DESIGN AND IMPLEMENTATION OF A KHN BASED FILTER FOR GRID SIGNAL CONDITIONING AND INTEGRATION

A DISSERTATION
SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY
IN
POWER ELECTRONICS AND SYSTEMS

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MAY, 2026

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CANDIDATE'S DECLARATION

I, KUSHANK SINGHSHUBHAM RAJ, Roll No. 2K24/PES/21 student of M. Tech (Power Electronics & Systems), hereby declare that the project Dissertation titled "DESIGN AND IMPLEMENTATION OF A KHN BASED FILTER FOR GRID SIGNAL CONDITIONING AND INTEGRATION" which is submitted by me to the Department of Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously submitted for the award of any Degree, Diploma.

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CERTIFICATE

I hereby certify that the Project Dissertation titled "DESIGN AND IMPLEMENTATION OF A KHN BASED FILTER FOR GRID SIGNAL CONDITIONING AND INTEGRATION" which is submitted by SHUBHAM RAJ (2K21/PES/21), Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ACKNOWLEDGEMENT

I would like to express my heartfelt gratitude to my respected teacher and mentor **Dr. Ankita Matta, Assistant Professor,** Department of Electrical Engineering for their invaluable guidance, unwavering support, and expert insights throughout this journey. Their dedication and expertise have been instrumental in shaping this work. Grateful to all the Electrical Engineering faculties, Power Electronics laboratory, PhD scholars, and laboratory assistants for their valuable inputs.

A special note of thanks goes to my mother and father, their boundless love, encouragement, and unwavering faith have been my pillar of strength. Her sacrifices and support have been the cornerstone of my endeavours.

Lastly, my heartfelt thanks to all my friends who have stood by me, offering support, encouragement, and moments of relief during challenging times. Your camaraderie and companionship have made this journey memorable.

Thank you to everyone who played a part, directly or indirectly, in the realization of this endeavour. Your contributions will forever be cherished.

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ABSTRACT

In this work, the design of an innovative phase-locked loop using KHN filters is presented. This PLL design was developed in order to synchronize the input signal under adverse conditions, particularly weak and distorted sources of electricity. In today’s environment of electrical power grids, synchronization becomes challenging due to the effects of harmonic distortion, voltage fluctuation, frequency deviation, and weak power grid properties. Traditional methods used in PLL technology may not be very successful in dealing with these adverse conditions in terms of accuracy and stability. Hence, a new PLL design with the use of a KHN (Kerwin-Huelsman-Newcomb) filter was implemented.

KHN Filter considerably enhances the performance of harmonic filters in distinguishing desired signals from unwanted distortions. This leads to improved phase detection performance and synchronization capability even under harsh conditions in the grid system. Moreover, the proposed design will also improve dynamic properties, making the PLL more responsive to changes in the grid voltage and/or frequency. This is particularly significant for modern applications such as renewable energy systems, smart grid, and power electronics applications that rely on robust synchronization for efficient operation.

The performance of the suggested KHN filter-based PLL algorithm has been verified using both simulation and practical tests. The outcome shows that it outperforms existing PLL techniques based on the SOGI filter especially in case of weak grid and harmonic distortion. The new solution ensures enhanced filter characteristics, more precise phases, and optimal transient process, making it an effective approach to dealing with the issues of grid synchronization in the current environment.

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LIST OF SYMBOLS AND ABBREVATION

List of Symbols

Q	Quality Factor
LP	Low-pass filter
HP	High-pass filter
BP	Band-pass filter
V_s	Source Voltage of Grid
V'_s	Filtered Direct Voltage
qV'_s	Filtered quadrature Voltage
K	Gain
$V(t)$	Distorted Grid
V_m	Maximum (peak-peak) Voltage
H_n	Order of Harmonics
n(t)	Noise
w_0	Fundamental Frequency

List of Abbreviation’s

PLL	Phase Locked Loop
SRFT	Synchronous Reference Frame Theorem
SOGI	Second Order Generalized Integral
DSOGI	Dual Second Order Generalized Integral
DER	Distributed Energy Resource
THD	Total Harmonics Distortion

CHAPTER 1

INTRODUCTION

1.1 General Aspects

Power quality (PQ) is the term used for maintaining the quality of electrical power in all power levels including generation, transmission, and distribution. PQ is measured in terms of voltage deviation, current deviations, and frequency deviations. Deviations from the recommended levels of above parameters make the power quality bad. PQ problems can be classified as either natural or artificial in nature [1] [2].

Natural PQ problems are mainly due to faulty operation of electrical components in the network, lightning and other factors that cause variations in the recommended levels of current and voltage. Artificial PQ problems are mainly due to the excessive use of non-linear loads in the electrical power networks and solid-state power electronics devices such as SMPS, Power converters, and variable speed drives [3]. Due to non-linear behaviour of these devices and less maintenance, they worsen the PQ problem. PQ is very important in power system operations, and any deterioration in it results in the failure of electrical machines and customers' equipment and leads to more losses in distribution [2].

Modern power converters, renewable energy systems, and smart grids require reliable grid integration. For synchronization, control, and protection, it is necessary to extract the main voltage and phase of the grid. In weak or distorted grids, self-sustained oscillations can produce voltage sags, swells, harmonics, frequency shifts, imbalance, and DC offsets [2] [3] [4]. These problems call for more advanced synchronization and filtering techniques able to work under distorted grid conditions. The conventional filters, as well as most PLL-based methods, often exhibit slow response, poor harmonic rejection, limited adaptability, and high sensitivity to variations in parameters, undermining the performance and reliability of the system [5] [6].

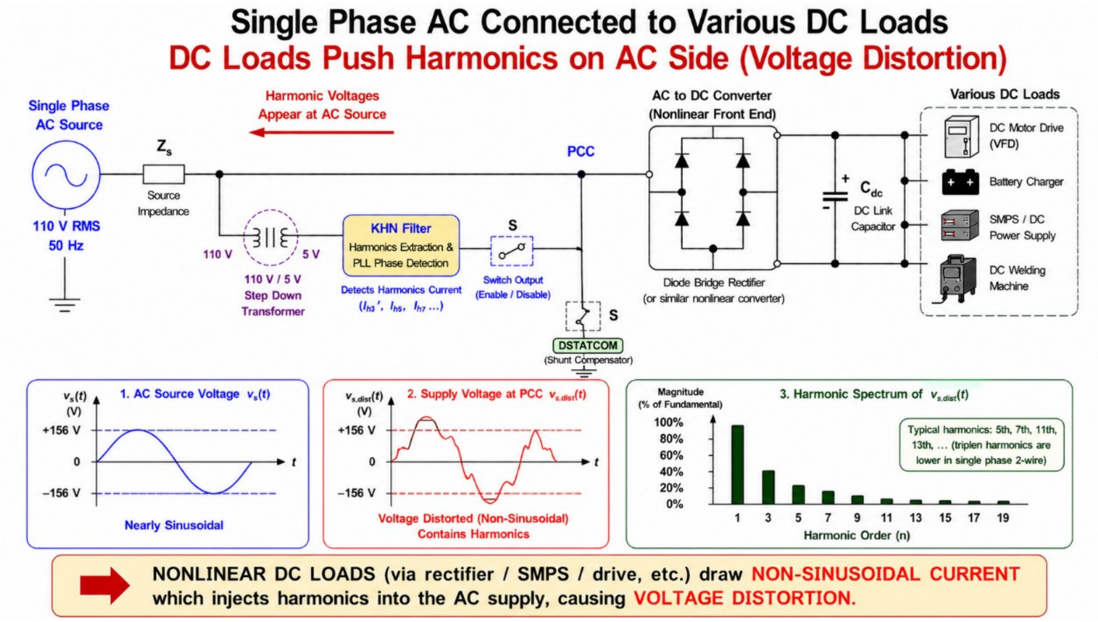

Fig. 1.1 Single phase AC grid fed various DC load
(Harmonics accelerates on source side)

Power quality issues can be categorized in terms of whether the problem is due to transient or steady state situations, the load-side problem or on the supply side depending on which there is variation in voltage, current, and frequency because of a number of reasons. Transient conditions include voltage flicker and short-term disturbance in voltage or current [7] [8]. Steady state condition includes long-term disturbance in voltage and harmonic current. Power quality problems in supply systems are generally due to voltage and current disturbances depending on the load connected to the grid [9].

This work deals with the design and implementation of a KHN state-variable filter for grid signal conditioning and integration. The KHN filter isolates the grid's fundamental component and suppresses unwanted harmonics, noise, and disturbances. Its tunable parameters improve adaptability to evolving grid conditions, offering distinct lowpass, band-pass, and high-pass outputs for robust signal extraction [1].

The proposed system couples the KHN filter with a grid-interface module and control algorithms in order to derive clean in-phase and quadrature components necessary for synchronization, power calculation, current regulation, and feedback control loops. By delivering stable amplitude and precise phase information, the KHN-based conditioning stage enhances PLL precision, reduces estimation errors, and improves the robustness of power electronic converters against disturbances in the grid.

1.2 State of The Art on Single Phase AC Grid

Synchronization between two grids is an indispensable need in modern power systems, especially with regard to renewable energy incorporation, grid-tied converters, microgrids, and Distributed Energy Resources (DERs). The process of synchronization makes power transfer smooth, accurate frequency locking, voltage regulation, and proper functioning of the converters possible. Historically, the process of grid synchronization has been carried out through traditional Phase-Locked Loop (PLL) approaches like the Synchronous Reference Frame PLL (SRF-PLL) and Second Order Generalized Integrator (SOGI)-based PLL methods due to simplicity of design and reasonable performance when operating at nominal conditions. These synchronization techniques have been widely employed in grid-tied power electronic systems for detecting the phase and estimating the frequency, as well as for controlling the converters.

The PLL systems suffer from problems related to poor harmonic rejection, inaccurate phase detection, slower transient response, and instability in synchronization when working in distorted grids. The increase in nonlinear devices, power electronics, and other renewable energy sources makes the problem worse by causing disturbances and harmonics in the grid. Therefore, there exists a requirement for better synchronization techniques that can sustain the PLL system under any type of grid condition.

One of the methods suggested in some of the literature studies is using the Kerwin-Huelsman-Newcomb (KHN) state-variable filter in the PLL system [6]. It is worth mentioning here that one of the major advantages offered by the KHN state-variable filter is that it generates accurate quadrature signals along with harmonic rejection. Besides, another advantage offered by the filter is that it allows controlling some of the important characteristics of the filter, such as the natural frequency, damping ratio, and gain independently [7].

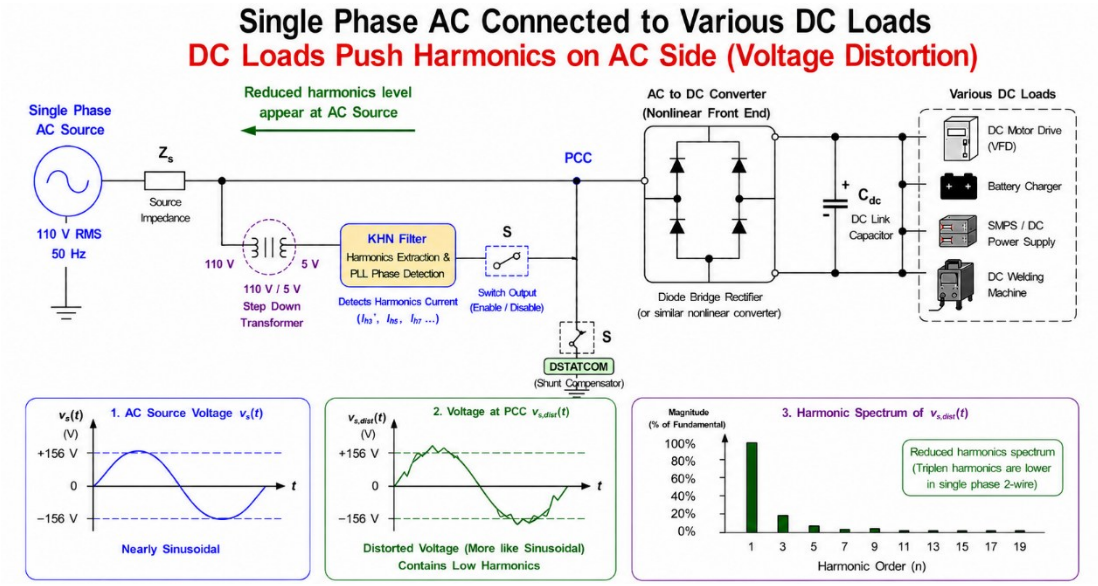

Fig. 1.2 Single phase AC grid fed via KHN filter to various DC load

(Distorted Voltage waveform filter out/gets cleaner AC line)

PLL using KHN can precisely measure the fundamental grid voltage component and also estimate the phase values even in the presence of harmonics and frequency variations, among others [8], [9] [10]. In addition, when the KHN filter is combined with the algorithms for controlling the grid interface, it becomes possible to produce highly accurate in-phase and quadrature signals for use in applications such as synchronization, power calculations, and converters, thus resulting in high performance [10].

Various simulation and laboratory experiments indicate that PLL utilizing KHN filter performs significantly better than the traditional PLL approach based on SOGI in terms of suppressing harmonics, phase tracking, disturbances rejection, and fast dynamics [7]. Hence, the KHN filter-based PLL system emerges as an efficient and reliable technique for synchronization in a variety of applications, including smart grids and microgrids.

1.3 Objectives of Present Work

The main objective of the thesis is to design a KHN state variable filter based Grid PLL system that can improve the phase synchronization performance for electrical grids in situations where there are disturbances like harmonic distortion, frequency deviation, and weak grids. In normal situations, the PLL systems cannot give appropriate responses or harmonic distortion resistance, especially when the input voltage is distorted, because their functionality relies on either pre-filters or digitally designed filters. The KHN filter, because of its properties, including the state-variable representation, built-in quadrature generation [8], and individually controlled natural frequency and damping factor, provides an organized method for improving the signal conditioning operation within the PLL system. This thesis aims at utilizing these properties to improve synchronization mechanisms for grid power converters [13], [14]. The objectives of the study are mentioned below: -

A proper KHN state variable filter needs to be developed and designed for the specific purpose of grid synchronization with the optimal natural frequency, damping ratio, and gain configuration that would enable the extraction of the fundamental frequency component from the grid voltage and suppression of harmonics and other sources of noise [12] [17].

i. In order to employ KHN Filter as the front-end conditioning of the PLL so that the PLL's ability in phase detection can be enhanced when used in a distorted and unbalanced power grid system in order to precisely create orthogonal components [6] [8].
ii. A dynamic analysis of the proposed KHN-assisted PLL needs to be done based on its state equations, small signal modeling, and transfer function to evaluate the stability margin and bandwidth limitation [16].
iii. The performance characteristics such as tracking performance, transient performance, and harmonic detection capability of the proposed KHN-PLL are under different grid disturbances, such as voltage sag/swell, frequency jump, harmonic injection, and unbalanced condition, which may occur in a microgrid environment [2].
iv. For comparing the performance of the suggested PLL system with other popular architectures such as SRF-PLL, SOGI-PLL, and MSOGI-PLL [5], emphasizing quantitative aspects such as phase error under distortions, settling time, harmonic rejection capability, and robustness to grid impedance changes.

Simulation will be carried out in order to validate the design concept proposed in the previous sections. This will be instrumental in showing the quantitative advantages of the KHN assisted PLL, especially in terms of disturbance tolerance, stability, and synchronization accuracy [10] [16].

1.4 Scope of Work

These distortions in the grids pose difficulties for the synchronizing methods which are based on the PLL concept. The conventional PLL method does not yield correct estimates for the phase and frequency because the harmonics in the second, third, and fifth order impact the wave shape. In addition, white Gaussian noise reduces the accuracy of the signal making the phase angle predictions inaccurate. The dynamic variation caused by frequency deviation between $49Hz$ and $51Hz$ continuously changes the PLL oscillator. This could result in a poor convergence rate and eventually tracking failure especially when dealing with the weak grids. The voltage sag and voltage swell of 20% each create abrupt changes in amplitudes causing temporary disturbance in the feedback control process of the PLL phase detector. These problems become even more serious when using microgrid whose grid impedance is quite high. Therefore, there is a need to determine the performance of SOGI-PLL and KHN-PLL.

1.5 Outline of the Thesis

Chapter 1: Introduction

The need for proper synchronization of the grid system due to its increasing demand in modern power electronics systems is discussed in detail in this chapter. Apart from that, various problems associated with synchronization such as voltage distortion, harmonics, frequency variation, dc offset, and instabilities in weak grids are explained in this chapter. Moreover, the objective of the study as well as its significance is discussed in this chapter.

Chapter 2: Literature Review and Existing Synchronization Techniques

In this chapter, a comprehensive literature review shall be done with respect to the works already carried out on synchronization techniques and signal conditioning. In particular, the limitations that exist in conventional methods, such as poor harmonic rejection, sluggish dynamic response, parameter dependence, and lack of robustness in case of distortion in the grid shall be considered. Why there is a need for an improved method shall be explained.

Chapter 3: Modeling and Analysis of the ‘SOGI and KHN Filter’

The current chapter forms the theory behind the Kerwin-Huelsman-Newcomb (KHN) state-variable filter, which includes the structure of the system, the mathematics involved, transfer functions, and the procedure used to set the tuning of the parameters. Besides this, there is a discussion on the importance of the simultaneous use of low-pass, band-pass, and high-pass filters in order to achieve selective filtering of the signals. Furthermore, it will be seen how the KHN filter is used in the grid interface system to generate pure in-phase and quadrature signals.

Chapter 4: System Implementation and Performance Analysis of Control Algorithms

This chapter will focus on the actual implementation of the suggested design of the KHN filter and will analyse its results in terms of simulation and experiments in a scenario where the grid suffers from harmonic distortion, variations in frequency, voltage sag/swell, and disturbance due to noise in the grid. Comparative analysis with other conventional filters, along with the SOGI technique of PLL estimation, has also been carried out.

Chapter 5: Conclusion and Future Work

The conclusions presented in this chapter consist of a review of some of the key findings that emerged from the study, as well as an analysis of the potential advantages associated with utilizing the KHN approach in ensuring grid synchronization, managing inverters, operating microgrids, island detection, and incorporating DERs. Suggestions for further studies are proposed in relation to software realization of the algorithm, hardware optimization of the same, and integration of the KHN filter with PLLs.

CHAPTER 2

LITERATURE SURVEY

2.1 General Aspects

The KHN filter is one that has extensively studied in the domain of analog filters, and which has the characteristics of a second-order state variable filter or biquad filter [11]. Because of its design, whereby the signal is filtered by using a summing amplifier followed by two stages of integration, it becomes possible for the filter to produce both the low pass, band pass, and high pass signals at the same time from a single input [12] [13]. The centre frequency 'wo' is determined by the time constants of RC network, while the gain of the summing amplifier provides the necessary feedback to determine the quality factor '*Q*'.

Researches on KHN filters have demonstrated how versatile the topology is in a number of applications that range from low-frequency filtering to biological signal conditionings, audio processing, and instrumentation [12]. Researchers also proposed improved variants of the KHN filter with a view to enhance stability, reduce component sensitivity, and extend the operating bandwidth, such as the current feedback implementations, grounded-capacitor designs, and current-mode realizations. Together, these demonstrate the strength and maturity of the KHN filter as an architecture with great potential for problems relating to the extraction of precise signals. In spite of its maturity, the prospective application of a KHN filter in power-system synchronization is still scant in the literature. Extra data provided by LP/HP outputs are useful for grid monitoring, while BP output generated by the KHN naturally isolates a fundamental sinusoidal component by attenuating harmonics [13] [14]. These intrinsic characteristics tend to indicate that the KHN filter could provide a better input signal for PLL operation, particularly in situations where the grid is weak or distorted.

2.1 Challenges of Grid Synchronization in Distorted Grids

Synchronization with the grid has become an indispensable need in current power systems, especially in applications such as grid-tied inverters, incorporation of renewable sources of energy, and microgrids [6]. Nonetheless, keeping track of accurate synchronization has become an even greater challenge when the grid is operating in distorted conditions and is undergoing dynamic changes in real-time. Nonlinear loads, inverter-interfaced Distributed Energy Resources (DERs), switching converters, and system reconfiguration have been responsible for the creation of disturbances within modern power networks [8]. Therefore, the voltage profile of the grid is affected by harmonic distortion, noise, and transient phenomena, affecting the performance of synchronization systems employing PLLs.

Low-order harmonics like those at the second, third, fourth, and fifth order affect the waveform shape and introduce substantial phase and frequency errors. As PLLs depend on correct waveform data to establish phase synchronization, this will adversely impact the accuracy of the phase detection function and lead to oscillation in the feedback control system. Moreover, voltage irregularities like sagging, swelling, switching events, and load change events lead to instantaneous fluctuations in signal amplitude and waveform. Besides that, frequency variations and poor grid operation make synchronization difficult due to constant changes in the internal oscillator.

To make sure that reliable operation is achieved in such an environment, the pre-filtering stage of the PLL needs to be equipped with high harmonic rejection capabilities, low sensitivity to electrical noise, minimal phase shift on the fundamental frequency component, and rapid response to transients [3] [4]. Clearly, this highlights the importance of designing complex filters that can offer better signal conditioning. This has resulted in interest being shown in various filters other than the SOGI-based filtering approach, like the KHN state variable filter.

2.2 SOGI-Based PLLs: Advantages and Drawbacks

Due to its capability to generate orthogonal (α–β) components from a single-phase voltage for SRF detection, SOGI-PLLs have been widely adopted. The bandwidth and filtering characteristics can be tuned due to its adjustable gain parameter. Extensive literature deals with variants of SOGIs, namely modified SOGIs, adaptive SOGIs, and SOGI-FLL structures that attempt to improve frequency tracking and robustness under dynamic conditions. SOGI is a reliable benchmark because several works prove that SOGI-PLLs work properly under medium distortion [3] [4]. The effectiveness of the SOGI technique in comparison purposes is well established since various studies have demonstrated the feasibility of implementing SOGI-based PLLs under moderate levels of distortion. Transient behaviour when faced with hard sags, swells, and frequency steps is far from satisfactory, while the trade-off between bandwidth and selectivity leaves much to be desired regarding harmonic rejection performance. In response, attempts have been made to improve SOGI characteristics; however, in essence, this structure has fundamental limitations due to its single-resonant nature [4].

2.3 Comparative Results and Determined Research Gaps

Though the KHN has many attractive features as a PLL prefilter-including high selectivity, minimal phase error, numerous output possibilities, and defined *Q* factor control-no scholarly work has been published on how effective the KHN filter is in the realm of grid synchronization. Most publications about the KHN deal either with its general purpose or its stability. Thus, the topic of its effectiveness in grid PLLs remains largely unaddressed. Although SOGI-based PLLs, on the other hand, have been investigated more thoroughly, their deficiencies under extreme distortion suggest that alternative approaches are needed.

One glaring research gap is that there are no comparative data available on the performance of KHN-prefiltered PLLs and SOGI-PLLs for realistic microgrid scenarios of high THD, noise, frequency drift, and sag/swell disturbances. In any case, quantitative measurement of variation in performance through systematic simulation and hardware verification is needed on account of: -

i. Phase and frequency tracking accuracy.
ii. THD reduction and harmonic attenuation.
iii. Dynamic reaction and settling time.
iv. The capability of noise rejection.
v. Robustness under conditions of a weak grid.

By carrying out an in-depth performance evaluation of SOGI and KHN filters within PLL structures under various different distorted grid situations, this thesis fills that gap.

2.4 Summary

Among the extensive existing literature, it can be seen that SOGI-based PLLs are indeed used widely today but fail to show better performance under highly distorted or weak-grid conditions. Extensive literature has shown that while SOGI-based PLLs are widely used today, they give poor performance in highly distorted or weak-grid conditions. This makes it possible to investigate if KHN filtering can improve PLL robustness in microgrid and smart-grid systems. In this paper, this investigation is conducted through a comparison analysis and in-depth simulation.

CHAPTER 3

MODELING AND ANALYSIS OF ‘SOGI AND KHN FILTER’

3.1 General

The Phase Locked Loop techniques developed for synchronization of single-phase non-ideal and weak grids are discussed. Further, the performance is tested under several grid disturbances like distorted grid conditions, voltage sag, voltage swell, frequency change, phase change, and DC offset. The effectiveness of the proposed PLLs in steady state and dynamic conditions is studied in Matlab-Simulink and through hardware prototype developed in the laboratory under several grid conditions. The unit template-based scheme can be realized as the simplest PLL but does not work well under distorted grid conditions. Hence, there is a need to design, develop and test new synchronization techniques for their effectiveness. several grid disturbances are utilized to test the performance: DC offset, frequency shift, phase shift, voltage sag, and voltage swell. Even though the unit template-based approach is the most straightforward PLL, its performance is poor in situations in which the grid is deformed. Therefore, new synchronization mechanisms must be designed, developed, and tested for efficacy.

3.2 Mathematical Analysis of PLL Schemes

This section covers the mathematical analysis of different conventional and adaptive PLL techniques that are designed to generate filtered voltage and sinusoidal unit template in weak grid conditions and detect the phase angle accurately.

3.2.1 Second Order Generalized Integrator (SOGI) PLL

Using a quadrature signal generator, SOGI-PLL functions as an adaptive pre-filter to produce in-phase ($V_s{}'$) and in-quadrature ($qV_s{}'$) signals. Figure 3.1 displays the SOGI PLL control diagram. The transfer function, which has the characteristics of a band pass and low pass filter, connects the two outputs ($v_s{}'$) and ($qv_s{}'$) as follows [3]:

$$V_{s\alpha}(S) = \frac{V'_s}{V_s} = \frac{Kws}{s^2+Kws+w^2} \qquad 3.1$$

$$V_{s\beta}(S) = \frac{qV'_s}{V_s} = \frac{Kw}{s^2+Kws+w^2} \qquad 3.2$$

where 'K' determines the filtering capability and influences the bandwidth of the closed loop system. A low value of "K" results in a narrower bandwidth and a slower dynamic response.

For improved performance, the SOGI filtered signals $V_{s\alpha}, V_{s\beta}$ are now supplied to the SRF-PLL Fig. 3.1 depicts the complete scheme. Two feedback loops in a cascade make up the SOGI PLL; for example, the QSG (Quadratic Signal generator) gives the frequency and phase angle to the Park transformation block [7].

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \begin{bmatrix} sinwt & -coswt \\ coswt & sinwt \end{bmatrix} \qquad 3.3$$

The PLL is locked to the input phase angle and the detected frequency is tuned and made adaptive by feeding the frequency back to the SOGI-QSG [3] [4] [8]. To obtain the equal component of in-phase and quadrature components, the center frequency matches the input frequency.

The bandwidth of both the filters (Band-pass and low pass Filter) is controlled by Gain "K," which is connected to the settling time 't_s' and may be calculated by: -

$$K = \frac{9.2}{t_s * w} \qquad 3.4$$

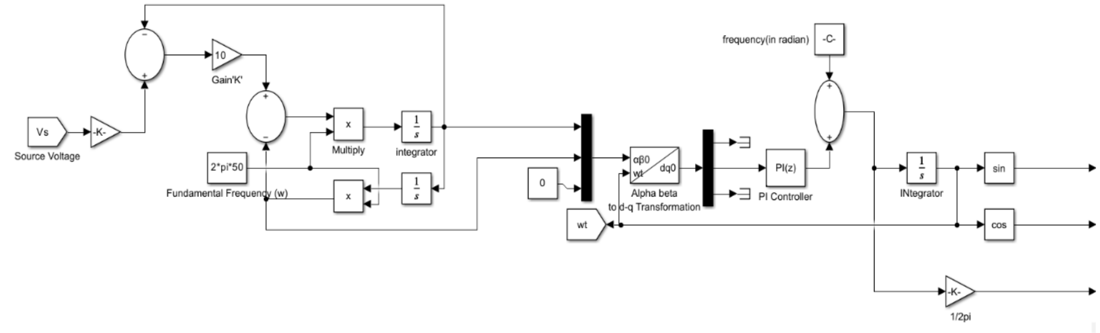

Fig. 3.2.1. Block Diagram of simple SOGI PLL

The fundamental sinusoidal component, harmonic distortion, random noise, amplitude fluctuations, and frequency drift are all combined to create the input grid voltage. The whole model can be expressed as:

$$V(t) = V_m \sin(wt + \emptyset) + \sum H_n \sin(nwt) + n(t) \qquad 3.5$$

where:

- H_5, H_7, and H_{11} will denote the amplitudes of the fifth, seventh, and eleventh harmonics respectively, which are predominant in inverter dominated microgrids.
- White Gaussian noise or n(t) is utilized in order to simulate sensor noise and inverter switching effects.
- In particular, the grid operating frequency dynamically changes between 49 and 51 *Hz* for testing weak-grid or islanding events.
- Injecting sag and swell disturbances (10–30% amplitude dip or increase) can be a representation of common grid faults.
- This combination guarantees that the PLL is tested under realistic and challenging power-quality disturbance conditions.

3.2.2 Kerwin-Huelsman-Newcomb Algorithm (KHN-Filter)

A second-order state-variable biquad filter, the Kerwin–Huelsman–Newcomb (KHN) filter simultaneously produces three outputs: -

- Band-Pass (BP) used for basic extraction of signal to PLL.
- Low-Pass (LP) can be used to detect the amplitude and DC.
- HP (High-Pass) used for harmonic and transient monitoring.

This triple-output feature of the KHN filter is extremely useful for PLL-based grid synchronization [14].

KHN Filter Configuration: -

a) A single summing amplifier.
b) Two cascaded integrators.
c) Gain '*K*' that can be adjusted to adjust the quality factor (*Q*).

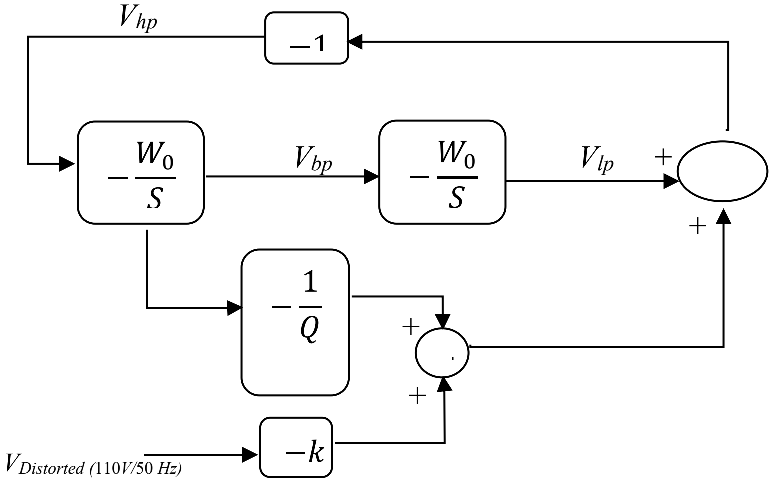

Fig. 3.2.2. Single Line Diagram in Laplace Domain of KHN Filter.

Let V_{in} be the input.

The output transfer functions are given below: -

Band-Pass Output

$$V_{BP}(s) = \frac{\frac{s}{w_0}}{\left(\frac{s}{w_0}\right)^2 + \frac{\left(\frac{s}{w_0}\right)}{Q} + 1} V_{in}(s) \tag{3.6}$$

Low-Pass Output

$$V_{LP}(s) = \frac{1}{\left(\frac{s}{\omega_0}\right)^2 + \frac{\left(\frac{s}{\omega_0}\right)}{Q} + 1} V_{in}(s) \tag{3.7}$$

High-Pass Output

$$V_{HP}(s) = \frac{\left(\frac{s}{\omega_0}\right)^2}{\left(\frac{s}{\omega_0}\right)^2 + \frac{\left(\frac{s}{\omega_0}\right)}{Q} + 1} V_{in}(s) \tag{3.8}$$

The standard expression of the KHN Filter is given in standard form as: -

$$H(s) = \frac{ps^2 + qs + r}{s^2 + bs + a} \qquad 3.9$$

The requirements for different filters are: -

$$\begin{cases} \text{P = q = 0} \rightarrow \text{low-pass filter} \\ \text{q = r = 0} \rightarrow \text{high-pass filter} \\ \text{p = r = 0} \rightarrow \text{band-pass filter} \\ \text{q = -pb, r = pa} \rightarrow \text{notch filter} \end{cases}$$

The real component of v_{actual} is calculated from the KHN filter by the equation shown below [16]: -

$$V_{actual} = \sqrt{(V_{bp})^2 + (V_{lp})^2} \qquad 3.10$$

It is necessary to match the frequency of KHN to the input supply frequency and the Quality Factor (*Q*) for the optimum value. The value of gain '*K'* is set by trial-and-error method to achieve the optimum result.

Tuneable Parameter Interpretation

(a) Natural Frequency (w_0)

Specifies the centre frequency at which the signal with the highest magnitude passes through the band-pass filter. This is aligned with grid standards at 50 *Hz*.

(b) *Q*, the Quality Factor

Controls selectivity and bandwidth:

- Greater bandwidth will lead to faster transient response or (*Q* = 5).
- while for stronger harmonic rejection, the bandwidth is kept narrow or (*Q* = 10).

This tunability lets the researcher evaluate PLL behaviour under different filtering conditions.

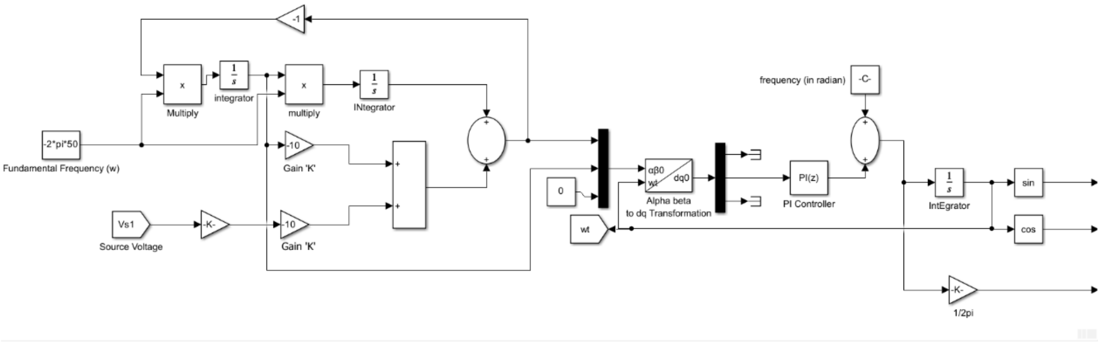

Fig. 3.2.3. Block Diagram of KHN Filter of Grid PLL

3.3 Simulation Result of SOGI-PLL

Mitigation of voltage-based power quality disturbances present in the system in terms of weak grid conditions, including voltage sag, swell, DC offset, phase change and frequency change conditions, are discussed in the below section by using the designed SOGI-PLL.

For the voltage sag/ swell of 20%, presented in Fig. 3.3.1 and 3.3.2 respectively, it can be seen that the Voltage (V_s) is estimated accurately within 2 cycles, and the synchronization templates θ and $sin\theta$ are well tracked. The frequency disturbance is minimal; after that, the frequency converges to 50 Hz.

For harmonics in the grid voltage of 20% in terms of frequency in the range of 0.4 s to 0.5 s in Fig. 3.3.3, it can be seen that there are minimal oscillations in (V_s) and frequency. However, the phase angle θ tracks perfectly. The sine wave template $sin\theta$ obtained is accurate.

With 20% DC offset in the supply voltage as in Fig. 3.3.4, tracking of (V_s) and frequency can be seen. There are very small oscillations in vsd and tracking frequency. The θ and $sin\theta$ are also tracked correctly.

For the phase change introduced as 30° in the grid voltage as in Fig. 3.3.5, a significant deviation of voltage vsd has been observed along with frequency, which comes down to 50 Hz after 5 cycles. Proper synchronization templates, i.e., θ and $sin\theta$, have been tracked correctly after 2.5 cycles, and $sin\theta$ matches perfectly with the grid voltage.

In the case of frequency variation of 2 Hz (from 50 Hz to 52 Hz) of grid voltage introduced in Fig. 3.3.6, it is observed that there is a significant drop in the magnitude of voltage and frequency. Oscillations in (V_s) and frequency are also observed, and it finally settles after 2.5 cycles. Proper synchronization templates are generated after 2.5 cycles.

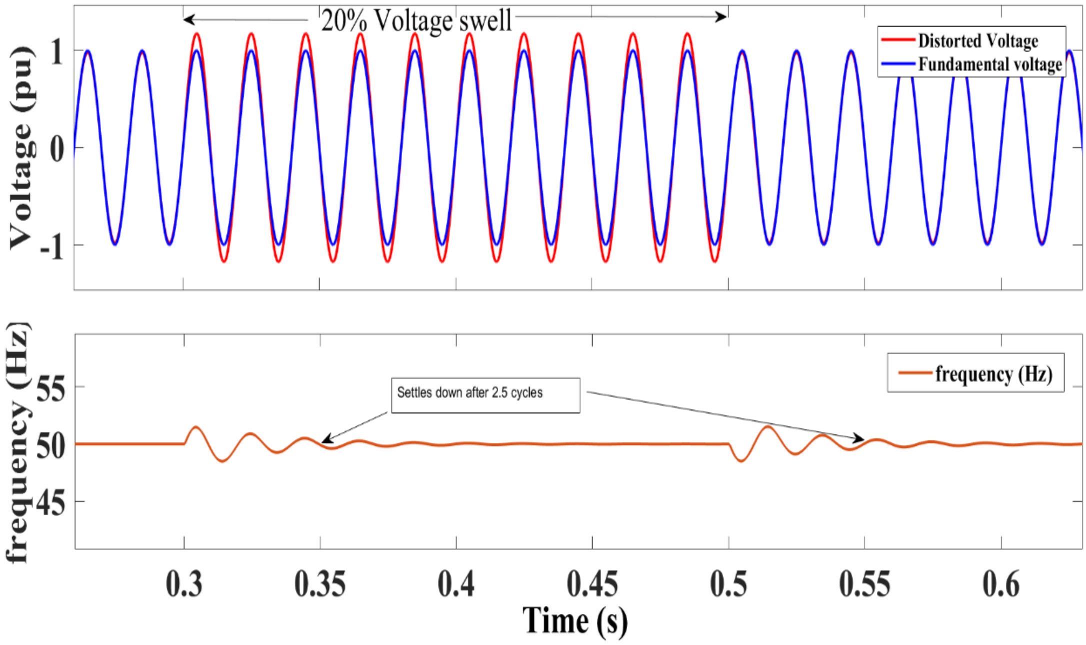

Fig. 3.3.1 Simulation Result (a) voltage swell of 20% of SOGI-PLL

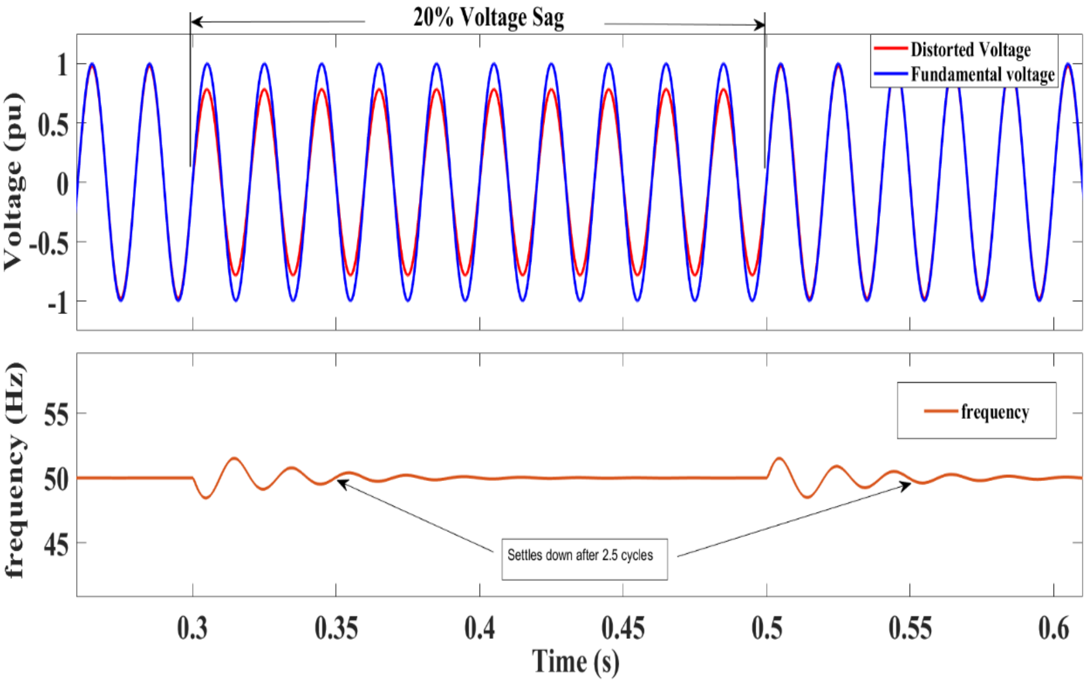

Fig. 3.3.2 Simulation Result (b) voltage sag of 20% of SOGI-PLL

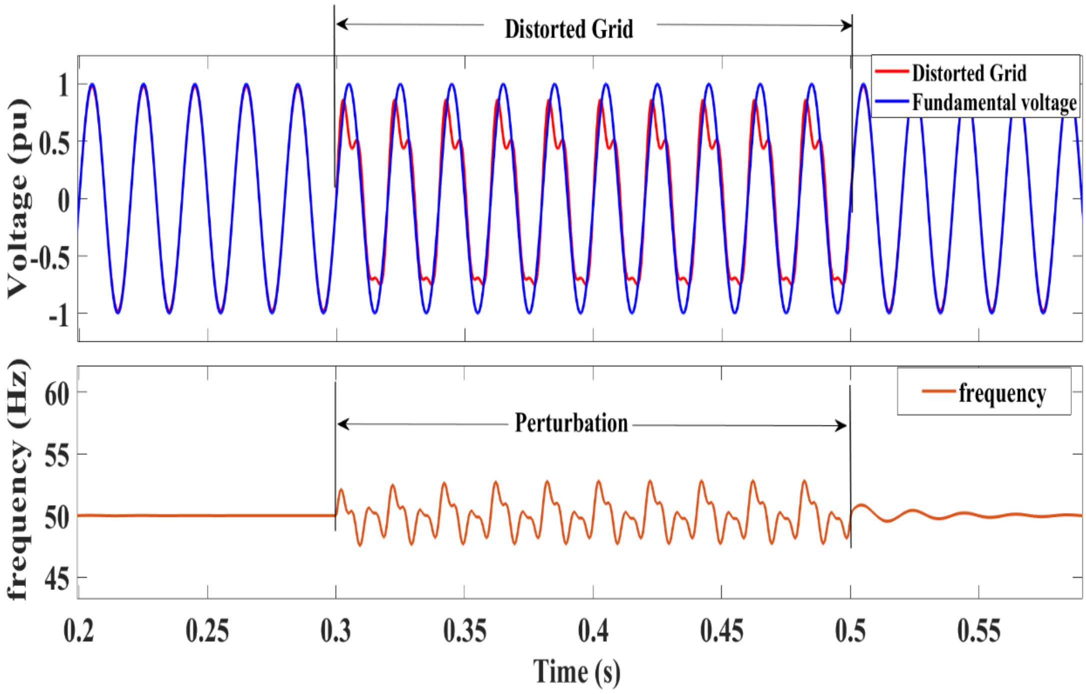

Fig. 3.3.3 Simulation Result (c) 20% DC offset of SOGI-PLL

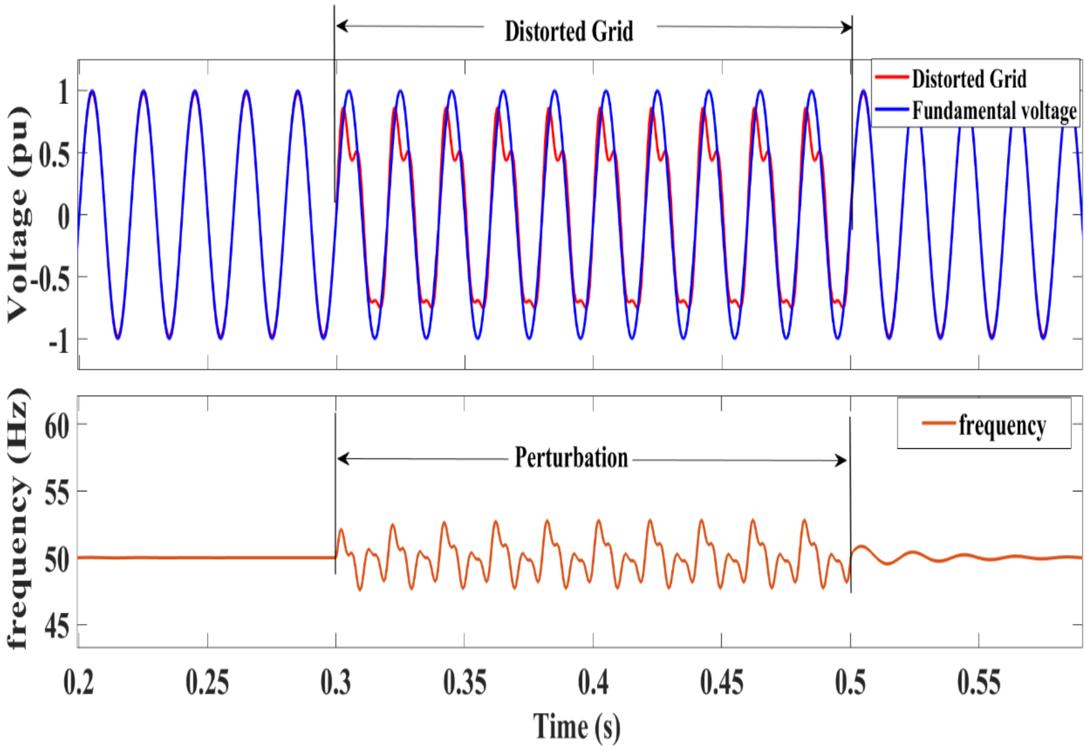

Fig. 3.3.4 Simulation Result (d) Distorted Grid of SOGI-PLL

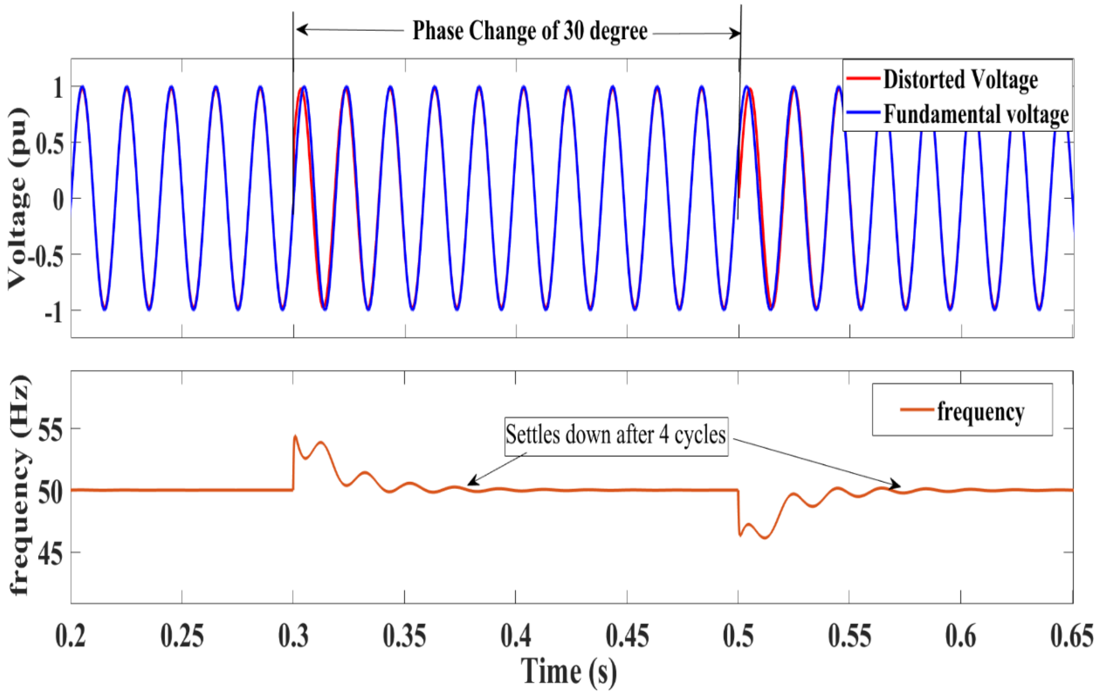

Fig. 3.3.5 Simulation Result (e) phase change of 30º of SOGI-PLL

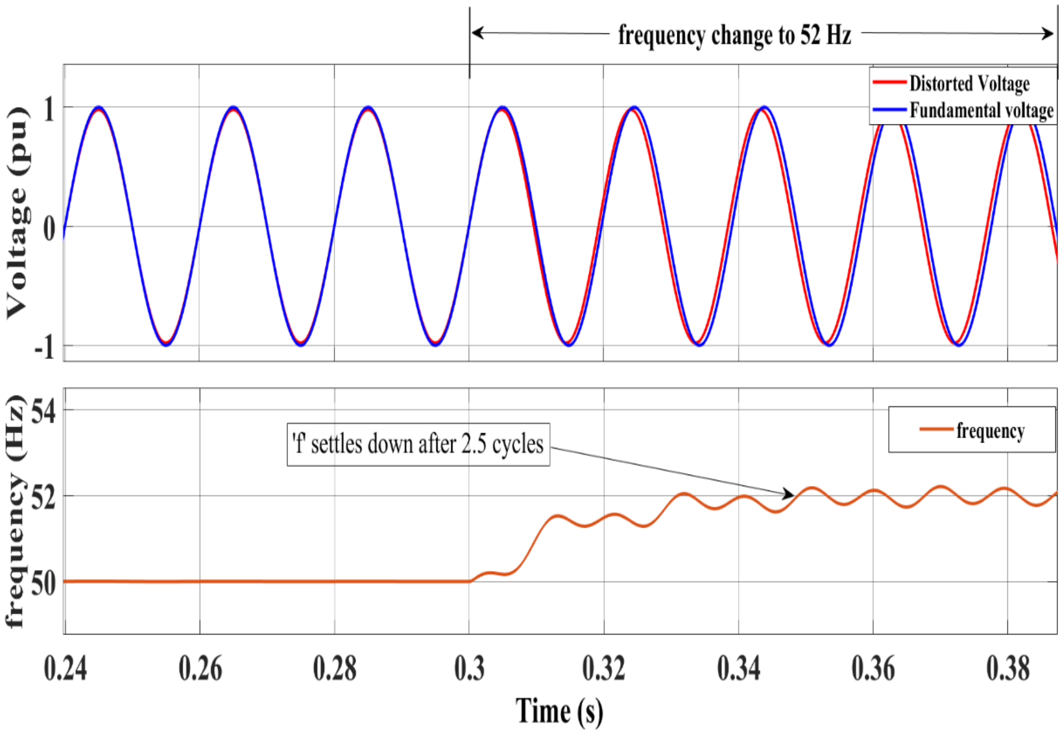

Fig. 3.3.6 Simulation Result (f) frequency change to 52Hz of SOGI-PLL

3.4 Simulation Result of Kerwin-Huelsman-Newcomb Algorithm (KHN Filter) PLL

The section below discusses the use of designed KHN-PLL to mitigate voltage-based power quality issues that arise in weak grid conditions, including voltage sag, swell, DC offset, phase change, and frequency change.

The Voltage (V_s) is accurately determined within two cycles and the synchronizing $sin\theta$ are accurately tracked under the 20% voltage sag and swell of 20% depicted in Figs. 3.4.1 and 3.4.2. The frequency fluctuates very little before settling at 50 Hz.

Under harmonics (20%) in grid voltage from 0.2s to 0.3s shown in Fig. 3.4.3, the little oscillations in (V_s) and frequency are observed. The phase angle θ is perfectly tracked. The obtained unit-in phase template $sin\theta$ is exactly sinusoidal.

With 20% DC offset in Fig. 3.4.4 in the supply voltage, tracking of (V_s) and frequency is observed. When compared to SOGI-PLL, the fluctuations in (V_s) and tracked frequency are extremely small.

A significant divergence in voltage vsd and frequency is seen during a 30° phase change in the grid voltage depicted in Fig. 3.4.5, which settles down to 50 Hz after five cycles. After 2 cycles, the synchronizing template, or $sin\theta$, is precisely tracked and in phase with the grid voltage.

It has been noted that there is a significant decrease in the predicted voltage and frequency during the $2Hz$ frequency adjustment ($50Hz$ to $52Hz$) added to the grid voltage in Fig. 3.4.6. After five rounds, the oscillations in voltage (V_s), and frequency stabilize. After 2 cycles, appropriate synchronizing templates are produced.

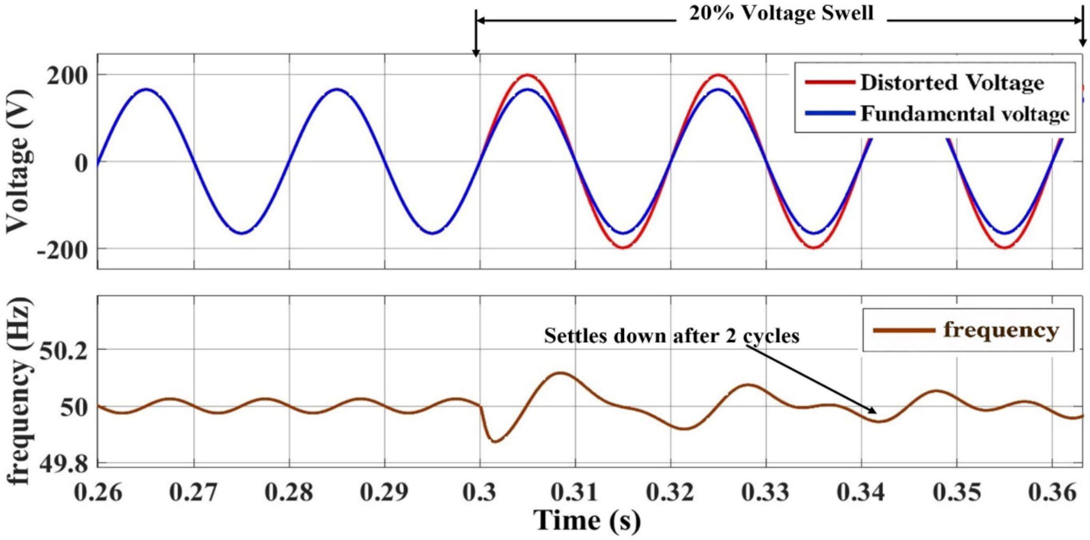

Fig. 3.4.1 Simulation Result (a) voltage swell of 20% of KHN-PLL

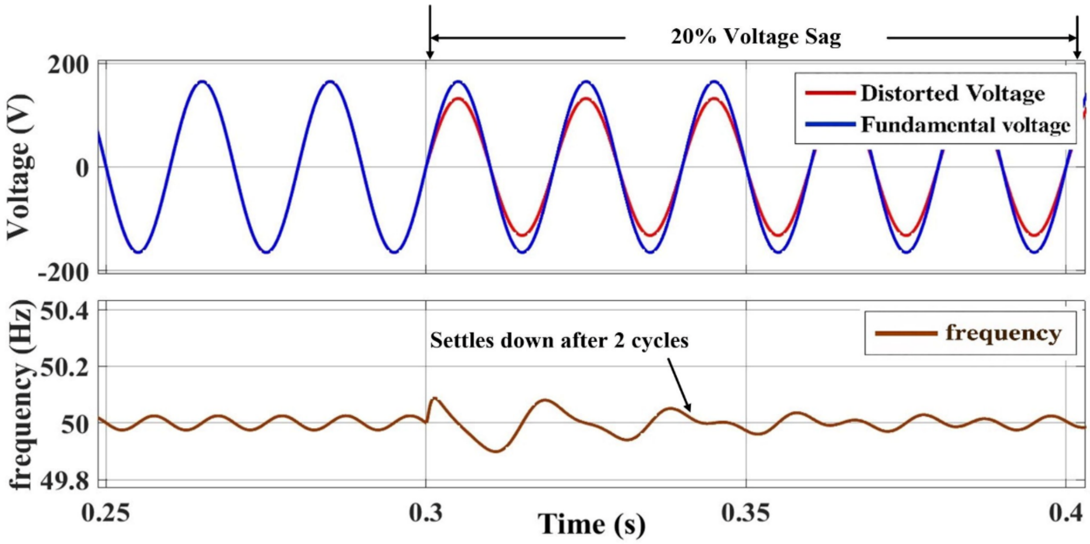

Fig. 3.4.2 Simulation Result (b) voltage sag of 20% of SOGI-PLL

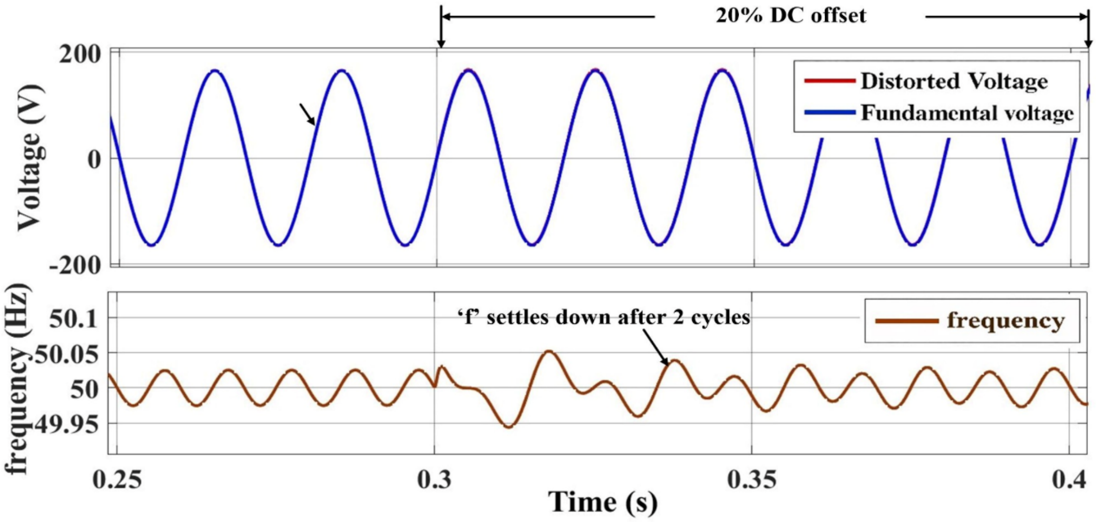

Fig. 3.4.3 Simulation Result (c) 20% DC offset of KHN-PLL

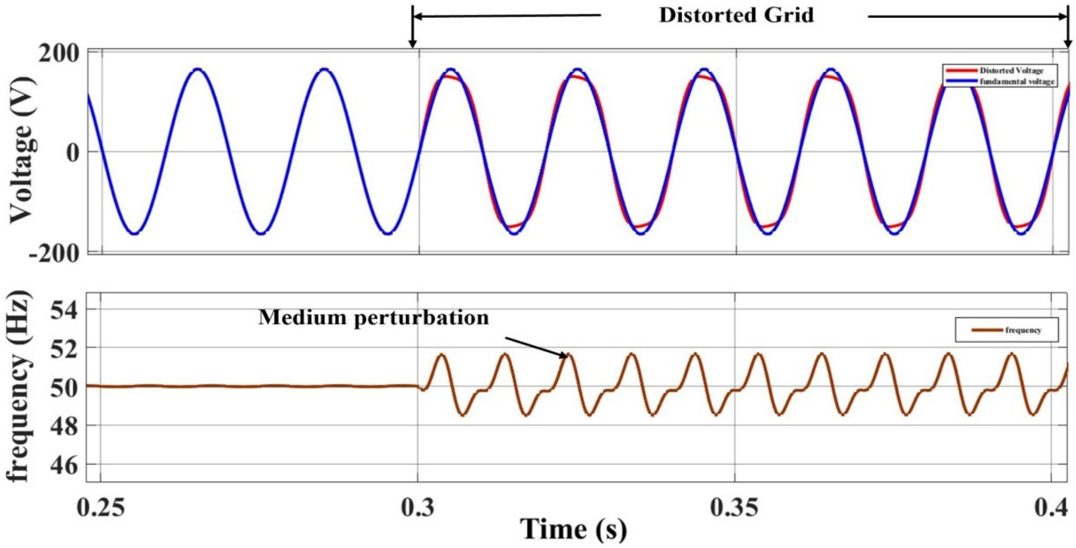

Fig. 3.4.4 Simulation Result (d) Distorted Grid of KHN-PLL

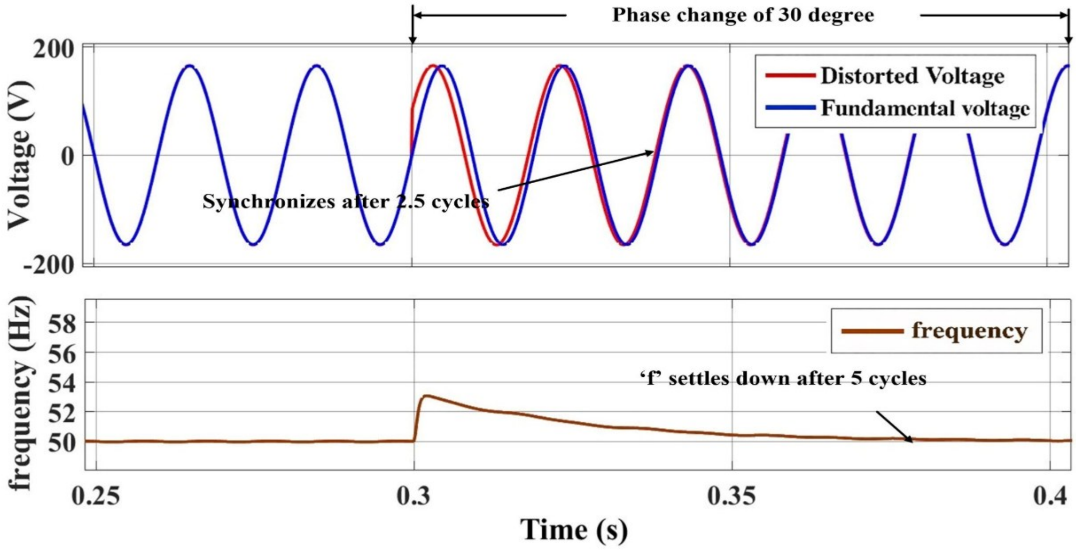

Fig. 3.4.5 Simulation Result (e) phase change of 30º of KHN-PLL

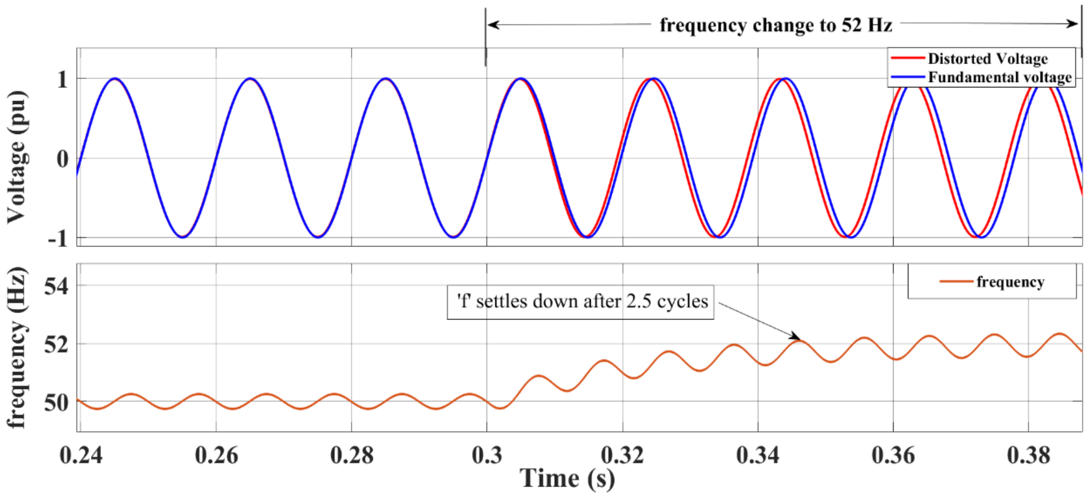

Fig. 3.4.6 Simulation Result (f) frequency change to 52Hz of KHN-PLL

CHAPTER 4

SYSTEM IMPLEMENTATION AND PERFORMANCE ANALYSIS OF CONTROL ALGORITHMS

4.1 General

A distorted single-phase 110 $V_{(rms)}$, 50 *Hz* sinusoidal supply with multiple harmonic components significantly affects the load and synchronization accuracy. The presence of harmonic distortions in the supply signal results in changes in the signal waveforms. The presence of harmonic distortions in the supply signal results in changes in the signal waveforms. The changes in the signal waveforms result in inaccuracy in the phase and frequency estimation of the PLL. The THD of the supply signal can be expressed as: -

$$\text{Total Harmonics Distortion (THD)} = \frac{\sqrt{\sum_{2}^{\infty} V_n^2}}{V_1} \tag{1}$$

Where V_1 represents the fundamental component and V_n represents the n^th harmonic component.

The filtered signal ensures improved quality of the reference signal used in the control of the voltage, ensuring that the supply voltage is nearly sinusoidal in nature. The THD of the voltage is significantly reduced, and hence the power factor is improved, ensuring that the system is in compliance with the power quality standards set by IEEE 519 [2], which defines the acceptable level of harmonic distortion in the voltage and current in electrical power systems.

4.2 Comparison Result of SOGI and KHN-PLL

During the weak grid conditions like voltage sag and swell, frequency shift, and grid voltage phase shift, evaluation results on the performance of SOGI and suggested KHN technique have shown below.

4.2.1 Voltage Swell

The voltage has risen to 20%, and the SOGI model and the KHN model are being compared. It has become clear that the KHN model performs better, as its results converge faster than those from the SOGI model.

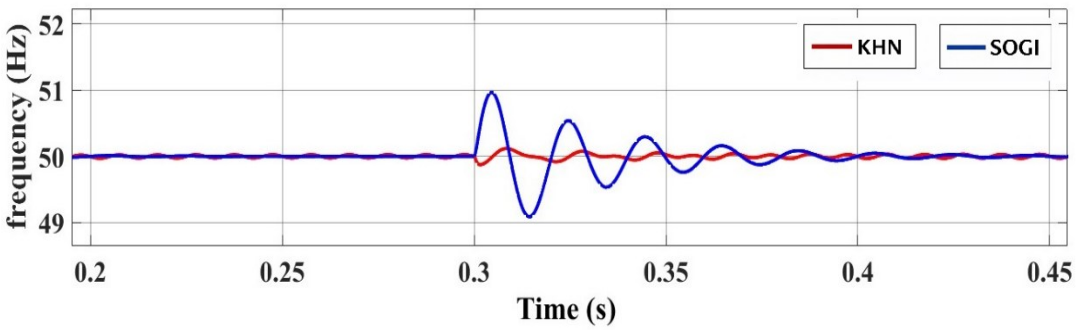

Fig. 4.2.1 Comparative Frequency Behaviour of KHN and SOGI during Voltage Swell

4.2.2 Voltage Sag

The decrease in voltage is 20%, and there is an analysis of the SOGI and KHN models. The result converges the same as voltage swell.

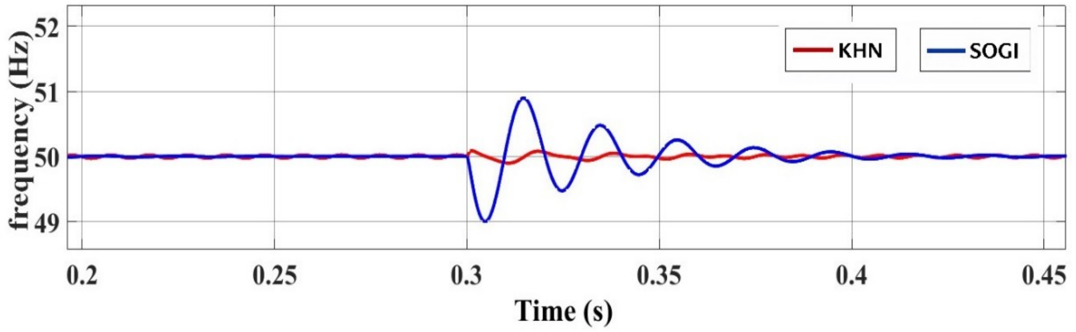

Fig. 4.2.2. Comparative Frequency Behaviour of KHN and SOGI during Voltage Sag

4.2.3 DC Offset

The effect of 20% DC on the peak-to-peak voltage of 156 *V* in the supply voltage is given in fig. 4.2.3. The maximum voltage increases from about 156 *V* to 187.2 *V*, and decreases to 124.8 *V* in KHN model. Frequency in KHN model initially slightly varying but it stabilizes itself after 2 cycles only while SOGI model continues oscillation.

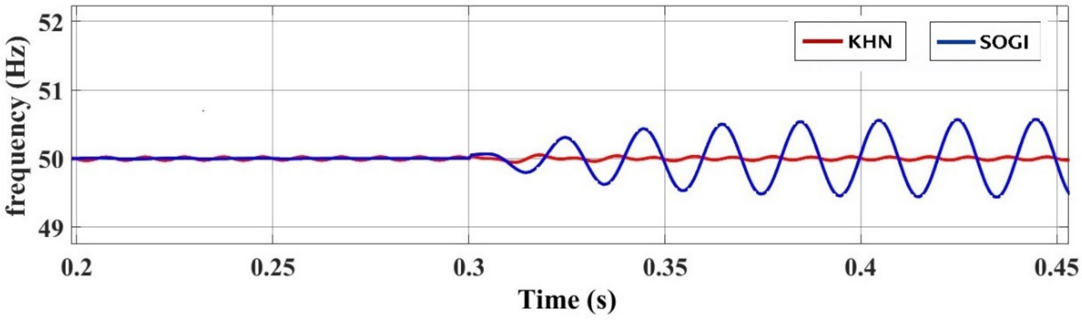

Fig. 4.2.3. Comparative Frequency Behaviour of KHN and SOGI in effect to DC Offset.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

Table 1: The Following Observation is based on The Above Simulation Results Comparing SOGI and KHN-PLL.

Performance Matric	**SOGI_PLL**	**KHN_PLL**
Phase error under (THD = 20%)	4°– 7° (increases with distortion)	1° – 3° due to selective BP filtering
Settling time (after sag/swell)	50 - 60 ms	30 - 40 ms
Noise Immunity (5% Gaussian noise)	Moderate (jitter observed)	Superior (Band Pass eliminates high frequency noise)
Response to Voltage Sag (20%)	Transient spike at PLL output	Controlled response (PI controller receives filtered Band-Pass)
Response to Voltage Swell (20%)	Overshoot more pronounced	Minimal overshoot
Complexity	Relatively simple (single -biquad block)	Slightly more complex (tuning ‘K’ & ‘Q’)
Analog Implementation	Widely used	Slightly sensitive to RC tolerances

Both KHN-PLL and SOGI-PLL exhibit high efficiency and reliability when used in grid synchronization applications despite distorted and changing operating environments. Nevertheless, upon careful comparison of the two systems, it becomes clear that KHN-PLL outperforms its counterpart, SOGI-PLL, in several ways. For instance, KHN-PLL gives higher accuracy in phase estimation, is more efficient when synchronizing, and generates lesser phase jitter. The state-variable form of the algorithm allows for the efficient management of perturbations, such as voltage sags, harmonics, zero sequences, and phase shifts.

While the SOGI-PLL receives commendation for its simple architecture and easy implementation, besides providing effective filtering of harmonics during stable states, it is quite slow in reacting to sudden changes or disturbances. However, in cases where there are abrupt variations such as those experienced in the case of inverters and rapidly changing grid networks, the KHN-PLL provides better adaptability and robustness. This is attributed to the flexible nature of the KHN filter, which can be designed to fit many operational parameters.

In conclusion, although both PLL algorithms have their strengths, the KHN-PLL's better dynamic response, reliability, and flexibility render it a much more desirable and effective selection for advanced phase lock loop applications within modern power grids.

5.2 Future Scope of Work

The design and mathematical model analysis of shunt compensation in single-phase and three-phase PV integrated grid-connected systems have been covered in the thesis work. The design and analysis of several phase-locked loop strategies in weak grid-connected systems are also covered. Additionally, grid-connected and islanding PV integrated battery systems are constructed and explored.

Matlab software was used in the development of the PV integrated systems. It is also possible to expand this work in hardware mode. It is possible to create and test new control algorithms for big interconnected systems, grid synchronization, and larger, multi-machine systems. As an extension of this thesis, stability features of various control algorithms can also be thoroughly examined.

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LIST OF PUBLICATION

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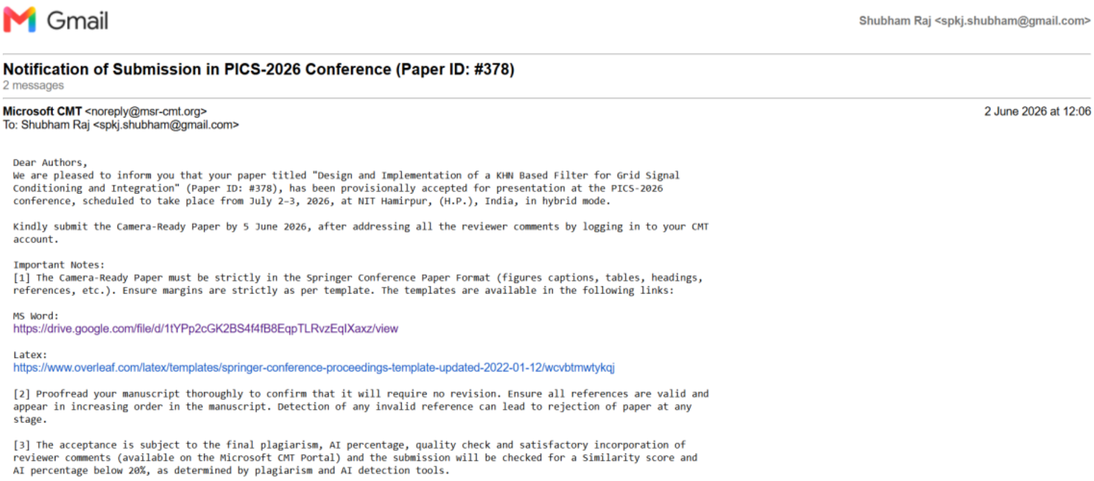

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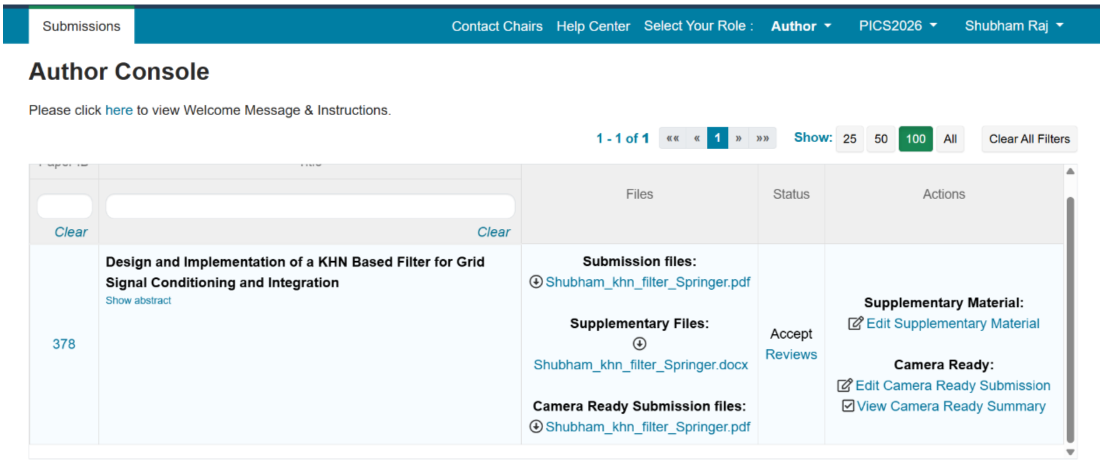

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