Study of Grid Synchronization Techniques

Project report submitted to
Visvesvaraya National Institute of Technology, Nagpur
in partial fulfillment of the requirements for the award of the degree

Bachelor of Technology
In
Electrical and Electronics Engineering

by

Aditya Deshmukh (BT17EEE006)
Abhishek Bhavsar (BT17EEE018)
Kalpit Jangid (BT17EEE036)
Ankit Kanojia (BT17EEE038)

under the guidance of

Dr. M.K.Khedkar

Department of Electrical and Electronics Engineering
Visvesvaraya National Institute of Technology
Nagpur 440 010 (India)

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Declaration

We, Aditya Deshmukh, Abhishek Bhavsar, Kalpit Jangid, Ankit Kanojia hereby declare that this project work titled “Study of Grid Synchronization Techniques” is carried out by us in the Department of Electrical and Electronics Engineering of Visvesvaraya National Institute of Technology, Nagpur. The work is original and has not been submitted earlier whole or in part for the award of any degree/diploma at this or any other Institution / University.

Date: 15th April, 2021

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Certificate

This is to certify that the project titled “Study of Grid Synchronization Techniques”, submitted by **Aditya Deshmukh, Abhishek Bhavsar, Kalpit Jangid, Ankit Kanojia** in partial fulfillment of the requirements for the award of the degree of **Bachelor of Technology in Electrical and Electronics Engineering**, VNIT Nagpur. The work is comprehensive, complete and fit for final evaluation.

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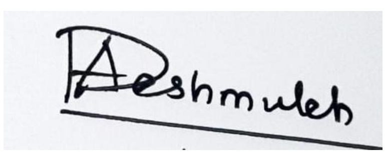

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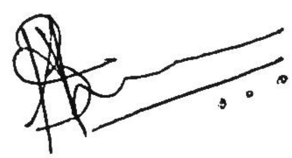

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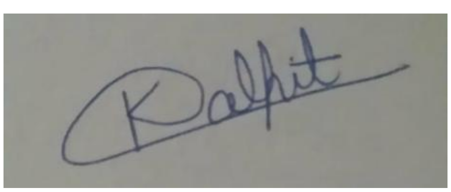

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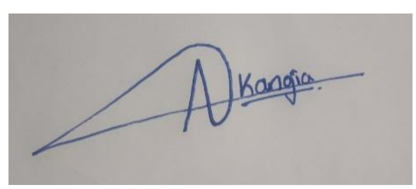

Ankit Kanojia

ABSTRACT

As of 31st December 2020, the national electric grid in India has an installed capacity of 375.32 GW. Of this total installed capacity, Renewable energy sources account for about 33%. With increasing penetration of Renewable energy sources in the current grid, the need of establishing an efficient control on the distributed power generating systems (DGs) becomes even higher.

When synchronizing the renewable resources into grid will faces various power quality problem like sag, swell, unbalance current, voltage flicker etc., instability of grid, frequency deviation. So, to overcome these problems, grid synchronization with controlling techniques is implemented. Therefore, grid synchronization techniques play a major part in keeping the grid stability.

The purpose of Grid Synchronization is to monitor, access, enable, and automatically take the control action to prevent the abnormalities of voltage and frequency by the minimization of difference in voltage, frequency and phase angle between the corresponding phases of the generator output and grid supply. The values of grid voltage frequency, amplitude and phase are necessary for carrying out grid synchronization.

Our project deals with the study of various grid synchronization techniques which can be used. Starting off with the conventional SRF-PLL method for grid synchronization, the study also includes other techniques based on ANF filter and DSOGI-PLL.

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CHAPTER 1

INTRODUCTION

In general practice, a grid system consists of a multitude of generating sources, transmission systems and loads. It is generally a very complicated network and requires a great deal of real time monitoring of circuit parameters to keep the entire system stable.

1.1) Grid

An electrical grid, is an interconnected network for delivering electricity from producers to consumers. It consists of generating stations that produce electric power, substations for stepping up voltage for transmission or stepping down for distribution. Increasingly, intelligence is being built into electric grids. Smart grid initiatives seek to improve operations, maintenance and planning by automating operations and ensuring that components of the grid can communicate with each other as required.However, for this project, we will be looking into the connection of 3-phase 2-level VSI with the grid.

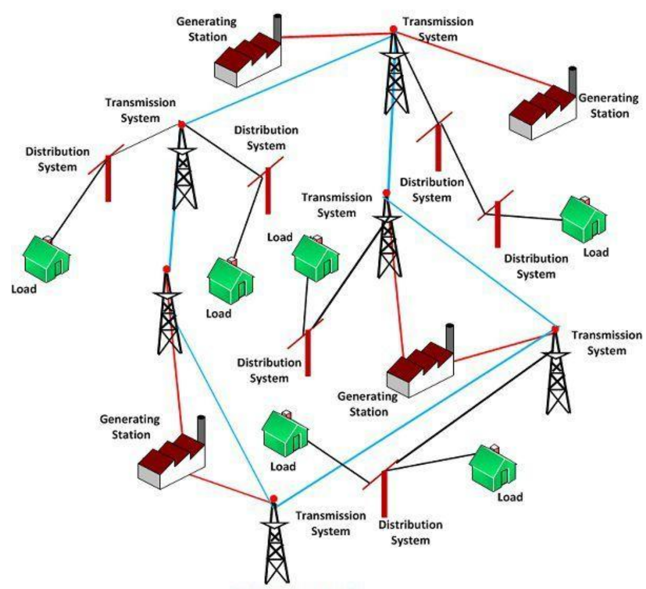

Fig 1.1. General Schematic of an Electric Grid

1.2) Grid Synchronization

The purpose of **synchronization** is to monitor, access, enable, and automatically take the control action to prevent the abnormalities of voltage and frequency by the minimization of difference in voltage, frequency and phase angle between the corresponding phases of the generator output and **grid** supply.

There are five conditions that must be met before the synchronization process takes place. The source (generator or sub-network) must have equal line voltage, frequency, phase sequence, phase angle, and waveform to that of the system to which it is being synchronized.

Waveform and phase sequence are fixed by the construction of the generator and its connections to the system. During installation of a generator, careful checks are made to ensure the generator terminals and all control wiring is correct so that the order of phases (phase sequence) matches the system.

Connecting a generator with the wrong phase sequence will result in a short circuit as the system voltages are opposite to those of the generator terminal voltages. The voltage, frequency and phase angle must be controlled each time a generator is to be connected to a grid.

Generating units for connection to a power grid have an inherent droop speed control that allows them to share load proportional to their rating. Some generator units, especially in isolated systems, operate with isochronous frequency control, maintaining constant system frequency independent of load.

1.3) Reason for Study of Synchronization

If a fault condition pops up in a certain part of the grid system, it has to be ensured that the affected part is isolated from the grid without hampering the power supply to the rest of the grid. Although, this is an interesting area to look into, our project mainly deals with how to get an isolated system back in tune with the grid so that maximum transfer of power can take place.

Another case where the synchronization study is required is the effect of dynamic loading on the grid network. In a practical system, loads can be variable. For example, in case of industrial load, it requires maximum power transmission during the daylight period and nightfall generally beckons the start of minimal power requirement period. This dynamic loading can cause the supply current to get out of phase with the supply voltage which leads to avoidable losses. So, it is necessary that there is a system in place to counter and solve this problem so as to minimize losses and increase efficiency.

CHAPTER 2

OVERVIEW OF METHODS OF GRID SYNCHRONIZATION

2.1) Methods of Grid Synchronization

2.1.1) Zero Crossing Detection

One of the simplest ways to obtain grid information such as phase angle is by detecting the zero-crossing point of the utility voltages. This method was reported as being robust to frequency variations and offering stable performance with only a small amount of distortion. However, during voltage variations such as sags, notches, and harmonics (which are regarded as power quality problems), the zero-crossing point is detectable only every half period of the utility voltage/frequency.

This is insufficient detection as the dynamic performance will degrade, being sensitive to transient, noise, and grid voltage distortions as it is. Besides, the method requires additional hardware, which increases costs, so is not preferred.

2.1.2) Kalman Filter

The Kalman filter is one of the signal processing techniques applied in frequency measurement of power system signals, providing an ideal estimation of the state variables of a given dynamic system. An extended complex Kalman filter for estimation of power system frequency and grid phase has been found to be stable and accurate even with noise present. Nonetheless, it has quite a complex structure and needs to cope with the burden of computation, and its performance under other disturbances is not well presented. The drawbacks render this method not very popular among the others.

2.1.3) Discrete Fourier transform

Another grid synchronization method is DFT, which actually is one of the first approaches to detecting harmonic and frequency. A recursive DFT was used for power converter line synchronization, to filter the incoming grid voltage. This method offers a high degree of invulnerability to noise, but when the time window of the DFT does not match with the grid period, a phase shift occurs between the incoming grid voltage and the filtered output. A sliding DFT (SDFT) is used to overcome this limitation. This method which is based on phase detection system has been found to be more efficient than conventional DFT as it requires less operation and simpler implementation to extract a single frequency component. As a result, computational complexity is reduced.

2.1.4) Nonlinear least-square

An alternative technique for frequency estimation is the least square-error method where the target is to minimize the square error between the modeled and the measured signal. However, the width of the observation window, the Taylor series truncation, and the choice of sampling frequency influence the performance of this algorithm. For the NLS algorithm, the common problem occurs during the estimation of the harmonic content of the periodic signals. Therefore, a tuned resonator-based filter bank was used to solve the NLS problem for periodic signal estimation.

It is a model-based recursive calculation method that guarantees smaller computational demand, less memory space as compared with matrix-based algorithms, and easy implementation. A new method of estimating grid frequency is based on multi-harmonic least-square fitting. This method expands a Taylor's series derivation to avoid the matrix inversion and recursive version in conventional approach. It estimates frequency well and computes well.

2.1.5) Adaptive Notch Filter

A synchronization method of ANF-based algorithm is gaining more attention for its simplicity. A second-order notch filter is used to update the frequency and two extra integrators replaced the voltage-controlled oscillator (VCO). Instead of a simple structure (no VCO), the modified technique offers higher immunity to noise compared with other conventional methods. The transient response is also faster than the PLL-based method, but some responses are not so accurate in some conditions.

A new adaptive notch filtering approach is composed of a master ANF and a multiplicity of slave ANF. This approach is not only able to detect phase angle, frequency, and amplitude in frequency variations but also current harmonic, and extract reactive components for power quality purposes. A modified lattice-based discrete-time ANF is used for a three-phase system. The proposed ANF is composed of simple adders, integrators, and multipliers, making it simple to implement and frequency adaptive. This method is able to track frequency and a voltage variation, extract harmonics, and is also insensitive to grid disturbances, harmonics, and other types of pollution that may exist in the power grid.

A frequency estimation technique based on ANF concept for three-phase power signals comprises a frequency estimation loop with three parallel sub-filters. This technique can precisely estimate the frequency not only in unbalanced condition but also under frequency and amplitude variation. Other features are its simple structure and lower sensitivity to harmonics. Besides its simple structure, AANF method performs better than ANF method in the former's filtering characteristics, with its allowance for a wide range of frequency deviations. AANF can also be used to detect symmetrical components, harmonics, active power, and reactive power. The estimation scheme was compared by analysis of four adaptive frequency trackers: ANF, adaptive estimation scheme, multiple frequency tracker, and hyper stable adaptive line enhancer. In some cases, the study shows the convergence of ANF to be a bit slower than the other methods. However, some issues of filtering characteristics and transient response had not been considered for a wide range of frequency deviations.

2.1.6) Artificial Intelligence

Over the past decade, AI tools such as artificial neural network (ANN) and fuzzy logic became more significant and more broadly applied in agriculture, identification, process control, military science, medical diagnostics, automation, etc. Bose equalized AI to imitating human thinking and leading a new, future era in machine drive, power electronics, and motion control. ANN tends to mimic the nervous system of a human brain, is very powerful in control applications, owing to its learning aptitude. The use of ANN to observe harmonics in a power system is not a new concept. ANN can be applied together with least-square technique to identify the deviations of phase, amplitude, frequency, and harmonics in power systems. Simulation results show that this method has very fast response, high convergence rate, and the capability to handle situations that present incomplete information.

A radial-basis-function neural network (RBFNN) which represents a function of interest using family members of locally supported basis function was applied to the performance curve. This feature makes RBFNN more suitable for learning functions with local variations and less sampled data. Instead of a simple structure, this method is reported as needing only half a cycle to detect all the harmonic components without sacrificing its computational efficiency.

2.1.7) Delayed signal cancellation

DSC is a technique initially used in an unbalanced grid voltage scenario. The components of positive and negative sequences of the grid voltage are separated according to the voltage vector in a stationary (αβ) reference frame and the voltage vector is delayed by a quarter of a cycle. A novel grid fundamental and harmonic component estimation technique for a single-phase application is based on anti-conjugate decomposition of single-phase signals and cascaded delayed signal cancellation (CDSC) which uses a constant zero as the quadrature signal. Use of this technique enables efficient detection of the grid fundamental and harmonic components with zero steady-state error and very short transients. It is also immune to small variations in frequency. Some of the weaknesses can be avoided without much effect on power quality.

A three-phase CDSC phaselocked loop (CDSC-PLL) can detect power system harmonic selectively and disregards small grid-frequency deviations. Another useful feature of CDSC-PLL is the capability to eliminate undesired harmonics completely with zero steady-state error and very short transient. Synchronization of RES through variable sampling frequency has been analyzed to investigate the influence of DSC in harmonic estimation and to examine the use of DSC in discrete time domain. Validation by experiment found that both non-ideal sampling frequency and time-varying grid frequency influence DSC performance. Besides, the use of weighted mean average value can reduce the estimated error and the error due to grid frequency variation, which appears the same as the error caused by non-ideal discretization.

2.1.8) Phase Locked Loops

PLL is the most acknowledged, owing to its simplicity, effectiveness, and robustness in various grid conditions. In fact, PLL is an old technology since its concept was published in 1932. It has been used in a vast range of applications such as control systems, communications, instrumentation, and many more.

It is a nonlinear closed loop feedback control system which synchronizes its output signal with the reference input signal in frequency and phase. A basic PLL structure comprises three main blocks, which are phase detector (PD), loop filter (LF) and VCO. First, the PD will compare the two input signals and the error signal will be filtered by LF which is then used to drive the VCO to generate output phase θ_0. This process will continue until the phase error $\Delta\theta$ between the output and the reference phase θ^* reduces to minimum value. Once the error is zero, the output phase will be locked.

Various modifications and enhancements have been made to improve PLL performance in various grid conditions such as synchronous reference frame PLL (SRF-PLL), enhanced PLL (EPLL), fixed-reference frame PLL (FRF-PLL), and variable sampling period filter PLL (VSPF-PLL). The difference among these usually lies in how the PD block is implemented.

2.1.9) Frequency Locked Loops

A new grid-synchronization technique for three-phase system uses frequency-locked loop (FLL) to estimate the frequency of the input signal (instead of estimating the phase angle as in many classical approaches). A good feature of this technique is that it is not influenced by phase-angle jumps. One of the methods is based on two adaptive filters implemented by means of a second-order generalized integrator (SOGI) on a stationary αβ reference frame that can self-tune to the grid frequency. This technique is known as dual SOGI FLL (DSOGI-FLL) and is capable of estimating the phase and magnitude of symmetrical components precisely even in the presence of voltage sag. It is also less sensitive to sudden changes in the voltage phase angle, making it a very suitable solution when resonant controllers are applied to control the current injected into the grid. On the other hand, the DSOGI-FLL can be used not only in synchronization but also to control the disconnection, reconnection, and resynchronization of the microgrid. It is implemented in the αβ stationary reference frame with an intelligent connection agent competent in handling balanced and unbalanced conditions. It also has less influence in the transient condition of the phase jump.

A multiresonant frequency adaptive synchronization method for both single-phase and three-phase system can also detect the positive-sequence and negative sequence components at fundamental frequency and other sequence components at harmonic frequencies. This method uses a harmonic decoupling network that consists of multiple SOGI and FLL, hence the name MSOGI-FLL. In extremely polluted conditions, MSOGI-FLL permits accurate, low-computational-burden detection of symmetrical components of harmonics. It can also easily be programmed into low-cost digital signal processing (DSP) platforms.

2.2) Comparison of Grid Synchronization Methods

Table 2.1 Comparison of Grid Synchronization Methods

Grid Synchronization Methods	1-ϕ	3-ϕ	Advantages	Disadvantages
ZCD	Y	Y	• Simplest implementation • Robust under frequency variations	• Poor performance under grid voltage variation such as harmonics or notches • Sensitive to transient and noise
Kalman Filter	Y	Y	• Accurate under frequency variations • Stable and accurate even in the presence of noise	• Difficulty in covariance selection • Computational burden • Not able to cope with unbalanced conditions
Discrete Fourier transform	N	Y	• Suitable for very distorted environments that require good filtering characteristics • Noise immunity	• Produce phase shift when the DFT sampling is asynchronous with power grid
Nonlinear least-square	Y	N	• Easy to implement • Low computational burden	• Long transient time intervals in detecting frequency changes.
Adaptive notch filter	Y	Y	• Simple implementation • Transient response is faster than PLL-based	• The adaptation process is inevitably slow

			• Can also detect symmetrical components, harmonics, active power and reactive power	
Delayed signal cancellation	Y	Y	• Stable	• Insensitive to small frequency variations
Phase-locked loop	Y	Y	• Simple implementation • Accurate synchronization • Better rejection of grid harmonics & notches	• Might have negative impact on the performance of VSC-HVDC in weak ac system • During unsymmetrical voltage faults, 2nd harmonic produced by negative sequence will propagates through PLL system and will be reflected in the θ'. • Introduce double frequency oscillation to the phase error signal
Frequency-locked Loop	N	Y	• Most sophisticated and reliable under frequency variations, voltage unbalance and harmonics.	• High computational burden

2.3) Challenges for Grid Synchronization

Synchronization is a key issue to grid-connected converters in enhancing their capability during interrupted operation in abnormal utility voltage conditions. In spite of the economics and governmental support for fast integration of RES, there are still several designs and technological challenges to be overcome for a smart synchronization method.

- In most of the grid synchronization methods, detection of the phase angle and frequency is done in the same loop in PLL. This causes spurious frequency transients when there is a change in the phase angle. This transient will reflect back on the phase variable and can delay the estimation and synchronization processes. The same is possible during the startup operation of the PLL if the initial phase angle of the input signals is far from the initial phase angle of the PLL integrator. Therefore, efficient methods for detection of phase angle and frequency variation, with good dynamic performance during voltage depression and harmonics, need to be developed.
- Grid frequency variable is known to be firmer than voltage phase angle in the course of transient faults. However, most of the synchronization schemes presented so far is still based on estimating the input signal phase whereas the dynamic response during transients is very sensitive to phase-angle jumps. A synchronization scheme based on estimation of the grid voltage and frequency should therefore be given more attention in future studies.
- In general, there is still a lack of reports or studies on the use of artificial intelligence in the synchronization of grid-connected power converters. Correspondingly, a study can be initiated for a hybrid of this method with other conventional methods and an evaluation of its performance in grid fundamental estimation.
- The methods proposed to date can detect grid variables, tolerate the tradeoff between tracking ability and noise reduction, and identify system disturbance. However, they still lack in triggering the corrective procedures automatically to maintain power quality. A robust method with advanced features such as expert systems has been identified as efficiently injecting power into the grid, with low total harmonic distortion (THD) of the current.

CHAPTER 3

SYNCHRONOUS REFERENCE FRAME PLL

A common structure for grid synchronization in three-phase systems is a phase locked loop implemented in the d-q synchronous reference frame. The structure of PLL consists of two major parts, the transformation module and the PLL controller. The transformation module has no dynamics. In fact, the PLL controller determines the system dynamics. Therefore, the bandwidth of the loop filter determines the filter's filtering performance and its time response. As a consequence, the loop filter parameters have a significant influence on the lock quality and the overall PLL dynamics.Several studies have shown that SRF-PLL is widely used in three-phase grid-connected power converters for its simple implementation and fast and accurate estimation of the phase/frequency in ideal grid conditions.However, the three-phase voltage vector in abc natural reference frame need to be transformed to dq rotating reference frame first through Park's transformation. Proportional Integrator (PI) is then used to control the q variables and the output of this PI is the grid frequency. The utility phase angle is obtained by integrating this grid frequency which is then fed back into the PD (αβ-dq transformation).

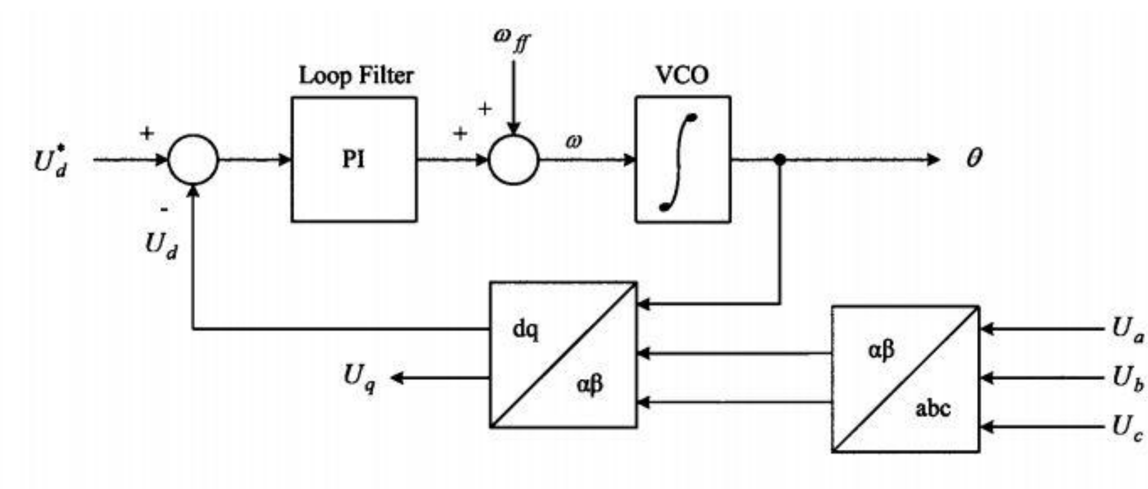

Fig 3.1 Basic dq-PLL structure

Conventional SRF-PLL allows fast and accurate estimation of phase angle and grid-voltage frequency in ideal condition. Unfortunately, during unbalanced grid voltage, frequency deviation, and in the presence of harmonic, the performance is highly degraded as it is very sensitive to immediate changes of phase angle (it has double frequency errors caused by negative sequence component).

3.1) Theoretical Concepts for SRF-PLL technique

3.1.1) Grid Connection Topology of 3-ϕ system

As a case study, let us take the example of grid connection of a PV module:

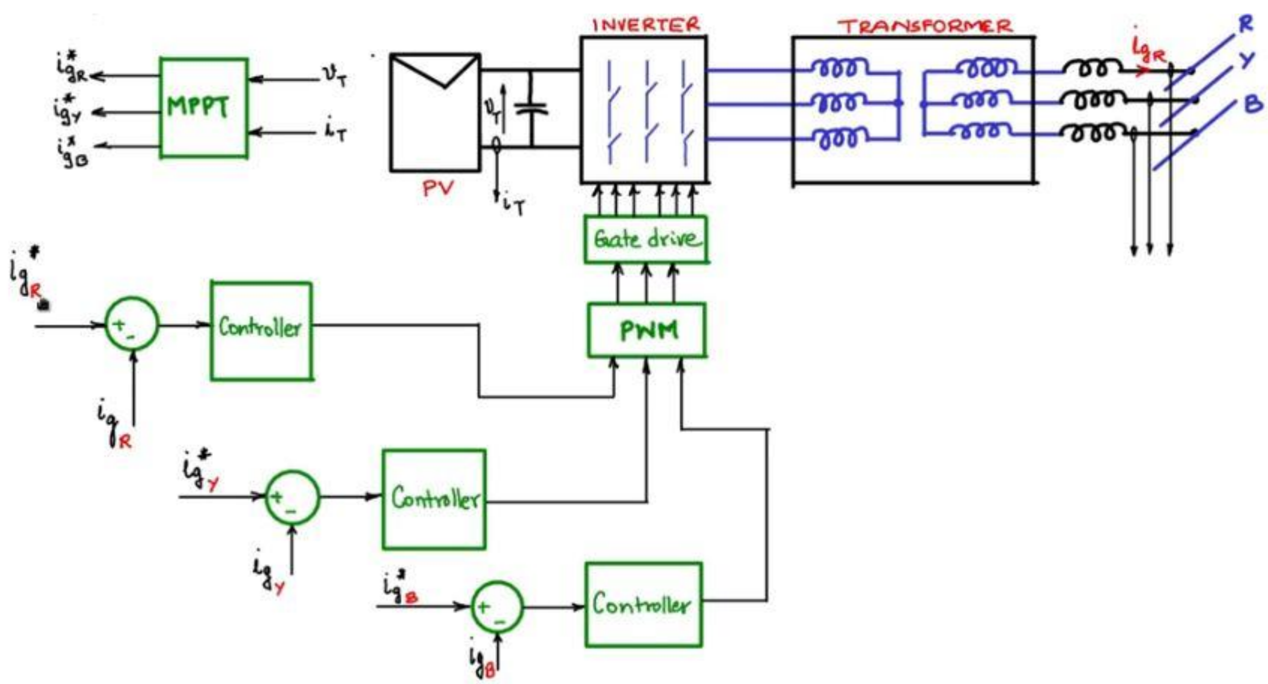

Fig 3.2. Example of Grid Connection for a three-phase system

- The 3-ϕ invertor output is connected to the primary of the transformer and the secondary is connected to RYB phases of the grid through inductors. The 3-ϕ invertor has 6 gate drives i.e. IGBTs and MOSFETs and they have to be driven by a gate drive circuit. The gate drive gets its control signal from a PWM block. The input to the PWM block will be the control signals coming from the PI/PID controllers.

- If suppose, we want to control the inductor currents, we sense the inductor current at each phase using a Hall sensor or using resistive shunts and differential amplifiers. We take a comparator block and input in the sensed current of each phase and the reference current for each phase. Thus, the outputs from 3 comparator blocks i.e. for each phase is then supplied to the PWM block.

- As for setting of reference current, we set up a MPPT block which will take the terminal voltage and current from the PV module and output the optimum peak reference currents which are then supplied to the comparator blocks. It is to be noted that the output of the MPPT module is a sinusoidal wave and not a DC signal.

- One of the drawbacks of this system is that since both inputs of the comparator are sinusoidal, it will become a tracking controller instead of a setpoint controller. The bandwidth in case of a tracking controller is significantly lower than that of a setpoint controller. Therefore, design will become more complex.

- Another drawback will be that due to presence of 3 comparator blocks and dynamic coupling of all three phases, the real time tuning of all three comparator blocks will become quite hard.

- In a 3-ϕ grid connection system, it would be ideal if the controller blocks are replaced with variables in the controller region as DC. All the signals in AC domain will be converted to DC signals by passing it through a frame transformation block.

- Therefore, to the controller, the variables will appear as DC and hence a setpoint controller can be made. This would give a much better response and the controller will be much simpler and will have a better bandwidth and performance.

To do the following, study of DQ-axis theory is required.

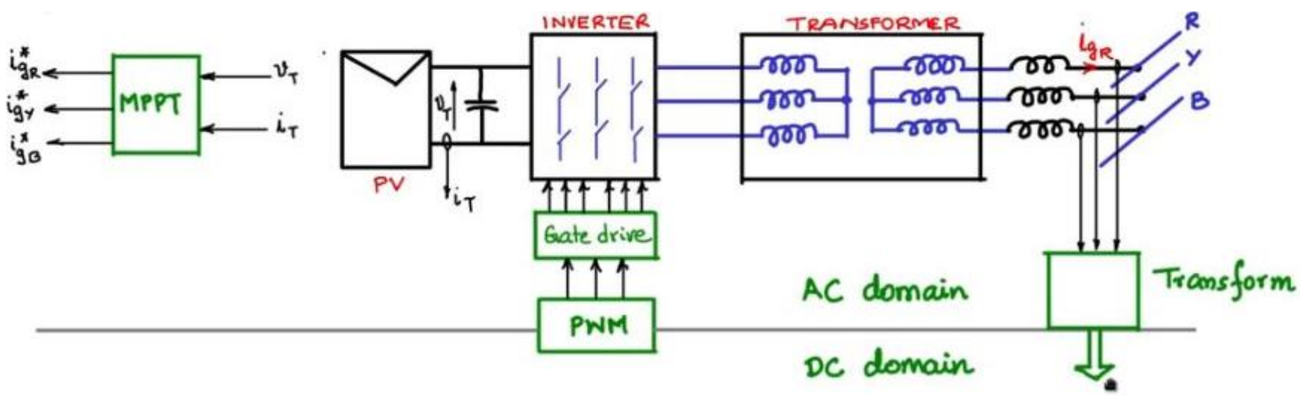

Fig 3.3. Block Diagram showing transformation of signals from AC to DC domain

3.1.2) DQ Axis Theory

The DQ transform is often used in the context of electrical engineering with three-phase circuits. The transform can be used to rotate the reference frames of AC waveforms such that they become DC signals. Simplified calculations can then be carried out on these DC quantities before performing the inverse transform to recover the actual three-phase AC results.

As an example, the DQZ transform is often used in order to simplify the analysis of three-phase synchronous machines or to simplify calculations for the control of three-phase inverters. In analysis of three-phase synchronous machines the transformation transfers three-phase stator and rotor quantities into a single rotating reference frame to eliminate the effect of time-varying inductances.

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}$$

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{bmatrix} \times \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix}$$

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\phi & \cos(\phi-\gamma) & \cos(\phi+\gamma) \\ -\sin\phi & -\sin(\phi-\gamma) & -\sin(\phi+\gamma) \end{bmatrix} \times \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}$$

where $\gamma = \frac{2\pi}{3}$ and ϕ = angle between the dq and $\alpha\beta$ reference frames

3.1.3) Grid Synchronization

One of the most important aspects to consider in the control of power converters connected to electrical grids is the proper synchronization with the three-phase utility voltages. This three-phase synchronization is not just a matter of multiplying by three the synchronization system used in single-phase applications, since the three phases of a three-phase system do not work autonomously but do it in a coordinated way, keeping particular relationships in terms of phase shifting and phase sequencing.

Therefore, the three-phase voltage should be understood as a vector consisting of three voltage components, which provides the capability of generating and consuming power in a three-phase system. Synchronization means the minimization of difference in voltage, frequency and phase angle between the corresponding phases of the generator output and grid supply.

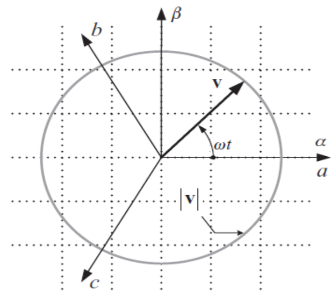

Fig 3.4. Conversion from abc to αβ domain

Park's Transformation:

$$V_{abc} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = V \begin{bmatrix} \cos(\omega t + \phi) \\ \cos(\omega t - \frac{2\pi}{3} + \phi) \\ \cos(\omega t + \frac{2\pi}{3} + \phi) \end{bmatrix}$$

$$|V| = \sqrt{v_a^2 + v_b^2 + v_c^2} = \sqrt{\frac{3}{2}}$$

A grid-connected power converter is particularly sensitive to voltage disturbances since its control system might lose controllability on the power signals under such distorted operating conditions, which could trip any of its protection systems or might even destroy the power converter.

Moreover, a power converter can interact with the grid at the point of common coupling in order to attenuate the voltage disturbances and reduce their undesirable effects. For these reasons, the voltage vector disturbances should be properly detected by the synchronization system, and the control system of the power converter should react to both ride-through such operating conditions and provide some support to the grid.

3.1.4) LCL Filter Design

- A filter is a circuit used to minimize the ripple content of a signal. Filters are used to reduce the harmonic content of a signal before passing it on to the load, to ensure maximum efficiency and prolonged life of the equipment. According to standard IEEE-1547 and IEEE-519, the Total Harmonic Distortion (THD) of the voltage input to any device should be lower than 5%. Thus, a filter is necessary to reduce the harmonic content of the input voltage after the inverter.
- A filter consists of components like inductor and capacitor whose resistance depends on the frequency of the signal passing through it. Harmonics are basically the frequency multiples of the fundamental frequency and are the unwanted components. Thus, an inductor is connected in series tuned to provide a higher resistance path to higher frequency component in the current, while a capacitor connected in parallel help to remove the higher frequency components in the voltage.
- LCL Filter: This is a third order filter and provides a very high attenuation of -60dB/decade. It is the most efficient and cost-effective filter, since it requires smaller values of L which reduces the size and cost compared to the same performance for an LC filter.

Calculations:

- Converting the following circuit into s-domain, and applying KVL we have:

$$\frac{Vi+Vx}{sL1} = Ig + \frac{Vx}{\frac{1}{sC}} \qquad \text{------ (1)}$$

$$Vx - Vo = Ig\, sL2 \qquad \text{------ (2)}$$

- Solving both equations, we have the following relation,

$$\frac{Ig}{Vi} = \frac{1}{s^3 L1L2C + s(L1 + L2)}$$

- Let $L_1 + L_2 = L$ and $L_p = \frac{L1.L2}{L1+L2}$ Resonant Frequency = $\frac{1}{\sqrt{CLp}}$

Therefore, the final transfer function is:

$$\frac{Ig}{Vi} = \frac{1}{sL(1+s^2CL)}$$

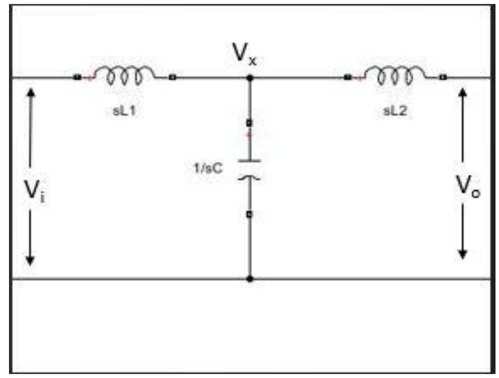

Fig 3.5 LCL Filter

- Selection of switching frequency: f_{sw} = 10 kHz
- Selection of resonant frequency: $f_{Res} = \frac{fsw}{10} = 1000\ Hz$
- Calculation of Capacitance:

  Reactive Power = 5% of Rated Power

$$\frac{V^2}{\frac{1}{\omega C}} = 5\% \ \times 100\ KVA$$

$$C = 100.28\ \mu F$$

- Calculation of Inductance:

$$V_L = 20\% \text{ of } V_{grid}$$

$$I_g = \frac{100}{230\times 3} \times 1000 = 144.92\ A$$

$$L = \frac{0.2 \times Vgrid}{\omega \times Ig} = \frac{0.2 \times 230}{2\pi \times 50 \times 144.92} = 1 \ \times \ 10^{-3}\ H$$

$$L_1 = L_2 = \frac{L}{2} = 500\ \mu H$$

3.2) Simulation of MATLAB circuit

3.2.1) MATLAB model of connection of Inverter to the Grid

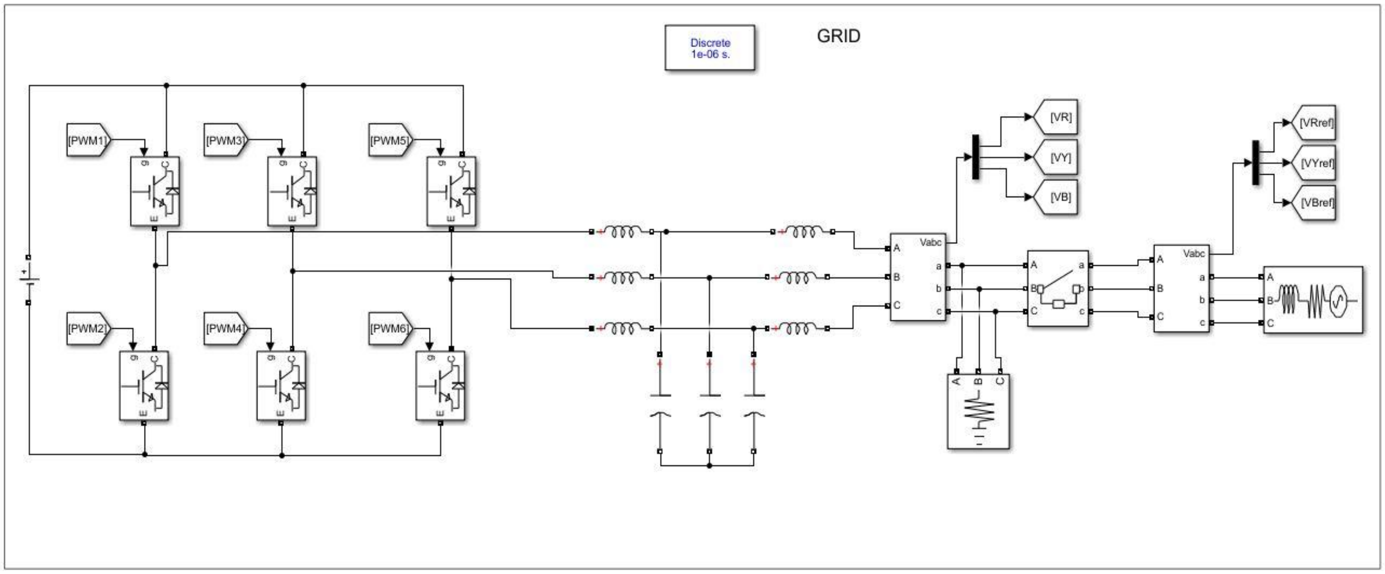

Fig 3.6 MATLAB Simulink model of grid connection of inverter to grid

The entire circuit can be divided into four components:

- Grid Connection of Inverter
- DQ Transformations
- PLL block
- Generation of Correction signals and Gate pulses to be supplied to the inverter.

Grid is connected to VSI. We have a 600V DC power supply which is connected to an IGBT bridge inverter circuit. The Gate pulses for the IGBTs were provided by the correction and Gate pulse generator circuit. Output of the Inverter is connected to LCL filter. We are using LCL filter because of its superior filtering performance. In the absence of a filter, the generated current contains harmonics. When we inject such current into the grid, it will deteriorate the grid voltage which will then cause power quality Issues. Therefore, we always use a filter at inverter output, so as to get a smooth sinusoidal current with less harmonics. The output of the LCL filter is connected to the V-I measurement block, such that it will be used further in correction circuit.

In between grid and inverter, a circuit breaker is connected. Initially circuit breaker is open, at t = 0.25seconds the circuit breaker is closed and the grid is connected with the inverter through a LCL filter.On the Grid side, from the V-I measurement block we get three voltages for each phase, which are termed as V_{Rref}, V_{Yref} and V_{Bref}. Similarly, on the inverter side we have V_R, V_Y and V_B.

3.2.2) DQ transformation and PLL blocks

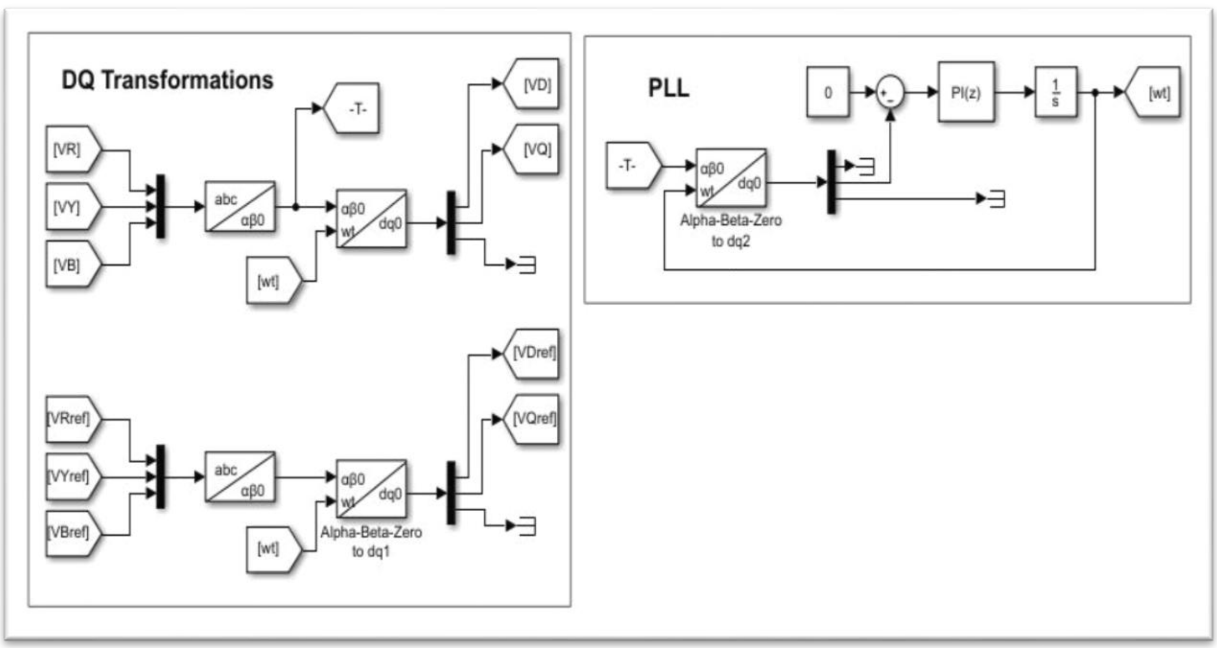

Fig 3.7 MATLAB Simulink model of DQ transformations and PLL block.

Afterwards, Inverter output and Grid voltages are passed through the abc to αβ transformation block i.e. the signals are passed through Clarke's transformation. The generated αβ vector is then passed to the PLL block which is used to calculate the ωt value.

The generated αβ vector then undergoes a Park's transformation and the corresponding *dq* domain signals are forwarded to the correction circuit.

3.2.3) Correction and Generation of Pulses

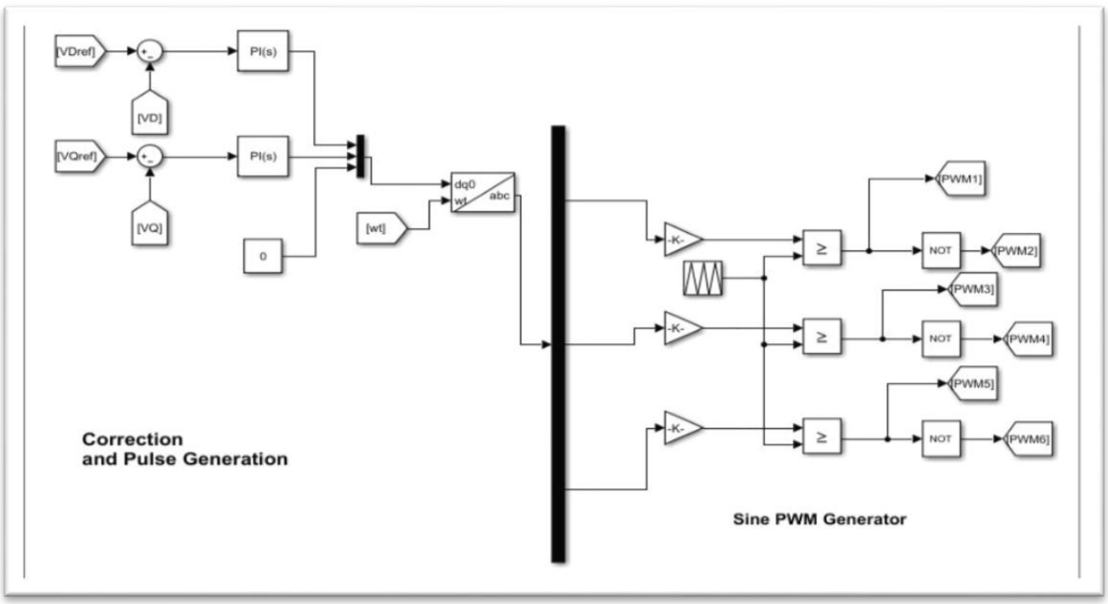

Fig 3.8 MATLAB Simulink model of Correction and PWM generation blocks.

The error signals generated as the difference of the two dq domain signals are passed through a PI controller which then undergo a dq to abc domain transformation i.e., a reverse Park's transformation followed by a reverse Clarke's transformation. The generated signals are then passed through a SPWM circuit to generate the gate pulses required to drive the inverter.

3.3) Simulation Results

3.3.1) Inverter Voltage Output

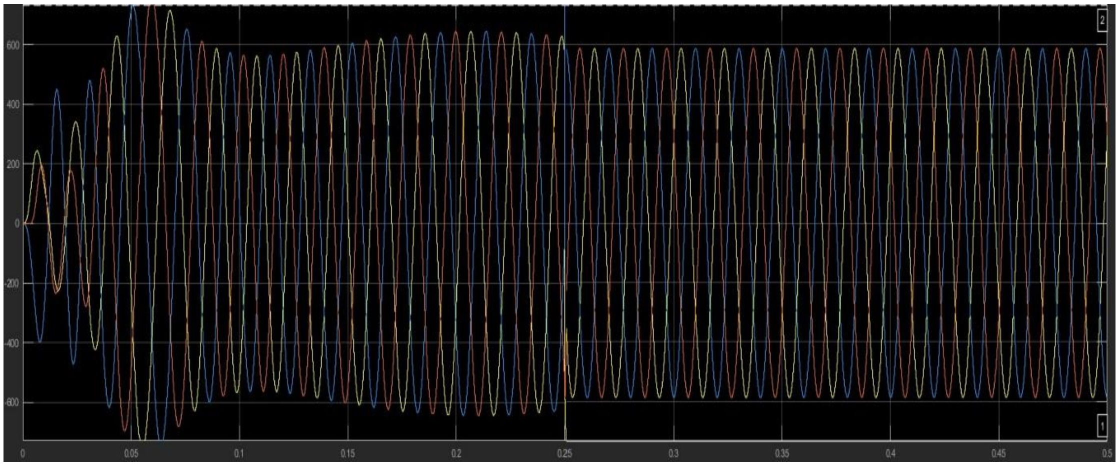

Fig 3.9 Inverter Voltage output over a simulation period of 0.5 sec.

Initially the inverter and the grid are not connected. So, the output of the inverter can be observed. At t = 0.25 seconds the grid was connected with the inverter. Hence, synchronization of inverter with grid was successful as observed from the waveform after t=0.25 seconds.

3.3.2) Frequency and Phase Angle Variation

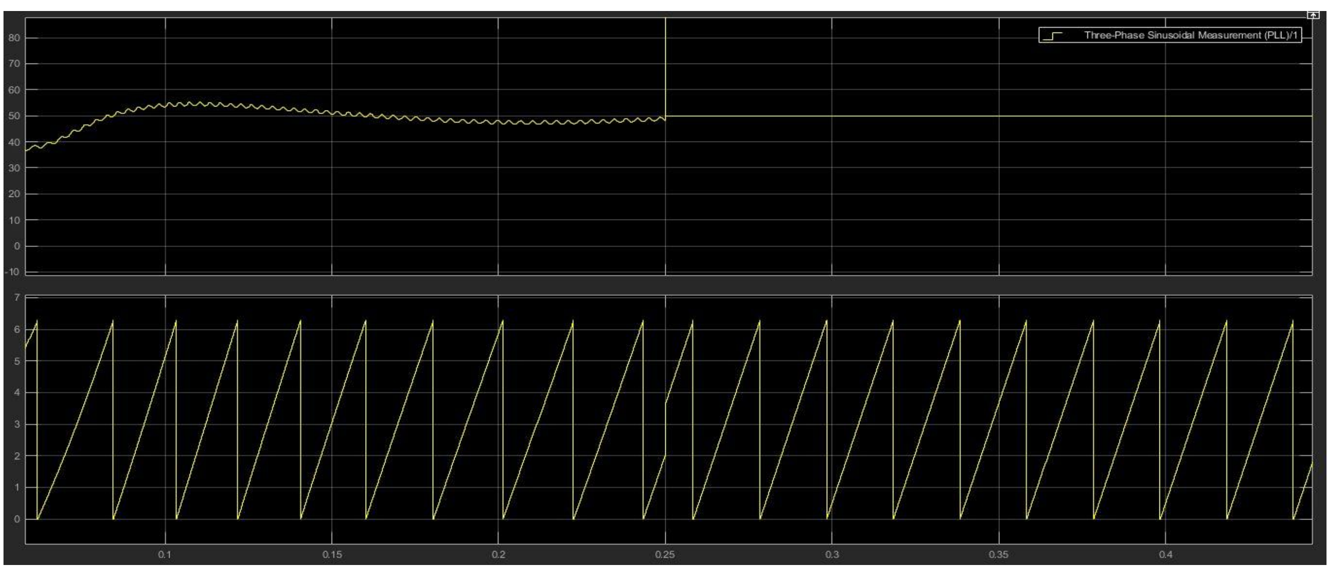

Fig 3.10 Frequency and phase angle variation before and after the Synchronization

Frequency and phase angle variation was observed before and after the Synchronization takes place. We found that after synchronization our frequency of the output of the inverter is constant at 50Hz. Synchronization Time is the time required for completing the process of synchronization after inverter and the grid are interconnected. It was found to be 958.581 nano seconds.

3.3.3) Synchronization Time

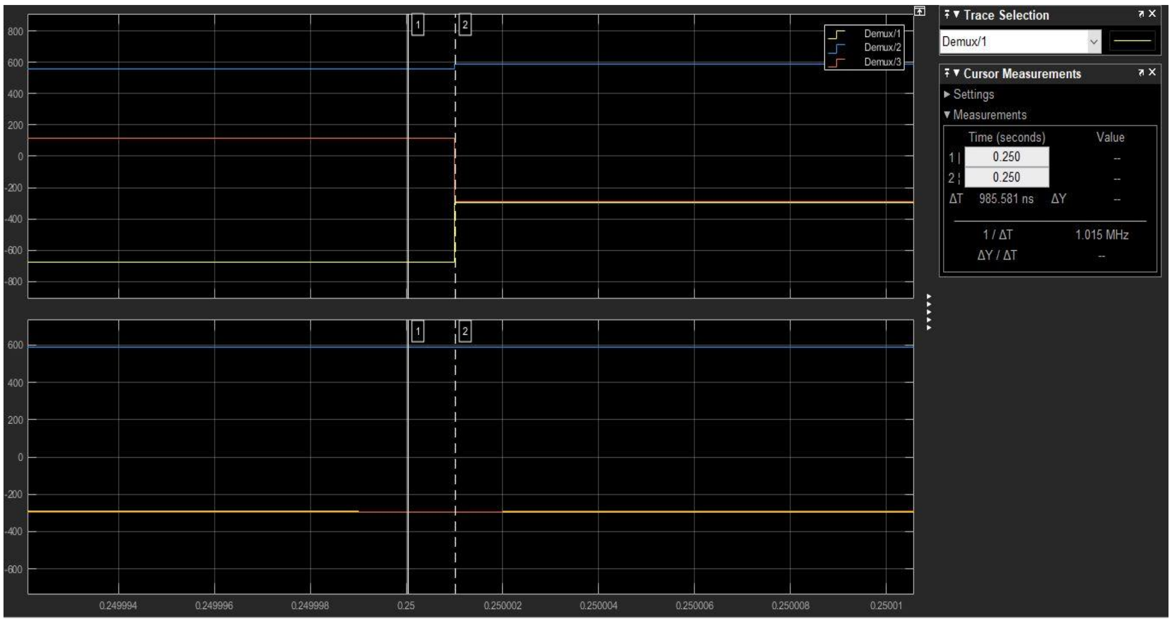

Fig 3.11 Calculation of Synchronization Time.

3.3.4) Gate pulses supplied to the inverter

The output from the correction and the gate pulse generation circuit was also observed.

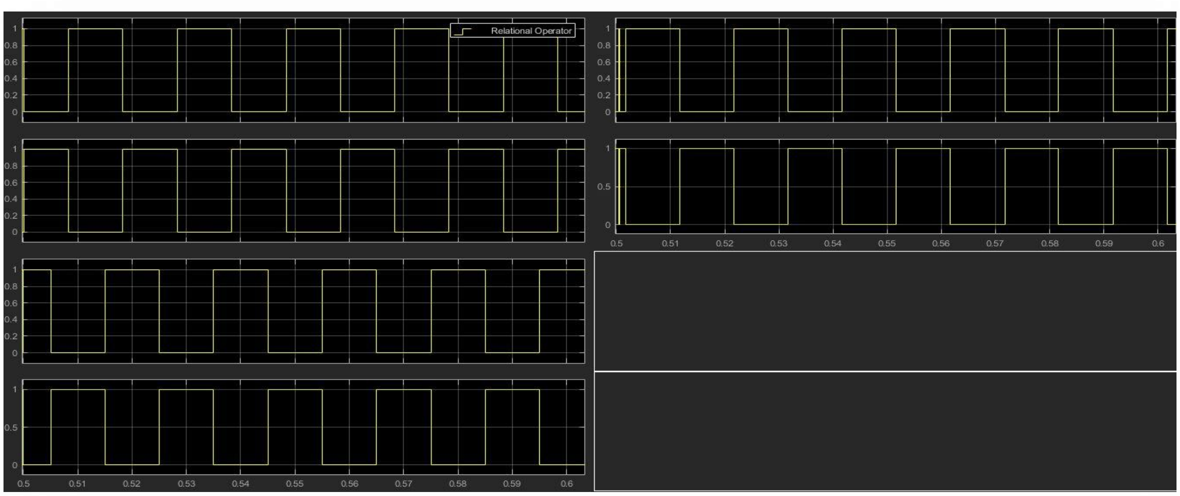

Fig 3.12 Gate pulses supplied to inverter

3.4) Adaptations of the SRF-PLL method

3.4.1) LSRF-PLL method

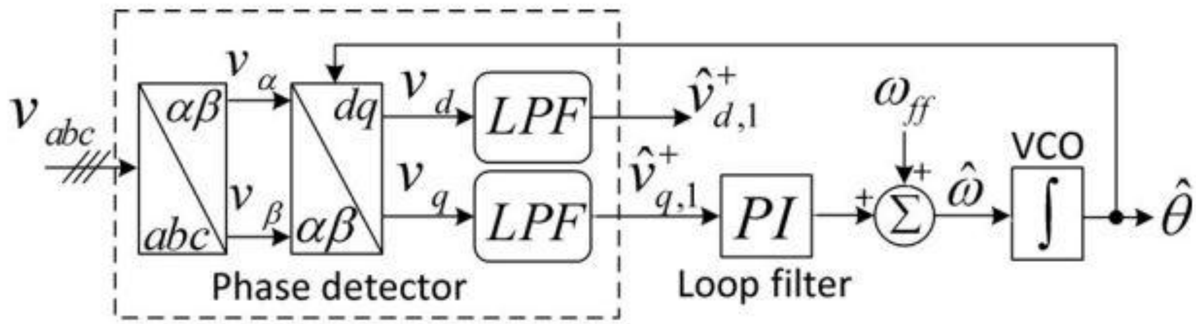

Fig 3.13. Basic scheme of LSRF-PLL

Fig. 2 illustrates the basic scheme of the LSRF-PLL, in which:

- $\hat{\theta}$ is the estimated angle
- $\hat{\omega}$ is the estimated frequency
- v_{abc} is the three-phase input voltage system
- ω_{ff} is the nominal frequency

The mean value of v_d gives an estimation of the amplitude of fundamental positive-sequence component, and the mean value of v_q gives information about the phase estimation error. This information may be extracted by passing v_d and v_q through the LPF.

To minimize the phase error φ_e and further attenuate the disturbance components, $\hat{v}_{q,1}{}^{+}$ is passed through the LF (here, a proportional-integral (PI) controller). The nominal frequency (i.e., ω_{ff}) is then added to the LF output signal, to reduce the control effort and expedite the initial lock-in process. The resulting signal (i.e., $\hat{\omega}$) is integrated afterward to generate the estimated angle $\hat{\theta}$.

Under the frequency-locked condition, the fundamental negative-sequence component of the input voltage appears as a disturbance input to the PLL linearized model, pulsating at twice the input voltage fundamental frequency [see (9)]. In the same way, the input voltage harmonics, which dominantly are non-triplen odd harmonics (e.g., $5th^{-}$, $7th^{+}$, $11th^{-}$, $13th^{+}$, etc.), are sensed by the linearized model as even harmonic components (i.e., $6th^{\pm}$, $12th^{\pm}$, etc.).

3.4.2) DSRF-PLL method

Dual Synchronous Reference Frame PLL (DSRF PLL) is a combination of two conventional SRF PLLs which are separated by a synthesis circuit. This PLL decomposes the voltage vector v into its positive and negative sequence vectors (v_+ and v_- respectively).

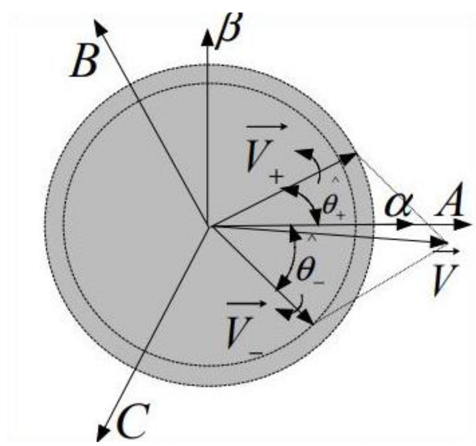

Fig 3.14. Voltage vector decomposition (Unbalanced voltage)

The two frames rotate in positive direction and negative direction respectively and detect the corresponding phase angle simultaneously. The d-axis component from the Park's transformation, which is the voltage amplitude in steady state, is fed to the synthesis circuit. The synthesis circuit, as shown in Fig. 3 is used to create decoupling signals. These decoupling signals are used as feedback. In rotating reference frame, the inputs to the two Park's transformation blocks give the output for positive sequence.

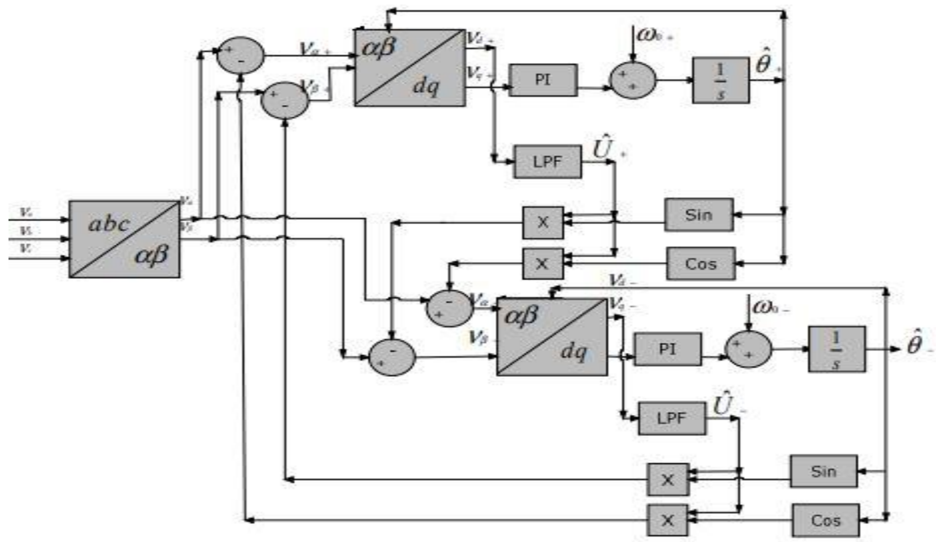

Fig 3.15. DSRF-PLL Structure

There are some 2ω ripples in the d-axis component which is attenuated by using a low pass filter. The decoupling of signals by the synthesis circuit begins when the input to each PLL achieves its steady state.

DSRF PLL detects the phase angle by decoupling the positive and negative sequence components and tracking the corresponding phase angles.

The DSRF-PLL model the positive and negative sequences are independent to each other. Further, the transient response of SOGI based PLL during grid abnormalities is better than DSRF PLL, even though both the PLLs can detect the phase angles accurately. However, the phase angle detection of the two sequence components is more accurate as in the case of SOGI PLL due to less harmonic oscillations during the steady state and transient conditions. This is due to the fact that, the estimated phase (*sin(wt) and cos(wt)*) by SOGI based PLL is perfectly sinusoidal and it takes less computation time at the time of real-time implementation in DSP or FPGA environment.

3.4.3) 3-ɸ EPLL based system.

The major improvement introduced by the EPLL is in the PD mechanism, which is replaced by a new strategy allowing more flexibility and provides more information such as amplitude and phase angle. An alternative phase-locked loop was reported, which provides the dominant frequency component of the input signal. The mechanism of this EPLL is based on estimating in-phase and quadrature-phase amplitudes of the desired signal, hence, has potential application in communication systems which employ quadrature modulation techniques.

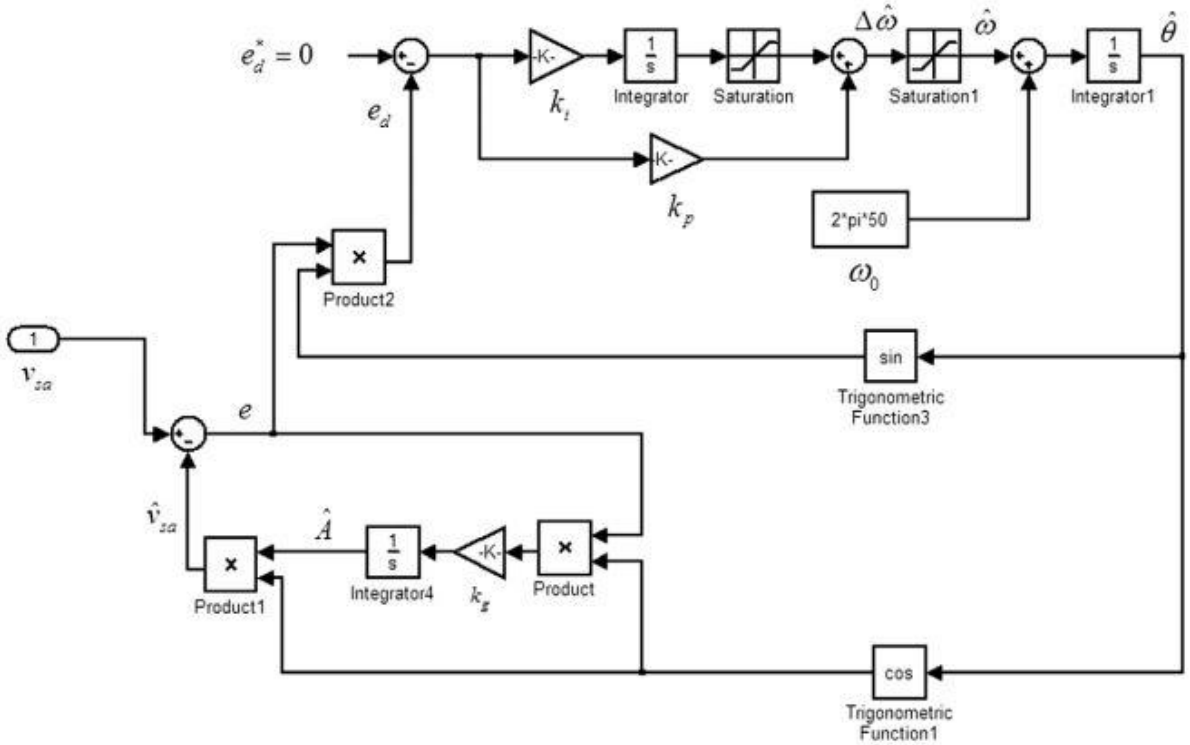

Fig 3.16. EPLL block model.

The MATLAB/Simulink diagram of this EPLL is shown in Fig. 3.15. It can be observed that there are three gains, denoted as k_g, k_p and k_i, which are selected to control the convergence speed for the amplitude, phase and frequency of the fundamental component of the input signal. The guideline for the selection of these gains, however, is not that trivial.

The control loop interaction exists since the amplitude, phase and frequency estimation are competing with each other, if any of these gains is varied, it would affect the performance and stability of the closed-loop algorithm. Generally, the gain for the frequency estimation (k_i) should be very small to ensure stability. However, it would result in slow dynamic performance under frequency deviation in the grid voltage.

If the frequency estimation is disabled by setting k_i to be zero, steady-state error may appear or the algorithm may even diverge under large deviations in the input. Therefore, this EPLL scheme is difficult to be practically implemented, especially for the grid-connected converters which has demanding requirements for tracking accuracy, stability and reliability of the synchronization algorithm.

The EPLL method can be implemented for 3-ϕ systems by using an EPLL block for each phase and tracking each phase individually.

CHAPTER 4

STUDY OF DSOGI-PLL BASED SYNCHRONISATION METHOD

A pair of signals can be defined as orthogonal signals when there is a phase difference of 90˚ between the two signals and the said signals should be continuous and magnitude and frequency should be same. There are many methods for generating the orthogonal signal for a given signal. By delaying the given signal for 90˚ also we can get orthogonal signal but it will affect the performance of the system and by using the Hilbert transform also orthogonal signals can be generated but there is a introducing of the error.

For generation of the orthogonal signal, a Second Order Generalized Integrator (SOGI) is the better replacement of Clarke's transform because it has a high capacity of harmonic rejection reason being it can perform current controller duty and also sequence components also can be detected easily.

By using SOGI based OSG the characteristics which can be avoided are high sensitivity to offset, high complexity so that chance of getting good dynamic performance and less sensitiveness to frequency variations can be achieved and it can be implemented very easily when compared to other OSG techniques. It is a most advanced method resulting from adaptive Kalman filtering theory.

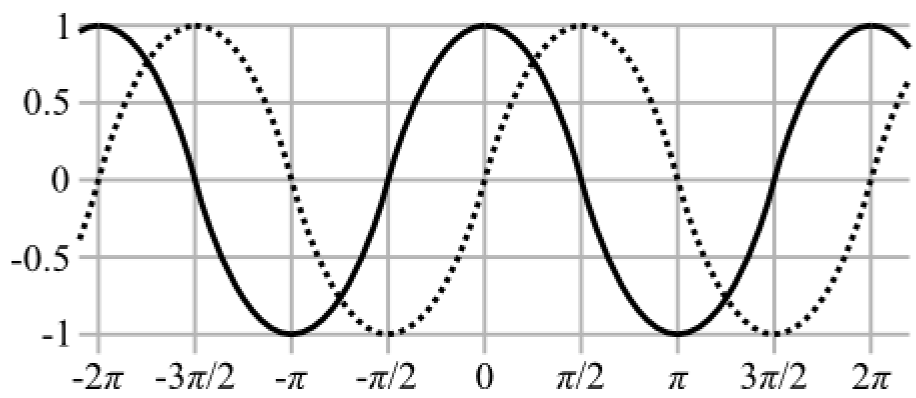

Fig 4.1. Examples of Orthogonal signals

4.1) Theoretical Concepts required for SOGI-PLL method

4.1.1) SOGI based Orthogonal Signal Generator

In a two-phase system for sequence component, the quadrature signal takes an important role. By using SOGI-OSG, it generates quadrature signal but also acts as a frequency adaptive band pass filter, an integrator and also a small change in SOGI helps to find the frequency.

Hence DSOGI PLL is preferred for grid synchronization because it will give better performance. Because of its selective nature of SOGI OSG it can suppress the utility voltage signal harmonic content.

The SOGI OSG is used to generate orthogonal signal of a given signal (V', qV') having a phase shift of $\frac{\pi}{2}$ and V' has the same amplitude and phase as the fundamental of the applied voltage signal and it is relatively simple to implement.

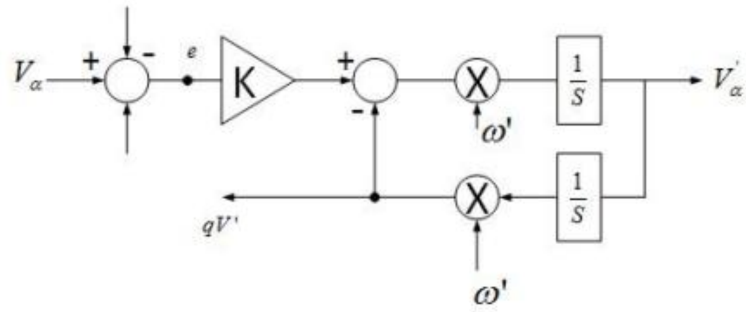

Fig 4.2 Block Diagram of SOGI-OSG

The transfer function of the SOGI is given by

$$\frac{qv'(s)}{V} = \frac{k\omega'^2}{s^2 + k\omega' s + \omega'^2}$$

$$\frac{V'(S)}{V} = \frac{k\omega' S}{S^2 + k\omega' S + \omega'^2}$$

where

ω' : undamped natural frequency of the SOGI it is equal to the estimated grid frequency.

k : gain of the SOGI band pass filter and it will affect the bandwidth of the SOGI.

The time response of the OSG-SOGI for a given sinusoidal input signal $V = Vsin(\omega t + \emptyset)$ is given by

$$V' = -\frac{V}{\lambda}\sin(\lambda\omega t)e^{\frac{kw'}{2}t} + V\sin(\omega t)$$

$$q_V' = V[\cos(\lambda\omega t) + \frac{k}{2\lambda}\sin(\lambda\omega t)]e^{\frac{k\omega'}{2}t} - V\cos(\omega t)$$

Here $\lambda = \frac{\sqrt{(4-k^2}}{2}$ and k < 2

$$t_s(SOGI) = \frac{10}{k\omega'}$$

where $V'\,and\,qV'$ are the outputs of SOGI OSG i.e., generated orthogonal signals respectively for single phase system.

It can be understood the settling time of the SOGI-OSG depends upon the gain of the system and it is inversely proportional. In order to meet above specifications and less settling time the value of gain is selected as k=1.414.

4.1.2) DSOGI block

For a two-phase system, in order to calculate sequence components, a quadrature element and in-phase elements are needed. Here 2 SOGIs are used to perform this duty, by using frequency locked loop to extract feed forward frequency (ω_{ff}).

The in-phase component and quadrature component of input signal are useful for finding the positive and negative sequence components of unbalanced input supply.

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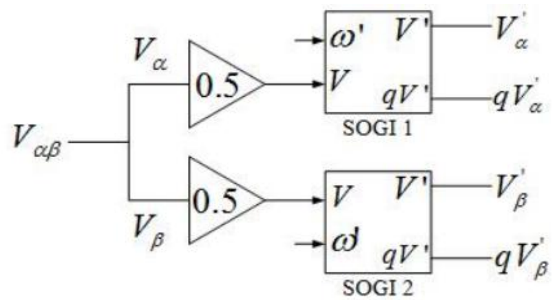

Fig 4.3. Generation of Orthogonal Signal from Stationary Frame

By mixing the DSOGI and reference frame the in-phase component and quadrature component has been generated. For the proper interfacing of grid and inverter, the main parameters are frequency, amplitude and phase of the grid voltage.

Three phase voltage signals are transformed into stationary αβ reference frame in terms of $V\alpha$ and $V\beta$. These two signals are passes through two SOGI blocks in order to produce two set of orthogonal signals

Two SOGI based QSGs are used to obtain the in phase and quadrature components of the α axis (represented by v'_α and qv'_α respectively) and β axis (represented by $v'_\beta$and qv'_β respectively).

The α and β axis voltages for positive and negative sequence components are calculated by the following equations:

$$V_{\alpha}' - qV_{\beta}' = V_{\alpha}^{+}$$
$$V_{\beta}' + qV_{\alpha}' = V_{\beta}^{+}$$
$$V_{\alpha}' + qV_{\beta}' = V_{\alpha}^{-}$$
$$V_{\beta}' - qV_{\alpha}' = V_{\beta}^{-}$$

To achieve the perfect electrical conditions like unity power factor, constant voltage etc the main is to compensate the negative sequence component and by using exact value of positive sequence component.

So it is necessary to finding the sequence components. And phase angle of line voltage is the factor for controlling the function of active or reactive power and to modify the feedback variables in voltage monitoring grid synchronization system.

By using Clarke's and Park's transformation the three-phase utility grid voltage has been transformed from natural reference frame to rotating reference frame in SRF PLL. By using feedback loop i.e., the reference frame's angular position we can make the positive sequence component's q component to zero.

Therefore, the measured d-component gives the voltage vector magnitude, while its phase angle is tracked by using the feedback loop. The SRF PLL takes in a linearization assumption so the results can be guaranteed locally only. The schemes which are based on the SRF PLL approach are sensitive to harmonic distortion. These drawbacks can be eliminated by DSOGI (doubly second order generalized integrator) PLL and additionally we can find sequence components under unbalanced condition.

4.2) MATLAB Simulation

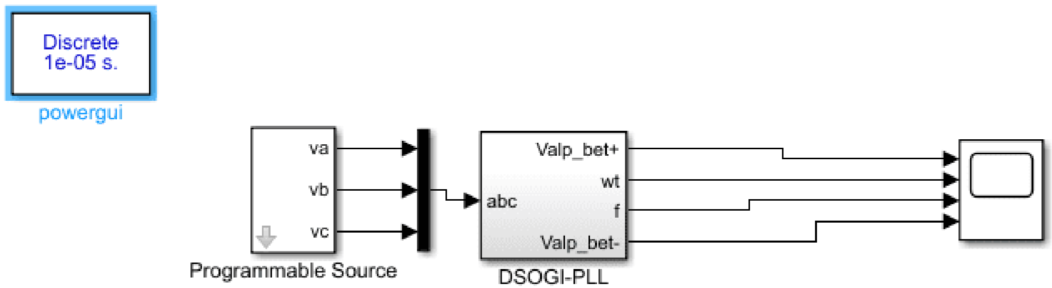

Fig 4.4. MATLAB Simulink model of grid connected to DSOGI PLL

From grid the voltages V_a, V_b and V_c information is fed into the DSOGI Block. In DSOGI block outputs are V_{alp_bet+}, phase angle (wt), frequency (f) and V_{alp_bet-}

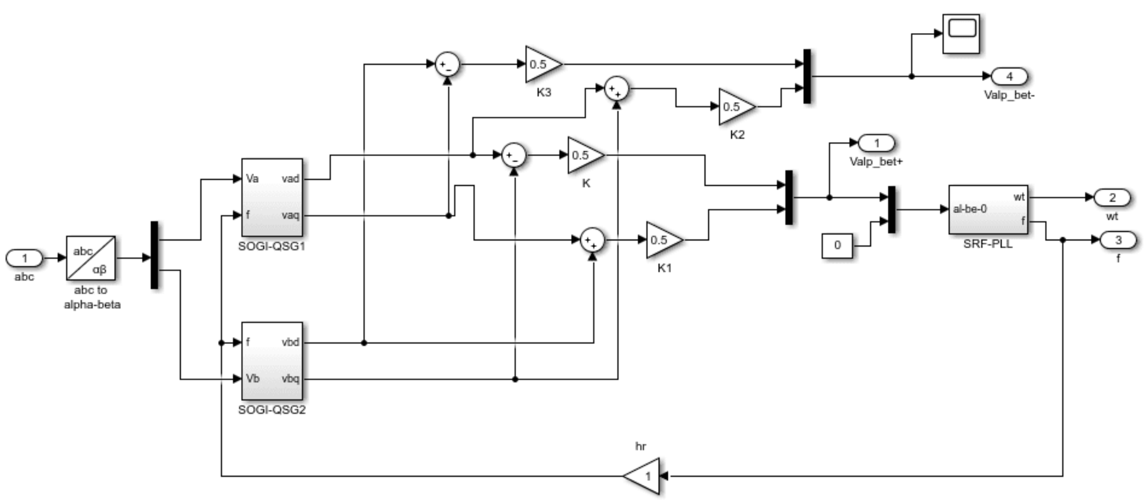

Fig 4.5. DSOGI-PLL Block.

In this circuit the grid information is fed into the DSOGI BLOCK. After that ABC to αβ transformation is done. $V\alpha$ and $V\beta$ is then used as an input for SOGI QSG1 AND SOGI QSG2 respectively. The output of SOGI QSG1 are $\boldsymbol{V_{\alpha}}'$ & $\boldsymbol{qV_{\alpha}}'$ and for SOGI QSG2 $\boldsymbol{V_{\beta}}'$ & $\boldsymbol{qV_{\beta}}'$.

These voltage signals are used to synthesize the set of positive sequence component and negative sequence components by proper mathematical operations.

V_{alp_bet+} is then used as an input in SRF-PLL block and the output generated is wt and frequency.

4.3) Simulation Results

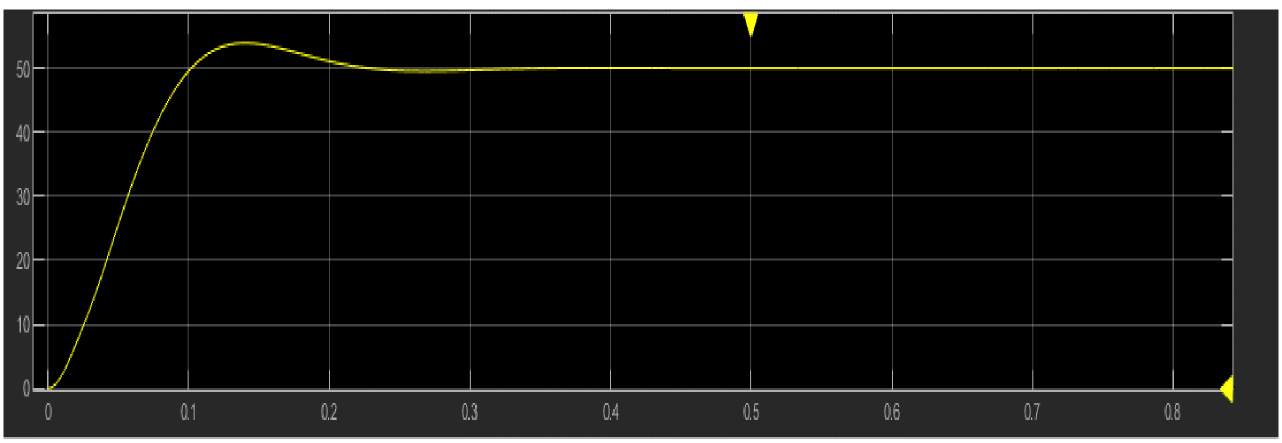

Fig 4.6. Frequency detection by DSOGI-PLL

The frequency output of the system is settled within 0.2 seconds and it is equal to the grid frequency i.e. 50Hz.

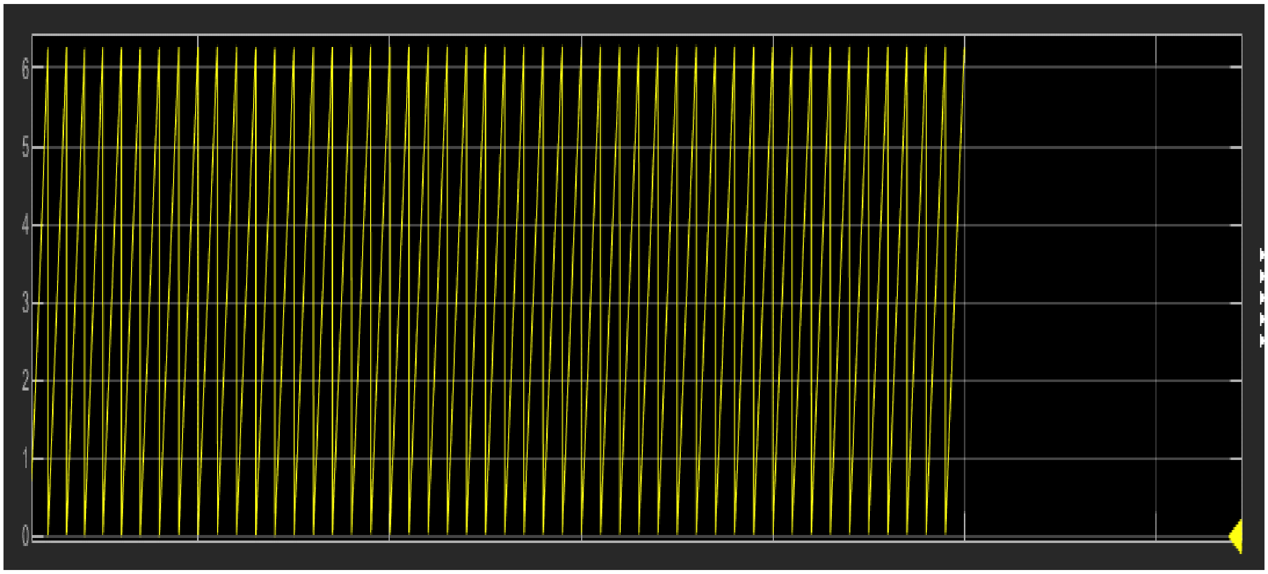

Fig 4.7. Phase angle detection by SOGI-PLL

The phase angle in radians is varied from 0 to 6.2 radians as shown. Hence, it can be observed that the SOGI PLL is able to track the grid voltage signal across the entire range.

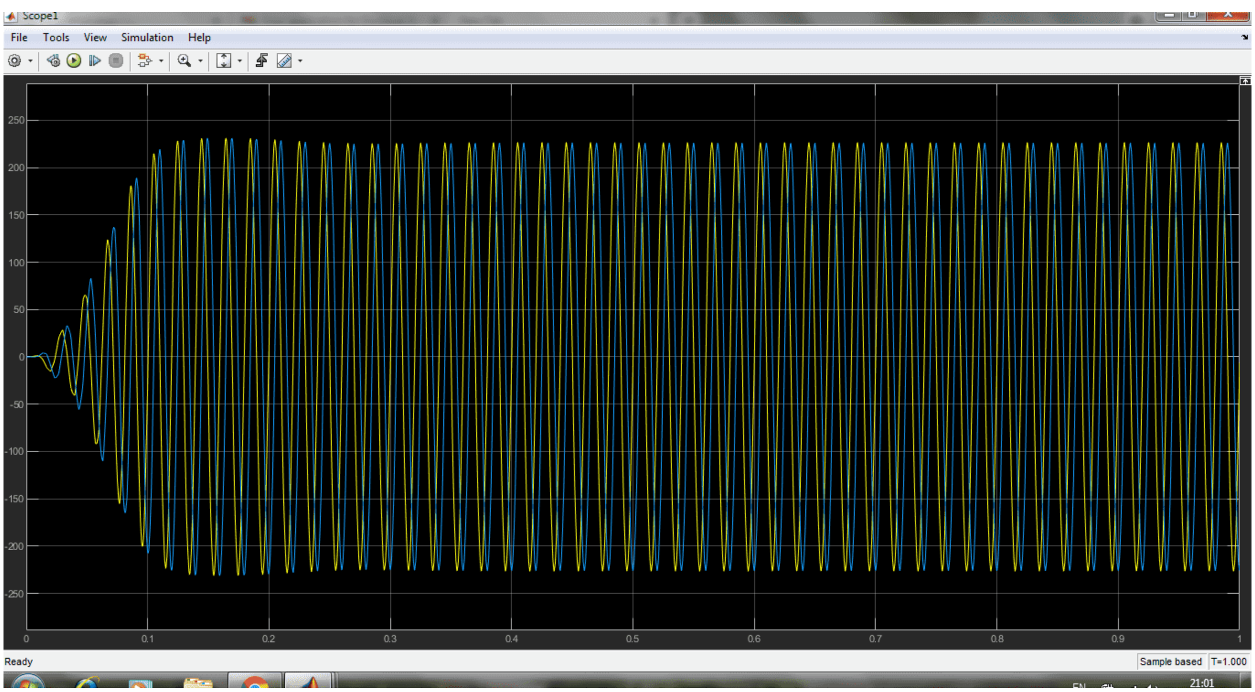

Fig 4.8. Positive sequence component Result of DSOGI

Here the 3 phase supply of 230 V is balanced so the magnitude of resultant positive sequence component magnitude value is 230 V as shown in Figure.

4.4) Comparison of DSOGI based PLL and SRF-PLL

As discussed, SRF-PLL is the conventional method followed for the grid synchronization and it works satisfactorily in balanced grid conditions but its performance deteriorates with unbalance grid condition or when some disturbances is there in the. In SRF-PLL, the angle is tracked in such a way that the maximum phase voltage is reflected on d-axis while component voltage along q-axis is zero.

During unbalanced grid condition, the existence of negative sequence component can be realized. As a result. The output waveform of the dq transformation consists a ripple of double the fundamental frequency component. On the basis of PLL bandwidth, this ripple gets enervated however they are circulated in the loop and possesses errors in calculating the frequency and angle θ. This causes the output waveform in distortions condition. The distortion can be resolved in terms of amplitude (THD) and phase angle difference in terms of tracing of the positive sequence of the input voltage. The disadvantages of SRF-PLL are that it is unable to track the angle and frequency during unbalance condition

Synchronous reference frame phase locked loop (SRF-PLL) has been widely used for synchronization three-phase grid connected photovoltaic (PV) system. On the grid fault, SRF-PLL distorted by negative sequence component and grid harmonic that caused an error in estimating parameter because of ripple and oscillation. This work combined SRF-PLL with dual second order generalized integrator (DSOGI) and filter to minimize ripple and minimize oscillation in the phase estimation and frequency estimation.

DSOGI was used for filtering and obtaining the 90 degree shifted versions from the $v\alpha\beta$ signals. These signals ($v_{\alpha\beta}$) were generated from three phase grid voltage signal using Clarke's transform. The positive-sequence $v\alpha\beta$ was transformed to the dq synchronous reference frame and became an input to SRF-PLL to create the estimation frequency. This estimation frequency from SRF-PLL was filtered by the low-pass filter to decrease grid harmonic. Moreover, the output of low-pass filter was a frequency adaptive**.**

Table 4.1. Comparison of DSOGI-PLL with other PLL methods

Synchronization Algorithm	**Advantages**	**Limitations**
SRF-PLL	• Simple implementation • Stability • DC offset • Low computational burden • Fast dynamic response	• Harmonics • Phase Jump • Voltage unbalances • Load rising • Frequency rising and overshoot
DDSRF-PLL	• Voltage unbalances • Load rising • Harmonics • DC offset • Stability • Phase Jumping • Low computational burden	• Frequency rising and overshoot • Average implementation simplicity
DSOGI-PLL	• Voltage unbalances • Frequency rising and variations • Phase jumping • DC offset • Stability	• Harmonics • Average implementation simplicity • Load Rising • High computational burden
EPLL	• Fast dynamic response • Harmonics	• Load rising

	• DC offset • Phase jumping • Stability	• Average implementation simplicity • Frequency rising and variations • Voltage unbalances • Slow dynamic response

4.5) Adaptation of DSOGI-PLL method

The MVF-DSOGI-PLL is based on a combination of two widespread techniques. The MVF is the multi-variable filter which can extract directly the fundamental voltage in the αβ axis and greatly reduce the direct and inverse harmonic components at the input signals of the DSOGI-QSG in the system. The DSOGI-QSG-PSC is a filter that can block harmonics and extract the fundamental positive sequence to the SRF-PLL where the latter makes the system frequency adaptive.

The use of this combined technique permits making insensible the MVF-DSOGI-PLL to the perturbations specifically to the high harmonic and unbalanced voltage.

4.5.1) Principle of MVF.

An extraction filter called "multi-variable filter" MVF can extract directly the fundamental signals (voltage or current) in the $\alpha\beta$ axis, without leading to either phase shift or voltage change amplitude. However, it can also be used to reduce the direct and inverse harmonic components of the input signals.

The transfer function of the block comes out to be:

$$H(s) = \frac{v_{\alpha\beta_f}(s)}{v_{\alpha\beta}(s)} = K_f \frac{\left(s + K_f\right) + j\hat{\omega}}{\left(s + K_f\right)^2 + \hat{\omega}^2}$$

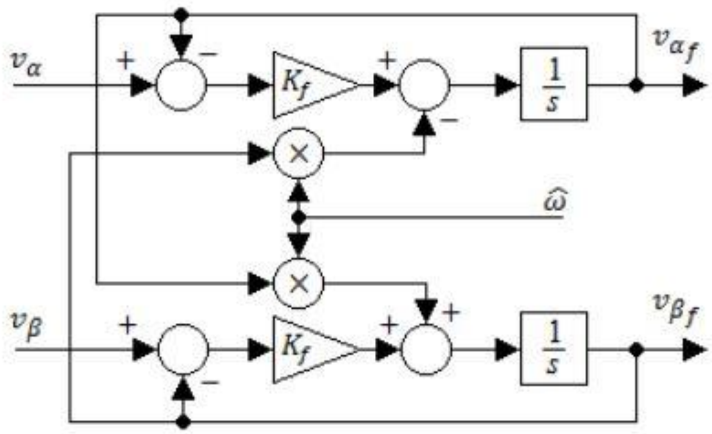

Fig. 4.9. Block Diagram of MVF.

The following expressions are obtained for the output signals:

$$v_{\alpha_f}(s) = \frac{K_f}{s}\left[v_\alpha(s) - v_{\alpha_f}(s)\right] - \frac{\hat{\omega}}{s} v_{\beta_f}(s)$$

$$v_{\beta_f}(s) = \frac{K_f}{s}\left[v_\beta(s) - v_\beta(s)\right] + \frac{\hat{\omega}}{s} v_{\alpha_f}(s)$$

where $\hat{\omega}$, K_f , $v_{\alpha\beta_f}$ and $v_{\alpha\beta}$ denote respectively the central frequency, the dynamic gain, the output and input voltages of the MVF.

4.5.2) PLL technique based on MVF-DSOGI

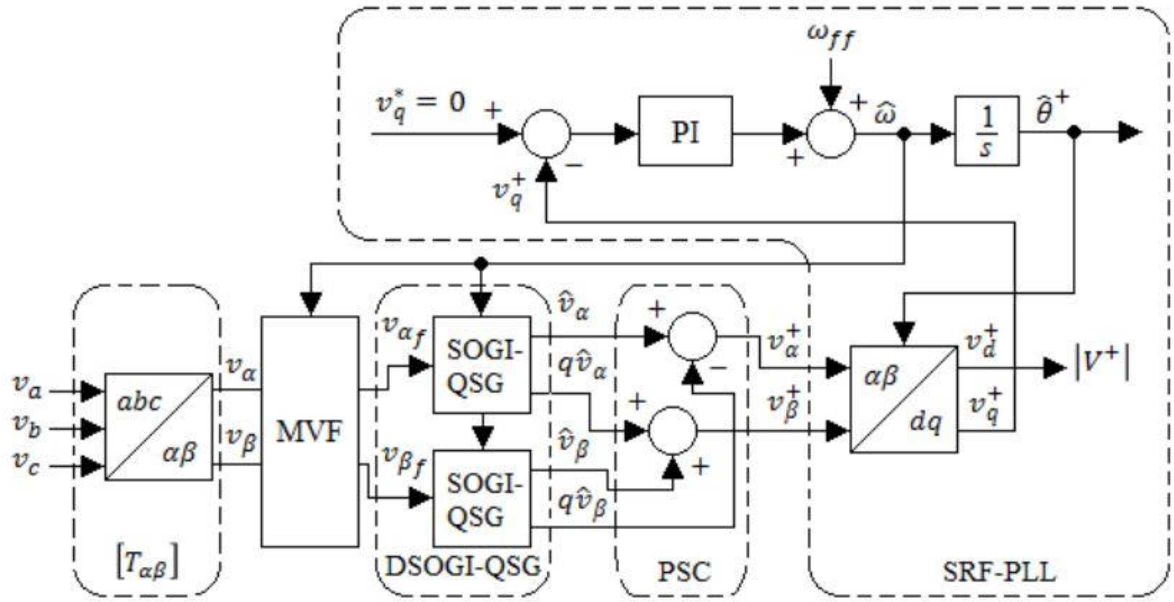

Fig 4.10. Block model of MVF DSOGI PLL method

The structure of the MVF-DSOGI-PLL is presented in Fig. 4.10, where the grid voltages v_a, v_b and v_c are converted to the voltages v_α and v_β in the stationary reference frame by using the Clarke transformation. Then, the MVF directly extracts the fundamental component from distorted and unbalanced grid voltages in the αβ reference frame, which can greatly reduce the rate of harmonic voltages at the input of the DSOGI-QSG in the system.

A combined filter MVF-DSOGI-QSG used for blocking the harmonics and for creating a phase shift of 90 degrees by respecting the fundamental frequency of the grid voltage from vα and vβ that are delivered to the positivesequence calculator (PSC). The positive-sequence voltages, v_α^+ and v_β^+ are then transformed to voltages v_d^+ and v_q^+ using the following Park's transformation.

The conventional SRF-PLL shown in Fig.4.10 is employed for grid frequency detection and MVF-DSOGI-QSG resonance frequency adaptation. The closed loop for the SRF-PLL is used to obtain the angular position $\hat{\theta}^{+}$ which drives the q component, v_q^{+} , to zero and estimates the utility frequency $\hat{\theta}$ utilized by the outer closed loop to adapt the resonance frequency of the MVF-DSOGI-QSG.

CHAPTER 5

STUDY OF ANF BASED SYNCHRONIZATION SCHEME

5.1) Introduction

The ANF based synchronization method demonstrates an advanced synchronization performance in a corrupted grid environment but also effectively handles the unbalanced situations. The proposed synchronization device does not require a synchronizing tool such as PLL, and its main building block is a modified adaptive notch filter (ANF) system of nonlinear dynamical equations.

The prime application of the proposed synchronization method is found in distributed generation systems, e.g., micro-grid systems, where grid synchronization is of concern in both grid-connected and islanding operation modes.

The proposed approach is adapted to meet special interests including the real-time extraction and measurement of harmonics and reactive components of a power signal of a time-varying characteristic. The adaptive nature of the proposed technique allows perfect tracking of frequency and amplitude variations.

The structural simplicity of the algorithm makes it desirable from the standpoint of digital implementation in both software, e.g., a digital signal processor (DSP), and hardware environments, e.g., a field programmable gate array (FPGA) or application-specific integrated circuit (ASIC) environments. A theoretical analysis is presented, and simulation results confirm the validity of the analytical work.

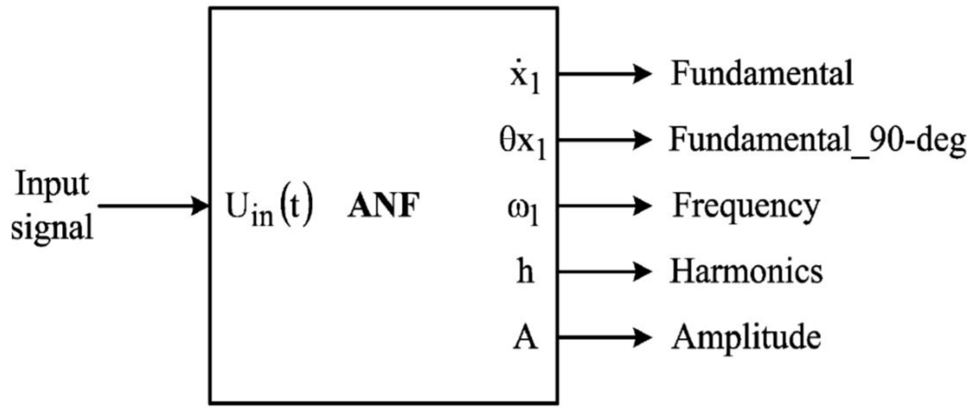

Fig 5.1. ANF block model and outputs

5.2) Applications of ANF based method

In the stationary frame, synchronization can be implemented by means of the three single-phase ANF systems. Grid information required for grid synchronization is extracted by the three ANFs in a very simple and straightforward manner with no need for a PLL system.

One advantage of this implementation is that it provides distinctive information about the amplitude, frequency and phase angle of each phase voltage. This distinguishing feature, as it provides additional information, is very beneficial for grid monitoring and island detection. In addition, the new synchronization technique employs mathematical tools that streamline the control formulation and thus the system implementation.

In fact, in all control functions that employ the synchronization scheme, the use of a PLL system and transformation module are unnecessary. Furthermore, the availability of the fundamental component of the grid voltages or currents, and its 90-degree phase shift is ideal for sequencing component decomposition under unbalanced system operations. This aspect is very beneficial in three-phase distributed power generation systems, where the ride-through capability of the synchronization tool under the unbalanced system situation and its capability for disturbance rejection are of great importance.

The structure also provides harmonic content of the voltage, peak fundamental components, and functions of phase angles of the voltage and current, and the phase angle difference between the phase voltage and phase current. A close observation reveals that the proposed structure, when compared to its counterparts, has the following advantages:

- an adaptive structure that can track signal variations,
- simplicity that results in a simple implementation,
- the lack of a need for a synchronizing tool like a PLL,
- simultaneous extraction of harmonics and all useful information, such as frequency, amplitude, and phase angle, embedded in a signal,
- adjustable accuracy and speed of response.

5.3) ANF Modelling

5.3.1) ANF Structure and Dynamics

Let the input signal be given by:

$$u(t) = \sum_{i=1}^{n} A_i \sin \phi_i, \qquad where\ \phi_i = \omega_i t + \varphi_i$$

Nonzero amplitudes, $A_i, i = 1,2, \dots, n$, the nonzero frequencies, $\omega_i, i = 1,2, \dots, n$, and the phases $\varphi_i, i = 1,2, \dots, n$ are typically unknown parameters. Estimating unknown parameters, especially unknown frequencies, is a required task in many applications and is a fundamental issue in systems theory and signal processing.

A modified lattice-based discrete-time ANF is employed. The dynamic behavior of this ANF is characterized by the following set of differential equations:

$$\ddot{x} + \theta^2 x = 2\xi\theta e(t)$$
$$\dot{\theta} = -\gamma x \theta e(t)$$
$$e(t) = u(t) - \dot{x}$$

Where θ, is the estimated frequency and γ and ζ are adjustable real positive parameters that determine the estimation accuracy and the convergence speed of the ANF. For a single sinusoid input signal $(n = 1), u(t) = A_1 \sin(\omega_1 t + \varphi_1)$, this ANF has a unique periodic orbit located at

$$o = \begin{pmatrix} \bar{x} \\ \dot{\bar{x}} \\ \bar{\theta} \end{pmatrix} = \begin{pmatrix} -\dfrac{A_1}{\omega_1}\cos(\omega_1 t + \varphi_1) \\ A_1 \sin(\omega_1 t + \varphi_{1)} \\ \omega_1 \end{pmatrix}$$

The third entry of O is the estimated frequency, which is identical to its correct value, ω_1 .

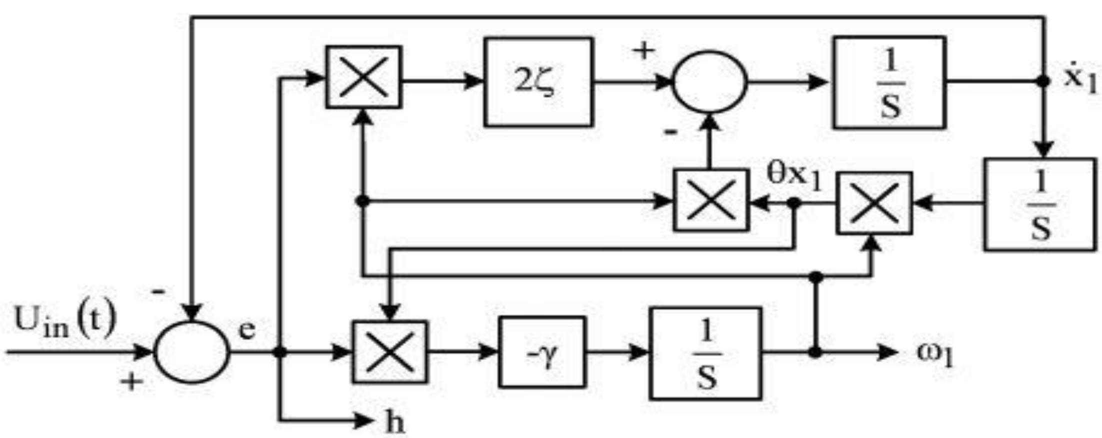

Fig 5.2. Detailed Implementation of Proposed Structure

5.3.2) ANF As Grid Synchronization Unit

Fig. 5.1 shows the schematic structure of the proposed grid-synchronization unit, where the ANF is functioning as the main cell. The input is a distorted sinusoidal signal or, in general, a periodic signal. The power of the proposed synchronization structure is that it outputs useful signal information such as the fundamental component, its 90-degree phase-shift, its amplitude, its frequency, sin/cos functions of its phase angle, and harmonics.

The state-of-the art technology in grid-connected converters is the use of a PLL device to find the phase angle of the grid voltage. We will show that in the proposed approach there is no need for a synchronizing tool such as PLL. In addition, having access to additional signal information enables the user to synchronize the on/off times of the switching devices, calculate active/reactive power, and transform the feedback variables to a frame suitable for control purposes.

A close observation reveals that the fundamental component and its 90 degree phase shift are essentially $\dot{\bar{x}}$ and $\overline{\theta x}$, respectively. Therefore, the amplitude of the fundamental component is easily determined from $A_1 = \left(\left(\overline{\theta x_1}\right)^2 + \dot{\bar{x}}_1^2\right)^{\frac{1}{2}}$.

A detailed implementation of the proposed structure is shown in Fig. 5.2. Output θ provides the fundamental frequency of the input signal, ω_1 , and the ANF is composed of simple adders, multipliers, and integrators.

Two additional multipliers, a summer, and a square root function determine the amplitude of the fundamental component.
The sin/cos functions of the phase angle are simply obtained by dividing the fundamental component and its 90-degree phase shift by the amplitude of the fundamental component.

5.3.3) Filter Parameters and Initial Condition

The basic structure of Fig. 5.2 has two independent design parameters, γ and ζ.

Parameter γ determines the adaptation speed, hence, the capability of the proposed algorithm in tracking the signal characteristics variations. Particularly, the convergence rate of the estimated frequency is proportional to γ.

Parameter ζ determines the depth of the notch and, hence, the noise sensitivity of the filter. A tradeoff between the (steady-state) accuracy and (transient) convergence speed can be carried out by adjusting design parameters γ and ζ .

By increasing γ, one can achieve a faster convergence speed; however, at the same time, ζ should be increased to avoid oscillatory behaviors. It can be proved that for micro-grid and distributed energy applications a wide range of parameters values, γ and ζ , is acceptable, i.e., the structure is robust with respect to variations in the internal parameters.

The proposed ANF structure has three integrators. The initial condition for the integrator that outputs the frequency, is set to the nominal power system frequency. In other words, the initial condition for this integrator is set to $2\pi 50$ or $2\pi 60$ rad/s (similar to the center frequency of the voltage-controlled oscillator in PLL schemes). The initial conditions for all other integrators are set to zero.

5.4) MATLAB Simulation and Result.

The ANF block is constructed in MATLAB/Simulink. The values of constants ζ and γ are calculated to be 0.6 and 1/800 respectively.

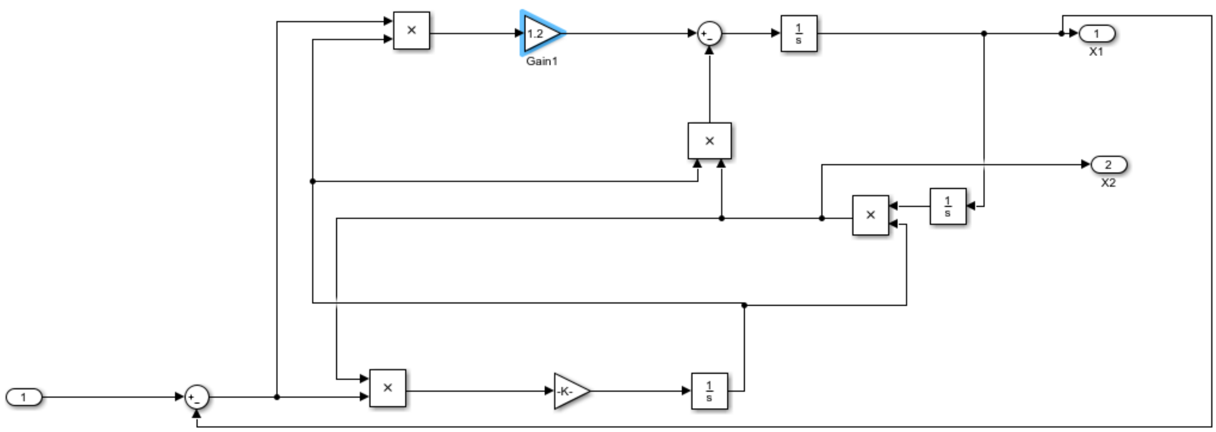

Fig 5.3. ANF block in MATLAB/Simulink

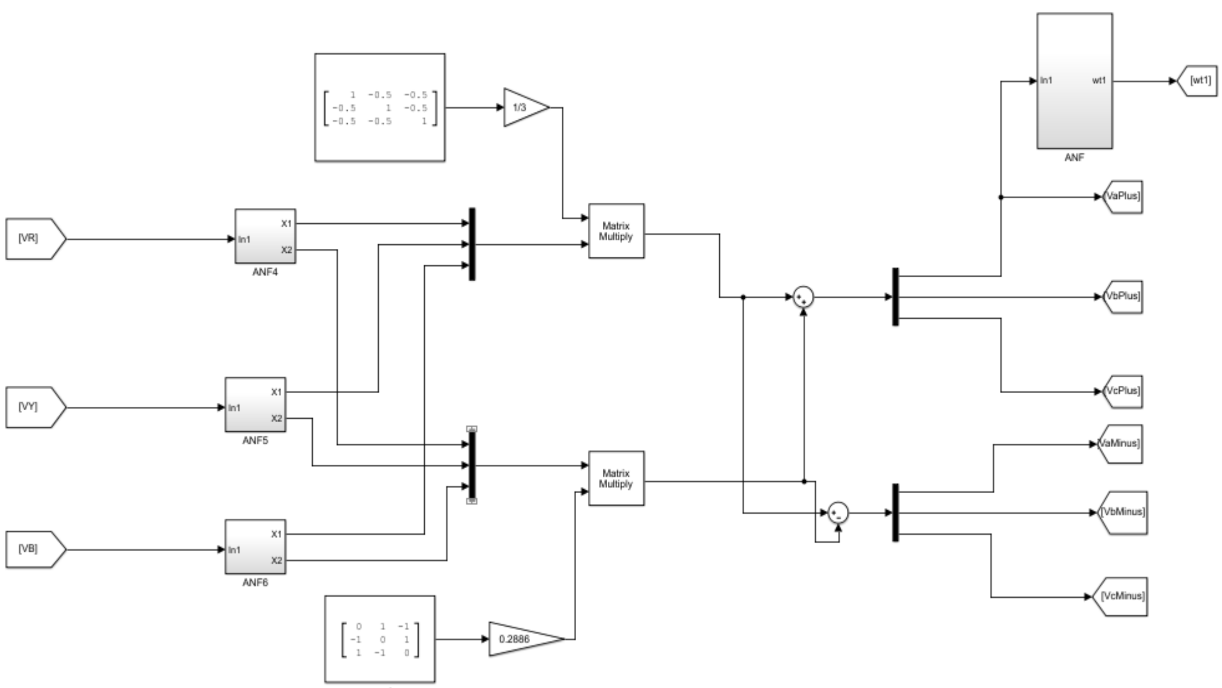

Fig 5.4. Frequency detection circuit using ANF.

Here, for any ANF Block,

X_1 represents output signal;

X_2 Represents Quadrature output signal.

The positive- and negative sequence extractor unit, as shown above, is comprised of three ANFs and simple arithmetic operators.

ANFs adaptively extract the fundamental voltages and their 90 phase-shift. The reminder system receives these components and calculates the positive- and negative-sequence voltages.

In the aforementioned 3 phase System, Positive and Negative sequence Components Are calculated as Follows:

$$v^{+}(t) = T_2 X_1(t) + T_1 X_2(t)$$
$$v^{-}(t) = T_2 X_1(t) - T_1 X_2(t)$$

where,

$$T_1 = \frac{1}{2\sqrt{3}} \begin{pmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{pmatrix}$$

$$T_2 = \frac{1}{3} \begin{pmatrix} 1 & -0.5 & -0.5 \\ -0.5 & 1 & -0.5 \\ -0.5 & -0.5 & 1 \end{pmatrix}$$

The extracted positive sequence component is then passed to another ANF that outputs useful information for grid synchronization or other control purposes.

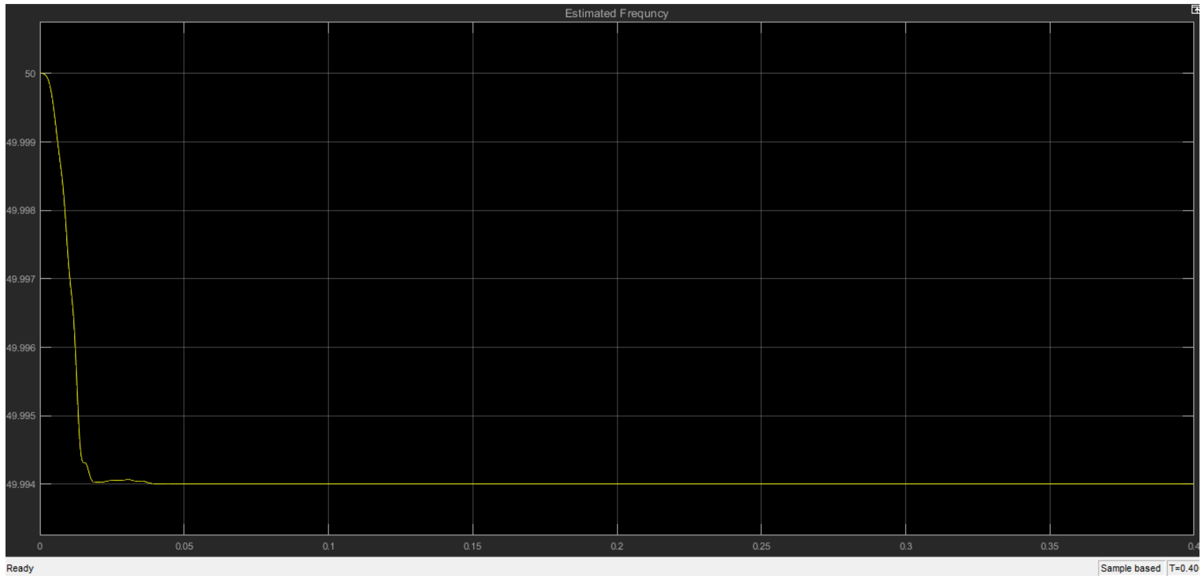

Fig 5.5. Frequency Estimation by ANF Block

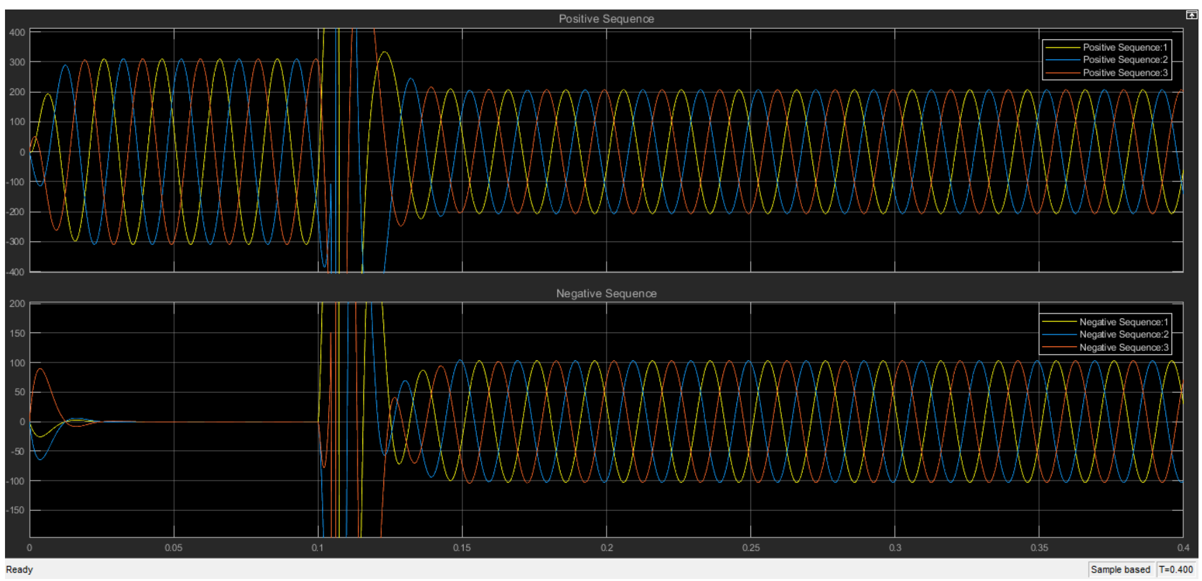

Fig 5.6. Positive and negative sequence Voltages For disturbance in system at 0.1 sec.

CHAPTER 6

POWER QUALITY ISSUES

Any problem manifested due to voltage, current or frequency deviations that result in failure of customer equipment is called a power quality problem. The reason why power quality is a subjectof interest is due to economic value. There are economic impacts on utilities, customers and suppliers ofload equipment. The quality of power may have a direct economic impact on many consumers.

With rising penetration of renewable energy sources, the importance of minimization of power quality problems is increasing rapidly. So, it becomes imperative to take note of these issues and have an understanding of any power quality issues which may accompany grid synchronization.

6.1) Overview of Power Quality issues

6.1.1) Harmonics

Harmonics are sinusoidal voltages or currents having frequencies which are integer multiples of the fundamental frequency. Periodically distorted waveforms can be decomposed into a sum of fundamental frequency and harmonics. Harmonic distortion originates in the non-linear characteristics of devices and loads.

Harmonic distortion is measured by the use of harmonic distortion levels. Total harmonic distortion (THD) is a measure of effective value of harmonic distortion. THD is defined as the ratio of root mean square of harmonic voltages to fundamental voltage.

$$T.H.D = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1}$$

Total Demand Distortion is a term that also characterizes current distortion. It is defined in the same way as THD, but is expressed in percentage of load current rather than percent of fundamental voltage.

$$T.H.D = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_n^2}}{I_{max}}$$

6.1.2) Long Duration Voltage Variation

Long duration voltage variations encompass all root mean square deviations at power frequencies for longer than one minute. A voltage variation is long duration when it exceeds the time limit set by ANSI or IEEE standards.

Long duration voltage variations can be either overvoltages, undervoltages or sustained interruptions.

- **Overvoltage**: An overvoltage is an increase in rms ac voltage greater than 110% at the power frequency for a duration longer than one minute. Overvoltages are caused due to load switching such as switching on large capacitor banks, etc.

- **Undervoltage**: An undervoltage is a decrease in the rms ac voltage less than 90% at the power frequency for a duration longer than one minute. Undervoltages are caused by switching event which are the opposite of overvoltage causes. Switching off capacitor banks may cause undervoltages.

- **Sustained Interruption**:A sustained interruption occurs when the supply voltage has been zero for a period exceeding one minute.

6.1.3) Short Duration Voltage Variation

Short duration voltage variations are the rms ac voltage deviations that occur within one minute. Based on their time period they can be classified as

a) **Instantaneous**

b) **Momentary**

c) **Temporary**

These variations are caused by fault conditions, energization of large loads or loose connections in wiring. These variations can further be classified as

a) **Temporary voltage drops – Voltage Sag**

b) **Temporary voltage rise – Voltage Swell**

c) **Complete loss of voltage – voltage interruption**

- **Voltage Sag:** A sag is a decrease between 0.1 to 0.9 pu in rms voltage or current at the power frequency for a duration of 0.5 cycle to 1 minute. Voltage sag effects sensitive equipment and proper measures must be taken to protect the equipment from the ill effects of voltage sag. Any voltage sag can be characterized with the following parameters:

  a) Magnitude of Sag

  b) Duration of Sag

- **Voltage Swell:** A voltage swell is an increase between 1.1 to 1.8 pu in rms voltage or current at the power frequency for a duration of 0.5 cycle to 1 minute. Swells are also characterized by their magnitude and duration.

- **Interruptions:** Interruption occurs when the supply voltage or load current decreases to less than 0.1 pu for a time period not greater than one minute. They can be due to power system faults, equipment failure, control malfunctions, etc. Interruptions are characterized by their duration.

6.1.4) Transients

Transients are momentary undesirable variations in the voltage or current waveform. Transients generally occur in circuits where inductance and capacitance are present. It can also be defined as the change in variable that disappears during transition from one steady state condition to another.

Transients can be classified into two categories

a) Impulsive Transients

b) Oscillatory Transients

- **Impulsive Transients:** Impulsive transient is a sudden, non-power frequency change in the steady state condition of voltage, current or both that is unidirectional in nature. It either has positive or negative polarity but not both. They are characterized by their rise and decay times.

- **Oscillatory Transients:** Oscillatory transient is a sudden, non-power frequency change in the steady state condition of voltage, current or both that is bidirectional in nature. This includes both positive and negative polarities. The polarity of this voltage disturbance changes rapidly.

Table. 6.1. Description of Power Quality Issues

Category	**Description**
Electromagnetic Interferences	• High Frequency Phenomenon • Interaction Between electric and magnetic field
Power System Transient	• Fast, short duration event • Produce distortion like notch, impulse
Power System Harmonics	• Low Frequency Phenomenon • Produce Waveform Distortion
Electrostatic Discharge	• Current Flow with different Potentials • Caused by direct current or induced electrostatic field
Power Factor	• Low power factor causes equipment damage
Power Frequency Distribution	• Low Frequency Phenomenon • Produce voltage sag/swell

Approximately 70% to 80% of all power quality related problems can be attributed to faulty connections and/or wiring. Among the discussed events, harmonics are the most dominant one. According to IEEE standard 519, harmonics in the power system should be limited by two different methods:

- One is the limit of harmonic current that a user can inject into the utility system at the point of common coupling (PCC), and
- The other is the limit of harmonic voltage that the utility can supply to any customer at the PCC.

In a grid- interfacing inverter for a 3- phase 4-wire system, the fourth leg of inverter is used to compensate the neutral current of load. The main aim is to regulate the power at PCC during, the inverter is actively controlled in such a way that it always draws/ supplies fundamental active power from/ to the grid. If the load connected to the PCC is non-linear or unbalanced or the combination of both, the given control approach also compensates the harmonics, unbalance, and neutral current. The duty ratio of inverter switches is varied in a power cycle such that the combination of load and inverter injected power.

If the load connected to the PCC is non-linear or unbalanced or the combination of both, the given control approach also compensates the harmonics, unbalance, and neutral current. The duty ratio of inverter switches is varied in a power cycle such that the combination of load and inverter injected power appears as balanced resistive load to the grid. The regulation of dc-link voltage carries the information regarding the exchange of active power in between renewable source and grid.

The grid-interfacing inverter with the proposed approach can be utilized to:

i) inject real power generated from RES to the grid,

ii) operate as a shunt Active Power Filter (APF).

This approach thus eliminates the need for additional power conditioning equipment to improve the quality of power at PCC. This approach thus eliminates the need for additional power conditioning equipment to improve the quality of power at PCC.

CHAPTER 7

CONCLUSION

Over the course of this project, various grid synchronization techniques were studied and some of them were simulated in MATLAB, namely, SRF-PLL, DSOGI-PLL and ANF based PLL. Among the various solutions to extract the phase angle, the SRF-PLL is used in almost all PLL techniques for three-phase systems. This scheme is extremely simple and provides a highly fast and accurate synchronization signal under ideal conditions where there is no voltage distortion/unbalance. The simplicity of this structure has encouraged some authors to propose new schemes based on this topology.

Improved versions of SRF-PLL are presented to overcome distortion/unbalance problems. The LSRF-PLL, DSOGI-PLL, and DSRF-PLL are among the newly developed solutions to improve SRF-PLL performance. These modified SRF-PLL techniques reported to have a better performance compared under unbalance situations. Another solution to extract the phase angle is ANF, which is frequency based. The three-phase ANF by means of three single-phase ANFs, and DSOOI-FLL are among the ANF-based methods. In all PLL-based and ANF-based methods listed above, when the signal is distorted by harmonics, the bandwidth of these methods should be reduced, thus the time response is increased. The proposed three-phase ANF with a multi-block structure overcomes this problem and offers high degree of insensitivity to power system disturbances, harmonics and other types of pollutions that exist in the grid signal. Moreover, it is capable of decomposing three-phase quantities into symmetrical components, tracking the frequency variations, and providing means for voltage regulation and reactive power control.

The advantages and disadvantages of the detection techniques for phase angle, frequency, and harmonic component in grid-connected converters have been analyzed and discussed. From literatures, some new methods are found to perform better than classical PLL yet PLL is still well accepted for its simplicity. Therefore, many modifications to PLL have been made to enhance and improve its performance during a weak grid. The synchronization performance of grid-connected converters can be concluded as quantifiable into aspects such as RES penetration, connecting time, converting characteristics, weather conditions, and control and modeling techniques. Hybrid and intelligent techniques for effective and robust grid synchronization especially in adverse grid conditions deserve more attention in possible future work.

REFERENCES

[1] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," IEEE Trans. Ind. Electron., vol. 53,no. 5, pp. 1398-1409, Oct. 2006.

[2] Jaalam, N. & Rahim, N.A. & Bakar, A.H.A. & Tan, ChiaKwang & Haidar, Ahmed M.A., 2016. "A comprehensive review of synchronization methods for grid-connected converters of renewable energy source," Renewable and Sustainable Energy Reviews, Elsevier, vol. 59(C), pages 1471-1481.

[3] S. Golestan, M. Monfared and F. D. Freijedo, "Design-Oriented Study of Advanced Synchronous Reference Frame Phase-Locked Loops," in *IEEE Transactions on Power Electronics*, vol. 28, no. 2, pp. 765-778, Feb. 2013, doi: 10.1109/TPEL.2012.2204276.

[4] M. Mojiri, D. Yazdani and A. Bakhshai, "Robust Adaptive Frequency Estimation of Three-Phase Power Systems," in *IEEE Transactions on Instrumentation and Measurement*, vol. 59, no. 7, pp. 1793-1802, July 2010, doi: 10.1109/TIM.2009.2028766.

[5] Rodriguez, P., Luna, A., Ciobotaru, M., Teodorescu, R., & Blaabjerg, F. (2006). Advanced Grid Synchronization System for Power Converters Under Unbalanced and Distorted Operating Conditions. In *Proceedings of 32nd Annual Conference of the IEEE Industrial Electronics Society* (pp. 5173-5178). Electrical Engineering/Electronics, Computer, Communications and Information Technology Association.

[6] I. Ullah and M. Ashraf, "Comparison of Synchronization Techniques Under Distorted Grid Conditions," in *IEEE Access*, vol. 7, pp. 101345-101354, 2019, doi: 10.1109/ACCESS.2019.2930530.

[7] B. Sen, D. Sharma and B. C. Babu, "DSRF and SOGI based PLL-two viable scheme for grid synchronization of DG systems during grid abnormalities," 2012 Students Conference on Engineering and Systems, Allahabad, India, 2012, pp. 1-6, doi: 10.1109/SCES.2012.6199073.

[8] N. Daou and F. Khatounian, "A combined phase locked loop technique for grid synchronization of power converters under highly distorted grid conditions," 2016 IEEE International Multidisciplinary Conference on Engineering Technology (IMCET), Beirut, Lebanon, 2016, pp. 108-114, doi: 10.1109/IMCET.2016.7777436.

[9] P. Rodríguez, R. Teodorescu, I. Candela, A. V. Timbus, M. Liserre and F. Blaabjerg, "New positive-sequence voltage detector for grid synchronization of power converters under faulty grid conditions," 2006 37th IEEE Power Electronics Specialists Conference, Jeju, Korea (South), 2006, pp. 1-7, doi: 10.1109/pesc.2006.1712059.

[10] Sevilmiş, F , Karaca, H . (2019). Performance analysis of SRF-PLL and DDSRF-PLL algorithms for grid interactive inverters . International Advanced Researches and Engineering Journal , 3 (2) , 116-122 . DOI: 10.35860/iarej.412250

[11] Grid Converters For Photovoltaic And Wind Power Systems, Remus Teodorescu Aalborg University, Denmark Marco Liserre Politecnico di Bari, Italy Pedro Rodr´ıguez Technical University of Catalonia, Spain.

[12] Kadam Supriya Sunil, Devi Rajan J., 2015, Phase Locked Loop for synchronization of Inverter with Electrical grid: A Survey, INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH & TECHNOLOGY (IJERT) Volume 04, Issue 02 (February 2015),

[13] Jiang Y, Li Y, Tian Y, Wang L. Phase-Locked Loop Research of Grid-Connected Inverter Based on Impedance Analysis. *Energies*. 2018; 11(11):3077. https://doi.org/10.3390/en11113077

[14] Rajan J. Devi, Supriya S. Kadam, 2015, Synchronization of Three Phase Inverter with Electrical Grid, INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH & TECHNOLOGY (IJERT) Volume 04, Issue 05 (May 2015), http://dx.doi.org/10.17577/IJERTV4IS050938

[15] R. 1.Bojoi, G. Griva, V. Bostan, M. Guerriero, F. Farina and F. Profumo "Current control strategy for power conditioners using sinusoidal signal integrators in synchronous reference frame", IEEE Trans. Power Electron., Vol. 20, n. 6, Nov. 2005 pp. 1402 - 1412