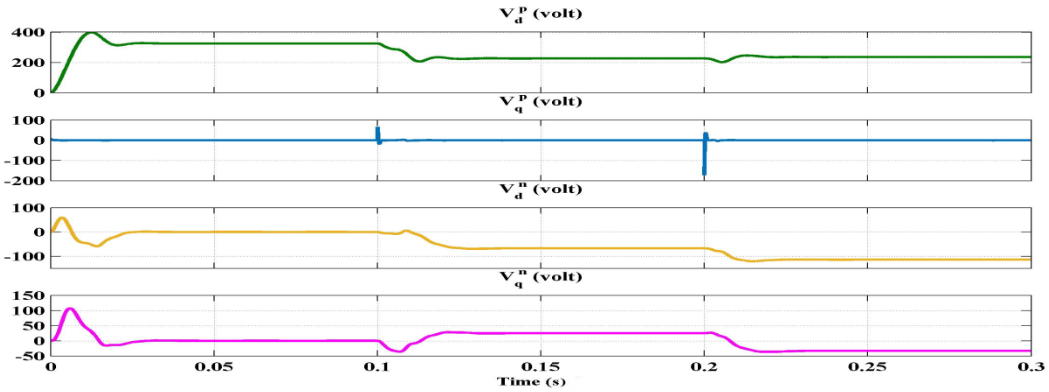

Fig.8: Wave of $v_d^p, v_q^p, v_d^n, v_q^n$ which are the output of DDSRF PLL,when the three phase supply voltage v_{abc} is balanced for the duration t=(0.00-0.01)s,for the duration t=(0.01-0.02)s magnitude unbalanced is present and for the duration t=(0.02-0.03)s both magnitude and phase unbalanced is present and frequency 50 hz is constant in all conditions.

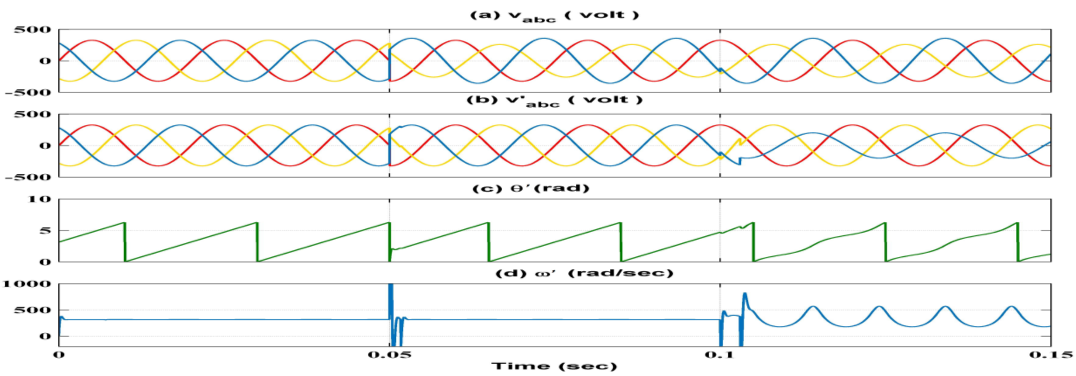

Fig. 9: Performance of voltage reforming synchronous reference frame PLL, (a) grid voltage (v_{abc}); (b) reformed grid voltage (v'_{abc}); (c) angular velocity of the grid voltage ($\theta^{'}$); (d) angular frequency of the grid voltage ($\omega^{'}$)

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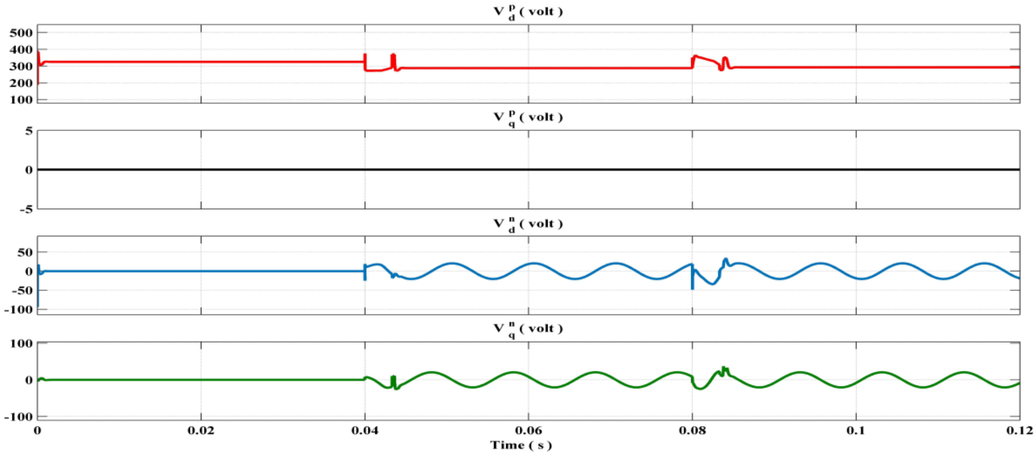

Fig.10: Wave of $v_d^p, v_q^p, v_d^n, v_q^n$ which are the output of VRSRF PLL,when the three phase supply voltage v_{abc} is balanced for the duration t=(0.00-0.04)s,for the duration t=(0.04-0.08)s magnitude unbalanced is present and for the duration t=(0.08-0.12)s both magnitude and phase unbalanced is present and frequency 50 Hz is constant in all conditions.

Techniques are voltage which induces second harmonic components in the $\alpha\beta$ and dq reference frames as in (5) and (6). The VRSRFPLL gives accurate results in the case of magnitude unbalance but when phase unbalance is introduced in the grid voltages then it does not give accurate results because the voltage reforming block only removes the magnitude unbalance from the grid voltage but in the case of phase unbalance the voltage reforming block does not reform the grid voltage as shown in Fig. 9 (b).. In case of magnitude unbalance grid voltages VRSRF-PLL gives steady state and transient response in comparison to DDSRF-PLL because it's settling time is very high in comparison to VRSRF-PLL. The settling time of the DDSRF-PLL is very high due to the presence of low pass filter for the determination of the average values, on the other hand, VRSRF-PLL does not contain any low pass filter hence, it's settling time is low as comparison to DDSRF-PLL. When both magnitude and base unbalance is present in grid voltages then DDSRF-PLL is used for the fundamental angular frequency determination. Hence, each PLL has some merit and demerit so, you have to select the PLL according to the grid voltages. The comparison of different PLL given in Table II.

TABLE II: COMPARISION PLL TECHNIQUE

Qualities	SRF-PLL	DSRF-PLL	DDSRF-PLL	VRSRF-PLL
Positive sequence detection	NO	Yes	Yes	Yes
Balanced	Yes	Yes	Yes	Yes
Magnitude and phase unbalanced	No	Yes	Yes	Yes
Settling time	2.5ms	1.5ms	20ms	1.5ms
Architecture simplicity	Yes	No	No	No
Transient spike	Very high	Very Low	Very Low	Very Low

V. CONCLUSION

In this paper analysis and performance of conventional and proposed synchronization technique is presented. For grid side converter control technique, the proposed DSRF, DDSRF and VRSRF technique tracks the signal unbalanced voltage and frequency conditions. The main important point of the technique is presented in this paper showed that the stationary reference frame PLL accurately detects the fundamental angular frequency in the case of balanced grid voltages, a voltage reforming synchronous reference frame PLL is a suitable solution for the detection of the fundamental angular frequency in the case of magnitude unbalanced grid voltages and a decoupled double synchronous reference frame PLL is a suitable solution to the detection of the fundamental frequency in the case of magnitude and phase unbalanced grid voltages.

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