Enhancement in Loop Filter of a Second Order Generalized Integrator - PLL by Using Proportional-Resonant Controller

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Abstract* - This paper describes a simple method for the estimation of amplitude, frequency and phase of an input signal with an improved performance for a second order generalized integrator phase locked loop (SOGI-PLL) using a proportional resonant (PR) controller. In order to enhance the performance of tracking which include steady state error, a PR control is suggested over proportional-integral (PI) control. The instantaneous tracking performance is improved because the PR controller resonates at fundamental frequency. The analysis and mathematical model of single-phase SOGI-PLL with PI and PR controllers are developed. The performances of these two controllers are compared for various tests under same circumstances. The results show that both PI and PR control can achieve good control effects but the PR control is simpler, better improvement of steady state accuracy and uses low cost computational resources. The effectiveness of the control is verified using simulation results.

Keywords— Second Order Generalized Integrator (SOGI), Phase -Locked Loop (PLL), Proportional-Integral (PI) Control, Proportional Resonant (PR) Control.

I. INTRODUCTION

EFFICIENT phase angle tracking capability is an important factor in converters, active power filters, UPS applications, controlled rectifiers, distributed generation and also for FACTS devices [1]-[2]. The Phase-Locked Loops (PLL) will estimate the phase angle accurately because of its merits like speed of response for disturbances like phase, frequency and voltages, steady state phase angle error and harmonic rejection.

Many topologies on PLL's have been introduced for detecting the amplitude and phase angle for grid-connected systems. A synchronous reference frame (SRF) PLL is performing well under ideal conditions but has poor performance under distortion [3]. Josep M. Guerrero and Saeed Golestan have been deeply analyzed the structures of two different PLLs namely SOGI (Second Order Generalized Integrator) and Park PLL [4]. But, the steady state error response is slower. The PLL should respond effectively in distorted load conditions by detecting the phase angle and amplitude at a faster rate. S.M Silva addressed the most recurrent algorithms on single-phase grid connected systems [5]. The estimation of the phase angle can be done by either open loop method or closed loop methods [6]-[8].

Two controllers which are used in SOGI-PLL are the PI controller and PR controller and their comparison is presented.

Due to the dynamics of the integral term in the PI controller, It is unable to track the sinusoidal reference without any steady state error, lack capability in disturbance rejection and also lower order harmonics due to limitation in bandwidth. This shortcome in the PI controller can be overcomed with the PR control which resonates at the resonant frequency and no gain exists at other frequencies [9]. In order to improve the performance of the PI controller, many changes in the controller like increasing the gain, multi state feedback and feed forward path are introduced. But, all these changes are increasing the bandwidth of the system and causing to violate the stability limits and also causing much more computational burden. A similar type of response with low cost, complexity and precise control can be achieved using a PR controller [10]-[11]. For eliminating the steady state error, the PR controller introduces an infinite gain at the selected resonant frequency [12]-[13]. The PR controller response is faster and also has high computational efficiency. This controller is less dependent on system model and performs well under system parameter variations.

This paper focuses on the performance improvement of second order generalized integrator by using PR controller instead of PI control for eliminating the steady state error and lower order harmonics.

The basic block diagram of the PLL is shown in Fig.1. This method is a closed loop system and widely accepted because of its simple structure with analog and digital simplifications that depends on *dq* transformations and feedback method. The basic PLL consists of three building blocks as shown in Fig.1. 1) Phase Detector (PD) that generates a signal which is the difference in phase between the input and feedback signal and then it is passed through the loop filter (LF). 2) LF is used to control the Voltage Controlled Oscillator (VCO). 3) VCO generates the frequency signal from its nominal frequency. The basic PLL has a disadvantage in unbalanced conditions. Hence an effective research is carried out by many researchers to overcome the problems.

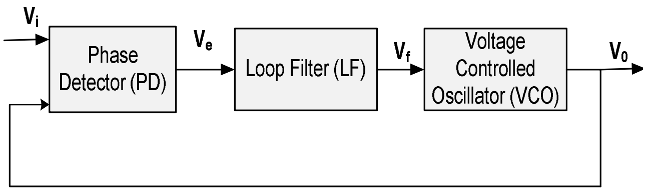


Fig. 1 Basic Structure of PLL

In general, The PD stage is the main topological difference between several Phase Locked Loops. In this paper, the research is diverted from PD to the LF for achieving optimal parameters. Furthermore, a PR controller based solution will be presented. The dynamic response of the SOGI PLL is also studied by taking into account aspects such as: Steady state error, disturbance rejection, settling time and overshoot [14].

II. SECOND ORDER GENERALIZED INTEGRATOR

The design of a SOGI-QSG (Quadrature Signal Generation) is shown in Fig.2. The *k* shown in fig.2 is known as damping factor which affects the bandwidth of the closed-loop system. The gain *k* decides the level of filtering and the dynamic response will become slower with the decrease in *k*. The bandwidth response with unit signal for several values of *K* is shown in Fig. 4. For K=1.6 the response was good and fast (~3.0ms).V_g is the grid voltage, $\widehat{W}$ and θ\` is the estimated frequency and angle respectively and W is the nominal frequency. When the grid frequency has fluctuations, problems may occur as the structure is frequency dependent. Hence, the $\widehat{W}$ value of the SOGI is tuned according to the frequency provided by the PLL structure as shown in Fig. 3. The Bode plots from the transfer functions of (2) & (3) are shown in Fig. 5(a) & 5(b) for various values of *k*. In order to get a balanced set of in-quadrature outputs with exact amplitudes, the SOGI frequency must be equal to the input fundamental frequency [14].

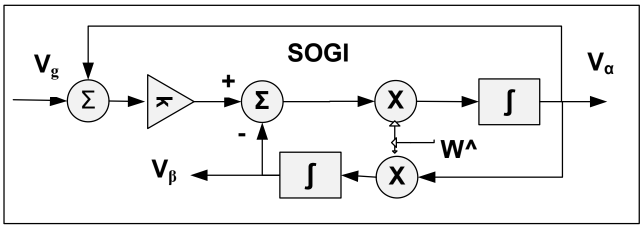


Fig. 2. SOGI-QSG Block

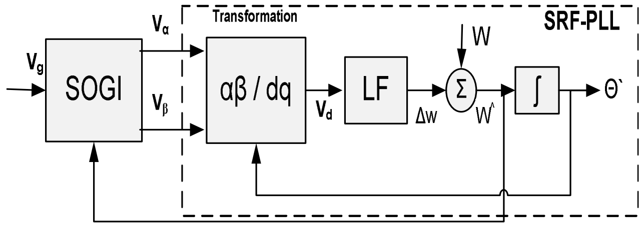


Fig. 3. SOGI-PLL Block Diagram

Two sine waves are produced with a phase shift of 90^0 from V_α and V_β as shown in fig 3. The SOGI Structure is as defined

$$SOGI(s) = \frac{\hat{W}}{s^2 + \hat{W}^2} \qquad (1)$$

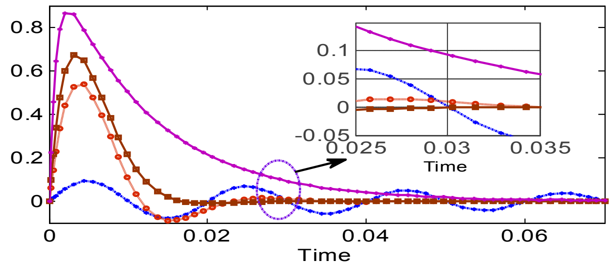


Fig. 4 Bandwidth Filter response for various values of K

The closed-loop transfer functions shown in fig.3 are defined as follows:

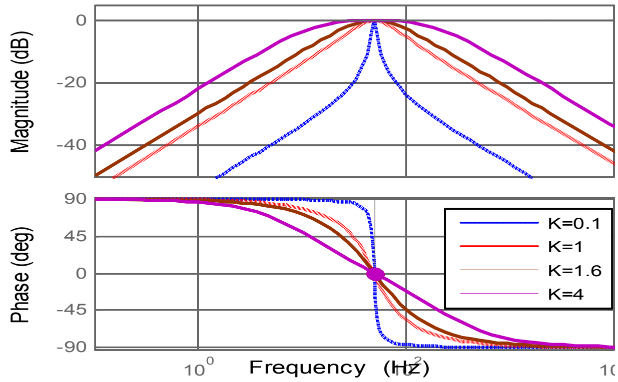
$$G_\alpha(s) = \frac{V_\alpha(s)}{V_g(s)} = \frac{k\hat{W}s}{s^2 + k\hat{W}s + \hat{W}^2} \qquad (2)$$

$$G_\beta(s) = \frac{V_\beta(s)}{V_g(s)} = \frac{k\hat{W}^2}{s^2 + k\hat{W}s + \hat{W}^2} \qquad (3)$$

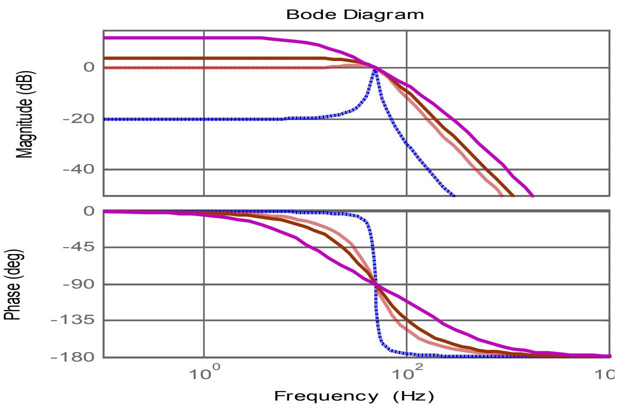
Park transformation is used to convert αβ to dq.

$$T = \begin{bmatrix} \cos\hat{\theta} & \sin\hat{\theta} \\ -\sin\hat{\theta} & \cos\hat{\theta} \end{bmatrix} \qquad (4)$$

The transformation output V_d is passed through a Loop Filter (LF) to eliminate high frequency noises and then added with fundamental frequency (W) to generate the estimated phase angle $\hat{\theta}$. In order to get a balanced set of in-quadrature outputs with exact amplitudes, the SOGI frequency must be equal to the input fundamental frequency ($W = 2\pi * 50$).



(a)



(b)

Fig. 5(a) $G_\alpha(s) = V_\alpha(s)/V_g(s)$, **(b)** $G_\beta(s) = V_\beta(s)/V_g(s)$

III. PROPORTIONAL RESONANT CONTROLLER

A classical PI Controller $G_{PI}(s)$ can be expressed by:

$$G_{PI}(s) = K_P + \frac{K_I}{s} \tag{5}$$

Where, K_P is the Proportional Gain and K_I is the Integral Gain of the transfer function. The equivalent of (5) in stationary frame is implemented in an Synchronous Reference Frame can be easily obtained as:

$$G_{PI}^{\pm}(s) = G_{PI}(s \mp jw) = K_P + K_I \frac{1}{s \mp jw_o} \tag{6}$$

Where, (s-jw) is a Positive sequence SRF and (s+jw) is a negative sequence SRF [15]-[16].

Adding eqn (5) & (6) results in a PR controller [17]. i.e.,

$$G_{PR}(s) = K_P + \frac{K_I * s}{s^2 + w_o^2} \tag{7}$$

Where, K_I=K_R is the Resonant gain and w_o is the angular frequency of the output signal. The above equ.7 represents an Ideal PR controller. It provides zero gain at other frequencies and infinite gain at fundamental frequency hence it leads to a large error when tracking the reference voltage. This error can be minimized if a a non-ideal PR controller is used as shown below.

$$G_{PR}(s) = K_P + \frac{K_R * w_C * s}{s^2 + 2w_c s + (6w_o)^2} \tag{8}$$

Where, w_c is the Cut-off frequency of the controller and it is given by:

$$w_c = 2 * w_o * \varsigma \tag{9}$$

where, ς is reasonably choosen to get low bandwidth and high value of resonant gain is choosen for obtaining high attenuation of harmonics. Therefore, w_c is the compromise between error of tracking reference signal and reduction of sensitivity.

The above eqn.8 makes the controller more reliable due to its finite precision and also proveides a very small steady state error when compared to a PI controller. The frequency response for various values of cut-off frequencies are shown in fig.6.

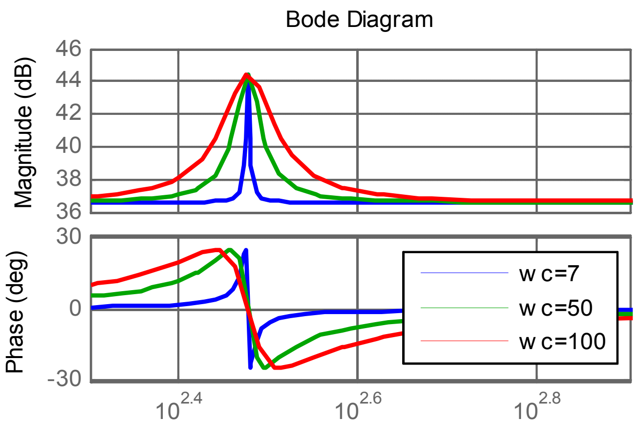


Fig.6 Frequency Response for various values of Wc.

IV. SIMULATION RESULTS

The performance of PI and PR controllers has been tested under different disturbances like volatage sag, phase jump and frequency step variations.

These tests are performed in MATLAB/Simulink Environment and all the simulations have a time interval of 4s which is proved enough to observe all the desired characterstics.

A. Voltage Sag:

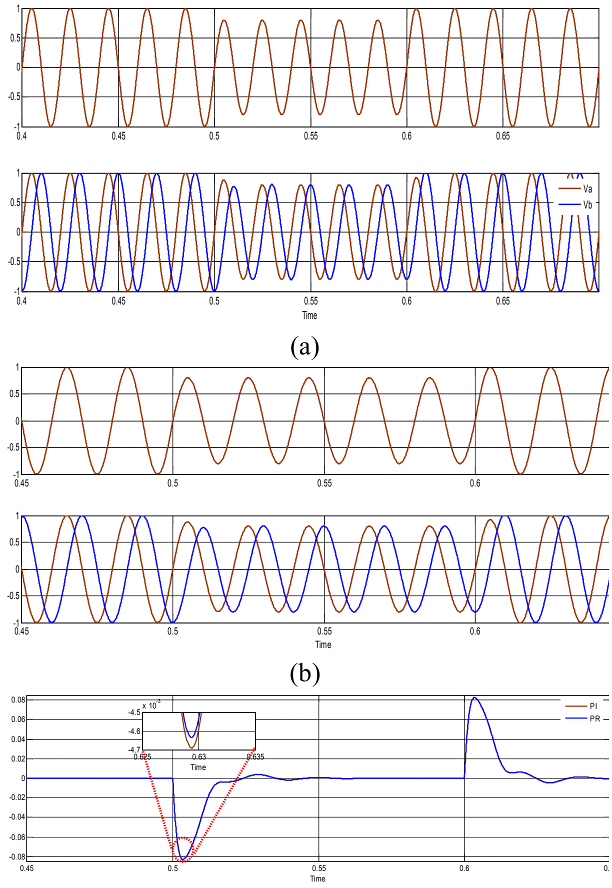


Fig.7 Voltage Sag - Input Voltage and Vα, Vβ (a) PI Control (b) PR Control (c) PI & PR Error Comparison

Fig.7 shows the simulation results for 20% of voltage sag at the grid voltage. It is used to evaluate the performance of the PLL with PI and PR control. The initial behavior of both the controllers are approximately equal but the peak response (Overshoot) of the PR control is less. The settling time can also be analyzed from Fig. 7(c). Fig.7(a) is the performance of SOGI PLL with PI control and Fig.7(b) is the performance of the SOGI PLL with PR control and Fig. 7(c) is error comparison between PI and PR control under voltage sag. In this case. Both the methods are fast and accurate to calculate the change in the amplitude of the grid voltage. The PR control has good dynamics with less overshoot and high steady state accuracy.

B. Frequency Response:

Fig. 8 shows the frequency response of the SOGI-PLL under step change in frequency. The frequency is varied by 20% of positive step to test the dynamics and behavior of the SOGI PLL. The results are shown in Fig.8 in comparison with PI nd PR control. It is clear that the PR control exhibits very less overshoot and the response is faster and accurate in comparison with PI control.

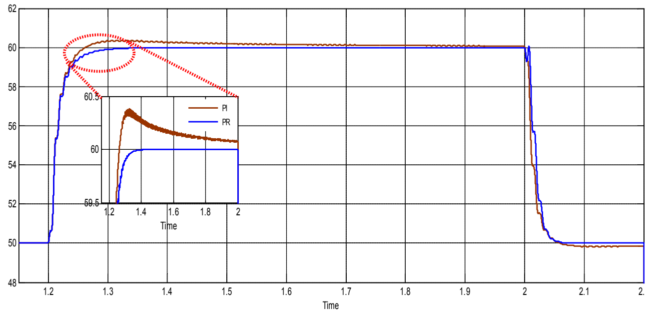


Fig.8 Frequency Step Change from 50 Hz to 60 Hz

C. Phase Jump:

A phase angle jump of 30^0 is applied to the SOGI PLL. The steady state peak response can be observed in Fig.9. It shows the PR control produces a high peak overshoot but the rise time and settling time are very much lesser compared to PI control.

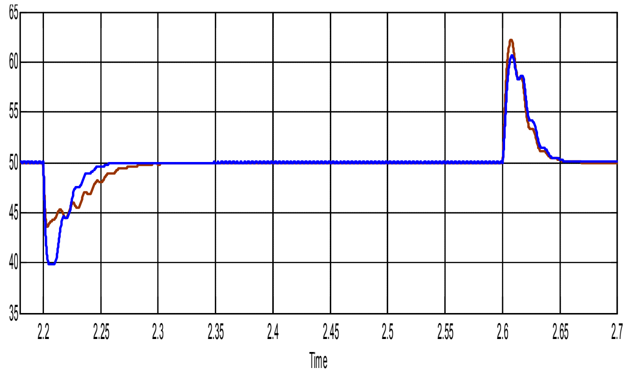


Fig.9 Frequency Response at 30^0 Phase Jump.

V. Conclusion

This paper presents a Second Order Generalized Integrator Phase locked loop with two controllers in its loop filter. Generally, a PI control is used in the loop filter but a comparison and a better study of PR control is done for single-phase grid connected systems. The algorithm used here is used to obtain the amplitude, Phase angle and frequency of the input voltage signal. The loop filter is having a major role in quadrature signal generation and accurate phase angle detection. Hence, extraction of the required information is done using PI and PR controllers and their performance under grid disturbances is also verified using simulation results.

Finally, considering the disturbances presented, it was verified that the proposed PR control has a very fast, good response with higher steady state accuracy and high rejection against various disturbances. Thus, a Loop Filter with PR control is expected to be a good choice for single-phase applications.

ACKNOWLEDGEMENT

Foremost, I would like to thank my guide Dr.M.S.R Murthy for his continuous support, patience, motivation and immense knowledge helped me for my research and my friend Mr.B.Anil Kumar who encouraged me in work, and incented me to strive towards my goal.

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