INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
B. Misra and B. Nayak, *Vol.8, No.1, March, 2018*

Modified Second Order Adaptive Filter for Grid Synchronization and Reference Signal Generation

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Received: 29.07.2017 Accepted:18.10.2017

Abstract-Grid synchronization is a very important phenomenon under distorted and polluted grid conditions. So design of the phase lock loop plays a very crucial role in the filtering performance during grid frequency variation and other transient conditions. Thus different adaptive filters are gaining popularity on the basis of their disturbance rejection capability and ability to extract the fundamental component from the polluted signal under grid frequency variations. In this set of work the polluted system performance has been analyzed on the basis of three adaptive filters, one is the second order adaptive filter (SOAF) based PLL technique, second is on the basis of second order generalized integrator quadrature signal generator (SOG-QSGI) based PLL technique and third being the proposed modified second order adaptive filter (modified-SOAF) based PLL technique. The performance of the proposed modified second order adaptive filter has been analyzed on the basis of different parameters like the total computation time of the adaptive filters, settling time of the extracted fundamental signal, dependency of the filter performance on frequency, gain value and damping factor.

Keywords Phase-Locked Loop (PLL), adaptive filter, variable frequency, bandwidth, settling time, frequency response.

1. Introduction

The increased penetration of distributed power generation systems (DPGS) into the power grid and use of large number of domestic and industrial nonlinear load deteriorates the power quality of the distribution system. In distributed generation system power electronic devices will be extensively used [1]. So here the challenge is to manage the power delivered by the distributed generators and correct synchronization of the power electronic converters with the electric grid voltage at the point of common coupling [2]. For this process to be executed accurately, correct information regarding phase, frequency and amplitude of the utility voltage is significant for the generation of the reference signals. So the quality of the injected power to the grid is highly interrelated with the precision of this information [3].Under normal operating conditions the grid voltage waveforms are sinusoidal and balanced but in case of grid faults and use of non linear loads grid voltage profile can easily become unbalanced and distorted. In such situation, the grid-connected converters should be properly synchronized with the grid to maintain continuity of grid service and to keep the generation uninterrupted and running [4-5].

In such situation phase-locked loops (PLL) are very popular for years to synchronize the control techniques of power electronic converters with the grid voltage [6]. Due to the ease of operation and simplified control technique many authors have suggested synchronous-reference-frame phase locked loop (SRF-PLL) to estimate the instantaneous grid voltage phase [7]. The operational technique of SRF-PLL needs to transform the three phase grid voltage from natural reference frame (NRF) to synchronous reference frame (SRF) [8-9]. The phase of the grid voltage can be estimated by a close loop control technique with the help of a proportional–integral (PI) controller [10-11]. After a lot of analysis regarding the dynamic behavior of a SRF-PLL, it has been concluded that this synchronization technique gives the best performance when the grid voltage is perfectly balanced and does not contain any harmonics other than the fundamental value [12]. But SRF-PLL fails to estimate the phase accurately if the system is polluted with harmonics and the three phase voltages are unbalanced. This wrongly estimated phase will deteriorate the quality of power to be delivered to the grid [13].

The disturbance rejection capability of the SRF-PLL can be improved with a proper tuning of the PI regulator, which will further slowdown the system performance and will affect the transient stability of the system. Secondly the phase can be estimated accurately and quickly by using a feed forward method which will improve the poor transient performance of the SRF-PLL by rejecting the undesired ripples in the considered phase [14-15]. But in all the above mentioned papers the behavior and performance of the synchronization technique is not taken into consideration if the grid frequency varies either in the grid fault condition or when a micro grid will operate in the islanding mode [16-17].

Adaptive resonant filters have the best disturbance rejection capability in case of grid frequency variation [18-19]. For the extraction of the fundamental component present in balanced and polluted harmonic grid signal, the most popular adaptive filters are the second order adaptive filters (SOAF) and second order generalized integrators (SOGI) [20]. In case of second order adaptive filters (SOAF) the system achieves very high gain within a narrow frequency band centered around the resonant frequency [21]. The gain value g_1 decides the width of this band. A high value of g_1 leads to a wider band while a low value of g_1 leads to a very narrow band. And in this case the band width of a band pass filter is not only a function of the gain g_1 but it also depends on the frequency of interest. So for a variable frequency system the stability can only be achieved by optimizing the value of both gain as well as frequency. But in case of second order generalized integrator (SOGI) type resonant filter stability can be achieved in a comparatively wider frequency band centered around the resonance frequency. The gain value g_2 decides the width of this band. A high value of g_2 leads to a wider band while a low value of g_2 leads to a very narrow band. In case of SOGI the bandwidth is a function of gain (g_2) only and it is independent of frequency, which makes it suitable for variable-frequency applications [22].

Considering all the advantages of SOGI resonant filter a third filter is proposed in this paper whose structure is analogous to the second order adaptive filter (SOAF), but it has been modified in such a way that its transfer function and performance is exactly the same as that of a SOGI resonant filter. This paper also analyzes the dependency of the bandwidth on the center frequency in modified SOAF filtering techniques and its selection in variable frequency applications. Finally a comparison has been made between all the filters on the basis of different parameters to evaluate their performance in all operating conditions.

2. Second-Order Adaptive Filter (SOAF)

When the grid signals are polluted with higher order dominant harmonics due to transient fault and non-linear loads SRF-PLL is unable to participate in the grid synchronization process [22-23]. For this, a second -order harmonic filter (SOAF) is considered, where two 90^0 shifted sinusoidal signals at the frequency of interest ω (as for example, for fundamental extraction ω is used) are used as reference signals for the adaptive algorithms. This is processed through least-mean-square (LMS) algorithms which can be implemented as forward discrete integrators processed by integrating sine and cosine blocks and resultant equivalent system is shown in Fig.1. The extraction of harmonic component of frequency of interest depends on the estimated fundamental positive sequence frequency from SRF-PLL and transition time is based on the gain (g_1). After deducting the extracted harmonic components from the polluted input signal the desired fundamental component can be obtained. Bandwidth increases with increase of gain and decreases with increase of frequency [24]. Since, only positive sequence fundamental component of balanced polluted grid signal is injected as an input to SRF-PLL, the accurate information of fundamental frequency can be carried out.

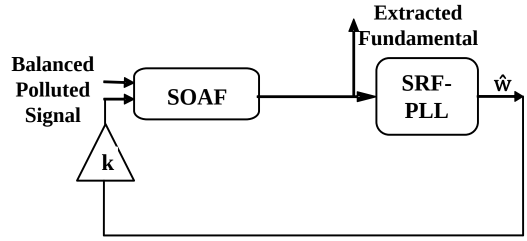

Fig. 1. Block diagram of Second order adaptive filter with SRF-PLL

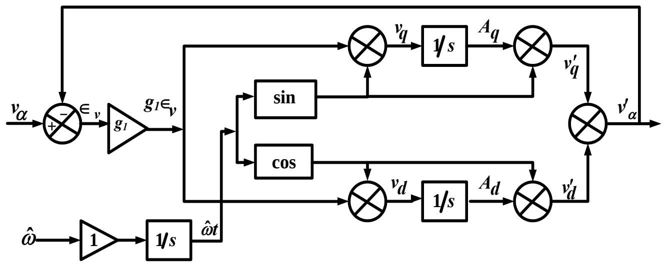

Fig. 2. Internal structure of second order adaptive filter for extraction of fundamental signals

Normally, during grid fault or application of non linear load the major harmonic components are 5th and 7th orders. The higher order of harmonics will be completely attenuated by properly selecting the bandwidth of SRF-FLL. In this paper, the fundamental component is extracted from the balanced polluted grid voltage using a SOAF [25-26]. The transfer function of SOAF which is an adaptive resonant filter is analyzed for extraction of fundamental component from the polluted input signal.

The transfer functions of SOAF structure as shown in Fig. 2.

is given as follows [28]:

Defining, $\mathrm{k} = g_1 \varepsilon_v$,

where g_1= gain of error signal ε_v

$\widehat{\omega}$ = frequency to be filtered, The response of the system shown in Fig. 1. consists of two second order transfer functions.

The transfer function of input to output known as adaptive band pass filter (ABPF) is given by,

$$ABPF(\mathrm{S}) = \frac{v_\alpha'(S)}{v(S)} = \frac{g_1 S}{S^2 + g_1 S + (\widehat{\omega})^2} \quad (1)$$

The transfer function of input to error is a adaptive notch filter (ANF), given by

$$ANF(\mathrm{S}) = \frac{\epsilon_v(S)}{v(S)} = \frac{S^2 + (\widehat{\omega})^2}{S^2 + g_1 S + (\widehat{\omega})^2} \quad (2)$$

The damping factor of adaptive band pass filter for fundamental component can be estimated as,

Damping factor and settling time (for fundamental),

$$\zeta_1 = \frac{g_1}{2\widehat{\omega}} \quad and \quad T_{s1} = \frac{9.2}{g_1} \quad (3)$$

The bandwidth of band-pass filter decreases with increase of gain g_1[14]. It is interesting to note that with an increase in the value of gain the band width of the filter increases which will reduce the settling time of the filter but system stability cannot be assured. From Eq. (3) it is clear that for variable frequency condition of the grid this filter is not a suitable choice [29].

3. Second-Order Generalized Integrator (SOGI)

The performance of another adaptive filter technique, based on the generalized integrator (GI) concept, called as second order generalized integrator (SOGI)as shown in Fig. 3 is analyzed under polluted grid condition [24]. From the transfer functions given for the SOAF it is evident that the band width of the adaptive band pass filter as given by Eq. (2) depend on the values of g_1 as well as $\widehat{\omega}$ [27].

The transfer functions of a second order generalized integrator (SOGI) as derived from Fig. 4. for a single sinusoidal signal is shown below [30]:

The transfer function of error to output i.e. known as resonant filter can be found as,

$$SOGI_{r1}(\mathrm{S}) = \frac{v_1'(S)}{\square_2\square_{\square}'(\square)} = \frac{g_2\widehat{\omega}S}{S^2 + \widehat{\omega}^2} \quad (4)$$

Input to output transfer function known as band pass filter is written as,

$$SOGI_{bp1}(\mathrm{S}) = \frac{v_1'(S)}{v_1(S)} = \frac{g_2\widehat{\omega}S}{S^2 + g_2\widehat{\omega}S + \widehat{\omega}^2} \quad (5)$$

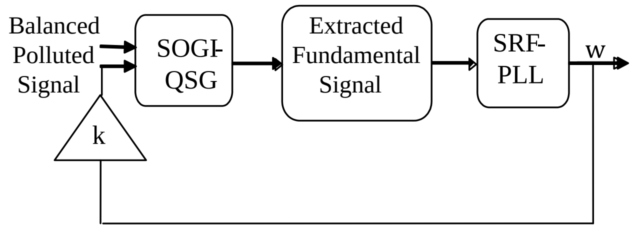

Fig. 3. Block diagram of SOGI-QSG with SRF-PLL

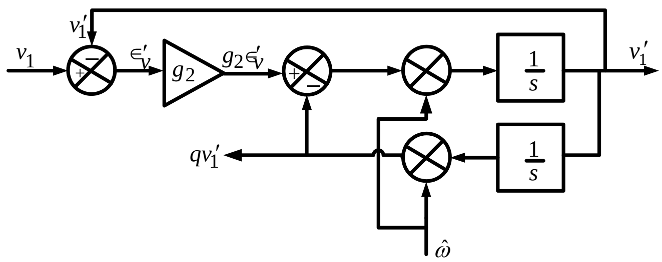

Fig. 4. Internal structure of SOGI-QSG for extraction of fundamental signals

Input to error which is notch filter transfer function can be given by,

$$SOGI_{nf1}(\mathrm{S}) = \frac{g_2\square_{\square}'(\square)}{v_1(S)} = \frac{S^2 + \widehat{\omega}^2}{S^2 + g_2\widehat{\omega}S + \widehat{\omega}^2} \quad (6)$$

The advantage of SOGI is that the bandwidth is not a function of frequency and gain as in SOAF but only depends upon the gain (g_2), which is suitable for variable frequency applications.

The time response of the SOGI based adaptive filter of a sinusoidal input signal $v = sin\widehat{\omega}\mathrm{t}$ is applied as an input to the transfer function is given by

$$v_1' = \sin(\widehat{\omega}\mathrm{t}) - \frac{\sin\left(\left(\sqrt{1 - \frac{g_2{}^2}{4}}\right)\widehat{\omega}\mathrm{t}\right)\mathrm{e}^{-g_2\widehat{\omega}\mathrm{t}/2}}{\sqrt{1 - \frac{g_2{}^2}{4}}} \quad (7)$$

The damping factor and settling time of SOGI based band pass filter for separation of positive and negative sequence components can be estimated as

Damping factor,

$$\zeta_1 = \frac{g_2}{2} \quad (8)$$

and time constant,

$$\tau = \frac{2}{g_2 \hat{\omega}} \quad (9)$$

So, settling time comes as,

$$T_s = \frac{9.2}{g_2 \hat{\omega}} \quad (10)$$

From Eq. (10) it is seen that settling time is inversely proportional to product of gain and frequency. So in SOGI based filter the band width increases with increase of gain just like SOAF. The simulation results and the frequency response for different values of gain of SOGI-QSG structure are analyzed in the following section. The settling time of the extracted fundamental signal for a particular gain value is shown in Fig. 13 and Fig. 14 which confirms the faster response of the SOGI filter as compared to the SOAF filter.

4. Proposed Modified Second-Order Adaptive Filter (modified-SOAF)

The grid voltage is perfectly sinusoidal with fundamental component only during balanced operating conditions. With the introduction of non-linear load or during grid fault conditions the grid voltage becomes unbalanced with higher order harmonics. During grid frequency variations the SOAF fails to operate. In this section a new method is proposed where the second order adaptive filter has been modified to give similar results as that of a second order generalized integrator. An effort has been made to make the transfer function of both the filters same so that the performance of the modified-SOAF technique will be independent of the system frequency variation. Under such situation it will be easier to extract the fundamental component from the polluted signal, which can be used as a reference signal for the SRF-PLL. So in the existing structure of SOAF filter as shown in Fig. 2, frequency $\hat{\omega}$ is multiplied with $g_3 \epsilon_v$ which can be represented as shown in Fig. 5. With this modification the filtering structures in Fig. 4 and Fig. 6 are comparable and both will reveal the same dynamic performance when performing as adaptive resonant filters. But the initial transient behaviour in both the cases will be different.

For the above to happen, the following modifications has been made.

$$\text{Defining, } k = g_3 \hat{\omega} \epsilon_v \quad (11)$$

v_{d1} and v_{q1} signals of Fig. 6 can be written as:

$$v_{d1} = k cos(\hat{\omega} t) = \frac{1}{2} k \left[e^{j\hat{\omega} t} + e^{-j\hat{\omega} t} \right] \quad (12)$$

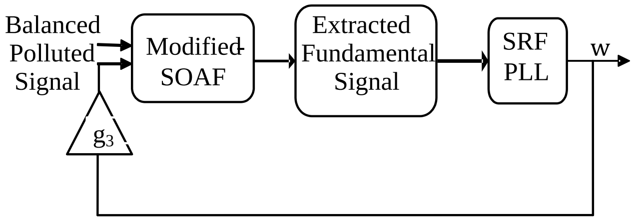

Fig. 5. Block diagram of Modified-SOAF structure

The output of integrator for v_{d1} and v_{q1} can be expressed in Laplace domain as

$$A_d(S) = \frac{1}{2S} \{ k(S + j\hat{\omega}) + k(S - j\hat{\omega}) \} \quad (13)$$

$$A_q(S) = \frac{1}{2jS} \{ k(S + j\hat{\omega}) - k(S - j\hat{\omega}) \} \quad (14)$$

$$v'_{d1} = A_d cos(\hat{\omega} t) \quad (15)$$

$$v'_{q1} = A_q sin(\hat{\omega} t) \quad (16)$$

Taking Laplace of Eq. (15) &Eq. (16),

$$v'_{d1}(S) = \frac{1}{2} \{ A_d(S + j\hat{\omega}) + A_d(S - j\hat{\omega}) \} \quad (17)$$

$$v'_{q1}(S) = \frac{1}{2j} \{ A_q(S + j\hat{\omega}) - A_q(S - j\hat{\omega}) \} \quad (18)$$

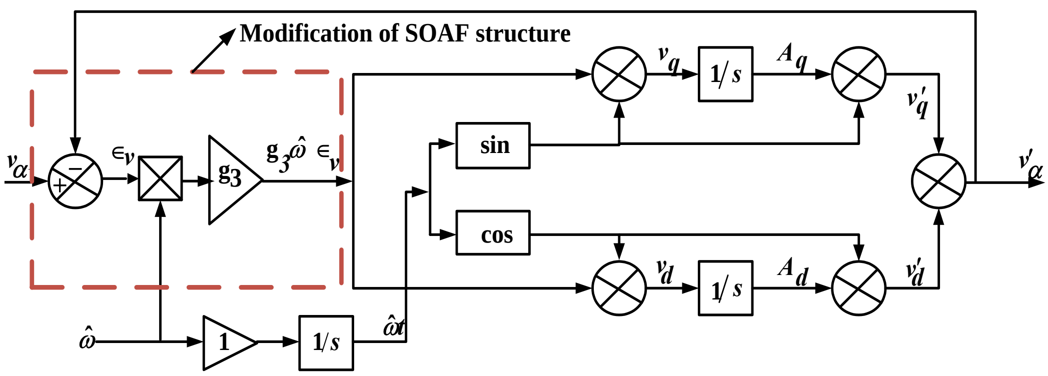

Fig. 6. Internal structure of Modified-SOAF for extraction of fundamental signals

Substituting Eq. (13) to Eq. (17),

$$v_{d1}^{'}(S) = \frac{1}{4(S+j\widehat{\omega})}\{k(S)+k(S+j2\widehat{\omega})\} + \frac{1}{4(S-j\widehat{\omega})}\{k(S)+k(S-j2\widehat{\omega})\} \quad (19)$$

Similarly, substituting Eq. (14) onto Eq. (18),

$$v_{q1}^{'}(S) = \frac{1}{4(S+j\widehat{\omega})}\{k(S)-k(S+j2\widehat{\omega})\} + \frac{1}{4(S-j\widehat{\omega})}\{k(S)-k(S-j2\widehat{\omega})\} \quad (20)$$

Finally, the addition of two equations Eq. (19) &Eq. (20), gives rise to

$$v_{\alpha}^{'}(S) = \frac{S}{S^2+(\widehat{\omega})^2}k(S) \quad (21)$$

Consequently, the transfer function of error to output is given by,

$$AF_1(\mathrm{S}) = \frac{v_{\alpha}^{'}(S)}{\epsilon_v(S)} = \frac{g_3\widehat{\omega}S}{S^2+(\widehat{\omega})^2} \quad (22)$$

The transfer function of input to output known as band pass filter is given by,

$$ABPF_1(\mathrm{S}) = \frac{v_{\alpha}^{'}(S)}{v(S)} = \frac{AF_1(\mathrm{S})}{1+AF_1(\mathrm{S})} = \frac{g_3\widehat{\omega}S}{S^2+g_3\widehat{\omega}S+(\widehat{\omega})^2} \quad (23)$$

The transfer function of input to error is a notch filter, given by

$$ANF_1(\mathrm{S}) = \frac{\epsilon_v(S)}{v(S)} = 1-ABPF_1(\mathrm{S}) = \frac{S^2+(\widehat{\omega})^2}{S^2+g_3\widehat{\omega}S+(\widehat{\omega})^2} \quad (24)$$

The settling time for a second-order system can be roughly estimated as, $T_{s1} = 4.6\tau_1$, where, τ_1 is the time constant [11]. The time response of the modified-SOAF for a sinusoidal input signal $v = sin\widehat{\omega}$t applied to the transfer function in Eq. (23)is as follows:

$$v_1^{'} = sin(\widehat{\omega}t) - \frac{\widehat{\omega}sinh\left(\sqrt{(\frac{(g_3\widehat{\omega})^2}{4}-5\widehat{\omega}^2)}t\right)e^{-g_3\widehat{\omega}t/2}}{\sqrt{\frac{(g_3\widehat{\omega})^2}{4}-5\widehat{\omega}^2}} \quad (25)$$

Now the above transfer functions of the modified-SOAF are in the form of the transfer functions of the SOGI filter so the damping factor and settling time of the modified-SOAF can be estimated considering Eq. (23) and Eq. (25) as,

$$\zeta_1 = \frac{g_3}{2} \quad (26)$$

Time constant (for fundamental),

$$\tau_1 = \frac{2}{g_3\widehat{\omega}} \quad (27)$$

So the settling time comes as,

$$T_{s1} = \frac{9.2}{g_3\widehat{\omega}} \quad (28)$$

Verifying Eq. (28) it can be concluded that the response of the modified-SOAF is faster when the value of gain is more. Gain value also determines the bandwidth of the modified SOAF. For low values of gain the filtering capability will be better but the settling time will be more. So a compromise has to be made between the gain value and bandwidth to get the best result of the modified adaptive filter. The above mathematical analysis also confirms that bandwidth is not a function of frequency and gain as in SOAF but only depends upon the gain (g_3), which is suitable for variable-frequency applications.

5. Simulation Results

A. SOAF PLL

In this section a complete analysis of the extraction of higher order harmonics from a polluted signal has been done in MATLAB/SIMULINK environment. In this paper, the 5^{th}, 7^{th}harmonic components are extracted from balanced distorted grid voltage using SOAF filter. From the transfer function of input to output and equations of damping factor, time constant and settling time the stability of the system has been analyzed using the frequency response. As seen in Fig. 11, this type of resonant filter can attain very high gain in a narrow frequency band centered around the resonance frequency. The gain value g_1 decides the width of this band. A high value of g_1 leads to a wider band while a low value of g_1 leads to a very narrow band.

In SOAF it is clear that the band width of a band pass filter as given by Eq. (1) is not only a function of the gain g_1 but it also depends on the frequency of interest. So for a variable frequency system the stability can only be achieved by optimizing the value of both gain as well as frequency. Again it can also be concluded that the value of damping factor ζ_1 cannot be kept constant for any change of frequency as seen in Eq. (3). Finally one of the major disadvantage of adaptive filter is the use sine/cosine functions, which requires large look up tables which increases the computation time of the filter and introduces noise into the system. So system has a slow response as compared to the SOGI-QSG structure.

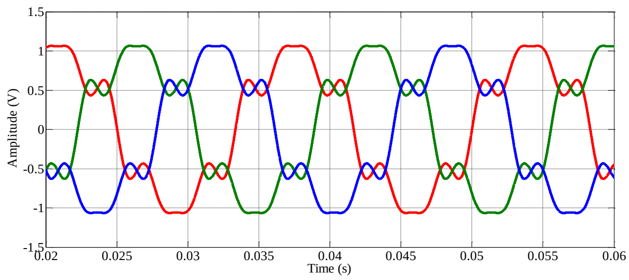

Fig. 7. Three phase grid voltages polluted with 5th & 7th, harmonic components

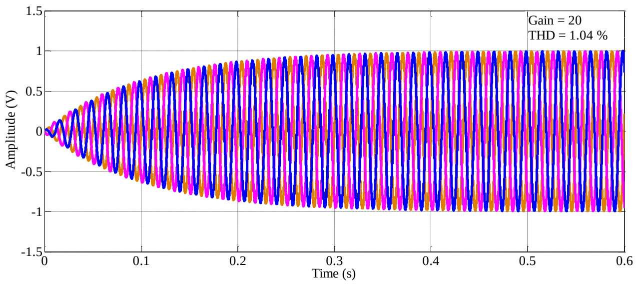

Fig. 8. Extracted fundamental component from three phase polluted grid voltages using SOAF technique

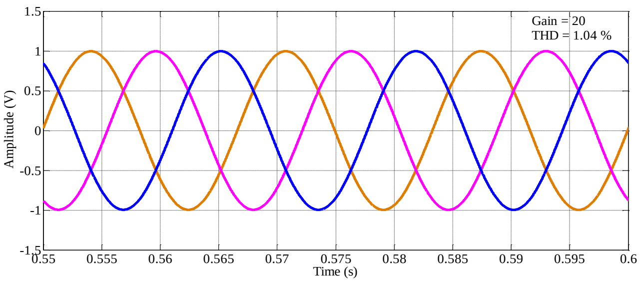

Fig. 9. Extracted fundamental component from three phase polluted grid voltages after settling time using SOAF technique

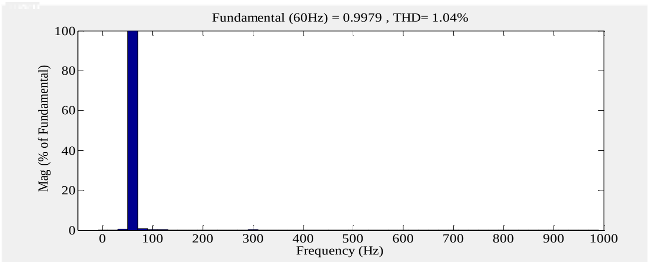

Fig. 10. Estimation of THD of fundamental component using the SOAF technique.

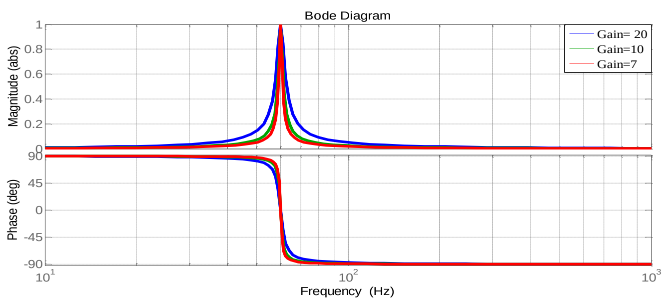

Fig. 11. Bode diagram of input to output transfer function (band pass filter) of SOAF with different values of gain

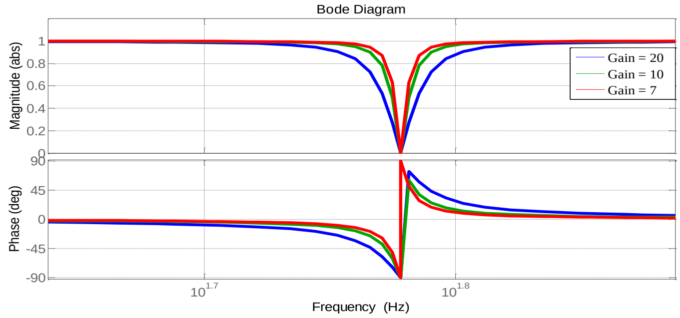

Fig. 12. Bode diagram of input to error (adaptive notch filter) transfer function of SOAF with different values of gain

In Fig. 7. a three phase grid voltage is considered polluted with the 5th and 7th harmonic voltages. Fig. 8. and Fig. 9. Gives an idea about the settling time of the system whereas Fig. 10. provides the total harmonic distortion of the extracted fundamental component. The bode diagram of the input to output transfer function and input to errortransfer function for different values of gain is given in Fig. 11and Fig. 12.Here is can be observed that for a high gain value the band width of the filter is more but the settling time will be less as analysed in Table-1.

B. SOGI-QSG PLL

Here in this segment the process of extraction of fundamental component from a polluted signal has been done in MATLAB/SIMULINK environment. The transfer function of SOGI-QSG has been derived and the stability of the system has been analyzed using the bode plot. As seen in Fig. 19, this type of resonant filter can attain stability in a comparatively wider frequency band centered around the resonance frequency. The gain value g_2 decides the width of this band. A high value of g_2 leads to a wider band while a low value of g_2 leads to a very narrow band [30]

Analyzing Eq. (8) and Eq. (10) it can be concluded that the damping factor ζ is inversely proportional to settling time T_{s1}. Settling time is inversely proportional to product of gain and frequency. The input and output time response and bode diagram for different values of gain of SOGI-QSG structure and modified-SOAF structure are same and are shown in Fig. 19. Here the band width increases with increase of gain just like SOAF filter. Fig. 20 analyses the bode diagram of input to output transfer function of SOGI (quadrature signal) filter. In Fig. 21 the bode diagram of input to error (adaptive notch filter) transfer function of SOGI-QSG and modified-SOAF with different values of gain is given.

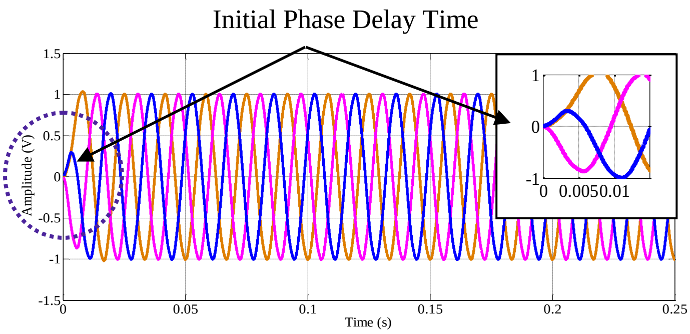

Fig. 13. Extracted fundamental component from three phase polluted grid voltages using SOGI technique

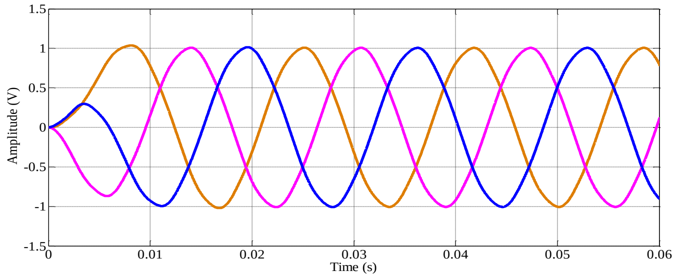

Fig. 14. Extracted fundamental component from three phase polluted grid voltages using SOGI technique

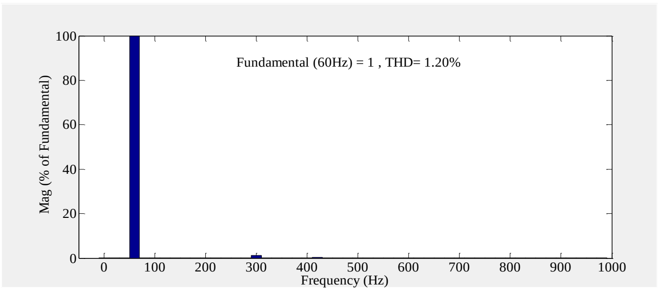

Fig. 15. Estimation of THD of fundamental component using the SOGI technique.

Fig. 13. & Fig. 14. are indicating the extracted fundamental component from three phase polluted grid voltages using SOGI technique. As compared to SOAF filter the advantage of SOGI-QSG is the absence sine/cosine functions in the structure, which makes the computation time faster. So system has a faster response as compared to the SOAF structure. The initial delay time, settling time of the system and the total harmonic distortion of the extracted fundamental is shown in Fig. 13, Fig. 14 and Fig. 15.

C. *Modified* SOAF- PLL

After studying the detail analysis of the above two adaptive filters (SOAF and SOGI-QSG) a modification has been made in the structure of SOAF filter so that the behavior of SOAF will be exactly the same as that of the SOGI filter. From the simulation results it is confirmed that the system output matches in both the cases with respect to the gain values and the transient period of the output signals. However the frequency response analysis shows that the lower is the value of gain the lower will be the damping factor hence better is the filtering performance. But at that time the system dynamic response will be slower. So a negotiation between the filtering capability and dynamic response decides the best value of gain to be less than 0.5 whereas in case of SOGI filter it was for a gain value of $\sqrt{2}$. So it can be concluded that though the performance of modified SOAF filter is same as that of SOGI filter but the transient behaviour is affected by the use sine/cosine functions in the structure. These functions requires large look up tables which increases the computation time of the filter so system has a slow response as compared to the SOGI-QSG structure.

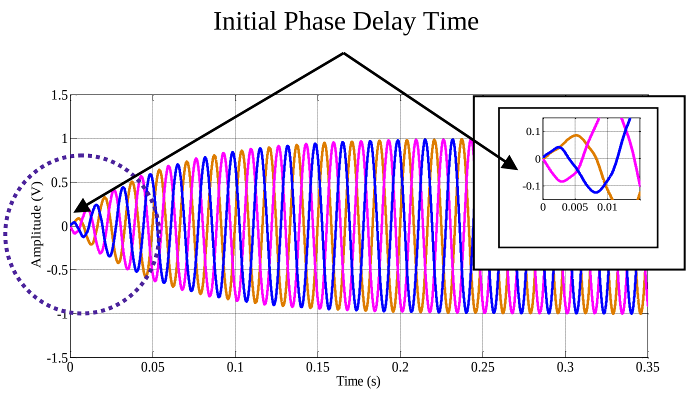

Fig. 16. Extracted fundamental component from three phase polluted grid voltages using Modified-SOAF technique for gain value $g_3 = 0.1$.

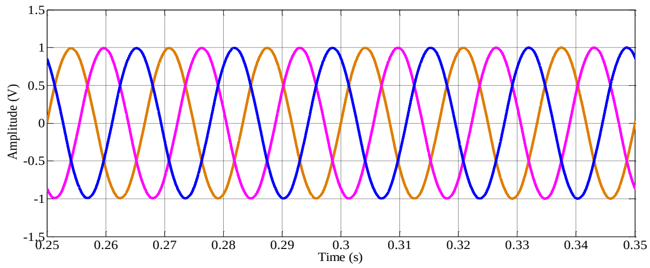

Fig. 17. Extracted fundamental component from three phase polluted grid voltages using Modified-SOAF technique

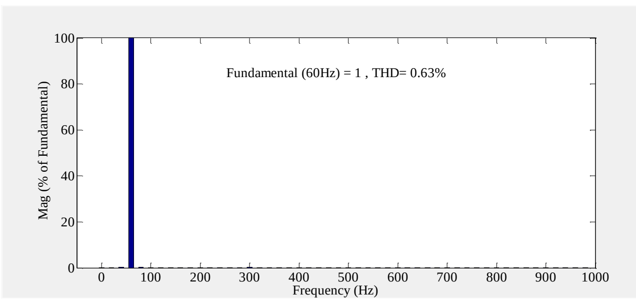

Fig. 18. Estimation of THD of fundamental component using the Modified-SOAF technique.

As seen from Fig. 13 and Fig. 16 it can be concluded that the phase angle delay between the actual signal and the extracted fundamental signal is more in case of SOGI filter. The transfer function given in Eq. (23) and Eq. (24) corresponds to the behaviour of a second-order band pass filter and a notch filter respectively with zero gain at the centre frequency. So it is obvious as shown in Fig. 16 & Fig. 17 that, for the same value of gain, the settling time for the modified-SOAF filter is nearly the same as that of SOGI filter and the total harmonic distortion is also the same for the lower value of gain. The comparative results are given in Table 1.

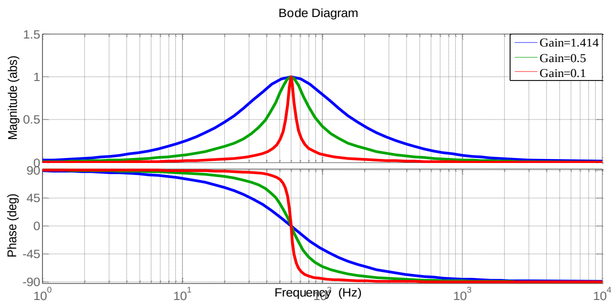

Fig. 19. Bode diagram of input to output transfer function (band pass filter) of SOGI and modified-SOAF (In phase signal) with different values of gain

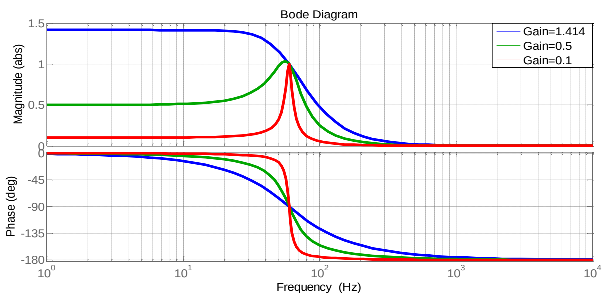

Fig. 20. Bode diagram of input to output transfer function (band pass filter) of SOGI (quadrature signal) with different values of gain

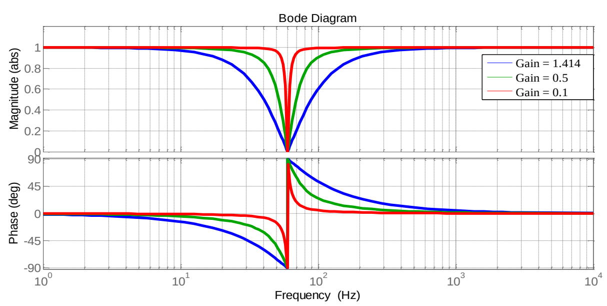

Fig. 21. Bode diagram of input to error (adaptive notch filter) transfer function of SOGI and modified-SOAF with different values of gain

The frequency response of this filter is given in Fig. 19 and Fig. 21. The response is same for both the SOGI filter and the modified-SOAF filter.

The performance analysis of the above three adaptive filters (SOAF and SOGI-QSG) on the basis of various parameters can be shown in Table 1.

Table 1

Performance comparison for different adaptive filters

Type of Filter	Gain	Settling Time (Sec)	THD
SOAF	$g_1 = 20$	0.5	1.04 %
	$g_1 = 10$	1	2.03 %
	$g_1 = 7$	System Unstable	
Remark: *SOAF filter works best for gain value more than 20.*			
SOGI-QSG	$g_2 = 3$	0.03	2.27 %
	$g_2 = 1.414$	0.015	1.2 %
	$g_2 = 0.5$	0.06	0.44 %
	$g_2 = 0.1$	0.3	0.5 %
Remark: *In SOGI-QSG the best compromise between dynamic response and overshooting can be achieved with $g_2 = 1.414$*			
Modified SOAF	$g_3 = 3$	0.015	12.05 %
	$g_3 = 1.414$	0.02	6.35 %
	$g_3 = 0.5$	0.06	2.32 %
	$g_3 = 0.1$	0.3	0.63 %
Remark: *In modified SOAF the best compromise between dynamic response and overshooting can be achieved with $g_2 = 1.414$*			

6. Conclusion

In this paperthe second order adaptive filter (SOAF) has been modified in such a way that its behavior and performance is exactly the same as that of the second order generalized integrator (SOGI). The proposed modified-SOAF filter is used to extract the fundamental component from a balanced signal polluted with 5th and 7th harmonics. This extracted fundamental component is used as a reference three-phase signal for the synchronous reference frame phase lock loop to generate the required frequency which is used as a feedback signal for the modified-SOAF filter. It also improves the power quality by reducing the total harmonic distortion of the output which is because of the presence of a large number of non-linear load. A comparative analysis has been carried out between the SOAF, SOGI and the modified-SOAF filter to verify the dynamic response and robustness of all for different values of gain. It can be concluded that the proposed filter is very effective for the extraction of the fundamental signal and response is satisfactory for variable frequency environment as its dynamic response is good and harmonic rejection capability is comparable with the SOGI filter. Further work will focus on the improvement of computational time, lowering of the total harmonic distortion and experimental validations of the filter. This filter can be used in the adaptive resonant controllers used in case of distributed power generation systems (DPGS) to supply a good quality injected current and unity power factor during grid frequency variation.

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