Development of Phase Lock Loop System for Synchronisation of a Hybrid System with the Grid

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ABSTRACT: Phase locked loop (PLL) is an important part of the control unit of the grid connected power converter. The method of zero crossing detection (ZCD) does not produce accurate phase information when grid is non-ideal. In this work, a synchronous reference frame (SRF) PLL method to obtain accurate phase information when the grid voltages are unbalanced is proposed. The performances of the PLL have been verified for ideal and abnormal grid conditions such as unbalance, voltage sag, faults condition etc. Based on the results obtained, the developed PLL gives better fault ride when unbalances in the three phase input signals are overall handled well by the PLL system as it locks the two signal back within the first cycle. It also overcomes a phase jump after 5 milli-seconds from the time the fault was introduced and performs better tracking of the grid voltage and that of the renewable energy source.

KEYWORDS: Phase locked loop (PLL), grid synchronisation, simulations, PI regulator, hybrid system.

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I. INTRODUCTION

The integration of large scale wind and solar power systems to the grid is a growing trend in modern power system (Wei Zhao, 2012). The viability of this technique is in the ability to match the renewable energy resources with the running network with proper control strategy. Phase lock Loop is vital for control and tracking of phase and frequency of the incoming signal of grid connected systems such as distributed generation (Ghoshal, 2011).

To track the phase of any signal, information such as the frequency and the phase signal must be extracted (Levine, 1999).The system composed basically of three parts namely; the phase detector (PD), the low pass filter (LPF) and the voltage control oscillator (VCO). The phase detector generates an output signal proportional to the phase difference between the input signal ϕ_in, and the signal generated by the internal oscillator of the PLL ϕ_out. The low pass filter (LPF) on the other hand attenuates the high frequency AC components from the PD output. The voltage controlled oscillator (VCO), generates at its output an AC signal whose frequency is shifted with respect to a given central frequency ωc, as a function of the input voltage provided by the LPF (Arruda *et al*, 2001).

PLL structures can be broadly classified into the following three categories:

i) Zero crossing detection (ZCD) based PLL
ii) Stationary reference frame based PLL
iii) Synchronously rotating reference frame (SRF) based PLL

Significant success has been recorded in the development and implementation of the PLL system. In Ciobotaru *et al*, (2011), the Simulink model of the PLL as a grid current controller is presented. In their work, the SISO toolbox provided in MATLAB/Simulink environment was used to determine the gain of the controller manually, imposing a certain bandwidth and in the same time the phase margin was adjusted to ensure stability. Mishra *et al*, (2012), proposed the design and simulation of PLL parameter. In the work, the PLL parameters using mathematical model and the model behaviour of PLL were tested with MATLAB Simulink tool.

The performance characteristics and theories of the phase lock loop are fully discussed in Sangita *et al*, (2012). In this work, a phase lock loop was used to synchronize grid with PV. The Simulink models and results obtained show that the PLL was able to lock grid frequency and phase. The phase detection part of PLL is properly done by using the three-phase to two-phase transformation known as the Clarke or dq transformation in the three phase system. Arruda *et al*. (2001) proposed the Zero crossing detection (ZCD) based PLL structures for accurate phase angle tracking under unbalanced condition for utility connected systems in Industrial Applications. Ghoshal *et al* (2012) and Cherif (2007) reported techniques through which PLL performance can be improved in the event of grid pertubation. In their works, a proper PI regulator was designed and implemented to study the phase tracking and error rejection ability for control systems.

In Anirban (2012), a simple method based on digital filter to improve performance of SRF PLL under unbalanced phase voltage condition has been proposed. Performance of this PLL structure under single phase line to ground fault and other abnormal grid conditions were investigated and experimental results indicate a better performance of the proposed approach. The major limitations with some of the approaches are, firstly, the ZCD based PLL in the reviewed literature is although the simplest but its performance becomes poorer if frequency variation or line notching is present.

Stationary reference frame based PLL structure on the other hand is not capable of accurate phase tracking during unbalanced voltage condition. Since grid connected systems experience problems such as flicker, dip, improper phase jump, input phase shift, amplitude variation, notch and several others,

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this work adopted the synchronously rotating reference frame (SRF) based method of PLL design to develop a prototype capable of synchronizing a distributed generation with the grid under different perturbation, so as to improve the power quality. In order achieve this, a typical synchronous reference frame phase lock loop is represented in Figure 1.

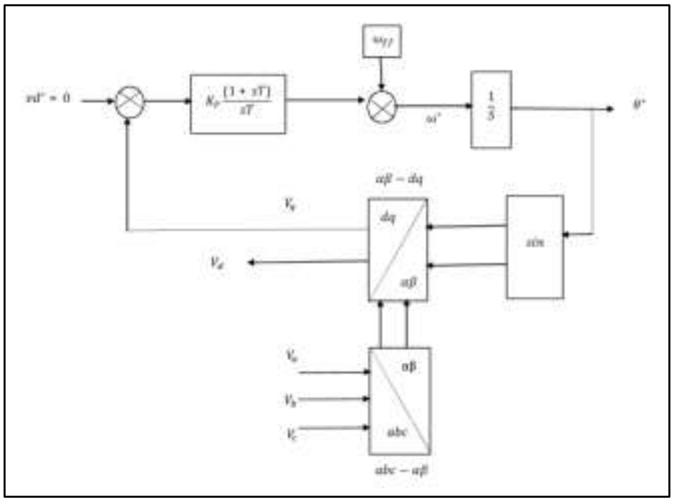


Figure 1: Basic Phase Lock Loop System in Synchronous Reference Frame.

The rest of this work is organized as follows: Section II, described the overall hybrid system and its synchronisation with grid. Section III, described the concept of the phase lock loop, system transfer function and the developed approach. Section IV Simulink Implementation of the developed approach. Section V details result, discussion and conclusion.

II. Model Of Hybrid Wind / Pv System Connected With Grid

A hybrid energy system usually consists of two or more renewable energy sources used together to provide increased system efficiency as well as greater balance in energy supply. In this work, the hybrid energy system is a photovoltaic array coupled with a wind turbine. Figure 2 shows the schematic diagram of the adopted system.

The grid interconnection converts the variable frequency and magnitude outputs from the hybrid wind/SPV system to the synchronous frequency of the utility grid. The variable frequency and magnitude output voltages from the hybrid wind/SPV system are converted to DC voltages or so called DC links. The grid side inverter converts the DC link voltages to the synchronous voltages of the grid. A Sinusoidal Pulse Width Modulation (SPWM) is employed for generating gate pulse. Figure 3 shows the MATLAB - Simulink implementation of hybrid wind/SPV system connected with grid.

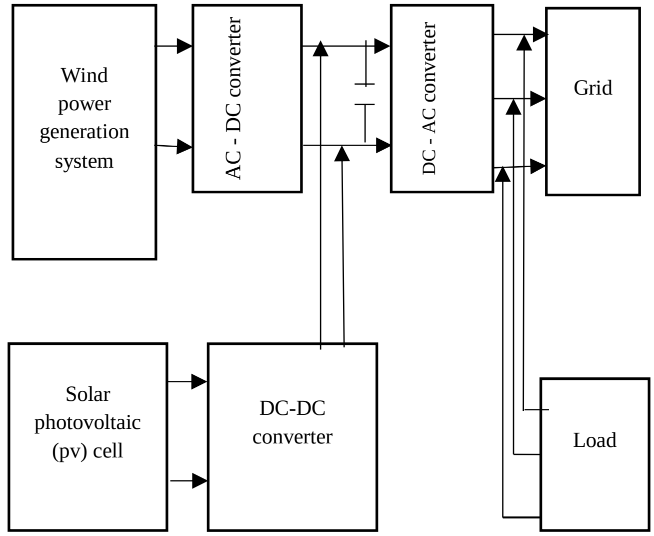


Figure 2: Diagram of Adopted Hybrid Connected System (Harini M *et al*, 2012).

III. Developed Approach

A basic PLL configuration is depicted in Figure 1. The phase voltages V_a, V_b and V_c are obtained from sampled phase voltages from the grid and inverter output terminal. These stationary reference frame voltages are then transformed to voltages V_d, V_q (in a frame of reference synchronized to the utility frequency) using $\alpha\beta$ and dq transformation (Ogren, 2011). The αβ transformation (Clarke transformation) allows to represent three phase system V_a, V_b and V_c as two phase V_α and V_β. The control in αβ frame has the feature of reducing the number of required control loops from three to two (Padua, 2005). However, the reference and feedback signals are in general sinusoidal functions of time. Therefore, to achieve a satisfactory performance and small steady state errors in magnitude and phase, the compensator design is not straight forward task (Ogren, 2011). The d-q frame based control offers a solution to this problem.

i. *Transfer Function*

Since the PLL to be developed will be working in a sampled system there is need to take into account the delay effect (Kaura and Blasko, 1997). The transfer function (TF) for the plant in Figure 1 is just a lag and an integrating element

$$G_P = \left(\frac{1}{1+ST}\right)\left(\frac{1}{s}\right) \quad (1)$$

The open-loop TF for the system in Figure 1 is described as follows

$$G_{ol} = \left(\mathrm{kp}\,\frac{1+S\tau}{S\tau}\right)\left(\frac{1}{1+ST}\right)\left(\frac{V_m}{S}\right) \quad (2)$$

The integrating element in the plant correspond to the following differential equation

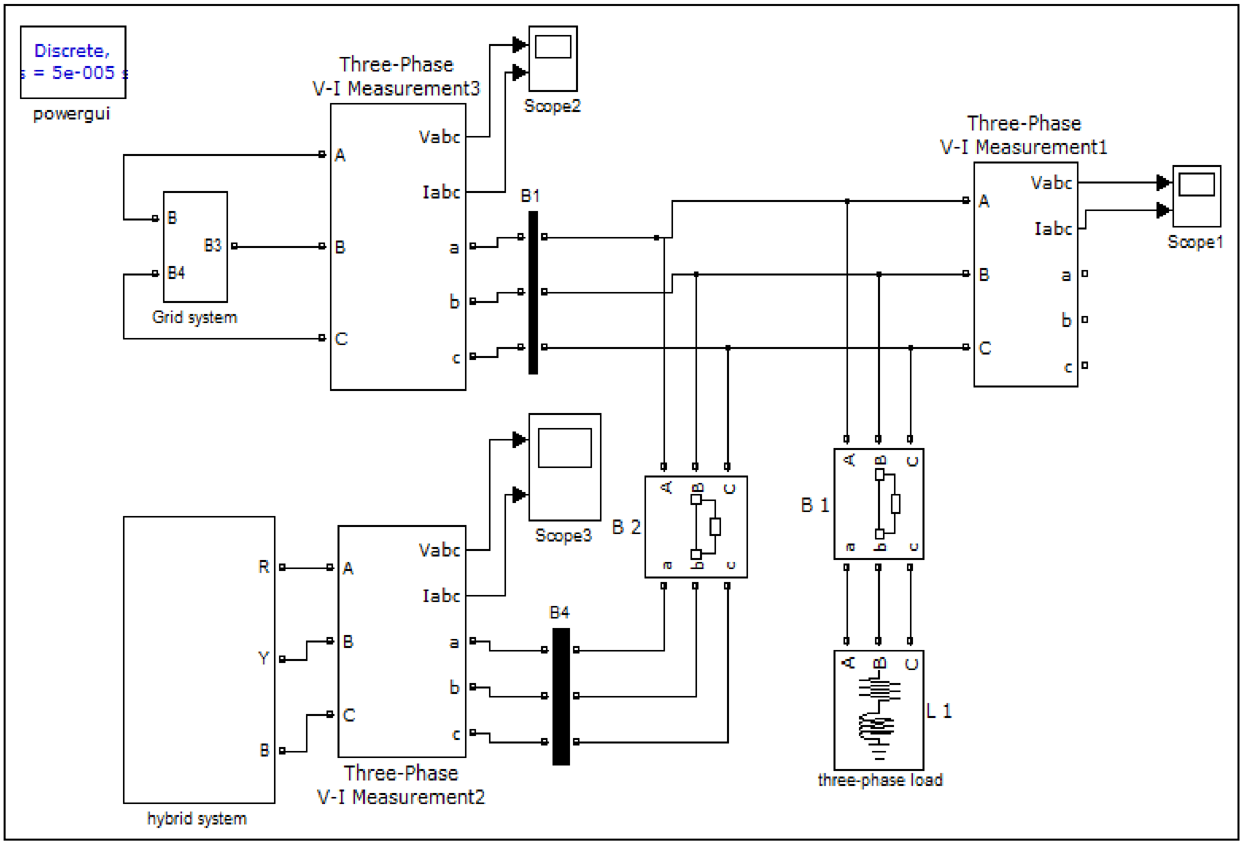


Figure 3: MATLAB-Simulink of hybrid wind/SPV system connected with grid

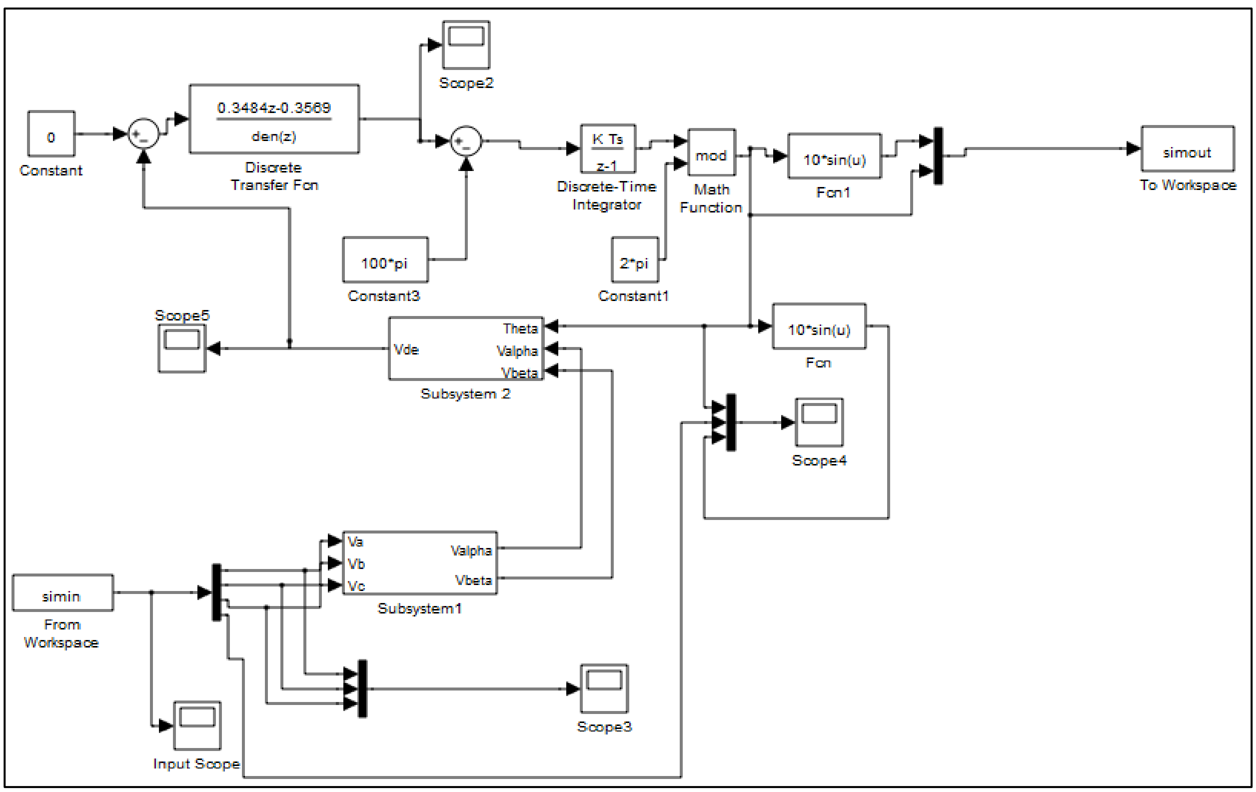


Figure 4: The Simulink Simulation Setup of the Phase Lock Loop System. The box named Discrete Transfer Fcn is the PI-regulator.

$$G(s) = \frac{F(S)}{E(S)} = \frac{1}{S} \Leftrightarrow \frac{df}{dt} = e(t) \quad (3)$$

Which has to be solved numerically using Euler forward (Kaura and Blasko, 1997), and taking the Z-transform gives

$$S = \frac{z-1}{T_s} \quad (4)$$

Using equation (5) the PI-regulator in the z-domain is expressed as follows

$$G_{pi} = kp\frac{1+s\tau}{s\tau} = Kp\frac{Z-1+\frac{T_s}{\tau}}{z-1} \quad (5)$$

Rewriting the TF for the PLL system in equation (2) yields

$$G_{ol} = \left(K_p\frac{1+s\tau}{s\tau}\right)\left(\frac{1}{1+sT}\right)\left(\frac{V_m}{s}\right) = \frac{K_p V_m\left(s+\frac{1}{\tau}\right)}{s^2\left(s+\frac{1}{T}\right)} = \frac{K_p V_m}{aT_s} * \frac{\left(as+\frac{a}{\tau}\right)}{S^2\left(s+\frac{1}{T}\right)} \quad (6)$$

Where;
G_p: transfer function of the entire system,
$\left(\frac{1}{1+ST}\right)$: Lag term of the system,
T: Sampling period in seconds,
$\left(\frac{1}{s}\right)$: Integrating element which depicts the voltage controlled oscillator.
G_{ol}: Open loop transfer function
V_m: Amplitude voltage level in volt and
K_p: Regulator gain

The second order transfer function structure of a dynamic system is written as;

$$F = \frac{\omega_0^2(Ks+\omega_o)}{s^2(s+k\omega_o)} \quad (7)$$

where a represent normalization factor and ωc is the crossover frequency which has the value of the grid and inverter output frequency. Comparing equation (6) and (7) gives the following identifications

$$\begin{cases} \omega_c = \frac{1}{aT} \\ \tau = a^2T \\ K = \frac{1}{aV_mT} \end{cases} \quad (8)$$

ii. System Characteristics

The inverter grid voltage is 1000V which is the value of the root mean square of the line-to-line voltage at the point of grid connection. The amplitude voltage level, V_m, is then calculated considering three phase voltage in a synchronous reference frame using $V_m = \frac{\sqrt{2}}{\sqrt{3}} * V_{rms}$ (Ogrin, 2011). Hence, $V_m = \frac{\sqrt{2}}{\sqrt{3}} * 1000 = 816$V,
T_s = 1/2000s = 0.5ms, choosing crossover frequency 50Hz and substituting the parameters for V_m and T_s in equation (8) yield:

$$\begin{cases} a = 6.3662 \\ \tau = 0.0203 \\ k_{p=}0.3484 \end{cases} \quad (9)$$

IV. Simulation of PLL with Designed Gains

With the PLL parameters set as$a = 6.3662, \tau = 0.0203, k_{p=}0.3484$, V = 816V, Ts = 1/2000s = 0.5ms and choosing crossover frequency 50Hz, the transfer function of the PI Regulator in equation (6) becomes

$$G_{pi} = Kp\frac{Z-1+\frac{T_s}{\tau}}{z-1} = \frac{0.3484z-0.3569}{z-1}. \quad (10)$$

The complete model description of the system with the PI regulator in MATLAB Simulink environment is implemented and shown in Figure 4. Based on the design, The PLL is developed for grid voltage of 1 kV rms and simulation of the entire system is done in Simulink.

V_{abc} is the sensed grid voltage which is transformed in to DC components using coordinate transformation *abc-dq* and the PLL gets locked by setting Vd* represented by the constant block to zero. The loop filter PI is a low pass filter represented by the Discrete-Transfer function block. It is used to suppress high frequency component and provide DC controlled signal to voltage controlled oscillator (VCO) which acts as an integrator represented by the discrete-Time integrator block. The output of the PI controller is the inverter output frequency that is integrated to obtain inverter phase angle θ. When the difference between grid phase angle and inverter phase angle is reduced to zero PLL becomes active which results in synchronously rotating voltages V_d = 0 and V_q gives magnitude of grid voltage.

V. Results And Discussions

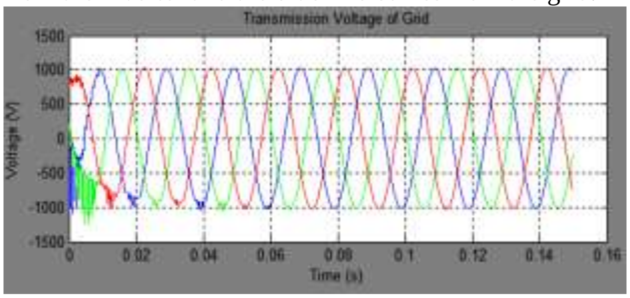
The model was simulated based on the following scenario:
Case 1: Model response under ideal grid condition.
Case 2: Model response under unideal grid condition.

Using Simulink based tools, the response of the developed model to the input cases are obtained in Figures 5, 6, 7, 8, 9, 10, 11, 12, 13 and 14.

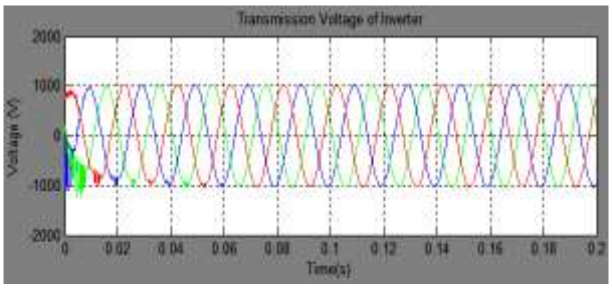
Case 1: Model Response under Ideal Grid Condition

The system performance is studied under an ideal condition when the root mean value of the line-to-line voltage is 1KV and the frequency of the inverter and grid are set at 50Hz. The three-phase voltages for the grid and the inverter system are shown in Figures 5 (a) and (b) respectively. Figure (5a) is the output voltage from the utility grid while figure (5b) is the output voltage of the renewable energy source comprising of wind and photovoltaic cell whose frequency and phase is supposed to be matched to that of the running network

For simulation, the required three phase voltage signals with controllable magnitude, phase and frequency as specified by the grid and inverter have been generated by writing their respective scripts in Matlab and imported using the Simin block. Based on the simulation, the output of PLL is in syn chronism with grid as shown in Figure 6. It can be observed that the PLL tie the grid and inverter phase voltages together, enabling them to operate in unison. The light green line comes from the inverter and the blue line comes from the grid.



(a)



(b)

Figure 5: Output Waveforms of (a) Grid (b) inverter Voltages

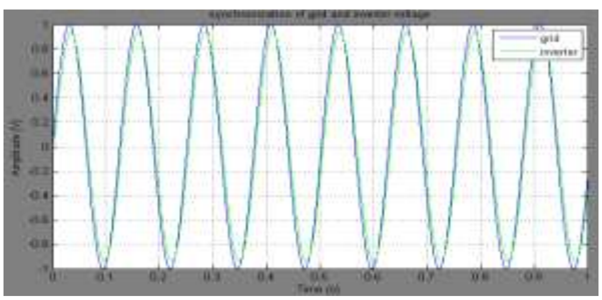


Figure 6: PLL Output with Grid Voltage (blue) Locked with the Hybrid Source Voltage Signal (light green).

Case 2: Model under Non-Ideal Grid Condition

The response of the grid to certain perturbations and the ability of the PLL to accommodate this disturbances will be shown. These perturbations and the PLL responses are described as follows;

i. Voltage Sag

Voltage sags or swells occur when large loads are suddenly connected to or disconnected from the grid. In this work, a sudden drop of voltage magnitude by 30% in all three phases was applied. The output when subjected to voltage sag is contained in Figure 7.

It can be observed that, the amplitude is varied in a way that after 2 periods, the amplitude decreased by 0.3 of the original value which indicates a voltage sag. The resulting PLL output in response to this sag is presented in Figure 8.

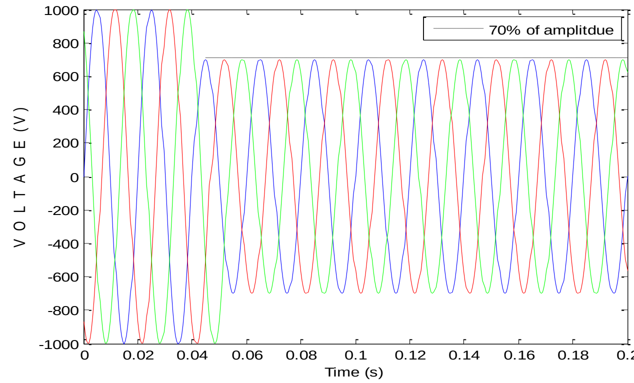


Figure 7: Input Voltage with Decreased Amplitude

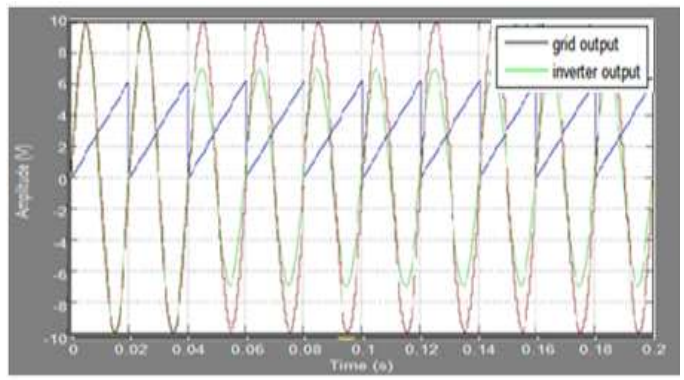


Figure 8: PLL Output for Input with Decreased Amplitude

It is observed that with the PLL already phase locked with the system, there was no change in d axis voltage and the q axis voltage accurately tracks the system voltage magnitude. So no disturbance was observed in phase tracking.

ii. Phase jump

Sudden phase change in load terminal voltage may occur if a large load is withdrawn from the supply system or due to faults in the grid. Figure 9, shows the grid response to phase jump. It is observed that the input signals making a phase jump was simultaneously applied to all three phases as presented in figure 9.

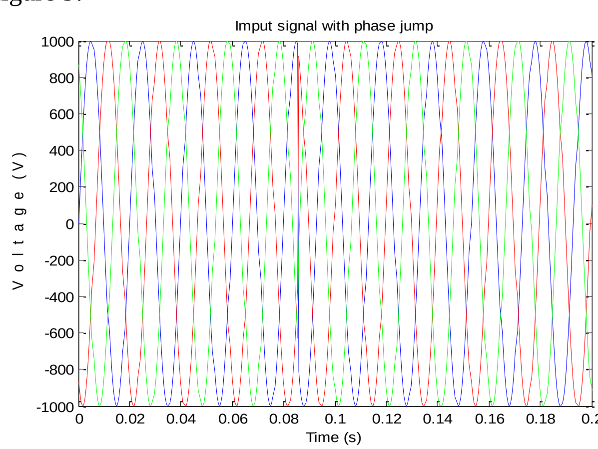


Figure 9: Input Voltage with Phase Jump

The PLL output for input signals making a phase jump simultaneously in all three phases is shown in Figure 10.

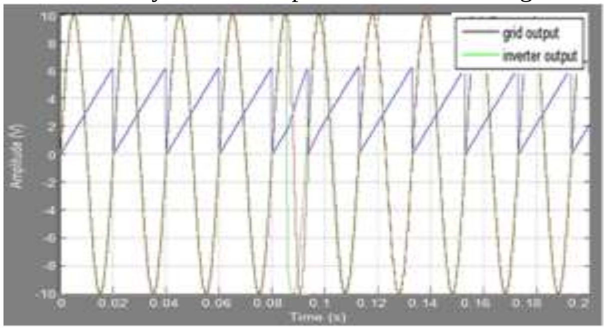


Figure 10: PLL Output for Input Signals with Phase Jump.

It can be observed that the phase jump occurs between the fourth and fifth cycle while the PLL synchronizes both phases together after the fifth cycle. The output of the PI regulator is presented in Figure 9.

The PI regulator output indicates that a phase jump occurs at about 0.085seconds and stopped at about 0.13 seconds for the input signal. An impulse response was observed simultaneously in all the three phases, the PLL was able to attained steady state within about 0.005 seconds.

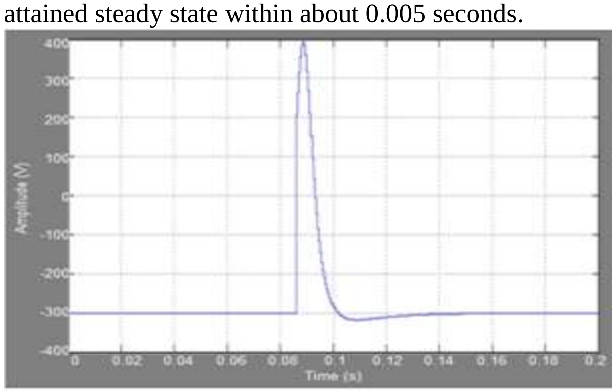


Figure 11: PI-Regulator Output from Scope2 for Input Signals making a Phase Jump.

iii. Voltage Sag

The PLL system when subjected to an Input signals with voltage unbalances between the three phases with an amplitude of V_b is 0.85*V, that of V_c is 1.15*V while that of V_a is unchanged. The performance of the PLL was analyzed under an unbalance condition as highlighted in Figure 12 and the response of the system was obtained as shown in Figures 13.

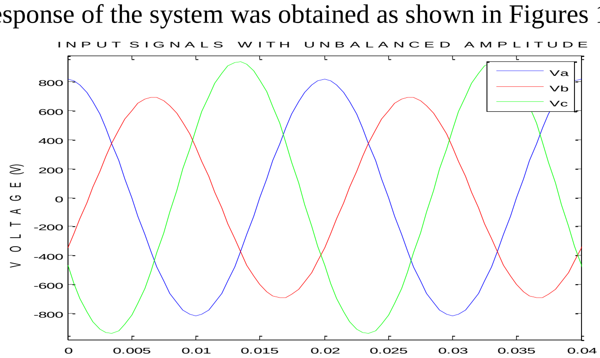


Figure 12: Three-Phase Unbalanced Voltages Input.

The PLL system was able to synchronize the grid and the hybrid system, in less than 0.02Sec, as shown in Figure 13.

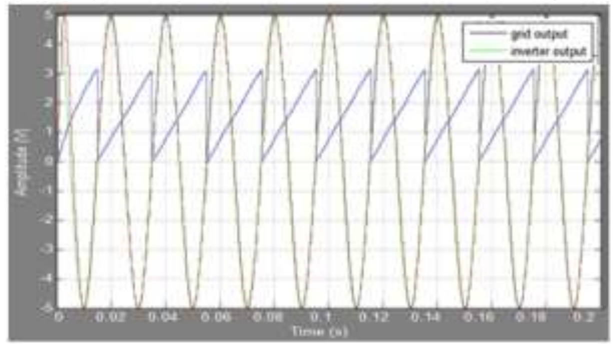


Figure 13: PLL Output for Input Signals with Unbalanced Voltages.

The observed impulse response of the system, the PI regulator output response to this disturbances is taken and presented in Figure 14.

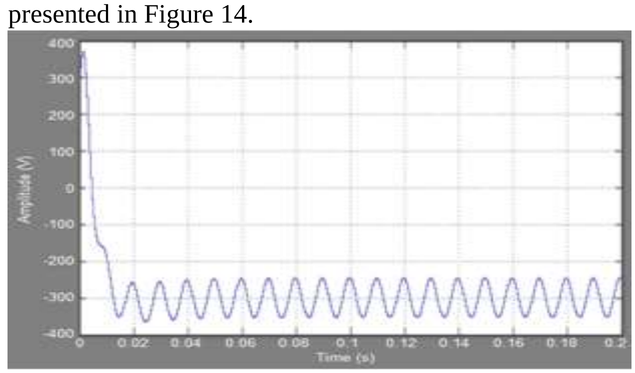


Figure 14: PI-Regulator Output with Three Phase Voltage Unbalance Input Signal.

It can be observed from figure 14 that the PI regulator changes to an impulse response within 0.01Sec, and attained an oscillatory state when subjected to voltage unbalance. Thus, leading to an inaccurate phase tracking.

VI. Conclusion

Design of a phase lock loop for synchronisation using MATLAB/ Simulink in order to track the phase angle of the grid and hybrid system has been successfully achieved. The PLL developed was able to synchronize the renewable energy source with the grid in the first cycle for the ideal and the non-ideal condition. The PLL system has less oscillations and high error rejection capability which is an indication of stability and better speed of response. The PI regulator gains designed using the symmetrical optimal method seems to work very well and the results indicates its ability to optimize the phase margin to have its maximum at a given crossover frequency.

VII. Recommendation

This study can be further enhance since the PLL offers better control and flexibility in synchronizing distributed energy sources and other renewable technologies. To further the course of this work for better performance analysis, it is recommended that a prototype of the system be implemented and tested with grid voltages as input signal. Also, more conditions such as flicker, dip and notch should be made for better performance analysis.

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