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L. Shi

Mariesa Crow
Missouri University of Science and Technology, crow@mst.edu

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Adaptive Quadrant Filter Based Phase Locked Loop System

L. Shi, *Student Member, IEEE*, and M. L. Crow, *Fellow, IEEE*

***ABSTRACT*--Phase-Locked-Loop (PLL) is one of the key technologies extensively used in grid connected power electronics system. A good PLL system can detect the grid phase angle and frequency fast and accurately, and additionally it can extract the positive sequence (or fundamental component for single phase system) exactly. In real applications, source signal (voltage or current) sensed for PLL usually includes harmonic distortion, unbalanced components, noises and frequency variations. Conventional PLL strategy cannot solve all the problems, especially the unbalanced and harmonic distortion. There is a trade-off between the dynamic response and phase angle tracking accuracy. Different PLL solutions are proposed in literature in recent years. The general considerations for these different approaches are to design positive sequence estimator to eliminate the negative sequence components and use filters to filter out the higher order harmonic distortions from the PLLs. In this paper, an adaptive quadrature filter based synchronous reference frame PLL (SRF-PLL) with positive sequence estimation feature is presented. The proposed PLL has good performances in filtering harmonic, eliminating unbalanced components and auto-adjusting frequency change. The simulation model is built in Matlab/simulink and the simulation results are given to verify the mathematical analysis.**

***Index Terms*--Phase looked loop (PLL), synchronous reference frame (SRF), unbalanced voltage, adaptive quadrature filter (AQF).**

I. INTRODUCTION

IN the applications of grid connected power electronic systems, such as the flexible ac transmission systems (FACT), high voltage dc systems (HVDC), generator/motor control systems, wind and solar power systems, active power filter systems (APF), active rectifiers, uninterruptible power systems (UPS) and grid connected inverter systems, one important issue need to be considered is the phase synchronization with the utility voltage and positive sequence component (fundamental component for single phase system) extraction [1]–[11]. Fast and accurate tracking of the utility voltage phase angle and frequency is essential, since the phase synchronization characteristic harmonic current compensation, active power factor correction and even the system protection in frequency variation system. And the positive sequence or fundamental component is used for the synchronization of the inverter output variables, power flux calculations or variable transformations to rotating reference frames. However, in the utility grid system, more and more non-linear power electronics loads which produce harmonics pollution to the power system are installed. Usually there are some unbalance components in real industrial application utility systems since the loads are not always balanced. Utility voltage frequency is not constant which affected by the several factors, for example in wind power system, the higher penetration may cause large utility frequency variation. Finally, sensed signals for synchronization contain random noises inevitably. So the signals are no longer pure sinusoidal. Traditionally, the synchronization is implemented by PLL system. Different PLL technologies are proposed in literature. Among these approaches, zero-crossing detection method is the simplest one [12]. It tracks the grid phase angle by detecting the zero crossing points of the line voltage instantly. However it is sensitive to the distortion of the singles and the variation of each phase is not considered in angle detection process. Further, the time delay is so large which is one-fourth of the time period. The most commonly used PLL technology is the so-called synchronous reference frame strategy, namely SRF-PLL [13]-[16]. The traditional SRF-PLL system is composed of two main parts, which is the phase detector part and the loop filter part. The phase detection is obtained by the transformation from the natural reference frame to the synchronous reference frame. The loop filter determines the dynamics of the PLL system. Therefore, the loop filter bandwidth selection is the trade-off between the filtering performance and the dynamic response for the conventional SRF-PLL. Unfortunately, the conventional SRF-PLL cannot solve the problems completely it is faced [12], especially for the unbalanced components and lower order harmonic distortions in the sensed source signals.

To have a better performance, several improved SRF-PLLs are proposed. In [17], a PLL structure is given to extract the positive sequence component in the unbalanced situation. This method uses three all-pass filters in each phase for the extraction purpose. However the harmonic distortion and noises are not filtered out by this PLL. Another disadvantage is that it is sensitive to the grid frequency variation. In [18]-[20], an enhanced PLL

L. Shi (lsx9d@mst.edu) and M. L. Crow (crow@mst.edu) are with the Electrical & Computer Engineering Department at the Missouri University of Science and Technology, 1870 Miner Circle, Rolla, MO 65409.

(EPLL) is provided to try to solve the problems in [17]. The EPLL structure is not simple enough, since it composed of four EPLL components and a positive sequence extraction unit for the whole PLL system. Its dynamic response is lower because of the low pass filters applications for a higher filtering performance. In [21], an alternative approach which uses the all-pass filters after the transformation from the stationary reference frame to the synchronous reference frame is reported. The performance is the same as [17]. The only advantage is that it uses two all-pass filters, not three. In [22]-[23], a double decoupled SRF-PLL (DDSRF-PLL) is reported. The main part of the DDSRF-PLL is its positive and negative sequence decoupling computational unit which is used for solve the unbalanced problem. The DDSRF-PLL includes two decoupling computational units and other four low pass filter for filtering the harmonic distortion and random noises. In [24], a sinusoidal signal integrator (SSI) based PLL used for active power filter application was reported. The SSI-PLL combines a harmonics filtering and positive sequence extraction in the stationary rotational reference frame condition. The dynamic response and filtering performance is still a trade-off for this method. The SSI unit actually is a two-input-two-output filtering network which contains four resonant filters. These disadvantages limit its applications extensively. Another approach based on the SSI idea is shown in [25]-[26], this strategy only use one resonant filter scheme to form the filtering and phase angle extracting block. It is relatively simple, but it can only tracking the phase angle, the positive sequence cannot get correctly.

Based on synchronous reference frame transformation technology, a novel adaptive quadrature filter based SRF-PLL (AQF-SRF-PLL) strategy is proposed in this paper. In section II, the AQF-SRF-PLL principle is given and the simulation model is built. In section III, the AQF-SRF-PLL performance is verified through the Matlab/simulink simulation results. In section IV, the useful conclusions are deserved.

II. PRINCIPLE OF THE PROPOSED AQF-SRF-PLL

A. *Problems of Conventional SRF-PLL Faced*

Fig.1 is the scheme of the conventional SRF-PLL strategy.

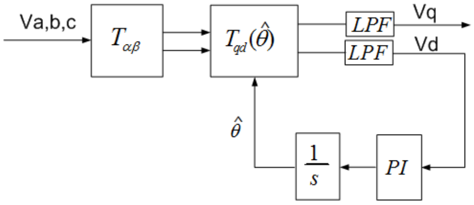

Fig.1. Conventional SRF-PLL structure with LPF.

Where,

$$T_{\alpha\beta}=\frac{2}{3}\begin{pmatrix}1 & \frac{-1}{2} & \frac{-1}{2}\\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2}\end{pmatrix} \tag{1}$$

$$T_{qd}(\hat{\theta})=\begin{pmatrix}\cos(\hat{\theta}) & -\sin(\hat{\theta})\\ \sin(\hat{\theta}) & \cos(\hat{\theta})\end{pmatrix} \tag{2}$$

For the unbalanced and harmonic distorted input signals, the conventional SRF-PLL cannot output accurate phase angle, electrical frequency and positive sequence components in a proper dynamic response [13]-[16]. In order to improve the PLL performance, new approach is needed.

B. *Adaptive Quadrature Filter Block*

In [27], a general filter block which includes band-pass, low-pass, high-pass and notch filters depending on the output nodes located is reported. Based on the filter block, we can just move the output node points of V2 and V3 to the new points, in the meantime replace parameter of "–K" in [27] with K, the updated filter block is in the form of Fig. 2 shown.

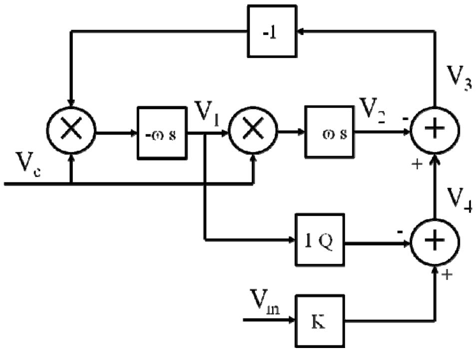

Fig.2 Updated general Filter block.

In Fig.2, Vin is the input voltage, Vc is the pole and zero control voltage and V1, V2, V3, V4 are the output node voltages. From the updated general filter block, the following transfer functions are given.

Band pass: $$\frac{V_1}{V_{in}}=\frac{K\omega_p s}{s^2+(\frac{\omega_p}{Q})s+\omega_p{}^2} \tag{3}$$

Low pass: $$\frac{V_2}{V_{in}}=\frac{K\omega_p^2}{s^2+(\frac{\omega_p}{Q})s+\omega_p{}^2} \tag{4}$$

High pass: $$\frac{V_3}{V_{in}}=\frac{Ks^2}{s^2+(\frac{\omega_p}{Q})s+\omega_p{}^2} \tag{5}$$

Notch: $$\frac{V_4}{V_{in}}=\frac{K\omega_p^2[(\frac{s}{\omega_z})^2+1]}{s^2+(\frac{\omega_p}{Q})s+\omega_p{}^2} \tag{6}$$

Where,

$$\omega_p=\omega_z=\frac{V_c\omega_o}{V_m} \tag{7}$$

Vm is the multiplier constant, Vc is the control voltage, ωp is the pole frequency, and ωz is the zero frequency.

In the PLL application, we do not need consider the control voltage Vc, since the poles and zeros are only decided by the grid frequency in our research. Now neglect the output nodes V3 and V4, the nodes V1 and V2 are left. Then the following filter block can be obtained in Fig.3. The two filters which are seen from V1 and V2 to Vin respectively are quadrature in phase shift at the poles frequency points. This will be shown in the following bode plots.

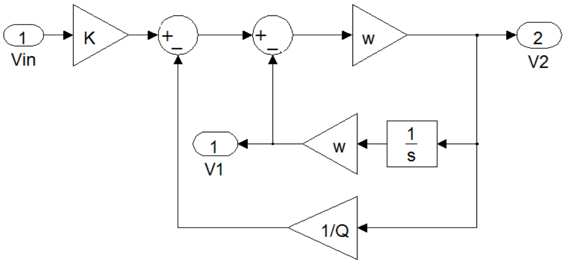

Fig.3 Derived quadrature filter block.

In our research interest, the gains at the poles frequency should be unity. This can be ensured by keeping Q=1/K. Then, the two transfer functions are in the form of equations (8) and (9) shown.

Band-pass: $$\frac{V_1}{V_{in}} = \frac{K\omega s}{s^2 + K\omega s + \omega^2} \qquad (8)$$

Low-pass: $$\frac{V_2}{V_{in}} = \frac{K\omega^2}{s^2 + K\omega s + \omega^2} \qquad (9)$$

The parameter K decides the filtering performance of the band-pass filter and the dynamic response.

In order to compare the influences of different K values to the filters performances, the Bode and Step response plots are given in Fig.4~Fig.7 with K=0.1, $\sqrt{2}$ and 5 respectively for 60Hz system applications (w=2π×60Hz).

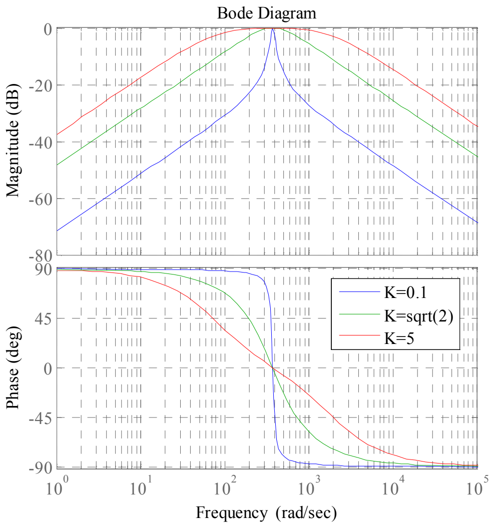

Fig.4 Band-pass filter bode plot.

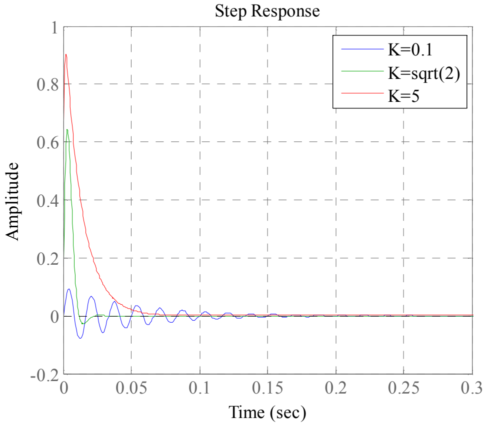

Fig.5 Band-pass filter step response.

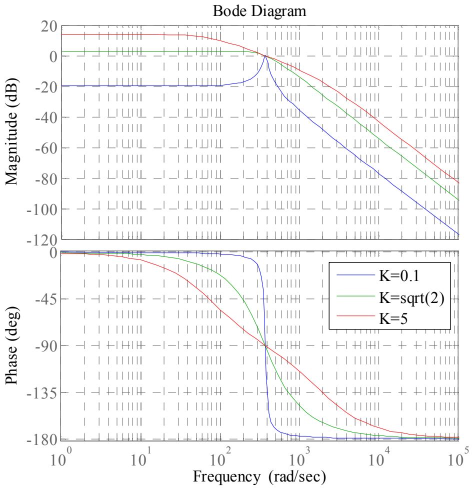

Fig.6 Low-pass filter bode plot.

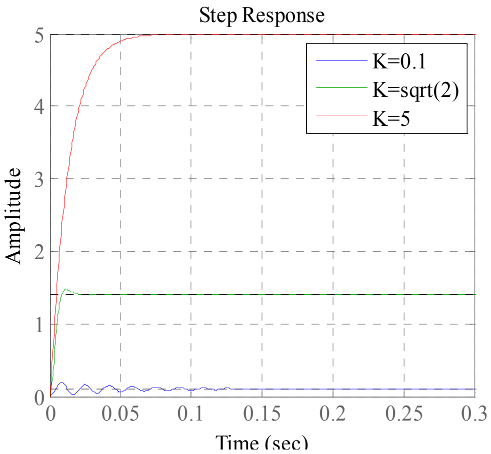

Fig.7 Low-pass filter step response.

From Fig.4 and Fig.6, it can be seen that: (a) at the pole frequency point, the amplitude is unity for both band-pass and low-pass filter. This assures the positive fundamental component pass through the filters whit out sacrificing the amplitude. For band-pass filter, other frequency signals are filtered. For the low pass filter, the signals which frequencies greater than that of the pole frequency will be filtered. However, the Signals which frequencies less than that of the pole frequency will be filtered or not depending on the K value. Fortunately, the harmonic distortions have higher frequencies higher than the gird frequency. So the harmonic distortions can be filtered by all the two filters. (b) The phase shift of band-pass filter is zero degree, while the phase shift of low-pass filter is 90 degrees lag. This characteristic is used for the positive sequence extraction in the following part.

The dynamic features of the two filters are shown in Fig. 5 and Fig.7. We can see that the larger the K value, the more stable is. But the slower the dynamic response will be. Another disadvantage is the larger K value leads to poor filtering performance. $K=\sqrt{2}$ is the point that the damping ratio equals to 0.707 which has the good dynamic response and stability performance.

The adaptation ability of the band-pass and low-pass filters is implemented by letting the estimated electrical frequency as the pole frequency. Then the pole frequency will be adjusted automatically by the estimated electrical frequency. We call it adaptable quadrature filter (AQF), which is shown in Fig.8. In Fig. 8, estimated electrical frequency is a changeable parameter which self-tuned to the grid variable frequency. The inputs and outputs have been labeled as α-axis and β-axis components which are the component of positive sequence estimator discussed below.

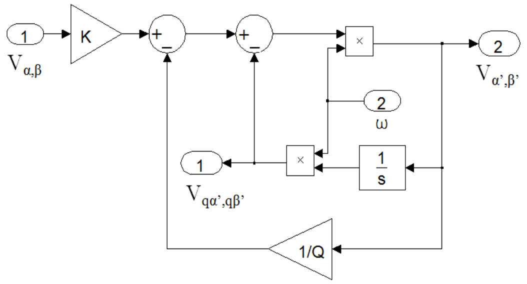

Fig.8 AQF filter block.

C. Positive Sequence Estimation

By the following tranfermations shown in equation (10), the α-axis and β-axis positive sequence components are deserved.

$$\begin{pmatrix} v_\alpha^p \\ v_\beta^p \end{pmatrix} = T_{\alpha\beta}\begin{pmatrix} v_a^p \\ v_b^p \\ v_c^p \end{pmatrix} = T_{\alpha\beta}T_{abc\_p}\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix}$$
$$= T_{\alpha\beta}T_{abc\_p}T_{\alpha\beta}^{-1}\begin{pmatrix} v_\alpha \\ v_\beta \end{pmatrix} \tag{10}$$
$$= \frac{1}{2}\begin{pmatrix} 1 & -q \\ q & 1 \end{pmatrix} v_{\alpha\beta}$$

Where,

$$\begin{pmatrix} v_a^p \\ v_b^p \\ v_c^p \end{pmatrix} = T_{abc\_p}\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} \tag{11}$$

$$T_{abc\_p} = \frac{1}{3}\begin{pmatrix} 1 & a^2 & a \\ a & 1 & a^2 \\ a^2 & a & 1 \end{pmatrix} \tag{12}$$

$$a = e^{-j\frac{2\pi}{3}} \tag{13}$$

$$q = e^{-j\frac{\pi}{2}} \tag{14}$$

Based on the analysis of above AQF and the positive sequence extraction computation principle, the positive sequence estimator is given in Fig.9. The positive sequence estimator is composed of two parts: AQF unit and positive sequence calculation unit. It has three main functions: harmonic elimination, quadrature component extraction and positive sequence estimation. It has the key role in the proposed PLL system.

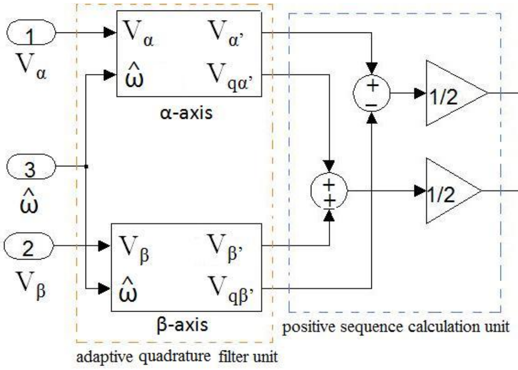

Fig.9 Positive sequence estimator.

D. Proposed AQF-SRF-PLL Scheme

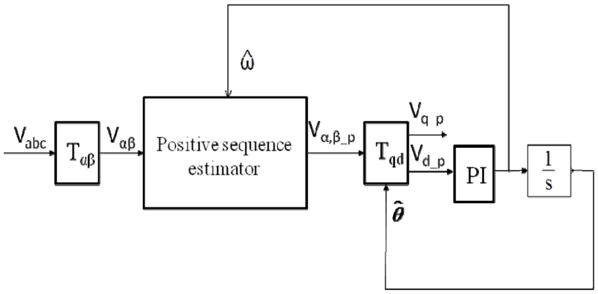

Fig.10 Proposed AQF-SRF-PLL.

Fig.10 is the proposed PLL system based on the novel positive sequence estimator. The PLL principle is the same as the conventional SRF-PLL technology except for the positive sequence estimator. The performance of the proposed PLL will be disscussed in detail in the next section.

III. VERIFICATION OF AQF-SRF-PLL STRATEGY

To verify the proposed AQF-SRF-PLL performance, The AQF-SRF-PLL model which is shown in Fig.6 are built by Matlab/simulink. The simulation conditions are: (a) PI controller parameters: Kp=2.22, Ki=61.69; (b) Unbalanced components: Phase-b: 30% surge during time period 0.2~ 0.3sec.; Phase-c: 60% sag during time period 0.2~ 0.3sec. (c) Phase fault: Phase-b: phase lost during time period 0.2~ 0.3sec. (d) Harmonic distortion: Phase-a, b, c: 5th order 25%, 7th order 5% and 11th order 2%. Time duration: 0.2~0.3sec. (e) Frequency variation: Step-up: 6Hz (10%) at 0.2sec; Step-down: 6Hz (10%) at 0.4sec.;(f) Resonant filter parameters: K=$\sqrt{2}$, Q=1/K.

Five typical scenarios are chosen for the two kinds of PLL strategies which are start-up and pure sinusoidal voltages, unbalanced voltages, phase fault, harmonic distortion and frequency step change. Fig. 11~Fig.16 are the simulation results. From top to bottom are (a) Source voltages, (b) Detected frequency and source frequency, (c) Detected phase angle and source phase angle, (d) Extracted positive sequence voltages and (e) Magnitude of the extracted positive sequence voltage respectively.

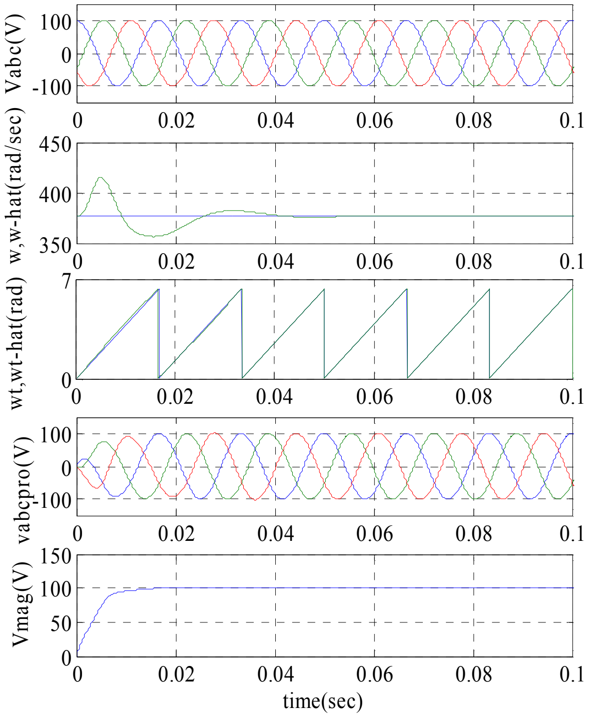

Fig.11. Start-up and pure sinusoidal.

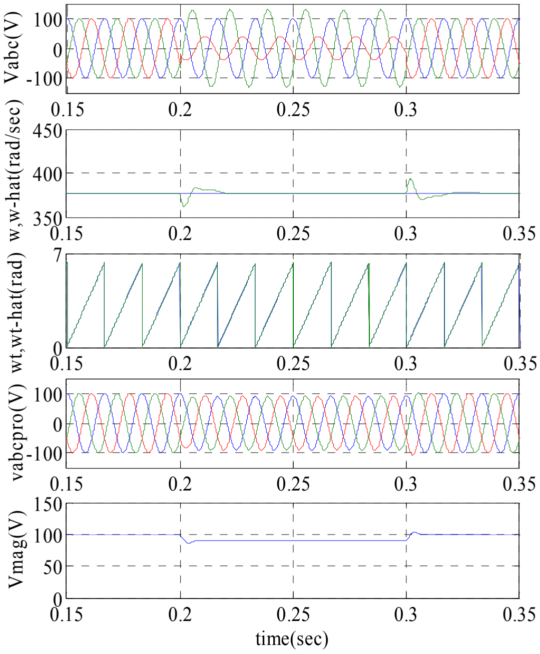

Fig.12 Unbalanced source voltages.

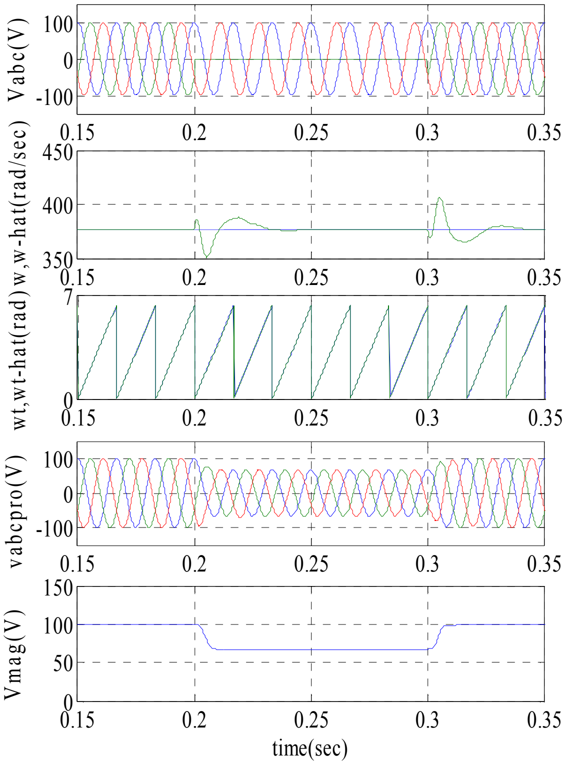

Fig.13 Phase fault source voltages.

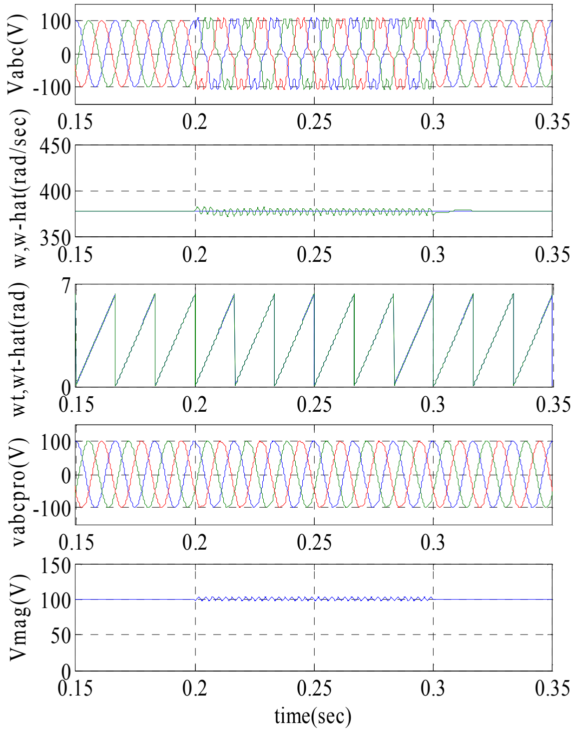

Fig.14 Harmonic distortion source voltages.

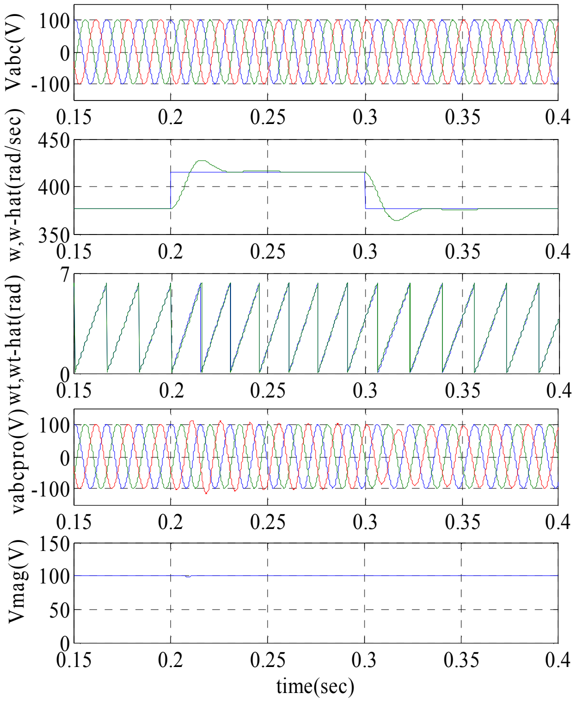

Fig.15 Frequency step change source voltages.

From the simulation results, we can see that:

(a) Start-up and pure sinusoidal voltages:
From the simulation results, we can see that the start-up speed fast: less than one time cycle. A pretty good phase angle tracking and magnitude extraction performance is also shown in the pure sinusoidal situation.

(b) Unbalanced components:
Since the positive sequence estimator can eliminate the negative fundamental sequence component produced by the unbalanced source voltages, the positive sequence can be extracted corrected. The simulation results show that the frequency, phase angle, three phase positive sequences and fundamental voltage magnitude are all obtained quickly and accurately.

(c) Phase fault
Similar to the unbalanced case, the AQF-SRF-PLL can be used for the phase fault situation. Based on the proposed PLL, the simulation results give us the good performance.

(d) Harmonic distortion:
A good harmonic distortion filtering feature is shown in Fig. 14. This is benefit from the AQF filter. For better performance, the K value can be chosen smaller without destroy the system stability requirement.

(e) Frequency step change:
The PLL performance of the frequency change is mainly decided by the system PI controller parameters and the dynamic characteristics of the AQF filter. Fig.15 gives us a pretty good frequency adaptable characteristic of the proposed PLL.

IV. CONCLUSIONS

The presented AQF-SRF-PLL system is suitable for the harmonics distortion and unbalanced source voltages conditions, even phase fault scenario. The proposed PLL strategy has more advantages than the conventional SRF-PLL: (a) Higher dynamic response while better accuracy, (b). Suitable for the systems which include unbalanced components and harmonics distortions, (c) Fast and accurate extraction of the positive sequences, (e) Good adaptability to the grid frequency variation, (f) Simpler structure than the reported DDSRF-PLL strategy.

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