SYNCHRONIZATION OF SINGLE-PHASE INVERTER WITH GRID CONNECTION SYSTEM BY USING ENHANCED PHASE LOCKED LOOP METHOD

MUHAMMAD ZULKARNAIN BIN ABDULLAH

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University Tun Hussein Onn Malaysia

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For my beloved wife, mother, father and my children

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ABSTRACT

This project is describing the synchronization technique for synchronization of inverter voltage output with grid or Alternating Current (AC) voltage. With the synchronization technique, renewable energy that has been generated through multiple sources can be used in the grid and the lack of energy or the dependence on fossil fuels can be automatically minimized. In order to fulfill the demands, grid synchronization techniques play a vital and critical role in the control of single-phase system. In this project, for the purposes of synchronization in diverse fields, a Phase Locked Loop (PLL) has been widely used as a control system. Most importantly, this control system is also used in synchronizing the inverter output voltage with grid voltage. The PLL has been a subject of great interest due to its significant and many projects as well as their improvements have been recommended for its execution. In order to meet the objectives, Arduino is used to play as a major part on processing the grid value and at the same time generating the desired Pulse with Modulation (PWM) for the inverter to make the synchronization happened. This project presents an Enhanced Phase Locked Loop (EPLL) for single–phase inverter which generates the orthogonal voltage that is merely the same with AC source or grid system. As a result, it is proven that EPLL has significantly proved its topology as an adaptive filter that filtering phase angle to the desired angle that can makes the synchronization takes place.

ABSTRAK

Projek ini adalah mengenai teknik penyegerakan bagi menyegerakkan voltan output *inverter* dengan voltan grid ataupun voltan ulang alik (AC) yang lain. Dengan teknik penyegerakan ini, tenaga yang boleh diperbaharui yang dijana dari kepelbagaian sumber dapat digunakan di dalam sambungan grid dan secara automatik kekurangan tenaga dan kebergantungan kepada minyak fossil dapat diminimakan. Teknik penyegerakan dengan grid ini memainkan fungsi yang penting dan kritikal dalam mengawal penyegerakan sistem satu fasa bagi memenuhi permintaan. Dalam projek ini, *Phase Locked Loop* (PLL) adalah teknik kawalan yang digunakan secara meluas bagi penyegerakan di dalam pelbagai bidang dan terutamanya di dalam penyegerakan voltan output *inverter* dengan voltan grid. Atas signifikasi ini, PLL menjadi subjek yang diminati di dalam pelbagai bidang dan penambahbaikannya sentiasa dicadangkan bagi tujuan pelaksanaan. Bagi memenuhi keperluan objektif, Arduino memainkan peranan penting dalam memproses bacaan grid dan dalam masa yang sama menghasilkan *Pulse With Modulation* (PWM) yang dikehendaki oleh *inverter* bagi menjayakan proses penyegerakan. Projek ini membentangkan *Enhanced Phase Locked Loop* (EPLL) untuk *inverter* satu fasa yang menghasilkan voltan orthogonal yang sama dengan sumber AC atau sistem grid. Sebagai hasilnya, terbukti bahawa EPLL secara signifikan membuktikan fungsinya sebagai penapis penyesuaian yang menyaring sudut fasa ke sudut yang diinginkan bagi menjayakan proses penyegerakan berlaku

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

PLL   -   Phase locked loop

EPLL   -   Enhanced phase locked loop

AC   -   Alternating current

DC   -   Direct current

IGBT   -   Insulated gate bipolar transistor

MOSFET   -   Metal oxide semiconductor field effect transistor

PWM   -   Pulse width modulation

VCO   -   Voltage controlled oscillator

THD   -   Total harmonic distortion
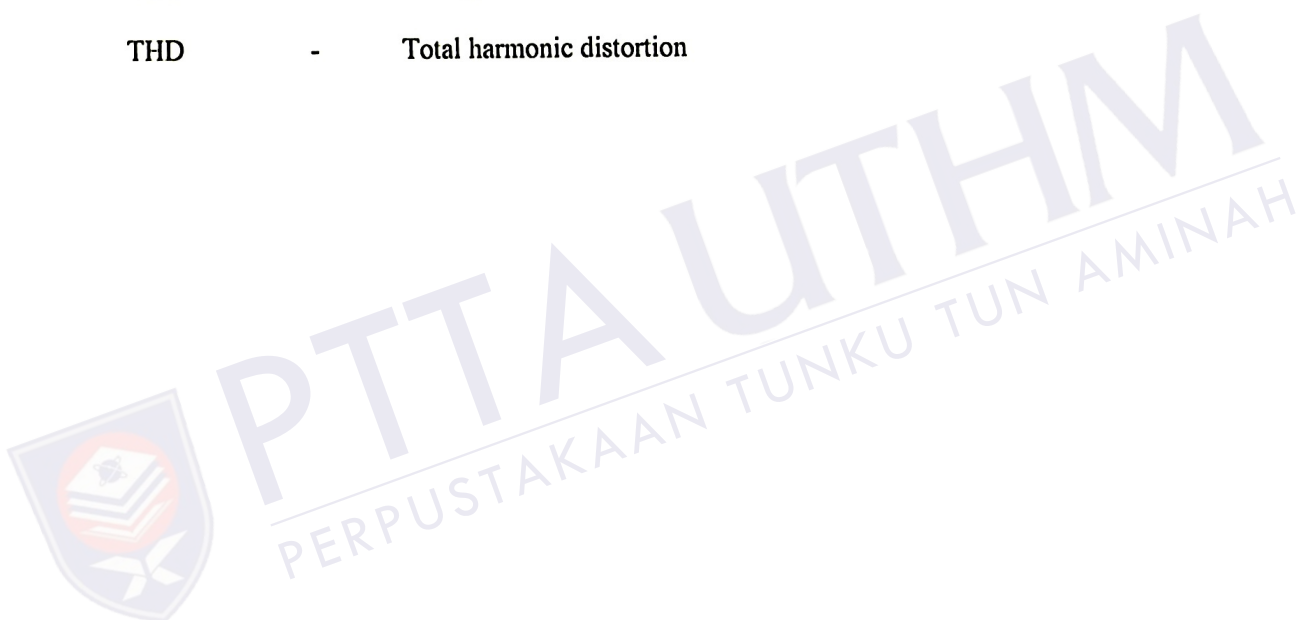
CHAPTER 1

INTRODUCTION

1.1 Introduction

In recent years, an increase in energy demand is associated with changing behaviors and lifestyles which is driven by technological innovation. With the increased demand and the lack of fossil fuels, many types of renewable energy can be a good alternative to counter the increased demand. Even though there is extraordinary growth in renewable energy market over the past decade which helps to reduce our dependence on fossil fuels, there are certainly shortcomings that need to be fixed. Hence, for enhancing the distribution and quality of energy in the utility grid at levels required by different standards, the transfer energy that coming from renewable energy can be used to meet consumers' demands. Based on the above, one of the major problems that need to be solved is the synchronization of inverter output with the voltage of the utility grid. [1].

Traditional synchronization methods of the control system and the grid voltage involve widely used algorithms based on the PLL. A PLL is a device which providing tracking of one signal by another one and as a result of this tracking the output signal is synchronized with the input reference signal in phase and frequency. Various PLL techniques have been proposed and are used because of the efficiency and robustness for single-phase systems.

Reference [2] contains an overview of the historical development of the phased-locked loops, general information about their operation as well as a more detailed review of the three major blocks building the general block-diagram of a single-phase PLL, presented in Fig.1.1. It resumes the structure of almost every PLL algorithm that can be found nowadays in the literature. The classic PLL consists of three general blocks that include a phase detector (PD), a loop filter (LF) and a voltage controlled oscillator (VCO). The classification and explanation of the basic operation of the most commonly used types of control and synchronization are presented in [3].
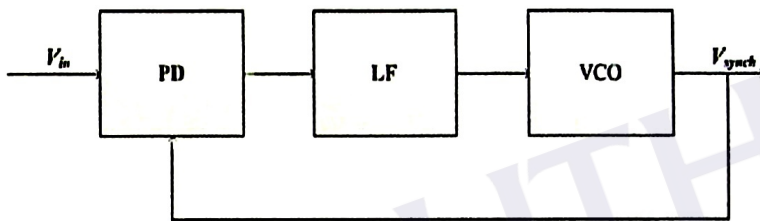
Figure 1.1: Block diagram of a single phase PLL.

A single-phase PLL proposed in [4] uses a phase detector multiplier and a phase shifter to obtain cosine from a sine function. Thus the PLL contains a low pass filter that decreases its response. The same filter is in the structure of the described PLL in [5], where the output signal is generated from a post-processor.

This project is to simplified realization of a PLL for single-phase on-grid inverters based EPLL. This project also focuses on the PLL for synchronization of a single phase AC connection system. For the inverter part, H-bridge Metal Oxide Semiconductor field Effect Transistor (MOSFET) has been used to generate AC output. While for the microcontroller, Arduino board has been chosen to generate the PWM for activating gate of all the MOSFETS. Figure 1.2 shows the block diagram for the overall project setup.
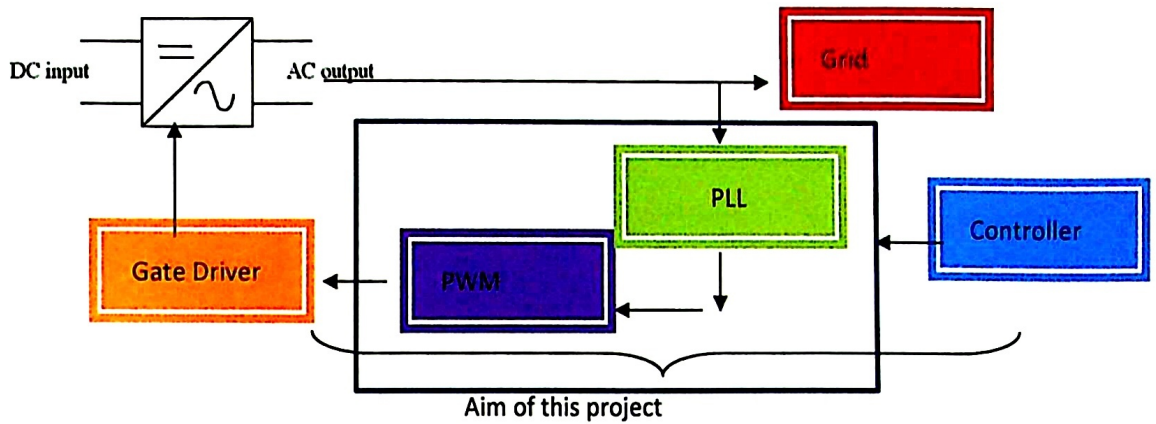
Figure 1.2: Overview the project

1.2 Problem Statement

Process of matching the frequency and speed of a generator or any source to an existing electrical system is being called as synchronization process. Only with the same frequency an AC generator can deliver power to grid systems. If the connection to the grid are been disconnected, the exchange of AC power only can be done when the exact synchronization has been brought up again.

In order to make the synchronization process become reality, apart from having equal line voltage, same waveform and same phase sequence, the two sources also must have same frequency and phase angle as well. Only with these five conditions, a synchronization process can be done then.

As the waveform and phase sequence was standardized in the construction of the generator, the precaution during installation needs to be done cautiously. This is due to the fact that the phase of the generator must be equal to the phase of the system. Failure to ensure the phase is equal on both systems can make a short circuit to the voltage systems.

For the DC generators, converting DC to AC needs to be done systematically. If the inversion process fails to produce similar frequency and phase angle, the output of the inverter

will not success to be synchronize to grid or other AC systems. As for this, PLL is one of the techniques in making the synchronization takes place.

A PLL basically is a control system that generates an output signal whose phase is related to the phase of an input signal. While there are many types of PLL topologies, finding the best type of PLL on different usage also will varies in different results.

1.3 Aim and Objectives

There are three main objectives to achieve as given below:

1. to design a single phase inverter for AC Connection System.
2. to synchronize between output from inverter and Grid (AC) system so that the output can be used in the grid system.
3. to developed the Enhanced-PLL mathematical model for fast synchronization of the inverter-grid voltage

1.4 Limitations / Scope of the Study

The limitations have been proposed as below so that the area of project can be focused to achieve the objectives above. The scope of study proposed as below:

1. Study power flow controller in the inverter and the synchronization
2. Software
   MATLAB/Simulink Software as a language in programming the microcontroller (ARDUINO)
3. PLL
   Only EPLL topology will be used for this project.

1.5 Outline of the Project

The first chapter is only the introduction of this proposal. The chapter covers the brief idea about the project that has to be done generally.

The second chapter covers all the literature review about the project that has been done before. It will cover all the fundamental principles, commercial product and the previous work that has been researched on.

Chapter 3 covers the methodology of this project. The methodology is on the works that must be done in order to achieve the objectives given before.

Chapter 4 covers the expected results from previous method.

The last chapter will summarize all the works that has been done. This chapter will summarize the problems faced during the project as well as the solution found to handle the problems occurred.

CHAPTER 2

LITERATURE REVIEW

2.1   Introduction

This chapter will emphasize the importance of this project, and the differences between it with other works. On top of that this chapter also will focus on studies, fact and past research project on related project title. This project is using inverter controller for a Grid Connection single phase system. The inverter is used to convert the DC to AC current to compatible with the AC source.

2.2   Inverter

Electronic device that transforms DC into AC is called as an inverter. During the transformation to AC, there is no power has been produced but the power has already been provided by the DC source. The design of the inverter device will reflect the output voltage and frequency of the AC output.

Most of the inverters that has been used nowadays are entirely electronic, but there were also some inverter that have mechanical combination that working together with electronic inverter. Static inverters are not using moving parts in the conversion process. A relatively stable DC power source that can supply adequate current for the intended power demands in the system are the typical power inverter been used nowadays.

In power system, inverters have widely been used especially in AC microgrid where the renewable energy has been used as an additional energy. This is because to the fact that most renewable energy source is producing DC voltage. Other than that, the inverters are also needed in transforming the energy storage system where the storage energy which is in DC form will be transformed to become AC [6].

2.3   Inverter Output Waveform

Square wave, modified sine wave, pulsed sine wave, and PWM wave were some of the output that depend with the electronic design of an inverter. However modified sine wave and sine wave are the most commercialized waveform types that been produced by inverter.

Since most of the DC output generated by the renewable energy only capable giving low voltage, producing household plug in voltage from the renewable energy necessitate major modification. In order to amplify the output, a part of using transformer that amplify the inverter DC to AC output, the other option is by using switching boost converter that can amplify DC value before it been converted to AC.

Many carrier-based PWM techniques have been developed due to fact that performance of an inverter depends on the modulation strategy [7–9] for the sake of producing the desired inverter value.

2.3.1   Square Wave

Square wave inverter is the cheapest inverter and was the first invented inverter and at the same time also the simplest inverter output. This wave is best suited to the application that is low sensitivity such as heating and lighting [10]. Square wave inverter also had odd number of

harmonics and can hardly be used to AC appliances except some lights and fans which eventually reduce their life time. Ironically square wave inverter output can also produce "humming" when it been used with audio equipment and for that square wave is not suitable for the sensitive audio device. Figure 2.1 shows the square wave waveform of an inverter.
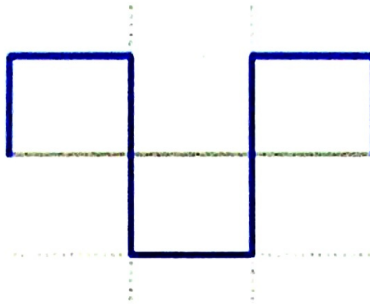
Figure 2.1: Square wave waveform

2.3.2 Modified Sine Wave

Modified sine wave is more like the square wave which has less harmonic distortion compared to square wave [11]. The edge corners of the square wave were eliminated for the purpose of transforming it to become a modified sine wave. This type of inverter mostly exits in today's market. Although it is less harmful to devises compared to the square wave, it still heats up the coil in filter due to large amount of harmonic distortion and dissipates power.

2.3.3 Pure Sine Wave Inverter:

A power inverter device which produces a multiple step sinusoidal AC waveform is referred to as a sine wave inverter [12]. Pure sine wave inverters maintain the best quality due to the least number of harmonic distortions present in it to compare with square wave and modified sine wave. Usually sine wave inverter is more expensive but it allows to us use all AC appliances and reduces the humming noise of inductive loads. Figure 2.2 shows the sine wave waveform

Figure 2.2: Sine wave waveform

2.4   H-bridge Inverter

The basic topology for single-phase DC to AC transformation is full bridge or H-bridge inverter. This topology can be easily extended to multiphase and multilevel configurations, for the purpose of obtaining different outp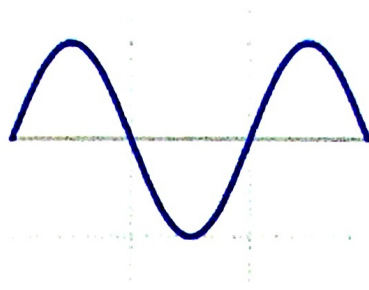ut of voltage. As for single phase configuration, this topology been used widely in many low – power (up to 10 kW) applications that ranged from stand alone to grid connected with the emphasis on renewable energy sources such as wind and photovoltaic power plants [13-15]. It is noted that many carrier-based PWM techniques have been developed in the last couple of decades as the performance of an inverter mainly depends on its modulation strategy, [7–9]. As for the performance, total harmonic distortion (THD) is one of the tool for evaluating the inverter performance that includes the THD of input and output voltages and also currents. Other than that switching losses and efficiency also been monitored seriously fpr the evaluation of the inverter performance.

By using Fourier analysis, periodic waveforms are represented as the sum of an infinite series of sine waves. The fundamental frequency is a sine wave which has the same frequency as the original waveform. The other sine waves is called harmonics which are perfect integer multiples of the fundamental frequency. Fourier analysis can be used to calculate THD. The formula of THD is the square root of the total of the squares of the harmonic voltages divided by the fundamental voltage:

$$THD = \frac{\sqrt{(V2^2 + V3^2 + \cdots + Vn^2)}}{V1}$$

The main function of full H-bridge inverter circuit is for converting DC voltage to a sinusoidal AC voltage so that the output desired voltage and frequency can be gained. Both positive and negative voltage across the load is required to generate a sine wave centered on zero voltage. The positive and negative voltage on generating AC value only can be gained when a single source DC connected to H-bridge source as shown in figure 2.3.
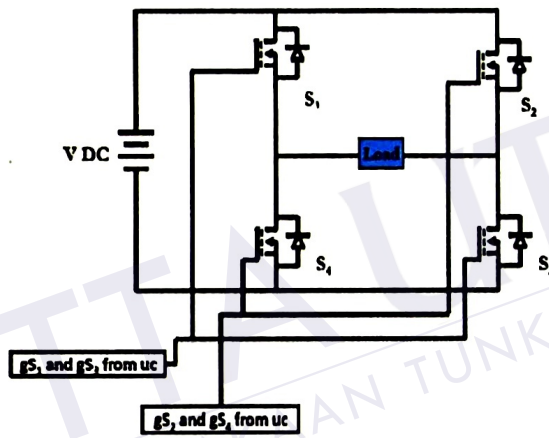
Figure 2.3: H-bridge inverter circuit

In H-bridge connection, S1, S3, S2 and S4 are the switches that had been arranged in this configuration [16]. In term of operation gating signal of GS1 and GS3 are been switched together at the same half cycle for producing positive output. While for generating negative output, gating signal of GS2 and GS4 are simultaneously been switched on the other half cycle [17, 18, 19]. The main difference is only GS1 and GS3 signals leading the GS2 and GS4 by half cycle or 180 degree of the switching time. As for the result, the output shows a periodic waveform. However this waveform still not in a sinusoidal forms [20].

As for fundamental knowledge, H-bridge is a circuit that enables opposite direction voltage been applied across a load in a circuit. With this connection, DC motors are allowed to run either in forwards or backward direction depends on the connection and input of the switching gate. There are also many other kinds of power electronics that is using H-bridges connection that include DC to AC inverter, AC to AC converters, DC to DC converter and other type of motor controllers.

2.5   Phase Locked Loop (PLL)

A PLL is a control system that related to phase of an input signal. This control system generates output phase signal by referring the signal with the input. There are few different types whereby the easiest is a circuit that contain a phase detector , loop filter and a variable frequency oscillator [21]. While a periodic signal been generated by the oscillator, the phase detector play a role on differentiate the phase of the input with the phase of the signal and this signal then been adjusted on the oscillator for matching purpose. As for this, the comparison of bringing the signal toward the input is called as feedback loop. The output of the phase is "feedback" toward the input from the output in term of making a loop.

For synchronization purpose, as phase of both input and output been locked as the same, the frequency of both also is using the same frequency value. More over in the synchronization process, the function of PLL also can track the input frequency and multiple the values. This roles are been used widely in various fields like demodulation and frequency synthesis.

Because of its flexibility characteristic, PLL are widely employed in many electronic applications such as telecommunications and radio. Demodulating a signal with the carrier and recovering it from a noisy signal also are the big roles of PLL. Apart from that in computer clock synchronization PLL also can distribute precise time for the digital logic circuits. The technique now is widely used in modern electronic devices, with output frequencies from a fraction of the frequency as a single integrated circuit can provide a complete PLL building block.

Classification and explanation of the basic operation of the most commonly used types of control and synchronization are presented in [22]. Increasingly in the literature, one can find separate approaches in the implementation of the PLL in single-phase application. The synchronous source frame is commonly used in grid connected to three phase applications [23], [24]. The main idea of the synchronous source frame PLL is the transformation of input signals in dq-frame by means of the well-known Park and Clark transformations.

2.5.1   The Concept of the PLL

Generating a sinusoid signal that is phase-locked with an external generated signal that have unknown phase and frequency value is the common problem that been raised in discussing a PLL. Mathematically, the equation formulated as bellow [25]:

Let the external generated sinusoid $x(t)$ be as $x(t) = cos(\theta_x(t))$. Where $\theta_x(t)$ is referring to the angle of the sinusoid and can be expressed as $\theta_x(t) = 2\pi f_x t + \Phi_x$. This angle is defined in radians which f_x and Φ_x present the frequency and the phase. For simplifying, Φ_x been assumed as 0 for the purpose of removing the value from the equation.

Another sinusoid signal then been generated by the PLL. Where the signal been defined as $y(t) = cos(\theta_y(t))$. As for this, $\theta_y(t) = 2\pi f_y t + \Phi_y$. The main function of PLL is to ensure that the frequency and phase been phased-locked so that the value of $\theta_y(t)$ is as same as $f_y = f_x$ and $\Phi_y = \Phi_x$.

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