STUDY OF A SINGLE PHASE GRID CONNECTED PV INVERTER PERFORMANCE UNDER A WEAK GRID CONDITIONS FOR CAMBODIA

SOVANNA PHOEURN

A Thesis Submitted to the Graduate School of Naresuan University
in Partial Fulfillment of the Requirements
for the Master of Science in (Renewable Energy)
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has been approved by the Graduate School as partial fulfillment of the requirements for the Master of Science in Renewable Energy of Naresuan University

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Title STUDY OF A SINGLE PHASE GRID CONNECTED PV INVERTER PERFORMANCE UNDER A WEAK GRID CONDITIONS FOR CAMBODIA

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ABSTRACT

A single-phase grid connected PV inverter performance under a weak grid condition is the integrated practice of renewable energy sources as hydro, wind, biomass, thermal energy and solar PV with the grid power or power penetration at point of common coupling (PCC). Study objects shall be analyzed PV inverter performance, a weak grid characteristics, the distorted grid and harmonic effects with correction and reliability. Nowadays, Cambodia does not yet comprise full electric power in utility needs for production chances and daily lives, but electric energies shall reach the households in 2020 by the royal government policy with renewable energy generation. Components of solar energy system comprise solar panels, charge controllers, batteries and PV inverters and PV inverters are used to convert DC to AC energies, more addition, as Off-grid or On-grid. PV inverters are being used currently as single-phase and three-phase types and particularly, the internal inverters comprise three types of output filters as L, LC and LCL categories. A weak grid system has internal impedance of grids which shall fluctuate from distribution generations (DG) and could lead voltage deviation (ΔV) at inverter terminals and the inverter instability. The low voltage fluctuation of Cambodia is not below -10% and over +6% of nominal voltage magnitudes, and system frequency fluctuation (Δf) is not above 50.5Hz and below 47.5Hz, otherwise, the max THD values are not allowed over 5% of nominal operation system. The distorted grid systems shall occur at the distribution generation

points and enhance power harmonic in a grid or otherwise, PV irradiations decrease due to low power operation, then PV inverters may generate more undesirable harmonics. This study presents a simulated modeling and control of a single-phase grid connected PV inverter performance under a weak grid condition. The control of a weak grid system is penetrated power to PV inverter at the point of common coupling (PCC), and before the power injections take place, the both-side power systems are controlled judiciously power transparency. A single-phase grid connected PV inverter under a weak grid condition is verified experimental applications of ideal grid system according to the results, the grid systems locate in simple operation conditions with corrections and reliabilities. The distorted grid voltage system is certified power systems stand in good operation conditions with correction and reliability, but THD current values spread up to 8.88% which harmonic effects could attract extremely grid system, therefore, power systems shall be disconnected immediately or the systems shall be allowed to transfer power. A weak grid system with impedance values (X_L) is modified the max PCC voltage increased to 221.77V, but the grid systems considered as normal operation network and THD current amplitudes expand higher than average values (<1%) which effects could absorb unsmooth current flow pathway and ripple current waveforms in the grids. More addition, a weak grid system is connected with X_L and R components reflected the max PCC voltage magnitudes grow up to 238.11V of basic voltage about 8% expansion according to power regulation of low voltage fluctuation in Cambodia passed by EAC, this grid system shall be disconnected automatically by protection equipment and the max PCC current decrement is a round 2A of total current 23A because of impedance value growth in a weak grid, whereas, THD current rates increase higher than average values (<1%) which effects could absorb unsmooth current flow pathway and distorted-ripple current waveforms in the grids. Overall conclusions of the inverter efficiency are fair good of the whole grid systems. The system is modeled and simulated in Laboratory and a distance, conductor sizes, length are calculated properly and results compare with appropriate data which have be installed already in households or other working places.

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ABBREVIATIONS

DC	Direct Current
AC	Alternating Current
LSCR	Low Short Circuit Ratio
PVES	Photovoltaic Energy system
BCC	Battery Charge Controller
BES	Battery Energy Storage
PIS	Photovoltaic Inverter Structure
CSI	Current Source Inverter
ZSI	Impedance Source Inverter
ST	Shoot Through
ICC	Inverter Circuit Control
SPWM	Sinusoidal Pulse Width Modulation
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
SPI	Single Phase Inverter
TPI	Three Phase Inverter
UPS	Uninterruptible Power supply
LCL	Inductance Capacitance Inductance
PFM	Pulse Frequency Modulation
PAM	Pulse Amplitude Modulation
SVM	Space Vector Modulation
SVPWM	Switching Vector Pulse Width Modulation
SRF	Synchronous Reference Frame
PI	Proportional Integration
CLC	Current Loop control
PLL	Phase Locked Loop
PCC	Point of Common Coupling
SCR	Short Circuit Ratio
ΔV_{PCC}	PCC Voltage Fluctuation
IRR	Inductive Resistive Ratio

GSA	Grid Synchronization Algorithm
Igq	Reactive Current Reference
EAC	Electricity Authority of Cambodia
MME	Ministry of Mine and Energy
TRD	Total Rated Distortion
ISC	Utility Short Circuit Current
IL	Customer Average Load Current
TDD	Total Demand Distortion
VU	Voltage Unbalance
RPA	Reference of Point Applicability
RLC Load	Resistive Inductive Capacitive Load
EUT	Equipment Under Test
LCC	Lined Commutated Converter
P_{PV}	Photovoltaic Power
VSC	Voltage Source Inverter
LVRT	Low Voltage Ration Through
Z_{eff}	Impedance Effect
L_{INV}	Inverter Phase
L_{GRID}	Grid Phase
VD	Voltage Difference
CD	Current Difference
PF	Power Factor

CHAPTER I

INTRODUCTION

The rationale for Study and Statement of Problems

The kingdom of Cambodia is a developing country and located in the southern portion of the Indochina peninsula in Southeast Asia and comprises great potential for the use of renewable energy such as hydro, wind, biomass and solar and can, therefore diversify its energy matrix and cope with the increasing demand in a sustainable manner. It has the land area of 181,035 square kilometres, bordered by Thailand to the northwest, Laos to the northeast, Vietnam to the east and the Gulf of Thailand to the southwest. The sovereign state of Cambodia has a population of over 16 million[1]. Currently, Cambodia hosts more population growth and economic increasing, so It needs particularly much more electrical energy to provide and support for peoples 'utility and run in the business sectors, actually Cambodia does not yet exist power balance to the user needs and the business. There are four main types of power stations in Cambodia, hydropower, thermal power, diesel power, and power plants using wood and other biomasses. Renewable energy plants, especially solar power farms, are in their early stages for need complete in utility and investment, moreover, investment in renewable energy production sources is encouraged by the government's aim of providing electricity to 100% of all villages by 2020[2]. Photovoltaic conversion is the direct conversion of sunlight into electricity with no intervening heat engine require very little maintenance[3]. The generated electricity can be instantaneously consumed or stored in batteries by a charging instrument to be consumed at night. This can be a challenging task, mainly when considering a fluctuation of solar insolation in a winter and a rain seasoning [4].

The PV arrays are getting very popular in Cambodia and in the world because of clean, inexhaustible and the little maintenance. The Photovoltaic energy systems can be converted from DC-DC converter and DC-AC inverter between the PV arrays and the grid, abnormally, these grid-connected inverters which brought the generated power from PV system for distribution to power system networks and a convectional photovoltaic system comprises a PV module, an inverter, and a battery, naturally, the power conversion from the DC to AC is used the DC/AC inverter and a battery is optionally added for energy storage. Currently, a PV system can either be operated as an Off-grid system or a grid-connected system”[5]. The solar electricity generation has been an exponential growth in - recent years and referring to the BP statistical review of 2018, the global cumulative installed capacity was approximately 400 GW by the end of 2017. BP Statistical Review of World Energy consumption 2019 is demonstrated Global energy consumption increased by 2.9% in 2018[6].

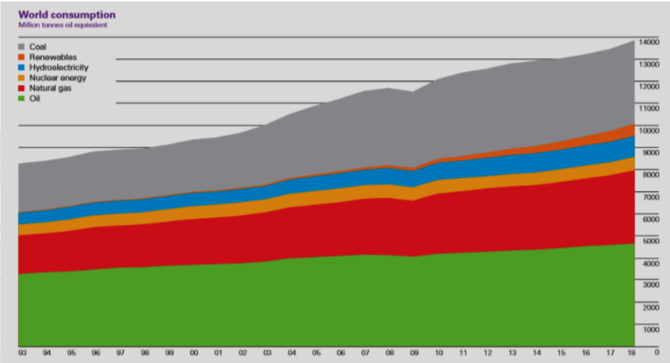


Figure 1 Growth of World Energy Consumption in 2019

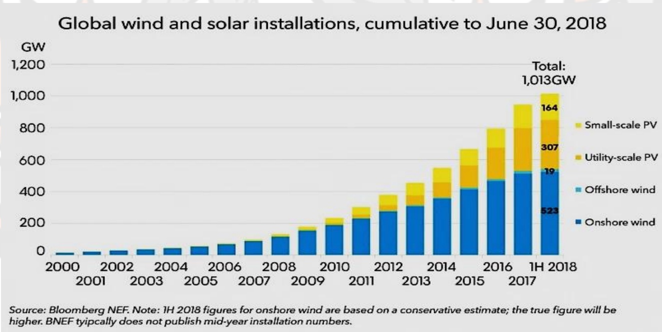


Figure 2 Global growth of wind & solar PV generation capacity

Presently Cambodia, power consumers like the industrial utility needs have been facing to the energy supply and householders are not seen yet about solar PV on-grid installation, but recently, the royal government of Cambodia has agreed and approved the private sector to construct solar farm projects for energy generation to reach its achieved policy in 2020. DC power of solar PV array should be converted to AC power for the grid-connected PV system with the actual voltage magnitude, frequency, and phase angle. Anyway, the inverters shall play an important role in the grid-connected PV system[7].

Cambodia has great potential for the use of renewable energy such as hydro, wind, biomass and solar and can, therefore diversify its energy matrix and cope with the increasing demand in a sustainable manner and It has approximately 5.8 peak sunlight hours per day and an average solar irradiation of 5.0 kWh/m^2 per day, consequently about 2120 hours per year and ranking among the world's top solar resources[8].

The most general power quality issues can be caused by the weak grid and power system distortion in the industrial utilities and others, for three-phase inverter, voltage grid is implied the three magnitudes of a three-phase system are the unequal size, frequency angle or phase displacement[9]. As the grid voltage gets weak then it shall cause the frequency variety and voltage fluctuation increase and reach to what is termed as flicker[10]. It gets mentioned worthily, HVDC line combined with AC grids across the long transferred line seems weak with low effective DC inertia constant and low short circuit ratio (LSCR), especially, with wind power farms which is far geographically from consumers and some trades zone. Furthermore, AC grids are transferred into long distanced line areas which cause many troubles to occur as well; like frequency deviation, harmonic distortion, voltage drop, and voltage flicker[11].

The objectives of the Study

1. To analyse the grid-connected to PV inverter performance under weak grid conditions, the distorted grid and harmonic effects.
2. To imply the situation of a weak AC grid integration point for grid correction and preventive reliability
3. To develop the recommendation practice of a single-phase grid-connected PV inverter performance under weak grid condition for Cambodia.

The Scopes of the Study

1. The research and the data collection of a grid-connected PV inverter performance under weak grid conditions will be carried out at the kingdom of Cambodia.

2. The grid-connected PV inverter performance shall be modelled utilizing a DC voltage input source, a grid simulation, PV inverter testing and using the accurate measuring instrument.
3. The input and output voltage inverter, power and current are going to be recorded for gird PCC synchronization like frequency deviation, harmonic distortion, voltage drop, and voltage flicker analysis.

Keywords

PV inverter, power regulation, phase-amplitude, grid synchronization, weak grid.

Benefits of the study

1. The study also serves as the specific regulator of the distributed network operator and grid consumers under a weak grid for solar PV on-grid.
2. The research plays a role as an actual guideline for EAC, network operator, and grid consumers to follow PV grid-penetration conditions in low voltage for renewable energy resources.
3. This paper provides an accurate assurance of a grid-injected PV inverter reliability at PCC of synchronous conditions with known frequency deviation, harmonic distortion, voltage drop, and voltage flicker which is referred to the technical regulation.
4. The study demonstrates the power loss characteristics of PV on-grid inverter performance for long-distance transmission.

CHAPTER II

RELATED LITERATURE REVIEW AND RESEARCH

Energy is a key factor for the social and economic development of each country. It is really needed for various economic sectors such as industry, agriculture, transportation, and business. The main commercial energy source of most countries in the world is fossil fuels, especially oil [12]. Cambodia has an opportunity to become a state which reduces down fossil fuel energy without air pollution back to green energy utilization (renewable energy sources) such as sun, wind, water and biomass energy abound. The sun provides an effectively unlimited supply of energy that we can use to generate electricity and heat. Solar PV can be grid-connected, but can also generate power in rural areas, islands and other remote places “off-grid”[13].

Photovoltaic Power System (PPS)

Solar photovoltaic (PV) energy systems are made up of different components. Each component has a specific role. A solar energy system produces direct current (DC). This is electricity which travels in one direction. The loads in a simple PV system also operate on direct current (DC). A stand-alone system with energy storage (a battery) will have more components than a PV direct system[14].

PV_{peak} is a peak power of the PV array under STC and can be calculated as the equation 1[15].

$$PV_{peak} = \frac{I_{stc}E_{el}}{QE_{glob}}(\mathrm{K}W) \qquad \text{(Eq.2.1)}$$

Cambodia is the potential state of high sunlight temperature for solar installation under the observation and a daily temperature experiment demonstrated that an average solar irradiation of 5.0 Kwh.m^2 per day, approximately 5.8 peak sunlight hours a day and a yearly total hour is 2120 hour [8].

Table 1 Cambodian sunlight average (Hours)

Month	Sunshine hour	Month	Sunshine hour
January	8.4	July	4.6
February	8	August	5.6
March	8.6	September	4.3
April	8	October	6.5
May	6.5	November	7.1
June	6.4	December	7.8

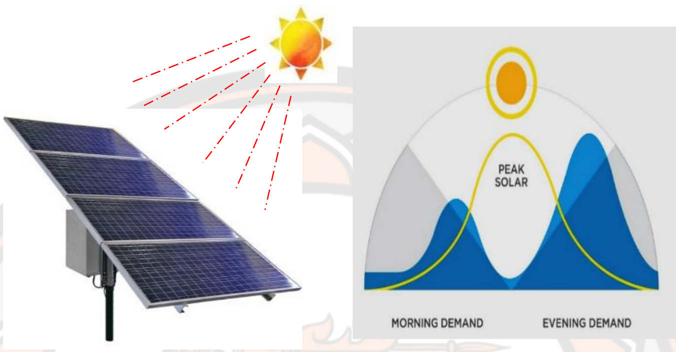


Figure 3 Observation of Peak solar irradiation

Battery Charge controller of Solar PV system

PV charge controllers either use a single stage or two stages, depending on the complexity of the system. In single stage schemes, the mathematical model used does not take in consideration MPPT implementation to improve the overall system efficiency. For proper MPPT operation, both the energy source and the battery must be considered in the open loop solution and In the two stage system, the first stage applies a MPPT algorithm, and the second stage charges the battery in one of many battery charging algorithms [16].

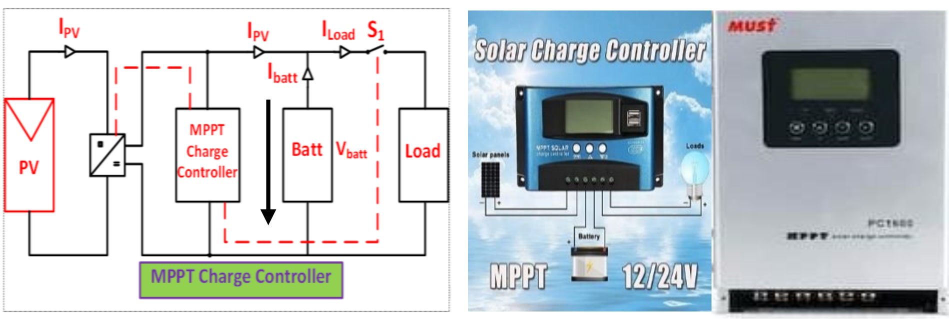


Figure 4 The 100A, 12V/24V MPPT Solar Charge Controller

There are four general types of charge controllers, categorized by the method used to regulate the charge from the solar modules to the batteries: (1) shunt type charge controllers, (2) Series type charge controllers, (3) PWM (pulse width modulation) charge controllers and (4) MPPT charge controllers and Battery charge controllers regulate the flow of electricity from the photovoltaic generator to the battery. Its function is to regulate the voltage and current from the photovoltaic arrays to the battery in order to prevent overcharging and also over discharging [17]. The charge controller amount of PV Battery can be computed as the equation 2 (C_c) [18].

$$C_C = \frac{PV_{peak}}{System\,volts} \qquad \text{(Eq.2.2)}$$

Where the system volt is 12 volt

Battery Energy Storage of Solar PV system

The battery energy storage is an essential component of photovoltaic system and its function for energy storage to supply the electrical devices or transfer to the grid. However, in many schemes, PV systems require rechargeable batteries for energy storage, and increased system dependability and in standalone PV systems, the main objective is to charge a battery from PV modules under certain operating conditions, while protecting the battery from over voltage and over current. It is recommended specifically that the battery shall disconnect from the system when it is fully charged, and no load is connected[19].

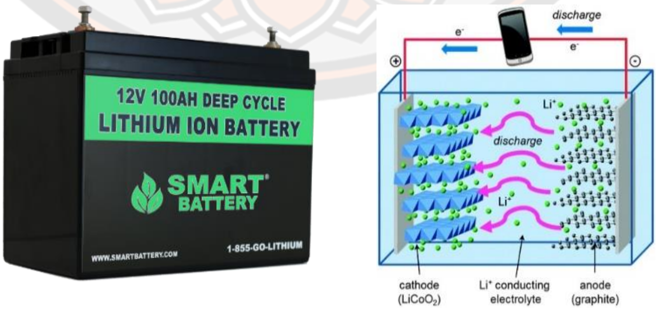


Figure 5 Lithium-ion batteries 12 V 100AH Deep Cycle

Self-consumption ratios can be improved by installing onsite electricity storage systems. Lithium-ion batteries are currently the dominant technology [20].

Photovoltaic Inverter Structures

Solar PV Inverter is a necessary component of photovoltaic power system. An inverter that converts a direct current into an alternating current is called a DC-AC inverter. However, the term "inverter" generally refers to the equipment that combines an AC-DC converter (that changes an alternating current into a direct current) and a DC-AC inverter so as to be able to generate arbitrary frequencies and voltages. There're a number of inverter topologies with the characteristic fluctuation and a suitable inverter should always be chosen by a solar PV plant designer for an accurate application[21]. The weak line voltage does not yet mostly cause of a long-distanced transmission, particularly, can be caused by the inverter efficiency, hence there shall be a method to boost the converter efficiency in a typical provision by high frequency transformers for the DC-DC converter on the output[22]. Since the technology was developed, the inverters have considerable increases in DC/AC efficiency and safety in energy conversion, achieving efficiencies of 98% in medium powers and high efficiencies even at load levels of 10 or 20% of power nominal and the inverters used in grid connected photovoltaic systems have a maximum power point tracking, anti-islanding protection, high conversion efficiency, automatic synchronization with the power grid, low harmonic distortion level and power factor close to the unit[23]. Diverse PV inverter structures are obtained the universal market result today, with typical efficiencies of greater than 98% and the method is utilized in computing an inverter efficiency [18].

$$\eta_{inverter} = \frac{P_{output}}{P_{input}} = \frac{I_{ac}V_{ac}\cos\theta}{I_{dc}V_{dc}} \qquad \text{(Eq.2.3)}$$

Classification of PV inverters

At the present time, a classifications of PV inverters are categorized as three main-huge types as well, Current Source Inverters (CSIs), Impedance Source Inverters (ISIs), and Voltage Source Inverters (VSIs). The VSIs are the most widely used because they naturally behave as voltage sources as required by many industrial applications, such as ASDs, which are the most popular application of inverters, as demonstrated in the figure 6 [24].

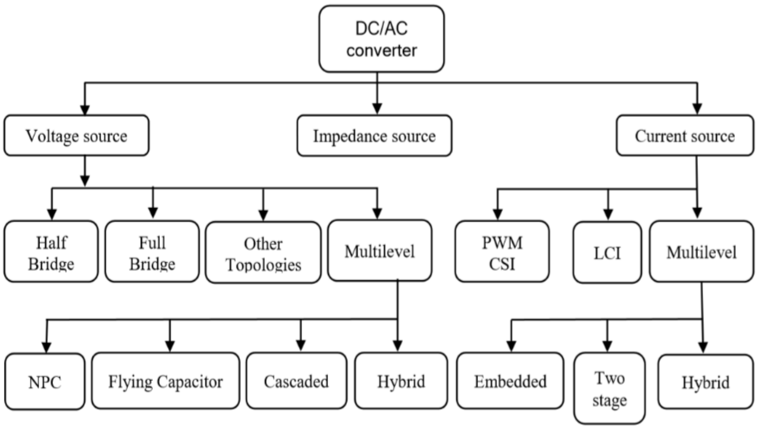


Figure 6 Classification of PV inverters

Each PV inverter power capacity shall be classified diversely with referring to a PV power plant configuration and verified actually the frequency value and the voltage worth on the utilized catalogue in table below [25].

Table 2 PV inverter power plant capacity

Nº	Names of Inverter Types	Power Plant Ranges
1	Module integrated inverters	50-400 W
2	String inverters	0.4-2 kW
3	Multistring inverters	1.5-6 kW
4	Mini central inverters	6 -100 kW
5	Central inverters	100-1000 kW

Voltage source type inverters (VSIs)

The output voltage of voltage source type inverters is controlled. A large-value capacitor is located on the input DC line of the inverter in parallel, and the inverter performances as a voltage source. The inverter output needs to exist characteristics of a current source. In the case of low impedance load, series reactors are needed for each phase, (See L1 to L3 in Figure 7) [20].

The traditional topologies for single-phase VSIs are half bridge and full bridge. The converter is composed of capacitor, switched and diodes, where an array of two switches is called "inverter leg". For instance, the inverter leg of the half bridge is composed of S_+ and S_- and the capacitors required to provide a neutral point N and large, such that each capacitor maintains a constant voltage [20].

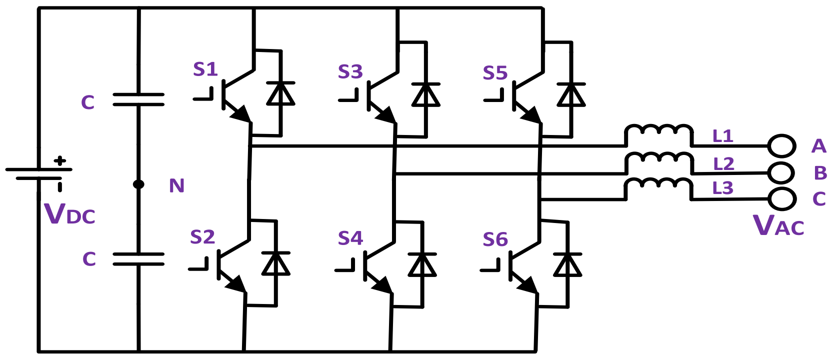


Figure 7 Voltage source type inverter

The voltage is possible to be adjusted directly by a voltage source inverter and the voltage operated to a load by fluctuating the conductional number. This type inverter does not need the reversed blocking diodes, hence, a high performance efficiency than current source inverter and with less voltage losses [20].

Current source type inverters (CSIs)

Current source type inverters are controlled the output current. A large-value inductor is placed on the input DC line of the inverter in series. And the inverter acts as a current source. The inverter output needs to have characteristics of a voltage source. In motor applications, capacitors are required between each phase-to-phase of motor input (See C1 to C3 in Figure 8 [20]).

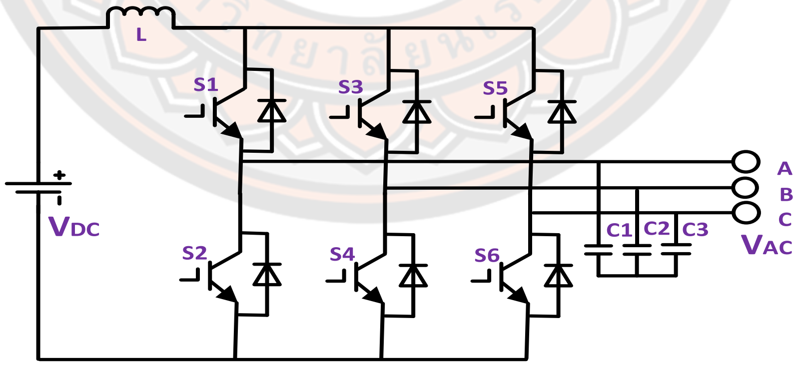


Figure 8 Current source type inverter

All home appliances and industrial power applications are normally utilized with a current source inverter but a voltage source inverters are easier to control than current source type. Furthermore, the power transmission of HVDC is used a current source inverter, more addition, a long distance power transaction is proportional to a

DC current before an AC conversion and a DC current is donated through a large reactor [20].

Impedance Source Inverters (ZSIs)

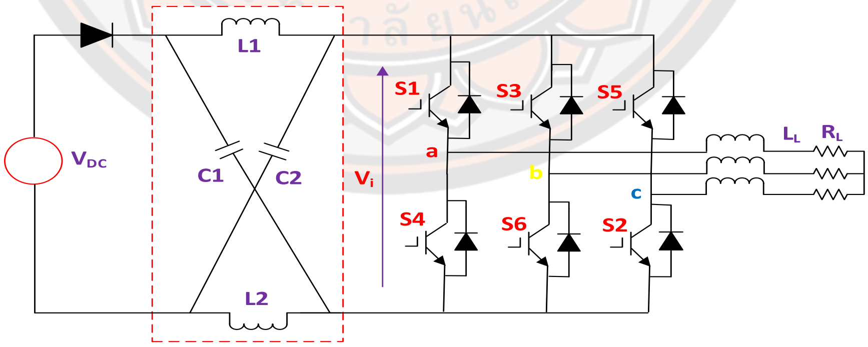
There are different topologies for single-phase ISIs, namely, "Z,"- "qZ,"- and "TZ"-source inverters. The converter is composed of capacitors and inductors, switches, and diodes. The capacitors and the inductors are arranged to form an input impedance for the inverter [20]. An applied system of DC-AC conversion and boosting sections are used the bridge technique of the last Z-source inverter (ZSI or ISI). ZSI shall donate a normal single-stage power conversion topology with an additional advantage because of shoot-through (ST) shall not enable to destroy long the inverter. The faced issues will be eliminated by natural VSI and CSI inverters, the exclusive impedance network is applied in both boost mode and buck[26]. In this case of computing method in an impedance value is applied as illustrated below.

$$Z^2 = R^2 + X_L^2$$
$$Z = \sqrt{R^2 + X_L^2} \qquad \text{(Eq.2.4)}$$

Z = Impedance in Ohm (Ω)

R = Resistance in Ohm (Ω)

XL = Inductance reactance in Ohm (Ω)



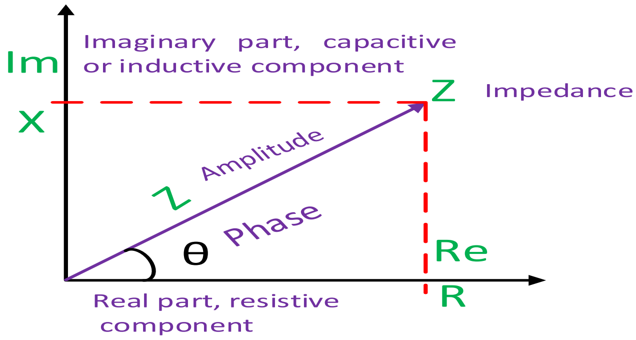


Figure 9 Network figuration of Impedance Source Inverter

Inverter Circuit Control (ICC)

Power inverters are devices which can convert electrical energy from DC power form to the AC power form. They come in all shapes and the sizes from the low power functions like powering a car radio to that of backing up a building in case of power outage[27]. Today referring to the recent modern technique research, a wide range of transformer-less PV inverter with very high efficiency performance more than 97% and maximum of up to 98% in a European country which are produced by SMA, Sunways, Conergy, Ingeteam, Danfoss Solar, Refu, etc [19].

The type of inverter is implemented in the system, voltage-source-inverter (VSI) and the control technique implemented in the system, is Sinusoidal pulse width modulation (SPWM). Using this technique, the microcontroller PIC 16F877A is used to generate the required PWM train of pulses to drive and switch on the H-bridge MOSFET transistors. The PIC generates a reference sine wave based from lookup table with frequency of 50Hz [28].

Single-Phase Inverters (SPIs)

Single-phase inverters can be classified by its input source; they are VSIs, CSIs, and ISIs. The operating principles are different in each converter. The main features of the different approaches are reviewed and presented in the following Fig 10. Although these converters cover the low-power range, they are widely used in power supplies or single-phase UPSs [20]. A full-bridge inverter has four defined states as describe in the table 3 and one undefined state, which is used for dead time. The undefined state is obtained when S_{1-} and S_{1+} or S_{2-} and S_{2+} switches are OFF.

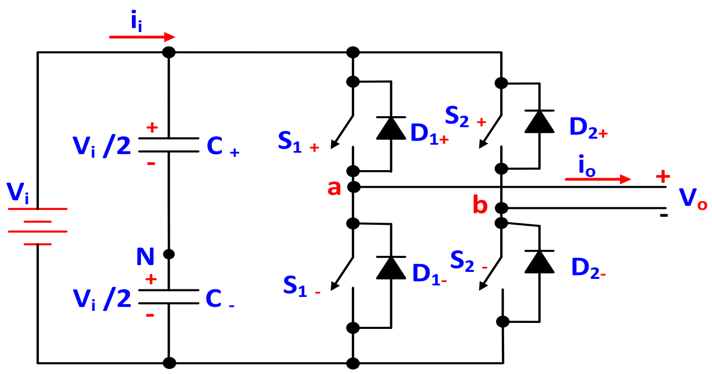


Figure 10 Single-phase full-bridge Inverter

Table 3 State of Single Phase Full -Inverter VSI

Switches-ON	State	Output
S_{1+}, S_{2-}, S_{2+} and S_{1-} are OFF	1	0
S_{1+}, S_{2-} are ON, S_{2+} and S_{1-} are OFF	2	+V
S_{2+}, S_{1-} are ON, S_{1+} and S_{2-} are OFF	3	-V
S_{1-}, S_{2-} are ON, and S_{1+}, S_{2+} are OFF	4	0

Table 3 is illustrated the application of the Full-Bridge inverter, when the inverter switches S1+, S2-, S2+ and S1- are OFF, the inverter performance does not yet apply (state1V= 0). When the switches S1+, S2- are ON, S2+ and S1- are OFF, the inverter application is in progress (state 2 +V). The switches S2+, S1- are ON, S1+, S2- are OFF, the inverter application is in process (state3 -V). Furthermore, the switches S1-, S2- are ON, S1+ and S2+ are OFF, the inverter performance does not work (state4 V = 0) [24].

Single-phase LCL Type grid-connected inverter (PWM Full-Bridge)

A topology of single-phase LCL type grid-connected inverter (PWM Full-Bridge) is demonstrated where switches Q_1-Q_4 (some documents verified switch" S") compose of two bridge legs, inductors L_1 L_2 and capacitor C compose the LCL filter, in that topology, the same bridge legs of diverse two switches are open in a complementary mode. For a single-phase full bridge inverter is chosen in universal the type bipolar SPWM and unipolar SPWM and The single-phase PV inverters are commonly used for applications up to 7kW [29],[30].

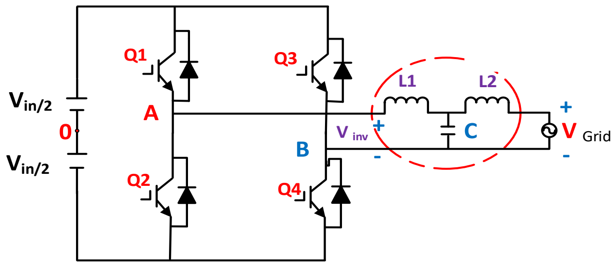


Figure 11 LCL type grid-connected inverter

Three-Phase Voltage Source Inverter (TVSI)

In grid-connected photovoltaic (PV) system, there is a based power electronic converter, that injects direct current (DC) from PV panels into the alternating current (AC) grid. The single-phase PV inverters are commonly used for applications up to 7kW. Above this value, three-phase inverters are recommended for ensuring a better power balance among the phases [26]. Single-phase VSIs cover low-range power applications, and three-phase VSIs cover medium- to high-power applications. The basic operation of a three phase VSI, the standard form is shown in the fig 11. Four comparison of eight possible switch stated. Out of the eight possible states, only 6 states manufacture non-zero outputs of alternating Vi, 0 or - Vi and the remaining two states produce a zero output [20].

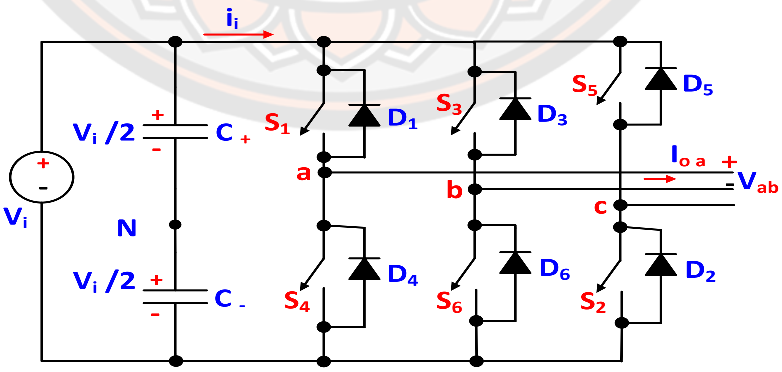


Figure 12 Three-phase VSI topology

Table 4 State of three Phase Full -Inverter VSI

Switch- ON	State	V_{ab}	V_{bc}	V_{ca}
S1, S2, and S6 are ON, and S4, S5, and S3 are OFF	1	Vi	0	-vi
S2, S3, and S1 are ON, and S5, S6, and S4 are OFF	2	0	Vi	-vi
S3, S4, and S2 are ON, and S6, S1, and S5 are OFF	3	- vi	Vi	0
S4, S5, and S3 are ON, and S1, S2, and S6 are OFF	4	- vi	0	Vi
S5, S6, and S4 are ON, and S2, S3, and S1 are OFF	5	0	- vi	Vi
S6, S1, and S5 are ON, and S3, S4, and S2 are OFF	6	Vi	- vi	0
S1, S3, and S5 are ON, and S4, S6, and S2 are OFF	7	0	0	0
S4, S6, and S2 are ON, and S1, S3, and S5 are OFF	8	0	0	0

Inverter modulation technique (IMT)

Three common techniques used to control (modulate) the power supplied to a load are pulse-width modulation (PWM), pulse-frequency modulation (PFM), and pulse-amplitude modulation (PAM) and PWM is the most commonly used technique [18]. This paper demonstrated in producing a sinusoidal output waveform with controllable magnitude and frequency, commonly PWM is employed. Sinusoidal Pulse Width Modulation technique is one of the most popular modulation techniques among the others applied in power switching inverters. In SPWM, a sinusoidal reference voltage waveform is compared with a triangular carrier waveform to generate gate signals for the switches of inverter[31].

A. Carrier Based Pulse Width Modulation Technique

Space Vector Modulation (SVM) of three-leg VSI is based on the representation in the three phase process quantities as vectors in a two-dimensional (α, β) plane. The line voltages V_{ab}, V_{bc} and V_{ca} are given:

- $\mathbf{V_{ab}} = +\mathbf{V_{dc}}$
- $\mathbf{V_{bc}} = \mathbf{0}$
- $\mathbf{V_{ca}} = -\mathbf{V_{dc}}$

The voltage V_{ab}, V_{bc} and V_{ca} of three phase voltage inverters are illustrated as three-line voltage vectors displace 120° in the place and represented in the α, β plane.

A carrier based PWM technique is presented based on the comparison of the modulating with the high triangular frequency triangular carrier waveform and 120°

out of phase[32]. For this comparison, the inverter switching pattern is received that the results in the generation of the sinusoidal output waveform.

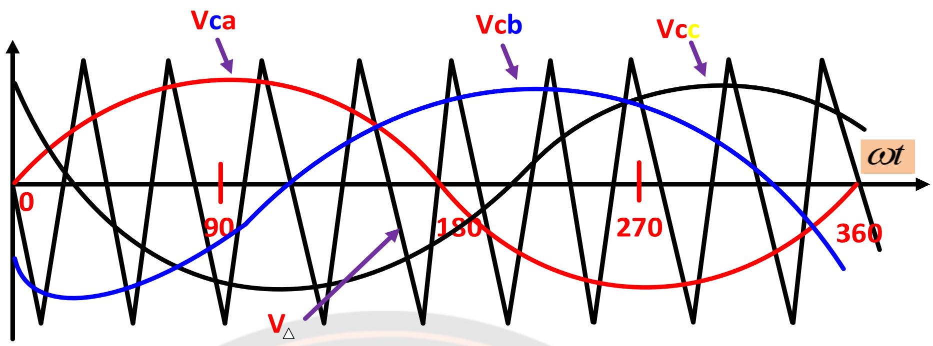


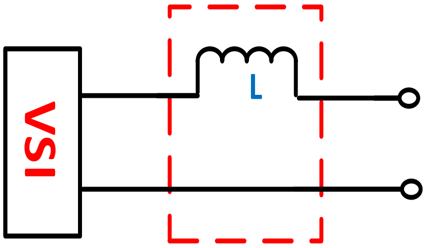
Figure 13 Carrier Based Pulse Width Modulation

B. Space vector Pulse Width Modulation

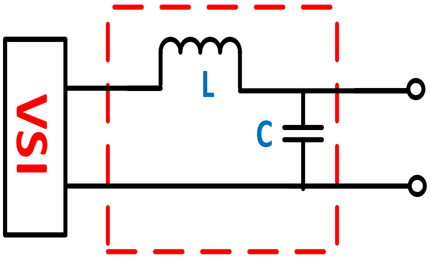
The SV-based modulating technique is a digital technique which generates PWM load line voltages that are on average equal to given load line voltages. The output waveform is the average of the input waveform but with a lower harmonic distortion [18]. The SV PWM is utilized directly for the control variable given by the control system and identifies each switching vector as the point in complex space of (α, β) [27].

Output filter of inverter (OFI)

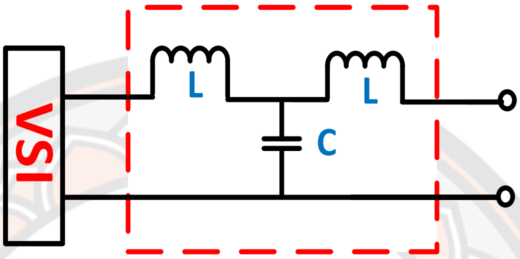
The output filter reduces the current harmonics generated by semiconductor switching. There are various topologies such as filter inductor (L) or combinations with capacitors (LC, LCL) of these filters which connect to the inverter's output[33]. In the grid-connected inverter, a filter is needed as the interface between the inverter and the power grid. Compared with the L filter, LC filter and the LCL filter is considered to be a preferred choice for its cost-effective attenuation of switching frequency harmonics in the injected grid currents[29].



14a. L-Filter



14b. LC- Filter



14c. LCL- Filter

Figure 14 Basic filter topologies

A. L-Filter of Inverter

The L-filter (Fig. 14a) is the first order filter with attenuation 20 dB/decade over the whole frequency range. Therefore, the application of this filter type is suitable for converters with high switching frequency, where the attenuation is succinct and inductance greatly decreases dynamics of the whole system converter filter [30].

B. LC-Filter of Inverter

The second order (Fig. 14b) filter provides 12 dB per octave of attenuation after the cut-off frequency f_0 and it has no gain before f_0, but it presents a peaking at the resonant frequency f_0 [30]. There are two main duties of the output LC filter, to attenuate the output voltage ripple and to limit the high frequency ripple current of inverter switches[25].

This filter should reduce the high frequency distortion of output voltage and control the switching current, by the way, it is designed a compromise between the value of the inductance and capacitor and it is suitable to for stand-alone inverter.

C. LCL -Filter of Inverter

The attenuation of the LCL-filter (Fig. 14c) is 60 dB/decade for frequencies above resonant frequency, therefore lower switching frequency for the converter can be used [30]. LCL filter provides better decoupling between the filter and the grid impedance and lower current ripple across the grid inductor and LCL-filter fits to our application. The LCL filter is usually employed since it has better ability of suppressing high frequency harmonics than the L filter [25].

Inverter Control strategy to grid (ICSG)

The most important and basic requirement for grid connected inverters is to keep inverters synchronized with the grid so that, an inverter can be connected to the grid. The inverter can feed right amount of power to the grid even when the grid voltage changes its frequency, phase and variation amplitude[34].

As mentioned, there should be a control system to ensure the high quality of the power defined the stored or injected power. Likewise, the harmonics for the nonlinear load drawn from the grid and the phase difference between voltage and current of network have to be compensated by capacitor and inductor as the loads. The output current, grid current, load current or any node current may be controlled and the control system is focused on such as harmonic detection, power control, and power factor correction. Also, the grid voltage phase should be inserted into the control system applied by a phase-locked loop [29].

One of the most important tasks of the control system performed on the grid-connected inverter, especially, the parameters of voltage, current, and power can be controlled and one or a number of these parameters depend on the requested demand made by a control system [30]. In this portion, the controllers are divided and summarized into six categories referring to their applications.

Table 5 Summary of Inverter controller design

Nº	Controller design	Recommend	Example
1	Robust controller	• Referring to Uncertainties • Robust stability	• H-infinity controller • Mu-synthesis controller
2	Nonlinear controller	• Complexed operation and design	• Sliding mode controller (SMC) • Partial feedback linearization (PFL) • Hysteresis controller
3	Linear controller	• Easy practice • Referring to Control system	• Classical controller (P, PI, PD and PID) • Proportional resonant (PR) controller • Linear-quadratic Regulator (LQR) Controller
4	Adaptive controller	• Complexed operation and design	• Control methods can automatically adjust the control action is based on the operating conditions of the system, no parameter
5	Predictive controller	• Easy practice • Numerous Calculation	• Deadbeat controller • Model predictive control (MPC) controller
6	Intelligent controller	• Based on emulation • Biological intelligence	• Repetitive controller(RC) • Neural network Controller • Fuzzy logic controller • Autonomous controller

Inverter control structures (ICS)

For inverter control structure are utilized to implement into one-phase or three-phase ones in the grid-connected systems that are compatible with the power system and generate a special capability for control systems with the design facility, transformation of one-phase and three-phase systems into other systems is used [29].

A. Single Phase Inverter control structure

In the industrial or commercial application is mostly required the AC power supply with single or three phase, H-bridge or Full-bridge referring to the material need. A Single phase, three phase H-bridge and Full-bridge inverter serve as an essential role for DC-AC conversion. Normally the load voltage shall be affected. In this portion, for the control strategy and ensuring the stable output voltage throughout the operation is utilized a controller instruments [35].

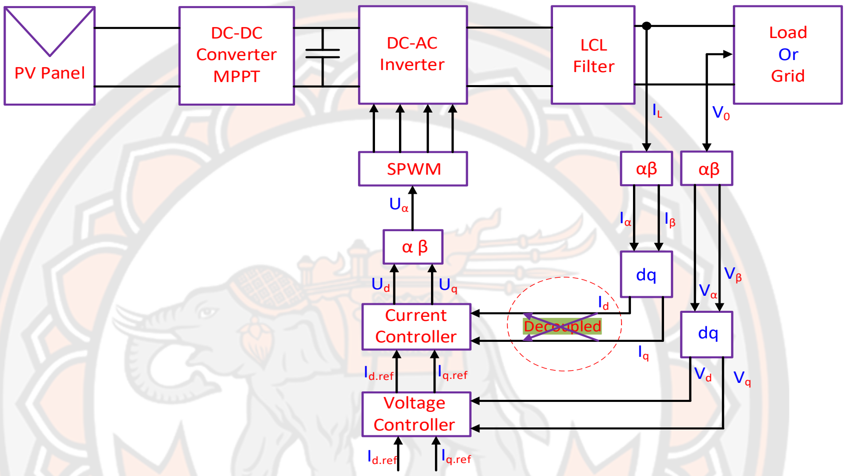


Figure 15 Control structure of inverter with SRFPI controller

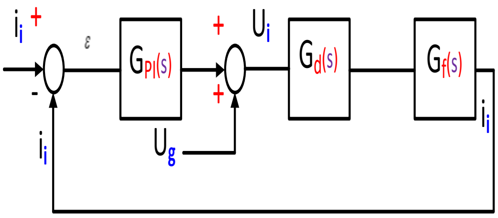
The block diagram of the proposed control scheme in figure 15 which the system comprises of the two feedback loops and one feedback loop with the inner current loop and outer voltage loop are the feedback loops. An orthogonal signal generation of single phase inverter for quality conversion (voltage or current) from αβ-frame to dq-frame is implemented and although, SRF controller (Synchronous Reference Frame) for single phase inverter is not well established as three phase inverter [33].

- Input power control

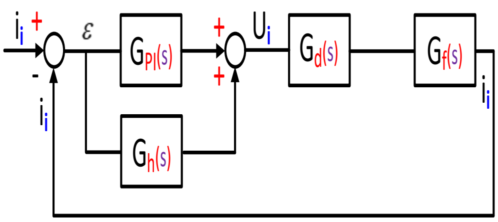
  The computed value of the current amplitude reference using the PV power (P_{pv}) and the RMS value of the ac voltage ($V_{ac\ RMS}$) is added to the output value of the dc voltage controller (i_r) resulting in the ac current amplitude reference (i_{Ref}) [36].

- Grid current controller

  The current-controlled PV inverters are universally used PI controller in current value control.



A. with PI controller



B. with PR controller

Figure 16 The current loop of PV inverter

In the current loop control (CLC) of PV inverter is defined by utilizing PI current controller $G_{PI}(s)$:

$$G_{PI}(s) = K_P + \frac{K_I}{S} \qquad \text{(Eq.2.5)}$$

As depicted in Fig. 16 a, this leads in turn to stability issues which related to the delay introduce in the system by the voltage feedback filter (U_g). The PR current controller G_C (s) is defined as:

$$G_C(s) = K_P + K_I \frac{S}{S^2 + \omega_0^2} \qquad \text{(Eq.2.6)}$$

The harmonic compensator (HC) G_h (s) as defined

$$G_h(s) = \sum_{h=3,5,7} K_{Ih} \frac{S}{S^2 + (\omega_0 h)^2} \qquad \text{(Eq.2.7)}$$

As designed to compensate the selected harmonics (3^{rd}, 5^{th} and 7^{th}) as they are the most predominant harmonics in the current spectrum [34].

B. Three Phase Inverter control structure

- abc reference frame

The stationary and dynamic regimes are implemented in three-phase systems, the application of “vector control”, is a powerful tool for the control of DC–AC converters and governed the behaviour of the three-phase system in independent rotating shafts [37]. This frame is applied in three-phase systems the same as three phase systems without any transformation. An individual controller has to be used for each phase current in an abc frame, but star or delta connection of three-phase systems has to be considered in the design of control systems [29]. abc control is a structure where nonlinear controllers like hysteresis or dead beat are preferred due to their high dynamics.

In the case that three PI or PR controllers are used, the modulator is necessary to create the duty cycles for the PWM pattern. The PI controller is widely used in conjunction with the dq control and its implementation in the abc frame is described. Also, the grid voltage phase should be inserted into the control system which applied by a phase-locked loop. As a consequence, PLL is used for synchronizing the fundamental reference current and the grid [29], [35].

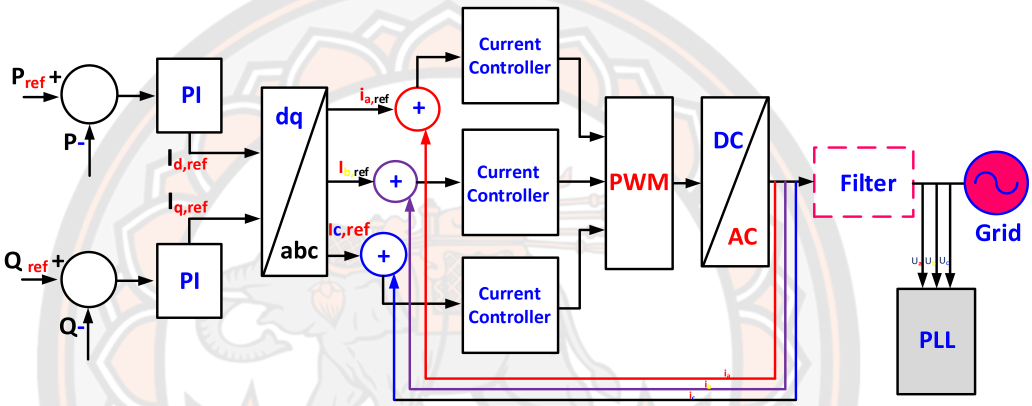


Figure 17 Generalized abc control structure

- αβ reference frame Control

This frame is utilized in three-phase systems and sometimes artificially in single- phase systems. An abc frame or single-phase is used to transform from a frame to αβ-frame and the grid currents are transformed into a stationary reference frame using the abc to αβ module, as shown in figure 17. It achieves a very high gain around the resonance frequency, thus It gets capable to eliminate the steady-state error between the controlled signal and its reference. The abc control system is equipped an individual controller for each grid current flow. The three controllers are utilized in abc control, should be demonstrated a high gain with the resonant frequency, to effectively eliminate the comparison error between the controlled signals and the reference [29,35].

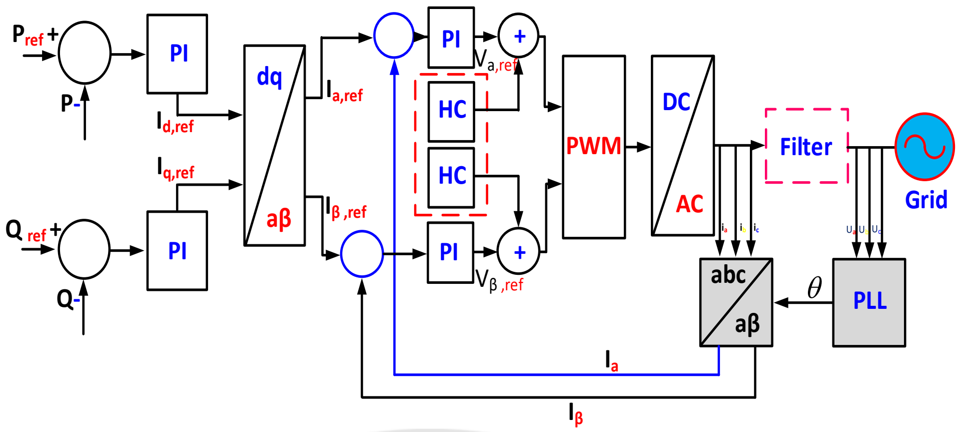


Figure 18 Universal αβ control structure

- dq reference frame Control

dq reference frame is used in three-phase systems and the transformation is utilized to delivery an abc frame to an dq frame. By the way, the transformation causes the grid current and voltage waveforms to be transferred into a reference frame that rotates simultaneously reference system with the grid voltage [29]. these variable control values are transformed into continuous. In this way, the ac current is decoupled into active and reactive power components, I_d and I_q, respectively. These current components are then regulated to eliminate the problem between the reference and measured values of the active and reactive powers, thus, the power control loop is followed by a current control system. Thereby, the reactive power has to be controlled, a reactive power reference must be imposed to the system [35].

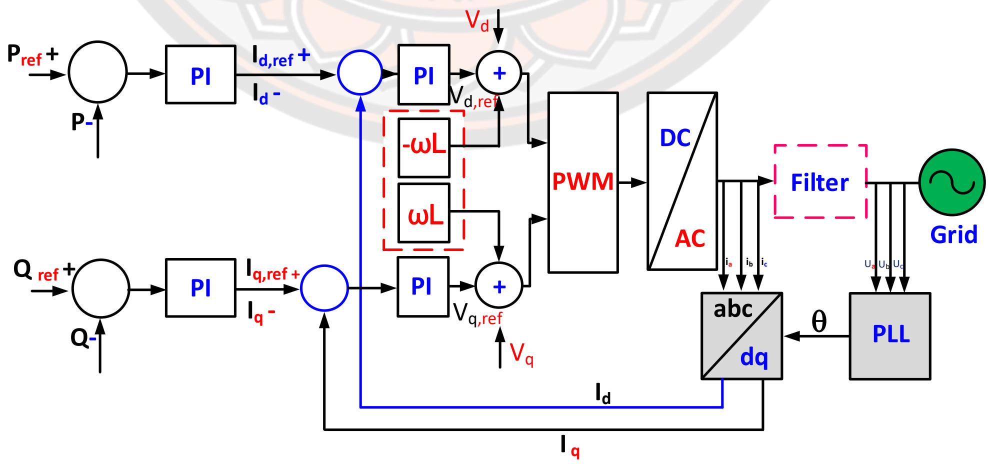


Figure 19 Universal αβ control structure

WEAK GRID SYSTEM

INTRODUCTION

AC voltage source grid comprises of an internal impedance Z_{grid} for the distribution network at point of common connection (PCC) bus and the impedance of the grid shall be able to fluctuate from the DG system connection point referring to the local behaviour and the voltage level [38]. The connection system analysis can be considered the grid voltage like a disturbance in the control diagram. In this portion of the common connection point scenario referred to the frequency response of the single-phase generation system and surely relied on the two excitation functions, the inverter output voltage and the voltage value of the single-phase grid. A weak grid can cause voltage fluctuations at the inverter terminals and consequently cause inverter instability[39].

In this paper, impacts of circuit and control parameters on the stability of voltage source inverters are studied using a small-signal state-space model in the synchronously rotating dq-frame of reference. Besides the filter and control parameters, a weak grid can adversely affect the stability of grid-tied VSIs. A weak grid is commonly defined as a power grid with a low short-circuit ratio (SCR), for instant, high impedance, and a low inertia constant (H), which are typical features of micro-grids [36]. The power transmission network normally consists of less or much voltage losses and existing of an internal grid impedance. An energy system is considered as the power network with the complex impedance (Z_n). In the content of this paper illustrated the common diagram of impedance considering the two actually sinusoidal source, $\mathbf{V_1}$ and $\mathbf{V_5}$.

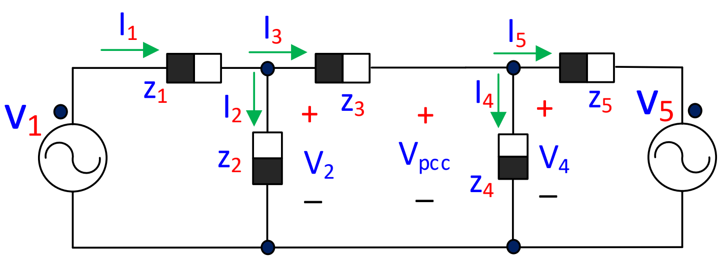


Figure 20 Common circuit with complex impedances at the PCC

Depending on the grid integration regulator is implemented at the PCC of a single-phase inverter to the power grid by considering the inverter output voltage, $V_{inv}(s)$ = V1(s), $V_4(s) = V_{pcc}(s)$, and $V_{grid}(s) = V_5(s)$, and whereas, $I_1 = I_{inv}$, $I_2 = I_c$, $I_4 = I_{local}$, and $I_5 = I_{grid}$. The function of the inverter filter parameters and grid parameter demonstrated in the circuit of the complex impedance characteristic as in the figure 20, $Z_1 = sL_1$, $Z_2 = 1/sC$, $Z_3 = sL_3$, $Z_4 = R_{local}$, $Z_5 = sL_{grid}$ [36].

Furthermore, the weak grids are usually found in more remote places where the feeders are long and operated at a medium voltage level. The more problems with weak grids connected to solar PV energy with the voltage losses from the inverter output. Due to the grid impedance amount of solar PV energy can be absorbed by the grid at the point of common connection is limited because of the voltage level limit [10]. The line impedance of PCC bus to the transmission considered as a problem, the impedance voltage regulator in the passage and the loads combined across the line and the power leading flow is demonstrated from the PCC to the distribution sub-station bus to the DG network combined to the distribution grid [36]

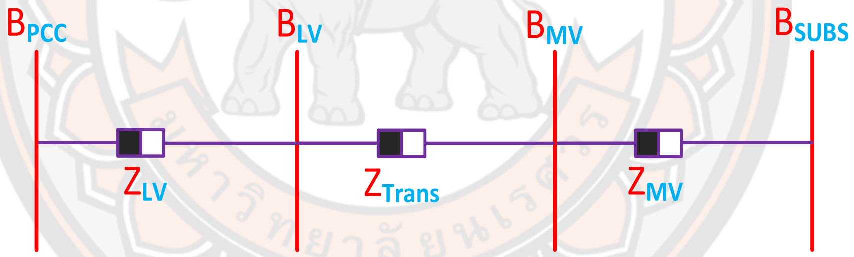


Figure 21 Power flow from the connection point to the substation bus

In the power system diagram of the power flow from the connection point to the substation bus is computed each impedance value of the grid blocks in the power transmission by utilizing the proper methods of grid impedance. The total impedance **Z total** is given by the expression:

$$
\begin{aligned}
Z_{Total} &= \sqrt{R_{Total}^2 + X_{Total}^2} \\
Z_{LV} &= R_{LV} + jX_{LV} \ (\Omega) \\
Z_{Trans} &= R_{Trans} + jX_{Trans} \ (\Omega) \\
Z_{MV} &= R_{MV} + jX_{MV} \ (\Omega)
\end{aligned}
\qquad \text{(Eq.2.8)}
$$

Hence, Z_{LV}: as the impedance value of Low voltage (Ohm)

Z_{Trans}: as the impedance compensator of transformer (Ohm)

Z_{MV}: considered as the impedance value of Medium voltage (Ohm)

R_{LV}: the resistance value of Low voltage (Ohm)

R_{Trans}: considered as the resistance compensator of transformer (Ohm)

R_{MV}: considered as resistance value of Medium voltage (Ohm)

jX_{LV}: the inductance value of low voltage (Ohm)

jX_{Trans}: the inductance compensator of transformer (Ohm)

jX_{MV}: the inductance value of medium voltage (Ohm)

PCC Voltage Control under weak grid

PCC voltage value is the most essential for the grid integration with other energies and PCC voltage value is measured and analysed properly before the grid combination. A weak grid shall always cause the voltage variation at PCC. However, particularly the measured PCC voltage feels a complex issue because of the sensing PCC is usually located outside of the inverter power [40]. The vector diagram analysis of the voltage variation at the PCC, the required amount of reactive current is calculated for the compensation with an adjustable margin of voltage variation. A nonlinear of the required reactive power focused on against the fluctuations of the active power output with a different value of voltage variation margin. The specification of the voltage fluctuation value (ΔV) is utilized the common formula [38].

$$\Delta V_{PCC} = V_{PCC} - V_{Ref} \qquad \text{(Eq.2.9)}$$

Hence:

ΔV_{PCC}. Voltage variation at point of connection coupling (V)

V_{PCC}. Voltage value between the grid and PV inverter output voltage (V)

V_{Ref}. Regulated voltage source/based voltage (220V)

So the angle of the voltage deviation vector is determined by the effective impedance, Z_{effect} [41]. In this portion, there are the two main indicators which take a measurement for the network strength, the short circuit ratio (SCR) at the PCC and is expressed by the SCR method or by the inductive-resistive ratio (IRR) and in the short circuit ratio of weak grids are characterized for SCR smaller than 10. SCR is defined by the expression [36]

$$SCR = \frac{V_{PCCnom}^2}{Z_{total}\, S_{nominal}} \qquad \text{(Eq.2.10)}$$

$S_{nominal}$ is the rated apparent power of the DG unit

Z total is the equivalent impedance

$\mathbf{V}_{PCCnom}$ is the generated rated voltage for the DG connection point

In another way, the grid strength measurement is computed by IRR ratio, this verified the equivalent reactance view of the connection point and the equivalent resistance R seen from PCC, when the grid is considered weak if IRR < 0.5.

$$IRR = \frac{X_{total}}{R_{total}} \qquad \text{(Eq.2.11)}$$

The grid is considered weak if the SCR indicator or the indicator IRR reaches values below 10 and below 0.5, respectively.

By the way, in the synchronous point between PV inverter output and the grid, the PCC voltage shall rise up, ΔV where $\Delta V = V_g - V_s$ (V_g and V_s are the rms value of υ_g and υ_s as shown in figure 22, when the PV system is injecting P_g and Q_g to the grid, can be derived as given [42].

$$\Delta V = \frac{P_g R_T + Q_g X_T}{V_g} \qquad \text{(Eq.2.12)}$$

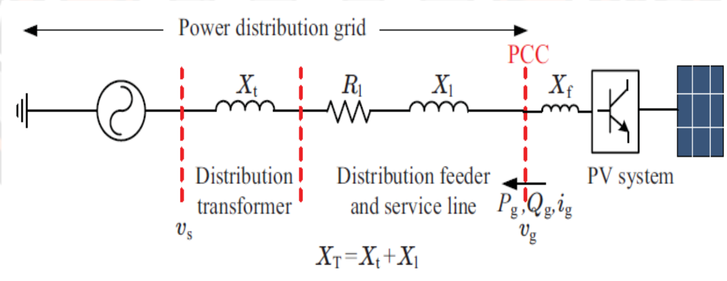


Figure 22 Simplified design of the distribution grid

As above the equation, the PCC voltage, Vg is sensitive to both active and reactive power injected to the grid by the PV system since the ratio R/X of the considered grid is greater than 1.

PCC current control under weak grid

A grid synchronization algorithm (GSA) is the heart of control system for grid integration of PV inverter power and then large transients may appear at the time of connection, which will damage the system. To realize the synchronization process accurate information of grid voltage amplitude, phase and frequency are required

[43]. In the synchronous reference frame, the reference voltage and current quantities are stable with the regulated current value for injection [36]. Q_{ref} and I_{qref} are the reactive power reference, the magnitude of the I_{gq} reactive current reference and the magnitude of the reactive current injected to the grid respectively. The response time for the DC-link voltage controller of the PV system is longer than that of the current controller [40]. In Fig. 23, only the peak reactive current I_{gq} is illustrated as the output of $G_{cc}(s)$ since the PCC voltage is controlled by regulating I_{gq} or the reactive power Q_g injected to the grid.

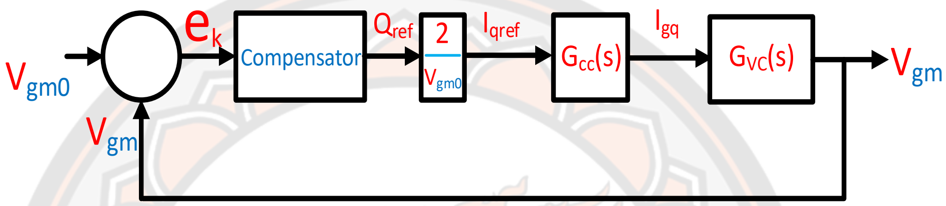


Figure 23 Control block diagram of the PCC voltage and current controller

In the kingdom of Cambodia, for the power synchronization and the power transmission shall be followed the power injection regulator and electrical law of Cambodia 2001 and recently the EAC has issued the general conditions on the renewable energy for low voltage in the grid penetration in January 26, 2018.

Table 6 Comparison of weak grid and strong grid characteristics

Weak/ Low grid capacity	Strong/stiff grid capacity
• Decreasing the grid SCR • The growth of high grid impedance • Characteristic of instable distributed system • Farther power generation location • Load variation of line • Low fluctuation of voltage over the grid injection regulator.	• Voltage still keep steady of line • Grid impedance is low • The impedance of line is inversely proportional to the SCR capacity at the point of common coupling (PCC) • Constant load of line and stable distributed system • Not the farther power generation location.

Power Quality System in Cambodia

Electric Power Quality in Cambodia

Currently, the Kingdom of Cambodia, the electrical powers system is provided into 3 levels like High voltage (HV), Medium voltage (MV) and Low voltage (LV). AC voltages standard shall be as follows in Table 7 [44].

Table 7 Power Quality System in Cambodia

Classification of Low voltage	Range of Nominal voltage	Nominal voltage	Highest voltage
Low voltage	600v or less	230V/400V	-
Medium voltage	More than 600V to 35 KV or less	22 KV	24 KV
	More than	115 KV	123 KV
Highest voltage	35 KV	230 KV	245 KV

In the relevant case to the power business or the development of the power sector in the Kingdom of Cambodia, it gets necessary to be used a nominal voltage other than that offered in the table above, the ministry of Mines and Energy (MME) may allow the use of such nominal voltage as a standard voltage through issuing the official announcement and law of electricity. For the present distribution system of medium voltage(MV) network exists of single phases in some rural areas and three phases in urbanized areas. MV line voltage system is usually utilized of 22 KV and designed as a looped system, but is operated radially. Thereby, the usage of the LV distributed system become perfectly radial and implemented as three phases and single phases including a distributed neutral wire, the line voltages and phases are usually used 230/400 V [45]. The impedance grid system in Cambodia for distributed overhead line is determined by using Carson's equations.

$$Z_{an} = \begin{bmatrix} Z_{aa} Z_{an} \\ Z_{na} Z_{nn} \end{bmatrix} \qquad \text{(Eq.2.13)}$$

Further, the LV-ABC-2Cores topology and 2x2 matrix of single-phase low-voltage distribution are shown in Fig 24.

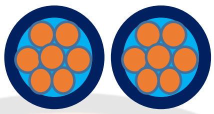


Figure 24 LV-ABC-2Cores cable

Grid interconnection requirement

Currently, the application of solar photovoltaic system is divided into two types in the electrical grid like a solar PV Stand-alone (off-grid) and solar PV on grid. Solar PV systems is the one of the fastest grown sources of renewable energy which are integrated into the distributed system for the utilized supply. The development of standards and guidelines are prompted to introduce to the penetration of photovoltaic network with assured safety and the smooth transmission of the electrical power and the reliability of the power supply. Guides and standards for solar PV penetration are covered the technical requirements including grounding, insulation, warning signals, limitation access, protection against islanding, operational safety and other considerations [46]. The grid requirements are so essential specification for grid penetrations and the grid operators.

Typically, the local power regulation of grid integration are followed by grid operators in most countries are some of the standard or guidelines are recognized internationally and widely utilized in countries which do not yet exist their own set of standards or guidelines, especially, international standards are applied more such as IEEE (Institute of Electrical and Electronic Engineers) in the US, IEC (International Electro-technical Commission) in Switzerland and DKE (German Commission for Electrical, Electronic and Information Technologies of DIN and VDE) in Germany, the dominant PV market, not only, the grid requirement specifications are remarked that impact heavily the solar PV inverter performance and design [19].

The Solar PV power plant guide is summarized from The IEEE standard 1547 and compared with the power specification in Cambodia.

General Guidelines and specifications

A. Voltage variation

The voltage variation can take place at the grid connection point of solar PV plant because of switching operation with the solar plant facilities, in those, collection circuit transformers, capacitor banks due to the rushed current [47]. Voltage fluctuations at the grid connection point of the low voltage distribution network which is penetrated with solar PV power plant become the most universal due to the intermittent nature of solar PV source and due to the customer load fluctuation, hence, the IEEE standard 1547 requires that the voltage changes within ±5% of the nominal voltage value [20]. Whereas, the electric authority standard of Cambodia, the low voltage at the grid supply point shall be maintained -10 (around 198V) and +6% (around 233V) of the normal voltage value as shown in table 8.

Table 8 Low voltage fluctuation in Cambodia

Nominal system voltage	Maintained Value
230V	$207V \leq U \leq 244V$
400V	$360V \leq U \leq 424V$

B. Grid synchronization

The grid synchronization is the most specific technical conditions to avoid the risks of equipment damage. The interconnection equipment is tested and illustrated accurately the technical specification by manufacturer before operating synchronization to the area EPS through an open paralleling circuit device (Power Circuit Breaker) with the allowable limitation in nominal voltage value of each source, the frequency of each source, and each phase-angle difference before the paralleling is allowed to close [47].

Table 9 Limitation of Grid Synchronization requirement

DER Capacity (KVA)	Frequency Deviation (Δf, Hz)	Voltage deviation (ΔV, %)	Phase-angle deviation ($\Delta\Phi$,°)
0–500	0.3	10	20
> 500–1 500	0.2	5	15
> 1 500	0.1	3	10

C. Power Factor

The power factor of solar PV system (IEEE) shall be illustrated the specific value and a unity power value by the Area EPS operator, therefore, the power factor is required at least greater than 0.90 leading or lagging. Whereas, the electric authority standard of Cambodia (EAC), power factor (PF) is required 0.95 leading or lagging [44].

D. Grounding

A genteel grounding should be installed for the current leakage protection on material and tools in demand IEEE standard 1547. The grounding installation does not affect the operational mechanism of the grounding fault protection, moreover, not for overvoltage exceeding protection of the equipment interconnected to the grid. The most consistent utilization should be adhered with the IEEE Std C37.90.1,2002 or IEEE Std C62.41.2, 2002. A single-phase inverter with neutral-to-line grid connection already is system grounded on the grid side [48].

Power quality requirements for solar PV

These requirement guides of all the solar PV plants interconnected to the grids shall be efforded to maintain the value of voltage wave-form quality at the grid connection point and solar PV system disconnection from the grid may be carried with a departure from the requirement limits.

A. Harmonic distortion

The harmonic distortion and the total rated current distortion (TRD) shall be ensured that the grid network will be operated at the reference point of applicability (RPA), shall not exceed the harmonic distortion from the limits defined in the CTS, whereas, users and operators usually desire that the solar PV system output to consist the low levels of current distortion in order to protect the equipment interconnected the grid system. The overall total rated current distortion (TRD) is limited 5% in IEEE standard 1547 and the harmonic current distortion levels are demonstrated in table 10 [47].

Table 10 IEEE Std 1547 Harmonic distortion requirement

	Harmonic order (h)	Limit (%)
	$3 \leq h \leq 9$	< 4.0
	$11 \leq h 15$	< 2.0
Odd harmonic	$17 \leq h \leq 21$	< 1.5
	$23 \leq h \leq 33$	< 0.6
	$33 < h$	< 0.3
Event harmonic	$2 \leq h \leq 8$	< 25 % of the odd
	$10 \leq h \leq 32$	Harmonic limits

The equation is used to calculate the total rated harmonic distortion (RTD), which includes the harmonic distortion and inter-harmonic distortion following.

$$\%TRD = \sqrt{\frac{I_{rms}^2 - I_1^2}{I_{rated}}} \times 100\% \qquad \text{(Eq.2.14)}$$

I_1 the fundamental current as measured at RPA.

I_{rated} DER rated current capacity (transformed to the RPA when a transformer exists between the DER unit and the RPA).

I_{rms} Square root of the DER current, including all frequency components, as illustrated the measured value at the RPA.

The harmonic voltage distortion is usually defined the grid system shall be cause the harmonics in the CTS to exceed the limits specified by EAC and the overall total rated current distortion (TRD) is limited 5% and the harmonic voltage distortion levels are illustrated [49].

Table 11 Harmonic voltage distortion in Cambodia

Bus Voltage at Point of Coupling	Max individual Harmonic Component (%)	Max Total Harmonic Distortion (THD) (%)
69 kV and less	3.0 %	5.0 %
69 kV < V ≤ 161 kV	1.5 %	2.5 %
Above 161 kV	1 %	1.5 %

Table 12 Harmonic Current Distortion of average load current

For voltage 69 kV or less						
SCR=ISC/IL	h<11	11≤ h<17	17≤ h<23	23≤ h<35	35≤ h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
For voltage 69 kV <V≤ 161 kV						
SCR=ISC/IL	h<11	11≤ h<17	17≤ h<23	23≤ h<35	35≤ h	TDD
<20	2.0	1.0	0.75	0.3	0.15	2.5
20-50	3.5	1.75	1.25	0.5	0.25	4.0
50-100	5.0	2.25	2.0	1.25	0.35	6.0
100-1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0
For voltage above161 kV						
SCR=ISC/IL	h<11	11≤ h<17	17≤ h<23	23≤ h<35	35≤ h	TDD
<50	2.0	1.0	0.75	0.3	0.15	2.5
50 or More	3.5	1.75	1.25	0.5	0.25	4.0

Where:

- SCR Short circuit ratio (utility short circuit current at the point of common coupling divided by the customer average load current)
- H, Harmonic number
- ISC, Utility short circuit current at the point of coupling
- IL, Customer average load current
- TDD, Total Demand Distortion

B. Voltage unbalance

Voltage unbalance is not determined and provided the valuable limit in IEEE Std 1547 [47]. It is illustrated as the fluctuation of the lowest and the highest grid voltage of three phases and divided by an average line voltage, whereas, the power generation by the solar PV plant get able to resist the voltage unbalance with the provision and permission from the responsible grid operator, not exceeding 2% for at least 30 second which is provided by Egyptian standard committee [46].

For voltage unbalance (VU) of the grid power transmission and power line operator in the kingdom of Cambodia is not limited in the general conditions for connecting solar PV generation sources to the electricity [49].

C. Flicker

The flicker levels are not given an accurate value by IEEE Std 1547 for solar PV plant system at the grid connection point, but the flicker value of Egyptian standard for solar PV plant are specified within the following limits:

Table 13 Flicker Requirements of solar PV plant

Short term (10 minutes)	$P_{st} \leq 0.35$
Long term (2 hours)	$P_{lt} \leq 0.25$

P_{st} Short term flicker factor over time periods of 10 minutes

P_{lt} Long term flicker factor over time periods of 2 hours

Whereas, the value of flicker levels for solar PV Project in Cambodia and shall not be created objectionable flicker for other consumers on the National Grid [49].

D. Limits of DC power injection

In the limitation of DC power injection is utilized to inject into the power grid and saturated to the distributed transformers which cause tripping and eventually overheating. DC current injection of DER shall not be allowed greater than % 5 by IEEE Std 1547 at the reference of point applicability (RPA) of the full rated output current. IEC standards put limitations on the maximum allowable amount of injected dc current into the grid of 1.0% of rated output current [48]. Whereas, in Cambodian, the solar PV project shall not inject DC current into the National Grid greater than 1% of the inverter rated output current [49].

Protection and safety requirement

A. Abnormal frequency trip

In the situation where the system frequency is not above 50.5 Hz or below 47.5 Hz, the solar PV project shall be disconnected from the grid supply within 0.2 seconds which is limited by EAC [49]. In IEEE 1547, when the grid frequency falls down, the frequency range and tripped time are recommended clearly of the solar PV power system shall be disconnected. Whereas, solar PV system with the capacity up to 30 KW is a set of frequency range, 60.5< f< 50.3 Hz with a disconnection time of 0.16 seconds [41].

B. Abnormal Voltage trip

The RMS voltage at the interconnection point of Solar PV project shall be given the specific range of abnormal voltage trip by EAC in the table below and It shall be disconnected from the grid system within time stated in the table [49].

Table 14 Response to Abnormal Voltage Trip

Voltage at (PCC)	Max trip time in seconds
$45\% > V_{nominal}$	0.2
$45\% \leq V_{nominal} < 60\%$	1
$60\% \leq V_{nominal} < 88\%$	2
$88\% \leq V_{nominal} < 110\%$	Normal operation
$110\% \leq V_{nominal} < 120\%$	1
$120\% < V_{nominal}$	0.2

Whereas, the range comparison of the abnormal voltage trips between the Electricity Authority of Cambodia (EAC) and IEEE 1547, the abnormal voltage trip range in IEEE 1547 at the RSM voltage of the point of common connection of the solar PV project and the grid deviates by the range in the table 12 below [47].

Table 15 Response to Abnormal Voltage Trip

Voltage at (PCC)	Max trip time in seconds
$V_{nominal} < 50\%$	0.16
$50\% \leq V_{nominal} < 88\%$	2
$110\% \leq V_{nominal} < 120\%$	1
$120\% \leq V_{nominal}$	0.16

C. Anti-islanding and reconnection

The Electricity Authority of Cambodia (EAC) has produced the technical procedures for design and installation of the solar PV project which shall be equipped with the accurately rated protective devices in order to sense any abnormality in the grid system and apply the automotive isolation of the solar PV project from the network system. The islanding or automotive isolation of the solar PV project should be sure for low or over voltage condition and the abnormal frequency and EAC shall authorize an islanding detection time of 0.2 seconds and reconnection shall only take place when the frequency and the system voltage fall down with the allowable range [49]. The islanding for grid connected PV systems takes place when the PV inverter does not disconnect for a very short time after the grid is tripped, i.e. it is continuing to operate with local load [50]. Otherwise, the fast acting circuit breakers and the adequate rates fuses on the input and output side of the inverters and isolating or disconnect switches to isolate DC and AC system for maintenance shall be supported [49].

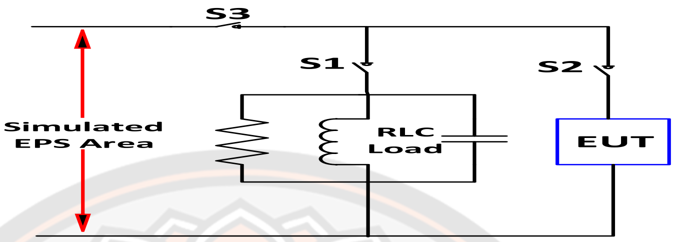


Figure 25 Anti-islanding Requirements

NOTES:

1. S_1 may be replaced with individual switches on each of the RLC load components.
2. Unless the equipment under test (EUT) has a unity output p.f, the receiver power component of the EUT is considered to be a part of the islanding load circuit [50].

Distorted grid performance

Particularly, the power distribution systems in interconnections of power grid and solar PV system shall enhance power harmonics in the power grid, then the effects of harmonics may cause many disturbances of the grid operation, especially, these factors shall distort the grid voltage. During a solar PV irradiation decreases due to low power operation, solar PV inverter may generate more undesirable harmonics. By the way, when harmonics are flowing through power grid impedance, produce the voltage harmonics and shall distort the supply voltage in the grid. The grid distortion harmonics comprise of order level content, for instant, 3rd harmonic, 5th harmonic or 7th harmonic. The effects of network power decrease may draw the distorted grid and all harmonics are measured increased order ranges from the 3rd to 13rd harmonic [51].

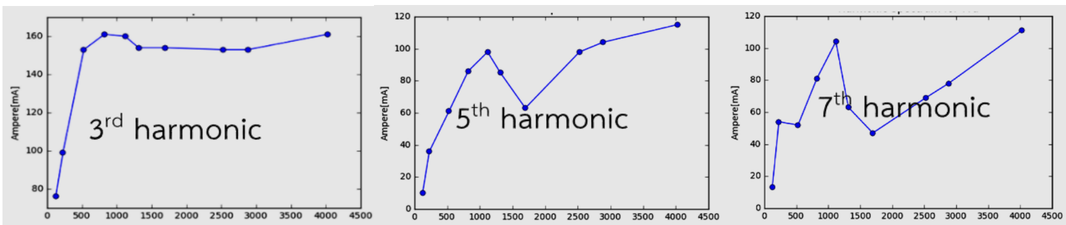


Figure 26 The 3rd, 5th and 7th Current harmonic vs power levels of inverter

Relevant literature review

V. Birunda Mary, D. I. W. C. , Dr. G. Themozhi[5] the PV systems require interfacing power converter DC-DC and DC-AC inverter between the PV array and the grid. The inverter filters are utilized to reduce down the harmonics and a high gain transformer is used which can convert a low-voltage DC 12-48V into a high-voltage AC 220V. The 3-swithch single phase inverter which can convert the DC voltage into controlled AC output voltage by designing the technology.

Jana, J.S., Hiranmay [7] the types of PV inverters can be used to in inject the grid, they have the diverse advantages and operating efficiency with the different size, weight and reliability. The standard of these inverters can fix the limits for the inverter voltage fluctuation, operating frequency variety, power factor, harmonics in the current penetrated into the grid, injection of DC current into the grid to avoid distribution transformer saturation and also address grounding issue.

Zhang, D.A., Ruichi Wu, Thomas [9] Voltage unbalance and distortion are the complex quality problem in the industrial utilization an when the terminal voltage is unbalance and distorted, this factor shall be caused th e induction motor to drop down the characteristics and damage. The distorted voltage waveform has enormous harmonics components, which distort the waveforms of the currents and flux densities in the induction motor.

Bindner, H [10] developing a power control concept with wind turbine and hydro pump, especially the power transmission from power firm to the remote place. To boost power in transforming controlled power storage or with an AC-DC converter. The AC-DC converters are designed as an integrated part of a variable speech wind turbine and when power transmission to a remote place is operated, some issues are controlled which cause the weak grid, actually these problems are controlled with power control, firm power, power fluctuation, voltage control, voltage peak limitation, control strategy, voltage fluctuation, voltage level and weak grid.

Khazaei, J.I., Peter Asrari, Arash Shafaye [11] HVDC power transmission line is connected AC grid through long distance delivering lines are usually weak with low short circuit ratio (SCR) and low efficient DC powerless stable. There are two types of HVDC system to compare their capacity of operation in line injection, Lined Commutated Converter (LCC-HVDC) and Forced Commutated Converter-Based (HVDC). The lower the SCR, the weaker the AC grid, which generates many problems such as voltage drop, voltage flicker, harmonic distortion, and frequency deviation. The weakness of an AC system is normally defined by the SCR which is in proportion with the AC system impedance. When an AC system is connected to an HVDC system, the SCR definition is modified to reflect the HVDC rate.

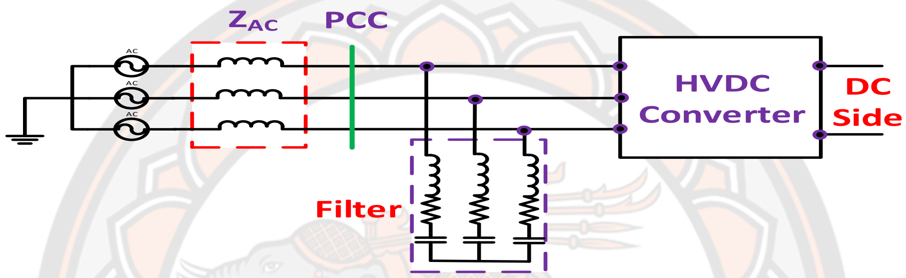


Figure 27 A typical topology for a HVDC connected to weak AC grid

Salas, V.S., W. Salas, R. A [16] the different PV inverters can be used in the implementation with the individual functions and power efficiency, and for power transmission line which power places not far from the power plants, boosting converters are utilized to implemented, actually even the grid connected inverters are operated in the AC couple systems. These inverters have a technology well known, and they only can be implemented in the PV Hybrid systems along with a bidirectional inverter in an AC coupling configuration. Then, they always are running as current source.

Corporation, T.E.D.S [18] the rotation speech of a three-phase AC induction motor which indicated RPM is inversely proportional to the number of poles (p) and proportional to frequency, therefore, the variable voltage, variable frequency to increase linearly as the output frequency increase. The control strategy of the voltage source inverter with a large value capacitor and the current source inverter with a large inductor are commuted on the input DC line of the inverter in parallel and in series. Particularly included the boosting technique and the output inverter filters.

Remus Teodorescu, M.L.a.P.R [19] the functions of H-Bridge inverter and Full Bridge inverter are mentioned of their path flow to each leg in the PV inverter. The boosting techniques are utilized with H. Bridge PV inverter including high frequency and boosting inverter with low frequency transformer. The general structure of PV inverter is detailed the stages for grid-penetration PV inverter, grid control requirement for PV, grid injection in single phase power converters and grid protection systems.

Scarabelot, L.T.R., Carlos R [20] the power transmission line is not stiff, caused by DC/AC conversion efficiency of inverter and the impedance grid, therefore, this fact shall make the complex grid and disconnect the grid or damage. Depending on the specific behaviour of each inverter, the adaptive hybrid mathematical model is fitted with greatest determination coefficient. These mathematical models describe the dynamic behaviour of the inverter and allow estimation of DC/AC instantaneous efficiency depending on the input parameters.

Vázquez, N.L., Joaquín Vaquero [20] the PV inverters are constructed from switches and diodes, which can lead to the waveform generation with the fast transition rather than smooth ones. These waveforms are produced up from a fundamental component which characterize as a pure sinusoidal and an infinite amount of harmonics, including single phase and three phase PV inverters in their voltage-, current-, and impedance source alternatives are verified specifically the topology, the modulation technique and the universal control aspects (UCA).

Hanif, M.B., M. Gaughan, K [22] the custom VSI and CSI technology comprise advanced characterises to Z- source inverter (ZSI). The traditional technology of pulse width modulated (PWM) VSI or CSI for PV conversion from DC-AC has advanced with the invention of ZSI and is utilized a unique impedance circuit to couple of DC power source to inverter bridge. A critical survey on ZSI performance in comparison to other standard inverter configurations used in PV applications (specially stand alone or utility integrated system) has been given and the following section will explain the details of the ZSI in terms of circuit calculations.

Jim Doucet, D.E., Jeremy Shaw [23] the main problems of the grid power transforming from the areas to the others usually consist of the grid power losses by the delivery distance, grid impedance, inverters output efficiency or transformers and these factors shall be to first convert the low voltage DC power to AC and then utilized a transformer to boost the voltage to 120 volts. MOSFET Drivers shall switch a DC voltage across load with highest voltage in the system. The inverter output filters are capable to optimize the efficiency and a switching frequency.

Ahmad Firdaus Ahmad Zaidia Sazali Yaacobd [24] when the power lines shall be penetrated to others, the worry and desire will occur If the technical errors taken place. Generated energy must be synchronized with voltage at the grid first before being phase shifted to make possible the power transfer to the grid. For smooth synchronization process exists 3 conditions, Voltage of generator must be equal to grid voltage, Frequency of both voltages must be the same, and Phase shift between the two sources must be zero with respectively power regulation as in figure 20.

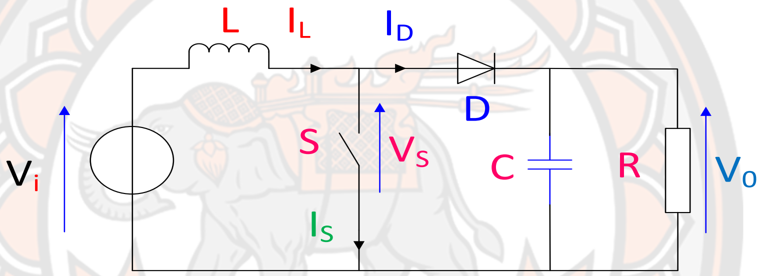


Figure 28 Boost converter schematic

Ruan, X.W., Xuehua Pan [25] the LCL filters should be actually designed to achieve the highest quality current, naturally PWM for single phase full-bridge connected, shall be implemented for the power flow depiction in switches (Q1-Q4), capacitor (C) and inductors (L1-L2). The key waveform of the bipolar PWM for single phase LCL type grid connected inverter is illustrated V_M is sinusoidal modulation signal by switches Q1, Q4, Q2 and Q3. For three phase LCL type as delta connection or star connection with the flow of switches leg, especially the mentioned structure of control in the modulation signal, frequency amplitude and voltage efficiency.

Xavier, L.S.C., Allan F [26] the control strategy for reactive power penetration and harmonic current compensation are explored. Furthermore, the inverter saturation serves as a main role, once high currents can damage the inverter or reduce its life time. When the harmonic current compensation is involved, a current limitation is very relatively normal for reactive power compensation and depending on the convectional structure of PV system.

Darshni M.Shukla, B.P [27] There are two methods of PWM compared and analysed the output harmonic spectra of various output voltage (poles voltage), line to line voltage (LLV) and line to neutral voltage (LNV) including the total harmonic distortion (THD). The advantages of Three-level inverter are observed with low harmonic distortion, low switching frequency, and lower general mode voltages, near sinusoidal output voltage less requirement of filtering and reduced the danger of motor failure due to high frequency switching dv/dt. The multi-carrier SPWM control methods also is implemented to increase the performance of multilevel inverters and classified according to vertical or horizontal arrangements of carrier signal.

Saleh, M.A., S. K. Moin Kalam [28] a matrix converter is used the direct AC-AC conversion by controlling the bidirectional power flow. Whereas, the orthogonal current/voltage component characteristics are utilized d-q by one machine and X-Y by other machines. The control decoupling is possible due to decoupling of the α-β and x-y components. The overall modulating signal is given to the PWM block and This PWM block shall then generate appropriate gate signals for the matrix converter, then produces appropriate voltages which drive the two series/parallel connected machines.

Athari, H.N., Mehdi Ataei [29] the inappropriate circuit design to deliver the power on grid, may cause instable, failure and the capable controller may be contrasted to the grid distortion. When the grid comprises of the distributed instability and failure, the grid operator may request ancillary service as the voltage harmonic compensation, local frequency, active filter, and voltage regulation and the comparison and the control systems are run with some parameters, the reference frame, control strategy, modulation method, output filter of inverter, controller and implementation.

A.E.W.H. Kahlane, L.H.a.M.K [30] the LCL filter is an important portion of the inverter utilized to combine an inverter to the used grid to filter the harmonics which generated by the inverter. The inverter's output is interconnected to the inductors, capacitor and resistor. There are many comparisons of inverter filter depicted the diversities of L, LC and LCL filter, as naturally, the LCL filter consists of a main function to have a reduction of the high order harmonic on the output side of the applicable inverters.

Ahmad Ale Ahmad, S.M [31] the inverter with an output LC filter may be implemented with solar PV energy (stand-alone) and utilized to the power on grid. The output LC filter is practised to attenuate the output voltage ripple and to determine the high frequency ripple current of the inverter switches. Those distortions are produced by the switching device. The main duty of inductor is the control of the switching frequency of inverter ripple current. Therefore, the maximum acceptable ripple current and the switching frequency of the inverter can determine the minimum inductor value.

Ms. Greeshma S1, M.J.P [32] the PV inverter performance structure in the power synchronized strategy is thought of the frequency amplitude, phase angle value and the voltage variation, but the radical step to be improved the inverter as the self-synchronized inverter, which may be automatically synchronized itself. The self-synchronized inverter may widen the system information measure, to reduce time and attenuate the complexness of the general controller. By the way, the PV inverter is injected to the grid, not be essential to equip the synchronization device.

Chander, A.H.K., Lalit [33] the output of inverter consists of a synchronous reference frame (SRF). The instantaneous output voltage of inverters are regulated with proportional integral (PI) controller and the demonstrated controller used the load current as the robustness of the power system is increased by considering the voltage decoupling feedforward loop. The sudden load fluctuation may cause the voltage of the inverter to receive affects and therefore a controller is important to ensure the stable output voltage throughout the operation.

Ciobotaru, M.T., R [34] the control strategy of the inverter synchronization by using the phase lock loop (PLL) and based on the delay. The input power structure utilized the DC voltage controller and power feed forward, especially, for the grid current control is applicable by the different-two strategies; PI and PR controllers. The PLL structure is also utilized for the grid voltage monitoring in order to receive the amplitude and the frequency value of the grid voltage. The computed current value of amplitude reference using the PV power (P_{pv}) and the RMS value of the ac voltage ($V_{AC\ rms}$) is added to the output value of the dc voltage controller (I_r) resulting in the ac current amplitude reference (I_{ref}).

Hassaine, L.O., E [35] the control structures of single phase and three phase inverters are investigated and demonstrated with the grid injected strategy. The structures topologies of inverters are depicted for grid connected photovoltaic and in those, verified the capacity and the efficiency of PV inverters, and consequently, compared the power ability and the operating efficiency of each inverter. The inverter structures are emphasized about the control strategy of the inverter output voltage and current flow.

de Aguiar, E.L., et al [36] naturally, the distributed generation (DG) is combined to the weak grid and that system line commonly exists of the involvement between the grid impedance and the voltage harmonic distortion. The PV inverter power is penetrated to the grid with the long distance, the line system actually suffers of the weak power and high impedance value of the operating grid. The current and voltage of PV power is continuous and comprise the low amplitude in general. The grid integrations are ensured the constant frequency value and the voltage compensation at load (PV stand-alone).

ASWAD ADIB1, S.M [37] the power transmission system of a weak grid can lead to voltage fluctuations at the inverter combination and consequently can cause inverters instability, moreover, the instability of PV power inverters is analysed in weak grid about a complicated problem. The control scheme, impacts of the grid and filter parameters based on the stability of an active power (P) and reactive power (Q) control. The grid-side line to- line voltages and line currents are sensed at the PCC and transformed to the dq-frame that are then used as inputs to the PQ-control schemes.

Im, J.-H., S.-H [38] the voltage fluctuation trouble of the most frequent power quality problem for the grid combination of large numbers of input power in a weal grid. The voltage variation at PCC is calculated and controlled by the parameters and output power of the wind turbine. The voltage output of the wind power turbine system can vary because of the changeable wind energy input and the impedance at PCC. The PCC voltage value can be computed, $V_{PCC} = V_{PCC0} + Z_{effect} + T_{WT}$.

Ji-Hoon 1m, S. -H. S [39] the wind turbine synchronization with the convectional diesel generator in parallel connection shall affect the convectional grid. The PCC deviation was the most critical item and the power penetration under a weak power is controlled and made the measurement by parameters or computer calculation. The weak grid is the power losses and make the grid instable by the equivalent load impedance including load impedance and the line impedance for load interconnection.

Brian K. Perera [40] the resistance (R) and reactance (X) ratio is greater than 1 when the PCC voltage of a solar PV system is connected to a single phase power distribution feeder. The power grid is mostly interfaced to the PV system throughout the voltage source converter (VSC) and the VSC can be regulated by controlling the reactive power integrated by VSC to the power grid. The PCC voltage regulated by controlling the reactive power which injected to the grid by PV system and the PCC voltage is sensitive to both the active and reactive power to the grid.

Chatterjee, A [41] the synchronization power strategy ensures process accurate information of grid voltage amplitude, phase and frequency are required. The synchronization methods are classified under two categories, open loop and closed loop methods. A current controller is employed to mitigate the harmonics in the current injected into the grid and regulate the power exchange between the plant and the grid. Additionally, the power integration between renewable energy and the grid is paid attention to the strategy of the power controller, power quality control, fault rid through and the proportional resonant current controller.

Sruti Keerti, V.M.B [42] the diesel generator interconnection requires the ideal power controlling strategy to the grid because of the loop cycle speech, which can make the grid power instability. A low voltage ride through (LVRT) capacity is connected generator, particularly, at the PCC is maintained during the fault conditions in the proportion to the proper LVRT profile. The lower short circuit ratio and higher grid impedance may cause the weak grid characteristic.

(EAC), E.A.o.C [43] the general requirement of electrical power technical standard of the kingdom of Cambodia is established as the electrical fundamental of power implementation, such as conditions of house and building wiring system, fuel oil generation plant and steam power plant, renewable energy system, hydro power plant, power transmission and distribution system referring to each article and technical power regulation in July, 2004.

Vai, V [44] the power distribution system in Cambodia is transferred to the end users from the high voltage/ medium voltage substation and isolated supply system exists of local MV grid with comprising their own generation and supplying a small area. The power losses are due to heating which takes place when an electrical current flow through a conductor. These problems may make the grid weak, power losses and energy losses, but the computing method is utilized to explore the compensation of the power and energy losses.

$$Power_{Losses}(t) = r\,L\,I^2(t)$$

$$Energy_{Losses}(t) = r\;L\;I^2(t)\,\Delta t \qquad \text{(Eq.2.15)}$$

Yuan-KangWu, M [45] the standard and guideline for power generation is reviewed and compared the power penetration strategy, especially, for PV power injection. Standards and guidelines for PV integration should be covered the operational safety, warning signals, limiting access, insulation, protection against islanding, grounding, and other considerations. The grid connected PV power inverter is controlled the power regulations, requirement for power quality, safety and protection.

Committee, E. T. G. C. a. T. E. D. N [46] a solar plant shall be injected a penetration unit with the grid before and after being connected to the grid, solar PV connected to the grid id controlled carefully the three main strategies with an inverter power can be connected to the grid and grid voltage variation, frequency compensation and phase angle amplitude.

21, I.S.C.C., IEEE [47] IEEE standard for interconnection and interoperability of distributed energy resource with associated electric power system interfaces is a series of standard developed with covering the conformance test procedure, application guide, guidance for monitoring, information change and DER interconnected with EPS, design, operation and integration, a recommended practice and guidance for conducting distribution impacts.

Soeren Baekhoej Kjaer [48] there are many solar PV systems not to be penetrated to the grid power and compared with more traditional energy sources such as coal, oil, gas, nuclear, hydro power, and wind. Particularly, grid connected PC inverter system can be paid attention to the inverter performance, inverter power control, DC power injection, power regulated regard, requirement for power quality, and safety and protective system. Additionally, the power of inverter types is depicted and its importance.

CAMBODIA, E.A.O [49] regulations in general conditions for connecting solar PV source to the grid is issued in 2018 on PV power regulations. Not only, Electricity Authority of Cambodia (AEC) is granted license for the private partner in the electric power investment and the granted license in power generation, national transmission and distribution license, and more addition, the PV regulated conditions is limited on PV power penetration to the grid.

R. Teodorescu, L.M.a.R., P [50] PV inverter structure and wind power analysed and controlled the output inverter power including the voltage and current operations. Hence, the grid requirement for PV and wind power are issued the power regulation and done the experimental test. power synchronization strategies are paid attention to power regulation control, requirement for quality control, safety and protection, the control of grid converter under the grid fault and the weak power line with the distribution transmission.

Related literature summary

From the study of the reviewed literature, it can be remarked that the grid connected PV inverter performance and und a weak grid is the most concerned problem for penetrating more renewable energy and power generation sources connected to the grid. Weak grid is the main cause which make the line power instable or until damage. The research result is illustrated this this paper refer mainly to the inverter operational process and the development of the inverter control strategy, which stand for PV power conditions experienced in the grid. Actually, the most exceedingly objective of the inverter control, erasing out the active and reactive power ripple and eliminate the output current harmonics of inverter. It is also the research proof from the literature, that a considerable regarding to be offered to the lightweight control strategy for power synchronization to the grid without focus on the way to affect the operational technique of the inverter performance. The foundational form of this study, which covers with the regulation about the relationship between PV inverter power regulation to grid, a weak grid control, grid impedance problem, the process of an inverter performance and the grid power synchronization requirement, especially, focused on the safety and protective requirements.

Table 16 Related literature summary

Nº	Author	Summary	Method	Year
1	V.Birunda Mary, D.I.W.C., Dr.G. Themozhi [52]	Utilized only three switches instead of convectional four switches and used three semiconductor switches, one is operating at high frequency and others at fundamental frequency. The simulation model of PV based 3S-SPI has been developed using MSTLSB Simulink.	Simulation Implementation	2017
2	Jana, J.S., Hiranmay [7]	Stand and specification of the grid-connected PV inverters shall sacrifice the safety and reliability to the users and the industries and more development of grid connected inverters, especially, the efficiency of grid inverter types.	Simulation Experiment	2016
3	Zhang, D.A., Ruichi Wu, Thomas [9]	The unbalanced and distorted voltage identified that the three vectors of three phase system are not the same magnitude and the loss characteristics of induction motors utilized.	Experiment Analysis	2017
4	Bindner, H [10]	The system of the power output control, storage strategies, power distribution transmission, and the power losses are investigated from a wind farm connected to a weak grid	Simulation experiment	1999
5	Khazaei, J.I [11]	HVDC is the best option to transfer the generated power to long distance. The power penetration control is another alternative for VSC-HVDC when the AC grid get very weak which related to the impedance ratios.	Simulation Analysis	2018

Table 16 (cont.)

Nº	Author	Summary	Method	Year
6	Salas, V.S., W [16]	The off-grid PV diesel Hybrid systems are encompassed the analysis about the current state by technique of converters, stand-alone inverters, grid-connected inverters and bidirectional practised in the AC coupled systems.	Simulation Analysis	2015
7	Corporation, T.E.D.S [18]	The motor circuit application is controlled between two phase and three phase modulation techniques based on the VSI and CSI and in more addition, in the market popularity application.	Experiment Analysis	2018
8	Remus Teodorescu, M.L.a.P.R [19]	The grid connected PV and wind power system are being developed quickly and a grid penetration operated, PV inverter structures and wind power converters are controlled carefully the power efficiency and power synchronization, especially, the control of power regulation, requirement for grid power, safety and protective strategy.	Implementati on Analysis	2011
9	Scarabelot, L.T.R., Carlos R [20]	The adaptive hybrid mathematical model of DC/AC average efficiency PV system inverter. The input and output electrical energy of inverter are controlled and the DC/ AC conversion efficiency based mainly on the relative power inverters.	Simulation Analysis	2018
10	Vázquez, N.L [20]	Single phase and three phase inverter circuits and the inverter functions with the voltage source, current source and impedance source inverters are depicted about the operated conditions and input and output power controlled strategies.	Simulation Analysis	2018

Table 16 (cont.)

Nº	Author	Summary	Method	Year
11	Hanif, M.B., M. Gaughan, K [22]	Z-source inverter (ZSI) is capable to build in an impedance network with the traditional pulse width modulated signal. Each inverter efficiency depended on the scheme design and the operational performance, especially, ZSI operation, inductors, capacitors and circuit equations designed carefully.	Simulation Analysis	2011
12	Jim Doucet , D.E [23]	Pour sine wave inverter simulated precisely the AC power which transferred by the wall outlet and the PWM inverter output comprises a PWM signal, transistors or other switching technologies connected to the load. A filtered sine wave of any frequency with phase shift changes provided by a designed circuit.	Simulation Implementati on	2007
13	Ahmad Firdaus Ahmad Zaidia [24]	The total wind power shall be controlled by the designed formula and depicted the principle of step-up boost DC-DC converter. The design DC/ AC inverter circuits simulated for the performance in current and voltage output.	Simulation Implementati on	2011
14	Ruan, X.W., Xuehua Pan [25]	LCL filter is controlled the valuable-effective attenuation of switching frequency harmonics in the injection grid current and the control strategies of PWM for 1 single phase full bride connected inverter.	Simulation Analysis	2018
15	Xavier, L.S.C. Allan [26]	PV inverter is analysed the ancillary service performance and control strategy for reactive power injection and harmonic current compensation of single phase and three phase inverter	Analysis	2018
16	Darshni M. Shukla, B.P [27]	The sinusoidal PWM technique and the space vector PWM technique for three level voltage source inverters are compared the output harmonic spectra of diverse output voltage and the total harmonic distortion	Simulation Implementati on	2017

Table 16 (cont.)

Nº	Author	Summary	Method	Year
17	Saleh, M.A., S. K [28]	Multi-phase converters are required mainly for feeding the fluctuated speech multi-phase drive systems and two stator windings of two five-phase machine connected in series/ parallel, input voltage and frequency control	Simulation Analysis	2011
18	Athari, H.N., Mehdi Ataei [29]	The grid tied inverter is controlled for PV system, these controlling system limited and analysed the reference frame, implementation platform, control strategy, inverter output filter, modulation method and controller	Simulation Analysis	2017
19	A.E.W.H. Kahlane [30]	LCL filter topology designed for a grid power penetration and the output filter shall serve as a harmonic reduction agent, especially this design id compared the filter efficiency of L, LC and LCL filter.	Simulation Experiment	2014
20	Ahmad Ale Ahmad [31]	The output LC filter is remarked the two main functions in the implementation operator, to attenuate the output voltage ripple and to limit the high frequency ripple current of inverter switches.	Simulation	2010
21	Ms.Greeshma S1 [32]	The method of power synchronization is required ideal data of voltage value, frequency amplitude and phase angel amplitude, but PV inverter improved the optimal use and easily, as a self-synchronized inverter.	Simulation Experiment	2017
22	Chander, A.H.K., Lalit [33]	A synchronous reference frame is implemented to regulate the instantaneous output voltage of inverter. The schematic designed to improve the robustness and method is ensured the performance of a stable output voltage of inverter	Simulation Analysis	2017
23	Ciobotaru, M.T., R. Blaabjerg, F [34]	The grid current controller is implemented by using PI and PR controller and a synchronous method utilized for PLL control based on delay.	Experiment Analysis	2005

Table 16 (cont.)

Nº	Author	Summary	Method	Year
24	Hassaine, L.O., E [35]	PV inverter is made the optimal control of power output, MPP, high efficiency, power control injected into the grid and low total harmonic distortion of current injected into the grid.	Simulation Experiment Analysis	2014
25	de Aguiar, E.L., et al [36]	The proposed DG system is controlled particularly the dynamic behaviour when connected to the weak grid with the relation between the voltage harmonic distortion and the weak grid impedance.	Experiment Analysis	2016
26	ASWAD ADIB1 [37]	The voltage source inverter id controlled significantly the grid-tied active and reactive power to reduce the grid impedance fluctuation and caused the power system stability.	Simulation Experiment	2018
27	Im, J.-H., S.-H. Song [38]	The size of PCC voltage variation id computed by utilizing the equivalent circuit parameter and the amount of reactive power can be compensated by the vector diagram method.	Simulation Experiment	2013
28	Ji-Hoon 1m, S.-H.S [39]	A voltage compensated method is proposed using the controlling strategy of the reactive power output and the PCC voltage changes compensation is effectively calculated.	Experiment Analysis	2009
29	Brian K. Perera, P.C.a.S.P [40]	A single-phase grid power feeder connected to PV inverter by considering as the grid with both reactance, resistance and the PCC voltage is issued the operational regulator.	Simulation Experiment	2013
30	Chatterjee, A. and K.B. Mohanty [41]	A review of the current control strategy is implemented for the single phase tied PV inverter and the current harmonic distortion control injected into the grid.	Simulation Experiment Analysis	2018

Table 16 (cont.)

Nº	Author	Summary	Method	Year
31	Sruti Keerti, V.M.B [42]	A weak grid is controlled carefully the lower short circuit ratio while injected to the diesel generator and higher grid impedance leading to higher risk of grid instability.	Simulation Implementation	2016
32	(EAC), E.A.o.C [43]	The general requirement for medium and low voltage distribution is issued the power regulator of supporting and structure, overhead, mechanical strength of isolator, MV/ LV transformer, protective device and grid specification.	Simulation Analysis	2004
33	Vai, Vannak [44]	The optimal method is developed for Pv power grid connected the grid to the substation (MV) with power transmission to the decentral station (LV) at the rural area.	Simulation Analysis	2018
34	Yuan-KangWu, M [45]	The standard and guideline for PV injection is developed to ensure the safety and reliability of power supply and covered the power regulation, requirement for power quality.	Simulation Experiment Analysis	2017
35	Committee, E.T.G.C.a.T.E.D.N [46]	Solar energy plant connection code is depicted the grid connection requirement, solar plant component control, power quality and grid protection.	Simulation Experiment Analysis	2017
36	21, I.S.C.C. [47]	Relevant requirements to the general power synchronization is emphasize performance, operation, testing, safety considerations, and maintenance of the interconnection, power regulation, power quality and safety and protection	Analysis	2018
37	Soeren Baekhoej Kjaer [48]	An inverter review for grid connection is emphasized the power control strategy covering the power process stage, the type of power decoupling, transformer selection and grid-connected power.	Simulation Implementation	2005

Table 16 (cont.)

Nº	Author	Summary	Method	Year
38	Soeren Baekhoej Kjaer [48]	An inverter topology review for grid connection is emphasized that the power control strategy covering the power process, the type of power decoupling, transformer usage and grid-connected power stage.	Simulation Experiment	2005
39	CAMBODIA, E.A.O [49]	The general technical conditions for connecting sources is approved to issue the investment license PV energy source generation and the limitation of power distribution license with power regulation.	Experiment Analysis	2018
40	R. Teodorescu, L.M.a.R. [50]	PV inverter and grid converter structure for wind turbine systems are connected to the grid power by issuing the power regulation in controlling the power synchronization conditions.	Simulation Implementation Analysis	2011

CHAPTER III

RESEARCH METHODOLOGY

In the research design and the research procedure on the study of grid-connected PV inverter performance under a weak grid condition for Cambodia has played an essential role in the power link with two power source injections and both power sources are set up as the single-phase grid simulator (220V/50Hz) and The PV simulator linked to the inverter. The procedure of the experimental application is selected single-phase commercial PV inverter as the first power source and the grid simulator as the secondary source which connected to the inductive reactance and the resistive elements to simulate the grid impedance. The experimental design and the research procedure are evaluated the power synchronization system under weak grid between PV simulation and a grid simulation. The PV simulation side is adjusted the 3-time power in 100%, 66% and 33% power of 5000W capacity as shown in table17. The PCC voltage and the voltage fluctuation shall be observed and recorded in the experimental result illustration and shall be analyzed the inverter performance under the distorted grid voltage, the total harmonic distortion, and its effect. The grid-connected PV plant model to the grid shall be applied by determining the commercial PV inverter with the power capacity 5KW and a single phase grid power simulator (220V/50Hz) including the area setting for the experimental process, Cambodian-Thai Skills Development Institute (CTSDI), Phnom Penh Cambodia.

Table 17 Power adjustment of experimental application

Percentage	**100%**	**66%**	**33%**
Power capacity (W)	5000	3300	1650
DC current (A)	8.0	4.46	2.25
DC voltage (V)	400	400	400

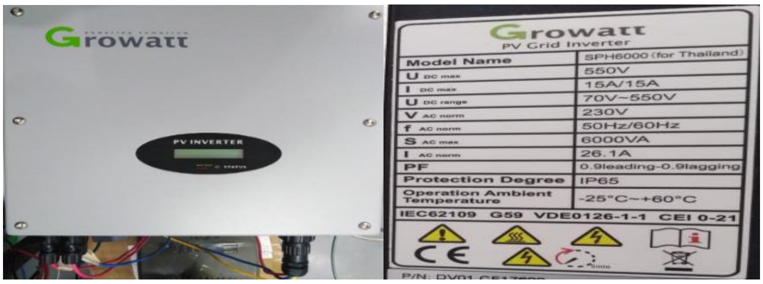


Figure 29 The 5 KW Growatt PV Grid Inverter (Thailand)

- Growatt brand, Power-5KW

- U $_{DC\ max}$ 550V, I $_{DC\ max}$ 15A, U $_{DC\ max\ range}$ 70V-550V

- V $_{AC\ nom}$ 230V, I $_{AC\ nom}$ 26.1A, S $_{AC\ nom}$ 6000VA

- Power factor 0.9 leading 0.9 lagging, Frequency-50Hz/60Hz

The global structure of the PV simulator system and the grid simulator shall be shown the individual source figuration.

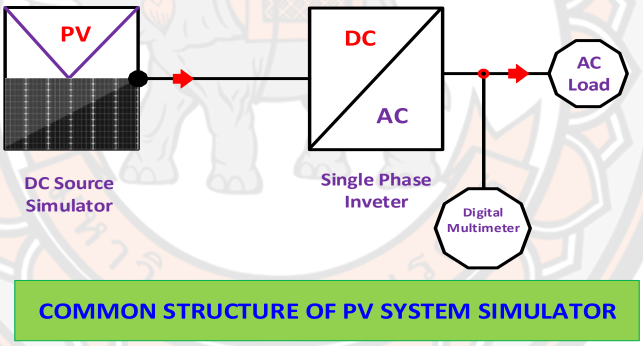


Figure 30 Single phase power of PV system simulator

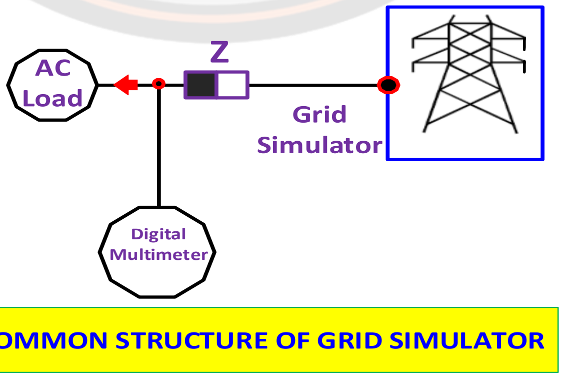


Figure 31 Single-phase power of grid simulator

Figure 31 is demonstrated the general structure of the PV inverter simulator for power supply and energy transmission to the loads in the constant grid power condition. Whereas, in the figure 32 illustrated the common structure of grid power simulator with the stable energy controlling condition for power supply and energy transfer to the loads without passing the impedance component of the grid, particularly in the power flow of the grid simulator to loads, the power transmission run across the impedance component to loads, in this situation shall loss the grid power and cause the voltage drop, therefore, the weak and unstable grid may be caused by above factors.

In figure 32 demonstrated the universal structure of the research design and defined actually the power synchronization with the individual two sources from the PV inverter simulator and the grid power. At the PCC serves mainly as both power source interface and PCC voltage shall increase in the ordinary operational condition, but the power transmission from the grid power simulator passed across the impedance component of grid (Z), hence, the transforming power of grid simulator may be lost and caused the weak grid with network instability with the voltage changes. The technical depiction of both power sources may be individually valuable, therefore, the technical specification of power penetration shall be controlled carefully, equipping the digital-meter controller for power measurement and depended on synchronous power regulation.

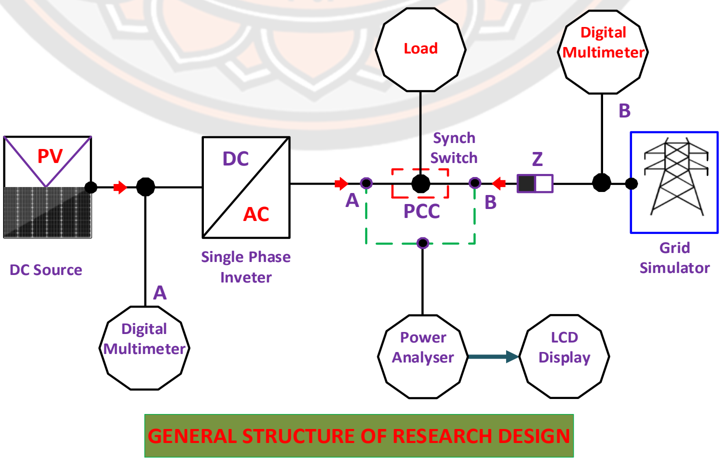


Figure 32 Experimental Design of Block Diagram

Equipment Depiction of Experimental Design

DC Source (PV model) - The DC Source shall provide the input into the tested inverter referring to the technical specification. The solar PV source is considered as a steady DC source, especially, operating mechanism inside is controlled. Even though DC-DC converter of output power is used mostly, its controlling strategy is utilized.

Single-phase inverter simulator- It is the electronic equipment under the most properly done the experiment and tested the accurate protection schema and the designed circuit can be converted DC power to AC energy, actually, in the inverter control strategy is illustrated, shall be subjected the fluctuated scenario of grid voltage and comprises the different voltage values.

Grid Simulator- for the operation of a grid simulator shall be utilized to mimic the accurate grid and make the creation in the casual penetrated scenarios seen in the line. The grid simulator shall be facilitated with a reliable environment and under the proper test of an inverter’ s operation, normally, it shall be allowed the operators or consumers referring to fluctuated voltage amplitude, frequency variation and the amplitude of phase angle.

Load- is considered as electrical operated appliances (linear and non-linear) where mostly need power for their operation and may cause the grid power variation.

Z point of the grid-The value of a grid impedance, as known in inductance and resistance and these compensations may cause the grid power system which is being utilized, weak and power losses until the grid instability.

Point of Common coupling or Sync Switch- is a main point for the electric grid system where the PV inverter simulator and the grid power simulator are penetrated under the proper value testing in bipartisan power systems and the accurate control condition, especially the grid operators should pay the most attention to a weak grid system which may fluctuate the grid power (line voltage and frequency).

The technical instrument utilized for measurement

Digital Multi-meter(**A**)-The electrical equipment is utilized to do the measurement of solar PV power DC from the solar array input DC voltage and current and controlled the DC power to inject to the inside of DC inverter.

Digital Multi-meter (**B**)- The electrical equipment is utilized to do properly the measurement of grid AC power connected from the electricity column of Cambodia and power flow linked into the PCC synchronization switch.

Power Analyse- At the point A and point B linked to the LCD display, used in order to control for recording and analyse both output AC voltage, current ratios of the PV inverter and recorded the grid current and voltage compensations.

LCD Display or Oscilloscope- is the most important instrument used to analyse and record the current and the voltage waveform compensators of electric energy.

Testing Operation and analyzing Conditions

Power control- the power control of PV inverter output and a grid power connected to an inductor and a resistor are investigated carefully by linking to the digital-parameter controller. The fundamental voltage and frequency of PV inverter output, including the basic grid voltage and a grid frequency shall be in the fundamental compensations of single-phase AC power and in the power integral regulator not to exceed the limits or the lower level of the power regulation.

PCC voltage control- in the ordinary operational system, the PCC voltage magnitude is observed that is not various (constant value). The technical specification of the individual power source penetration is regarded as the principles of power regulation with the same value of phase voltage, grid frequency, and phase angle amplitude. Particularly the fundamental state on the common structure of the research design in figure 23 verified that the power flow passed across the grid impedance (Z) to the PCC interface between PV inverter simulator and grid simulator. Therefore, the PCC voltage magnitude shall have fluctuated and voltage dip in the power system because of the impedance effect (Z_{eff}) and by the other hand, the voltage variation at PCC is caused by the local utilized loads.

The distorted grid performance- the distorted grid voltage at the PCC interface shall cause serious voltage change, THD levels of the grid system and voltage dip in the power systems. The power flow consists of two power sources, PV inverter simulator and grid simulator across the impedance component in figure 23. The impedance compensator shall cause the grid system comprising the voltage and current harmonic distortion in the grid system. The distortions of the original voltage or current waveform are tested and analyzed the operational waveform linked with oscilloscope power analyzer. Therefore, to make the optimal performance and operation of the power system, the undesirable voltage and current harmonic distortion are eliminated in compensating the reactive power. Harmonic distortion may cause operational disturbance and interference in the power system network. Particularly, there will be the individual power sources, and for the power synchronization is adopted phase voltage magnitude, frequency amplitude, and phase angle and the technical specification will be profiled with the same values for the grid penetration. A representative model of these regulations are checked in this framework and some as depicted in [49], but the transparency of the synchronized-grid power compensation is contrastable from the power injection regulation of the electricity law of Cambodia.

Frequency Amplitude

A. Frequency Amplitude value of inverter output
B. Frequency Amplitude value of the grid

In the grid synchronized conditions, the frequency value is clearly recognized about this condition and shall be profiled with the same value between the frequency amplitude value of inverter output and the grid frequency.

Phase Angle Amplitude

From the research method on the single-phase grid injection, phase angle amplitude is tested properly, whereas, the PCC power penetration is followed by focusing on the phase angle amplitude of the inverter output and the phase of the grid.

Over voltage condition-balance

Under this type, the line value to neutral voltage shall be increased up stepwise from the balanced state until the inverter takes autonomously off, naturally, guided by the EAC guideline [44]. The unbalanced injection method to be tested as follow.

- Balanced condition
- Single-phase balanced overvoltage
  - Phase (L_{inv}) to neutral- unbalance
  - Phase (L_{Grid}) to neutral- unbalance

Under-voltage condition-balance

Under this case, the line values to the neutral voltage shall be decreased down stepwise from the balanced state in pre-limited value by each step until the inverter takes off autonomously, similarly, introduced by EAC guidelines . Referring to the grid penetration regulation, the similar phase value of under-voltage and over-voltage unbalance shall be used.

Over and Under frequency condition-balance

The power system is being operated naturally with the fundamental allowed frequency is 50 Hz, but frequency value is between 47.5 Hz and 50.5 Hz, the electrical line power may be operated possibly or power synchronization but in this case, the system frequency compensation is above 50.5 Hz or below 47.5 Hz, the power systems shall be tripped autonomously with line protective equipment from the grid power supply in 0.2 seconds which is limited by EAC.

Weak grid criterion (WGC)

In the weak grid criterion is observed and analyzed that the power generation plants stayed far away from the power transmission site and distribution grid, by the way, the grid impedance compensation is high, low SCR value, load variation of line, under-over voltage fluctuations rise up or decrease of the grid injecting regulation, more severe voltage, these criterions pose a risk with loss of grid stability or weak grid.

Research Flow Chart

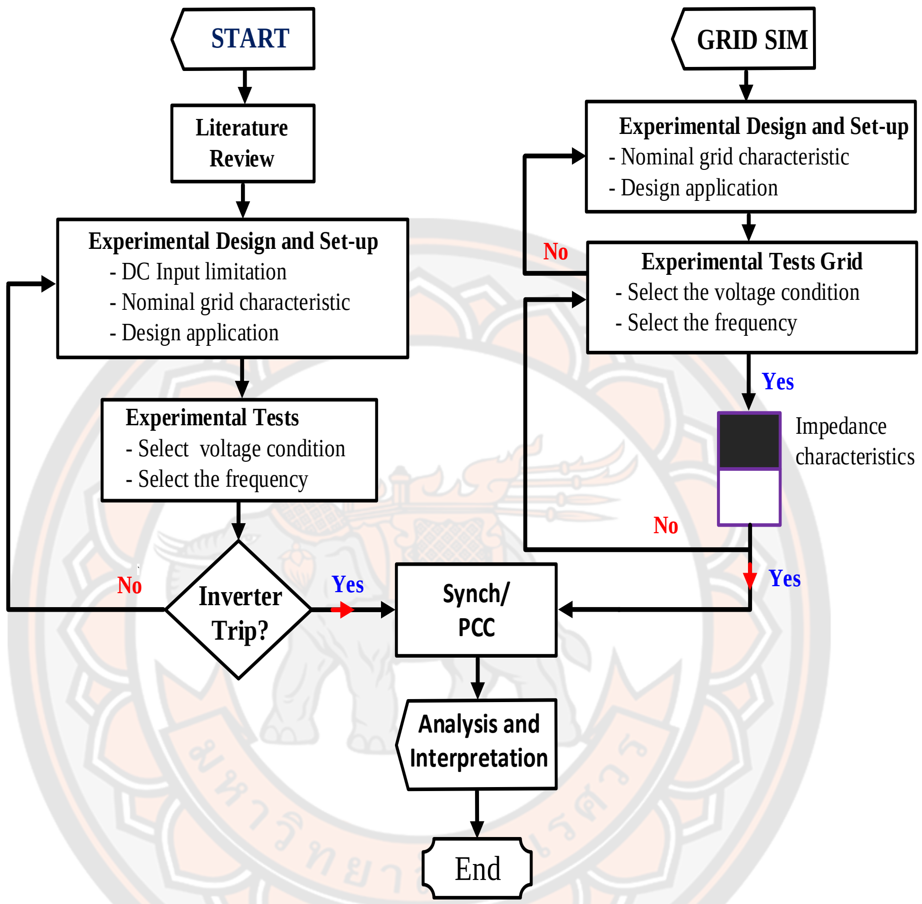


Figure 33 Research flowchart methodology

Table 18 The processes of research methodology are detailed as follow

Research method	Activities	Purposes
Literature Review	- Theoretical literature on power system biography - Solar PV components and inverters - Universal power regulation and grid-connected PV inverter requirement - Weak grid controlling strategy - Relevant study reviews	-To make an understanding of solar components, inverter operation, power regulation and PV synchronized requirement to the grid power under a weak grid.

Table 18 (cont.)

Research method	Activities	Purposes
Grid power process	A) Activities of Experimental Analysis. B) Experimental Design and set-up -Selective needs of the electrical measurement instrument to be utilized -Setting-up the experiment which focusing on the grid design	-To establish the original grid-connected solar PV system and analyze the power ratios.
Experimental application	-Testing for frequency amplitude, voltage observation of the national grid value with increasing or decreasing until the breaker is off -15 minutes long between intervals	-To collect the data for the grid performance analysis
PV Inverter process analysis	-Electrical measurement instruments selected to be used -Setting-up experimental conditions-according to the design.	-To establish **a** prototypical grid combined solar PV system
Impedance Characteristics	-the effective impedance of an electric circuit or component to alternating power, arising from the combined effects of ohm resistance and reactance.	-To be sensitive to know the compensation of power grid power run along the electrical wire after starting the application.
Experimental Implementation	-Various grid voltage, frequency value, and phase angle amplitudes identified the decreasing and increasing range until the inverter trips. -15 minutes long duration between intervals.	-To collect the data for inverter operational performance analysis

Table 18 (cont.)

Research method	Activities	Purposes
Sync Switch/ Device	-After testing frequency, phase angle amplitude and voltage value between PV inverter and the grid according to the power regulation. -The grid interconnection is combined between solar PV inverter and the national grid.	-To realize maximum power efficiency to load. -To know the voltage increasing and decreasing ratio due to solar PV. -To analyz the performance of PV inverter under distorted PCC voltage.
Analysis and Interpretation	-The data is measured and done the record to be analyzed by using Microsoft Excel in order to receive the inverter performance, inverter penetrated efficiency, grid unbalances, inverter unbalances, flicker and THD.	-To identify the grid injection efficiency with PV inverter system at PCC -To optimize the grid-unbalance value which causes the inverter trip/shut down -To limit the inverter’ s application under the grid unbalance condition at PCC
Actual data collection field	-The duration of electrical data collection in length one month at Cambodian-Thai Skills Development Institute (CTSDI), Phnom Penh capital- Cambodia	-To receive the data for comparative objective with the experimental data
Field Data Analysis	-The data analysis is used by the Microsoft Excel	-To set the grid to unbalance characteristic which used as the modelled proper field data.
Comparison and Analysis	-To compare the accurate result, experimental data and the conclusive drawing	-To set the suitable behaviour of a grid-connected PV inverter tripping and grid protective system is off -To determine the complexity of unbalance power synchronization in the electrical grid

Data Collection

The individual experimental data shall be collected from the input inverter, output inverter result, grid power, and the grid impedance value, and after the power network simulation and the obtained experimental result while the synchronized power is operated, referring to the penetrated power regulation and the electrical law from Electricity Authority of Cambodia.

Data analysis

In the grid synchronized conditions, DC current and voltage of the inverter input are determined on the power method definition.

$$I = \frac{V}{R}\ (A) \qquad V = I \times R\ (V) \qquad P = I.V.Cos\phi\ (W) \qquad \text{(Eq.3.1)}$$

At the point of common coupling (PCC) between the inverter output, the voltage and current unbalance of inverter output and grid shall be determined by referring to the community power definition [18].

$$V_{un} = \frac{V_i}{V_d} \times 100 = \frac{V_-}{V_+} \times 100 \qquad I_{un} = \frac{I_i}{I_d} \times 100 = \frac{I_-}{I_+} \times 100 \qquad \text{(Eq.3.2)}$$

The inverter efficiency is limited by using this equation.

$$\eta_{inverter} = \frac{P_{output}}{P_{input}} = \frac{I_{ac} V_{ac} \cos\theta}{I_{dc} V_{dc}} \qquad \text{(Eq.3.3)}$$

- Referred to the accurate experimental result and the actual grid result, the inverter performance is illustrated under the ordinary operating condition.
- The trend of total harmonic distortion (THD) passed and approved by EAC is < %5.

CHAPTER IV

RESULTS AND DISCUSSION

The Simulated Experimental Process

The topic under study is “the single-phase grid-connected PV inverter performance under a weak grid condition for Cambodia”. The single-phase grid-connected inverter performance is focused on the two applicable procedures (PV Simulator and Grid Simulator) with the ideal step-wise operation; this application will be carried out carefully. Firstly, the inverter performance- linked PV simulator the source depicted the operational process in order to deliver the power supply to loads or to the power penetration point (PCC) between PV simulator of inverter power and the grid source. In the data collection application, 5KW Growatt inverter brand (two strings) was used for the experiment. Moreover, the technical experimental procedure of this research shall be applied for linking the both injected power of the assayed data collection. The experimental data collection is applied and controlled attentively the both-side power systems, current (A), voltage (V), frequency (Hz), power factor (%), power difference (%) and harmonic distortion value (%), especially, these data values shall be analysed properly about a system transparency value between solar PV simulator system and grid impedance value sector at PCC to utilizing loads.

In the technical experiment application of an assaying data collection for the PV inverter performance under a weak grid condition between a PV power simulation linked PV inverter and a grid simulation, the experimental results shall be tested and linked to powering measuring equipment like a power oscilloscope analyser and a power meter. These data results shall be demonstrated in the experimental figures, waveforms data and analysed technically the single-phase grid-connected PV inverter performance under a weak grid condition. There are the three steps for the experimental applications to analyse the grid system faults in this paper; the grid network shall be implemented under the ideal grid, under the distorted grid voltage and the weak grid including inverter efficiency (%), harmonic effect levels (%), reactive power values, and the grid integration verification at PCC of the grid system, otherwise, the experimental application of this paper is assayed the length of power injection in the system. The experimental simulated model of two PV simulators units are set up for data collection with change in 100%, 66% and 33% power of the grid system which is linked to the PV inverter input power ($PV_{in.inv}$) with the 5000-Watt available power limitation. Moreover, with the voltage value limitation of a normal grid system is set up, 400 DCV and the current compensation 8A, whereas, the grid simulator sector is single-phase AC grid application (220V/50Hz) and in the second step of the simulated system is applied as above network but the grid simulator block is combined in series to an impedance element connection (inductive "X_L" and resistive " R" value) with their value to verify the accuracy and correctness of the proposed grid system. The simulated grid system shall be controlled the entire grid power of a system and analysed the level of a total current harmonic distortion (THD), because the high grid-impedance compensation may lead the distorted grid system or a power losing factor may lead the grid harmonic distortion in the grid system and in the experimental application for data collection, the experimental results are illustrated to link to Ms. Excel program, multi-power meter and oscilloscope analyser for data controlling and the systemized data assay.

Figure 34 The PV Simulator Power

The research of a single-phase grid-connected PV inverter performance under a weak grid condition is applied with Growatt Inverter brand which consists of the manufacturing capacity (Power-6KW), $U_{DC\ max}$ 550V, $I_{DC\ max}$ 15A, $U_{DC\ max\ range}$ 70V-550V, $V_{AC\ nom}$ 230V, $I_{AC\ nom}$ 26.1A, $S_{AC\ nom}$ 6000VA, Power factor 0.9 leading 0.9 lagging, Frequency-50Hz/60Hz.

Figure 35 Power manufacturing capacity of PV inverter

The Experimental Result and Analysis Under Ideal Grid System

The study of a single-phase grid-connected PV inverter performance under a weak grid condition is implemented as three criteria in the grid system in order to control power quality and to analyse the grid characteristics in progress for understanding the inverter operating performance, the inverter efficiency and the total harmonic distortions (THD).

The ideal grid system is simulated the experimental application in the 100%, 66% and 33% power changes for the data collection and the inverter efficiency analyses. The experimental structure and data results shall be demonstrated below figures.

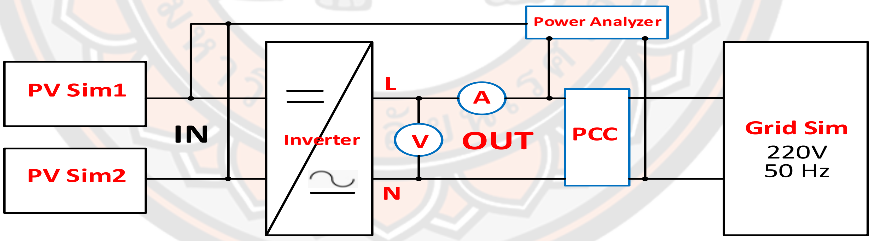
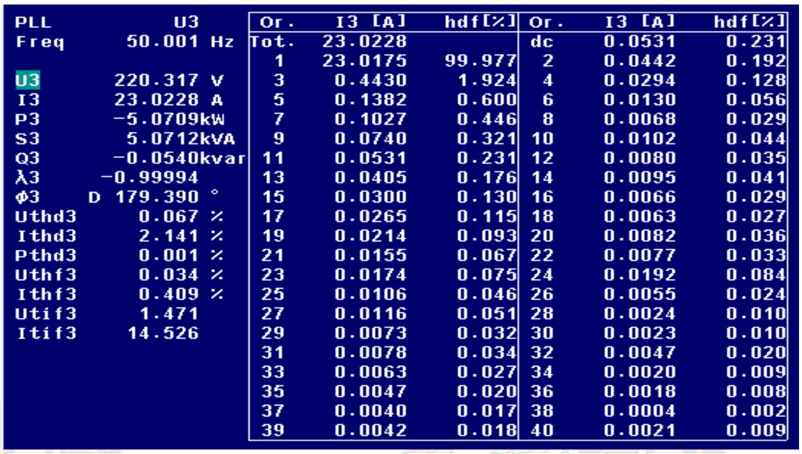


Figure 36 General experimental structure under the ideal Grid

The simulated result under the ideal Grid

The experimental result under the ideal grid is connected with two PV simulator sources which comprise of 5000W, available voltage 400DCV and limited current 8.0A with 100% power value, 3300W power, available voltage 400V and limited current 4.46A with 66% power value and for 33% power is with 1650W, available voltage 400V and limited current 2.25A to interconnect 5-kW Growatt Brand PV inverter where the experimental data is demonstrated, the inverter efficiency and correctness of the grid system, the total harmonic distortion (THD) and the THD spectrums. The duration of power penetration is delayed around 60 seconds between the grid sim and the PV inverter.

100% power result under the ideal Grid



PLL	U3	Or.	I3 [A]	hdf[%]	Or.	I3 [A]	hdf[%]
Freq	50.001 Hz	Tot.	23.0228		dc	0.0531	0.231
		1	23.0175	99.977	2	0.0442	0.192
U3	220.317 V	3	0.4430	1.924	4	0.0294	0.128
I3	23.0228 A	5	0.1382	0.600	6	0.0130	0.056
P3	−5.0709kW	7	0.1027	0.446	8	0.0068	0.029
S3	5.0712kVA	9	0.0740	0.321	10	0.0102	0.044
Q3	−0.0540kvar	11	0.0531	0.231	12	0.0080	0.035
λ3	−0.99994	13	0.0405	0.176	14	0.0095	0.041
φ3	D 179.390 °	15	0.0300	0.130	16	0.0066	0.029
Uthd3	0.067 %	17	0.0265	0.115	18	0.0063	0.027
Ithd3	2.141 %	19	0.0214	0.093	20	0.0082	0.036
Pthd3	0.001 %	21	0.0155	0.067	22	0.0077	0.033
Uthf3	0.034 %	23	0.0174	0.075	24	0.0192	0.084
Ithf3	0.409 %	25	0.0106	0.046	26	0.0055	0.024
Utif3	1.471	27	0.0116	0.051	28	0.0024	0.010
Itif3	14.526	29	0.0073	0.032	30	0.0023	0.010
		31	0.0078	0.034	32	0.0047	0.020
		33	0.0063	0.027	34	0.0020	0.009
		35	0.0047	0.020	36	0.0018	0.008
		37	0.0040	0.017	38	0.0004	0.002
		39	0.0042	0.018	40	0.0021	0.009

Figure 37 Experiment under ideal Grid at 100% power

Figure 36 demonstrates the experimental results which offered by power analyser. The experimental identification demonstrates PCC voltage increased a little bit, 220.31V of the foundation voltage (220V), a frequency value is constant (50Hz), the current amplitude at PCC point is 23A and the inverter efficiency (%) is calculated by the input and output power of the inverter. Particularly, the inverter output power at PCC expressed with value 5070.9W and the input power of the PV simulators are 5228.4W. the inverter performance efficiency is applied with the associated equation, the output power is divided to input power of PV inverter. The calculated result is shown, the efficiency is equal to 97% of the 100% power system and the current THD value is 2.14%. This amplitude leads to the unsmooth current flow path.

Figure 38 The total power of PV Simulator

$$\eta_{inverter} = \frac{P_{output}}{P_{input}} = \frac{I_{ac}V_{ac}\cos\theta}{I_{dc}V_{dc}} \qquad \text{(Eq.4.1)}$$

$$\eta_{inverter} = \frac{P_{output}}{P_{input}} = \frac{5070.9W}{2677.6W + 2550.8W} = 0.97\%$$

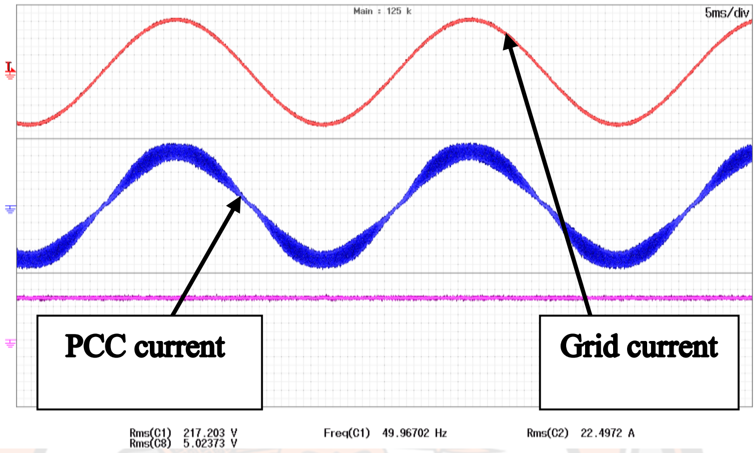


Figure 39 Waveform of PCC current and Grid current

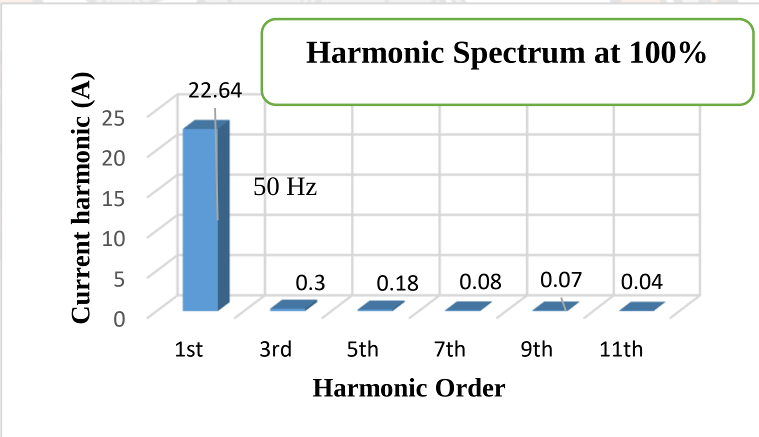


Figure 40 The harmonic spectrum of ideal grid

66% power result under the ideal Grid

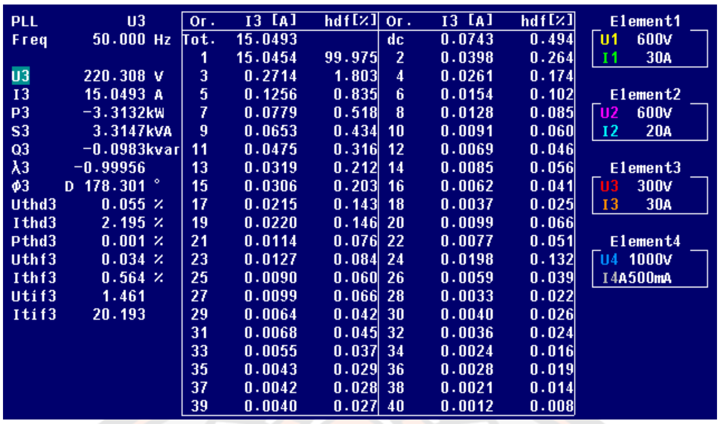


Figure 41 The experiment under ideal Grid at 66% power

Figure 40 depicts the experimental results where the power flows from DC PV simulators to AC (inverter operation) with the comparison between input power and output power value. Each input power (P_{input}) exists of 1720.1W (1st PV Sim) and 1723.2W (2nd PV Sim), the summation of the both PV sims are calculated with a result 3443.3W and the output power (P_{output}) at PCC is 3313.2W. The inverter operation of an ideal grid system proved its efficiency is 96%. The more experimental identification demonstrated PCC voltage increases a bit with value 220.30V of basic voltage, a frequency value is constant (50Hz), the current amplitude at PCC point is 15A. The total harmonic distortion of current increase up quite high 2.19%, larger than 100% power (THD 2.14%) of the ideal grid system. This THD current value is possible to draw the unsmooth current flow path which is shown in figure 42.

$$THD(\omega) = \sqrt{\frac{\sum_{n=2}^{10} Y_n^2(\omega)}{Y_1}} \qquad \text{(Eq.4.2)}$$

Naturally, calculations are performed up to the 10th order (n = 10).

Figure 42 The total power of PV Simulator

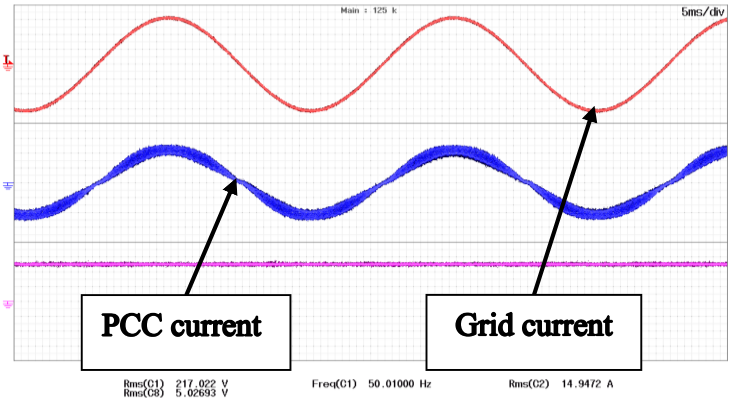


Figure 43 Waveform of PCC current and Grid current

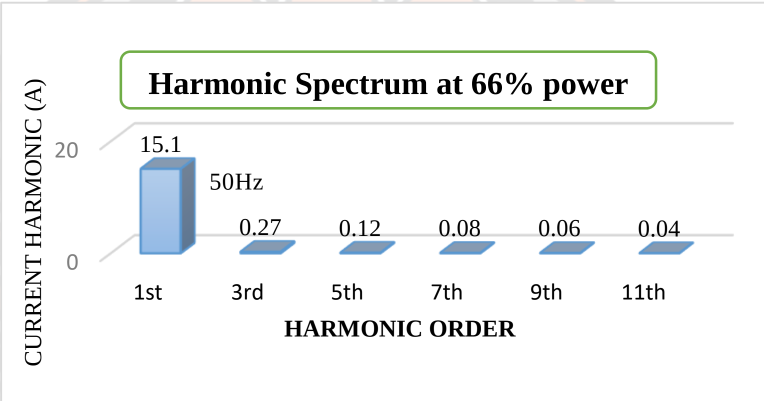
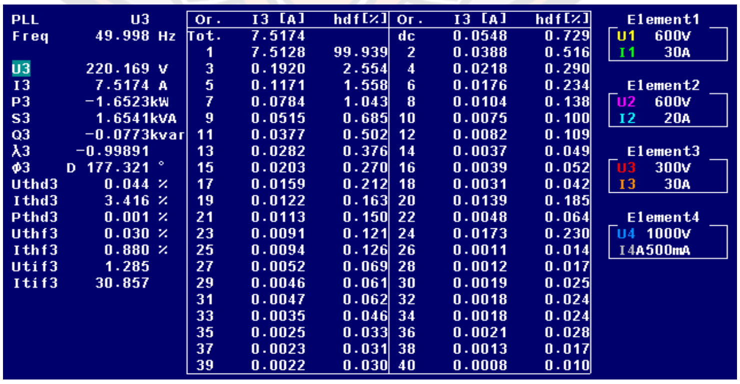


Figure 44 The harmonic spectrum of ideal grid

33% power result under the ideal Grid



PLL	U3
Freq	49.998 Hz
U3	220.169 V
I3	7.5174 A
P3	−1.6523kW
S3	1.6541kVA
Q3	−0.0773kvar
λ3	−0.99891
φ3	D 177.321 °
Uthd3	0.044 %
Ithd3	3.416 %
Pthd3	0.001 %
Uthf3	0.030 %
Ithf3	0.880 %
Utif3	1.285
Itif3	30.857

Or.	I3 [A]	hdf[%]	Or.	I3 [A]	hdf[%]
Tot.	7.5174		dc	0.0548	0.729
1	7.5128	99.939	2	0.0388	0.516
3	0.1920	2.554	4	0.0218	0.290
5	0.1171	1.558	6	0.0176	0.234
7	0.0784	1.043	8	0.0104	0.138
9	0.0515	0.685	10	0.0075	0.100
11	0.0377	0.502	12	0.0082	0.109
13	0.0282	0.376	14	0.0037	0.049
15	0.0203	0.270	16	0.0039	0.052
17	0.0159	0.212	18	0.0031	0.042
19	0.0122	0.163	20	0.0139	0.185
21	0.0113	0.150	22	0.0048	0.064
23	0.0091	0.121	24	0.0173	0.230
25	0.0094	0.126	26	0.0011	0.014
27	0.0052	0.069	28	0.0012	0.017
29	0.0046	0.061	30	0.0019	0.025
31	0.0047	0.062	32	0.0018	0.024
33	0.0035	0.046	34	0.0018	0.024
35	0.0025	0.033	36	0.0021	0.028
37	0.0023	0.031	38	0.0013	0.017
39	0.0022	0.030	40	0.0008	0.010

Element1
U1 600V
I1 30A
Element2
U2 600V
I2 20A
Element3
U3 300V
I3 30A
Element4
U4 1000V
I4A500mA

Figure 45 The experiment under ideal Grid at 33% power

Figure 44 depicts the experimental application under the ideal grid system of 33% power adjustment. The power data of both PV sims are proved actually the total input power (P_{input}) with a summation, P_{input} 1705.4W, The PCC voltage increased a little bit, 220.16V of the foundation voltage, a frequency value falls down a bit 49.99Hz (50Hz), the current amplitude at PCC point is 7.51A whereas, the total output power (P_{output}) comprises of 1652.3W, hence the inverter efficiency is shown by the calculation of the input and output power, equivalent to 96% of the operational system. The THD current goes up to 3.41%, this range is quite a high value which the harmonic effect could absorb the ripple current flow where associated to the figure 46. Even though, it is quite a high value, if referring to the grid code of Cambodia which passed by Electricity Authority of Cambodia (EAC), the total harmonic and current voltage distortion is not allowed to exceed over 5% of the system.

Figure 46 The total power of PV Simulator

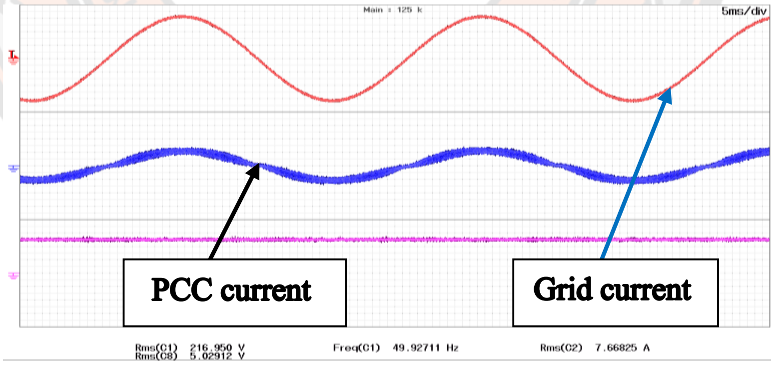


Figure 47 Illustrates waveform of PCC current and Grid current

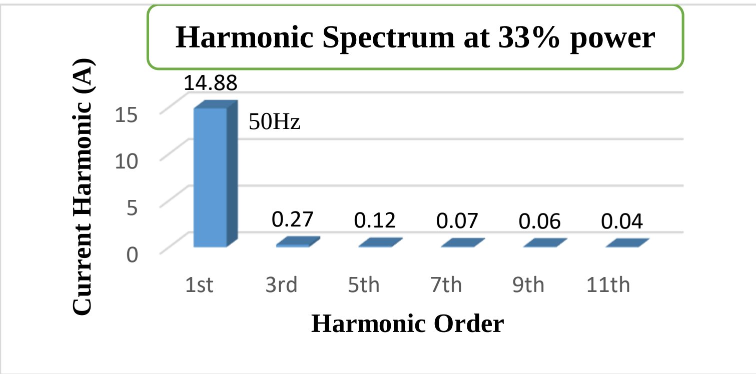
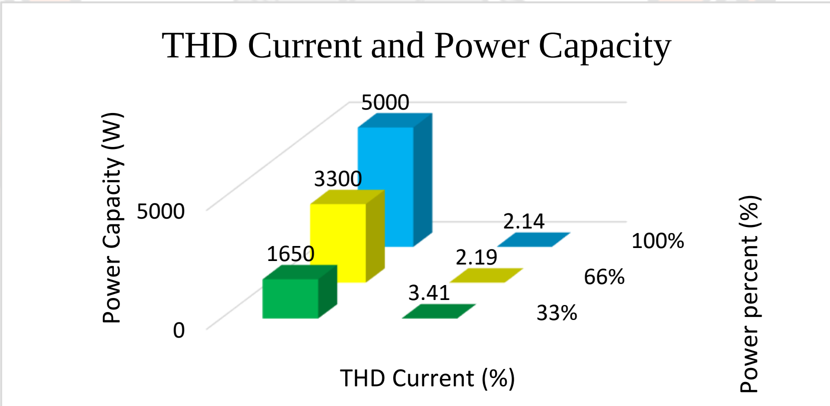


Figure 48 Shows the harmonic spectrum of ideal grid

Table 19 shows the total harmonic distortion comparison and power capacity

Name	33% power	66% power	100% power	Units
Power Capacity (P)	1650	3300	5000	Watts
PCC Current (I_{PCC})	7.5174	15.04	23.02	Ampere
TDH Current	3.416	2.19	2.14	Percent



The Experiment under the distorted grid voltage System

Figure 48 proves the harmonic order value adding which is provided total power and applied logically for the experimental criteria as mentioned, in those operating processes are operated with 100%, 66% and 33% power change conditions of 5-kW inverter capacity. The experimental application is properly implemented to judge the grid characteristics. This experiment is divided into the two figurations, adding the harmonic order value and percent rate (%) such as the 3rd harmonic, 5th harmonic, 7th harmonic, 9th harmonic order magnitude and the only 3rd harmonic order amplitude.

The power quality control of the grid system, the inverter efficiency and THD values are the most essential issues of the simulated experiment. The additional scenario illustrated the harmonic order value and the percent rates where is done the mathematical theory calculation and the results linked to Microsoft Excel program.

$$Q = VI\sin\theta \qquad \text{(Eq.4.3)}$$

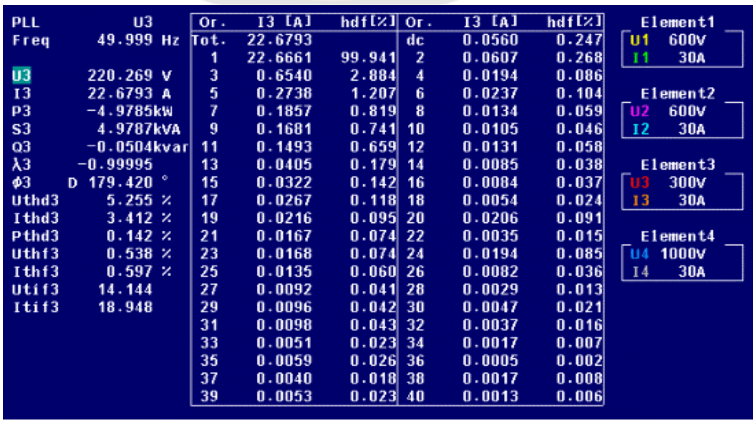
$$Uthd = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + ... + V_n^2}}{V_1} \times 100\% \qquad \text{(Eg.4.4)}$$

$$Ithd = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + ... + I_n^2}}{I_1} \times 100\% \qquad \text{(Eg.4.5)}$$

The harmonic order value addition with Percent amount (%)

The experimental results of the harmonic order value additions and the percent amount with the individual power adjustment of the PV simulation which connected to the grid system. These results shall be compared with the power adjustment stages of PV simulation and the percent rate to the harmonic order gap and the current flow identification. In the situation of the harmonic order value addition in the experimental application is observed the characteristics and the transparency of the grid system. Furthermore, the perturbation rate of the max total harmonic distortion value is not permitted to exceed over 5% of the grid code regulation in Cambodia. The perturbation insertion of the harmonic order as shown in table 18.

100% Power experimental under the Distorted Grid Voltage



Or.	I3 [A]	hdf[%]	Or.	I3 [A]	hdf[%]
Tot.	22.6793		dc	0.0560	0.247
1	22.6661	99.941	2	0.0607	0.268
3	0.6540	2.884	4	0.0194	0.086
5	0.2738	1.207	6	0.0237	0.104
7	0.1857	0.819	8	0.0134	0.059
9	0.1681	0.741	10	0.0105	0.046
11	0.1493	0.659	12	0.0131	0.058
13	0.0405	0.179	14	0.0085	0.038
15	0.0322	0.142	16	0.0084	0.037
17	0.0267	0.118	18	0.0054	0.024
19	0.0216	0.095	20	0.0206	0.091
21	0.0167	0.074	22	0.0035	0.015
23	0.0168	0.074	24	0.0194	0.085
25	0.0135	0.060	26	0.0082	0.036
27	0.0092	0.041	28	0.0029	0.013
29	0.0096	0.042	30	0.0047	0.021
31	0.0098	0.043	32	0.0037	0.016
33	0.0051	0.023	34	0.0017	0.007
35	0.0059	0.026	36	0.0005	0.002
37	0.0040	0.018	38	0.0017	0.008
39	0.0053	0.023	40	0.0013	0.006

Figure 50 Exhibits result of harmonic order value addition

Figure 49 depicts the experimental results under the distorted grid voltage system of 100% power stag. The total input power from both PV simulations is 5228.4W and the total output power exists of 4978.5W. The PCC voltage is various a bit 220.26V of basic voltage, a frequency value fluctuates a bit 49.99Hz (50Hz), the current magnitude at PCC point is 22.67A, this value falls down a bit, if comparing with 100% power of the ideal grid. Otherwise, the inverter efficiency is shown by the calculation of the input and output power, equivalent to 95% of the operational system, and the active power (S) is in better level, 4.9785 KVA and the reactive power (Q) reaches to more small range 0.05 Kvar. The PCC waveforms identify the THD current value increases quite highly 3.41% which harmonic effect could draw the unsmooth current flow pathway and the ripple current waveform. More addition, the results of harmonic order value insertion at 100% power are shown in the table 18.

Table 20 Illustrate the harmonic order value adding at 100% power

Harmonic Number	0	1	2	3	4	5	6	Units
Perturbation	0.0	0.0	**5.0**	**1.0**	**1.0**	**1.0**	0.0	%
Harmonic order	0.0	0.0	**3rd**	**5th**	**7th**	**9th**	0.0	Order
Harmonic result	0.0	0.0	**0.66**	**0.27**	**0.18**	**0.16**	0.0	%
THD current	**3.41**	0.0	0.0	0.0	0.0	0.0	0.0	%

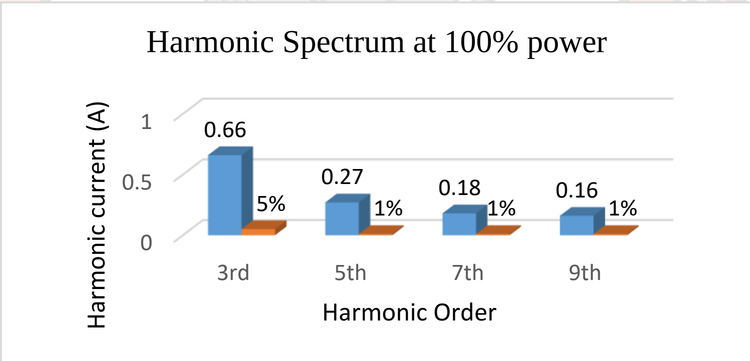


Figure 51 The harmonic spectrum of distorted grid voltage

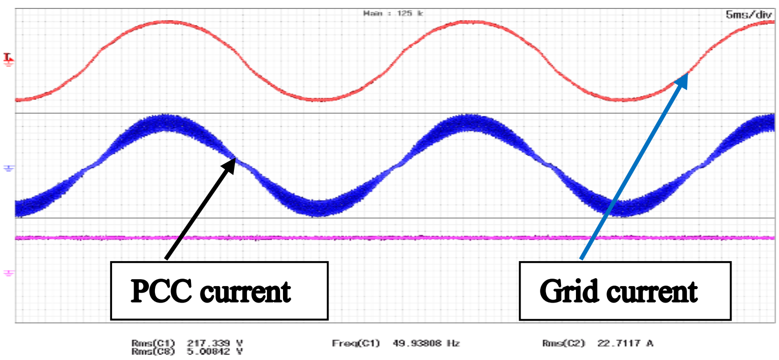


Figure 52 Grid current and PCC current waveform

66% Power Experimental under the Distorted Grid Voltage

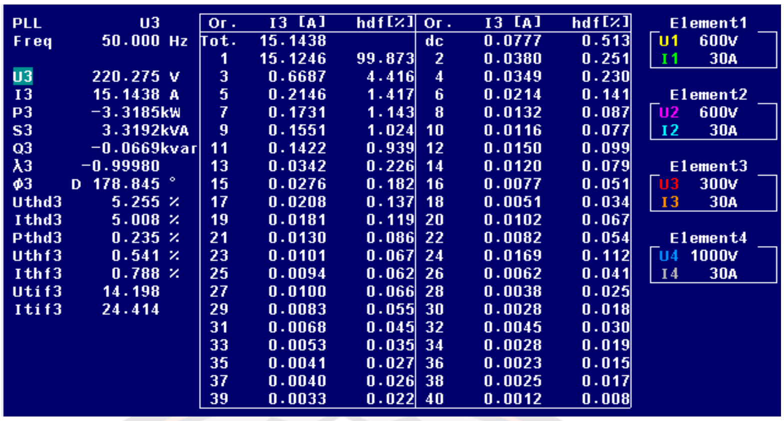


Figure 53 Result of the harmonic order value addition

Figure 52 depicts logically a grid characteristic of the distorted grid voltage, the total output power (P_{out}) comprises of 3318.5W and the input power of PV sims which adjusted 66% power (P_{in}) 3443.3W, thus, these values proves the inverter efficiency is good 96% of this system. The certification of PCC voltage deviates a little bit 220.27V from the foundational voltage 220V, frequency is constant 50Hz, the active power (S) 3319.2 KVA and the reactive power (Q) 0.06 Kvar locate in an enhanced value conditions. The total harmonic distortion (THD) current goes up to the high range until 5.0% which effect could lead unsmooth current flow pathway and so ripple current waveform as shown in figure 52, but this target reaches to the limitation of the grid code regulation (EAC) in Cambodia.

Table 21 illustrate the harmonic order value addition at 66% power

Harmonic Number	**0.0**	**1**	**2**	**3**	**4**	**5**	**6**	**Units**
Perturbation (%)	0.0	0.0	**5.0**	**1.0**	**1.0**	**1.0**	**1.0**	%
Harmonic order	0.0	0.0	**3rd**	**5th**	**7th**	**9th**	0	Order
Harmonic result (%)	0.0	0.0	**0.67**	**0.20**	**0.17**	**0.15**	0.0	%
THD current (%)	**5.008**	0.0	0.0	0.0	0.0	0.0	0.0	%

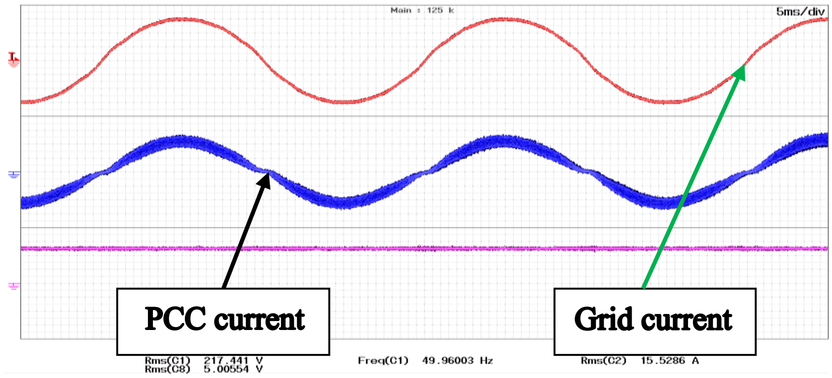


Figure 54 Grid current and PCC current waveform

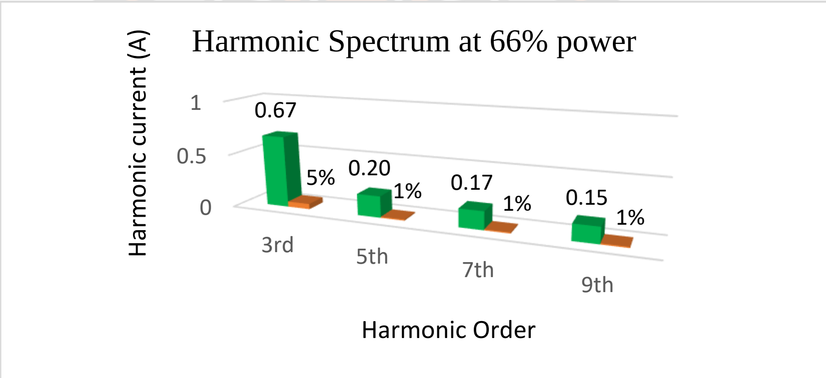


Figure 55 The harmonic spectrum of distorted grid voltage

33% Power Experimental under the Distorted Grid Voltage

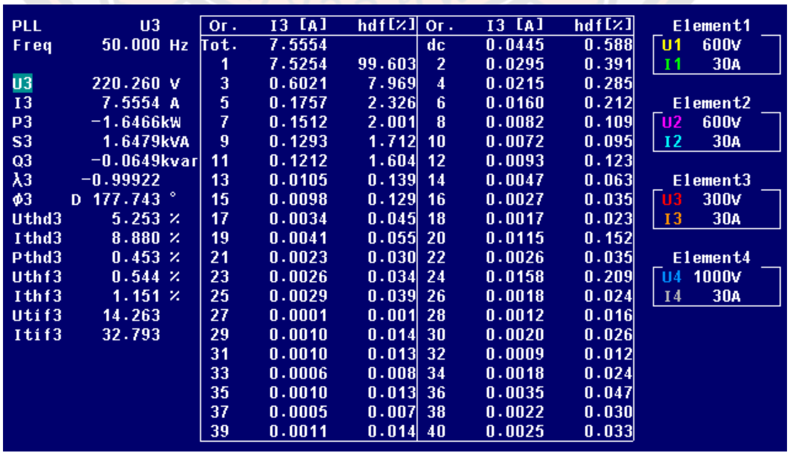


Figure 56 Result of harmonic order value addition

Figure 55 demonstrates the result of 33% experiment under the distorted grid voltage system. The PCC voltage deviates a bit from the foundational voltage

220.26V, the PCC grid current is various a bit 7.55A comparing with 33% ideal grid system 7.51A, a grid frequency keeps constant 50 Hz. Otherwise, the inverter efficiency stands in improving performance 96% with a calculation between P_{output} 1646.6W and P_{input} 1705.4W, the active power 1647.9 KVA (S) and reactive power (Q) 0.06 Kvar, their values reach to improving condition. The harmonic order values of the system are good as shown in table 21, but the THD current increases up to the highest value 8.88% of the system, this magnitude will not be allowed to transfer power because this value exceed over the power regulation of a grid code <5% in Cambodia, furthermore, the current flow pathway and current waveforms are extremely distorted in the system as illustrated in figure 56.

Table 22 The harmonic order value addition at 33% power

Harmonic Number	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**Units**
Perturbation (%)	0.0	0.0	**5.0**	**1.0**	**1.0**	**1.0**	**1.0**	%
Harmonic order	0.0	0.0	**3rd**	**5th**	**7th**	**9th**	0.0	Order
Harmonic result (%)	0.0	0.0	**0.60**	**0.18**	**0.14**	**0.13**	0.0	%
Ithd (%)	**8.88**	0.0	0.0	0.0	0.0	0.0	0.0	%

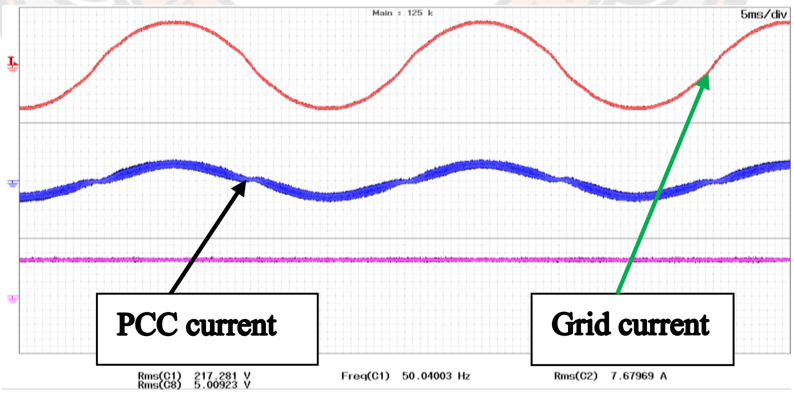


Figure 57 Grid current and PCC current waveform

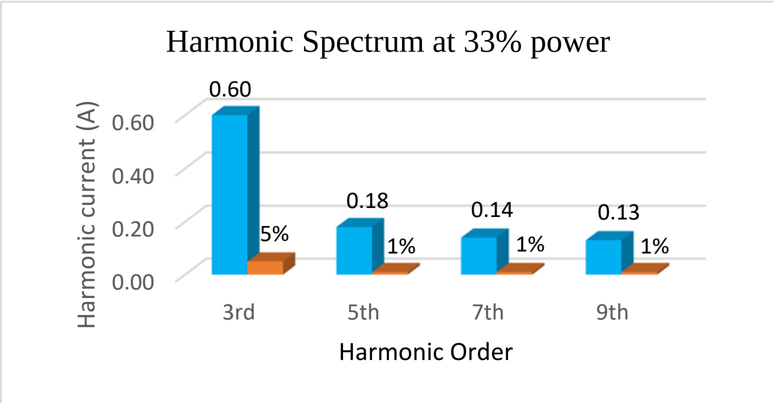


Figure 58 The harmonic spectrum of distorted grid voltage

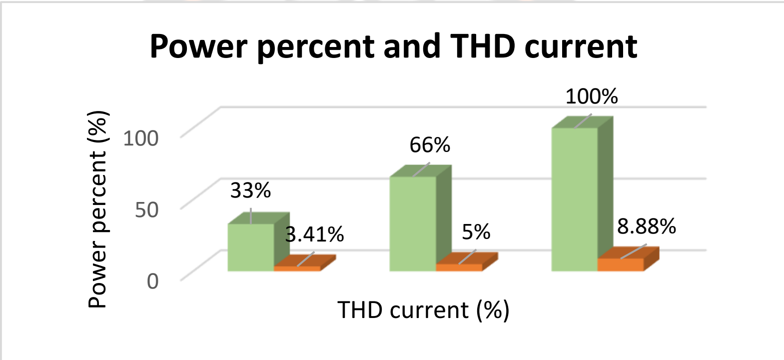


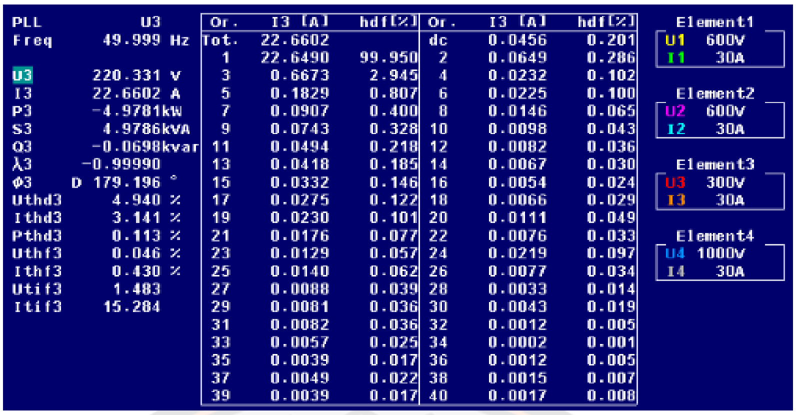
Figure 59 Comparison of THD current and Power percent

The data chart in figure 58 depicts the comparison between power Perturbation and the total harmonic distortion current (THD). As mentioned about the power adjustment into the three stages and the THD current value are shown in the data chart.

The experimental result of the only 3rd harmonic order value addition

In the practical system of the only 3rd harmonic value section is implemented to analyse the power system operation, the inverter efficiency, and the 3rd harmonic magnitude with three-stage power adjustment, especially, this grid system is paid an attention to the total harmonic distortion current (THD) because of the harmonic effects could distort the current flow pathway and the current waveform when the THD current range reach to the high level over the power regulation of the grid code, or the power transferring system shall not be allowed. The experimental results of the only 3rd harmonic order value insertion is operated attentively and, these result linked to Ms. Excel program.

The only 3rd harmonic order value addition for 100% Power



PLL	U3
Freq	49.999 Hz
U3	220.331 V
I3	22.6602 A
P3	−4.9781kW
S3	4.9786kVA
Q3	−0.0698kvar
λ3	−0.99990
φ3	D 179.196 °
Uthd3	4.940 %
Ithd3	3.141 %
Pthd3	0.113 %
Uthf3	0.046 %
Ithf3	0.430 %
Utif3	1.483
Itif3	15.284

Or.	I3 [A]	hdf[%]	Or.	I3 [A]	hdf[%]
Tot.	22.6602		dc	0.0456	0.201
1	22.6490	99.950	2	0.0649	0.286
3	0.6673	2.945	4	0.0232	0.102
5	0.1829	0.807	6	0.0225	0.100
7	0.0907	0.400	8	0.0146	0.065
9	0.0743	0.328	10	0.0098	0.043
11	0.0494	0.218	12	0.0082	0.036
13	0.0418	0.185	14	0.0067	0.030
15	0.0332	0.146	16	0.0054	0.024
17	0.0275	0.122	18	0.0066	0.029
19	0.0230	0.101	20	0.0111	0.049
21	0.0176	0.077	22	0.0076	0.033
23	0.0129	0.057	24	0.0219	0.097
25	0.0140	0.062	26	0.0077	0.034
27	0.0088	0.039	28	0.0033	0.014
29	0.0081	0.036	30	0.0043	0.019
31	0.0082	0.036	32	0.0012	0.005
33	0.0057	0.025	34	0.0002	0.001
35	0.0039	0.017	36	0.0012	0.005
37	0.0049	0.022	38	0.0015	0.007
39	0.0039	0.017	40	0.0017	0.008

Element	Voltage range	Current range
Element1	U1 600V	I1 30A
Element2	U2 600V	I2 30A
Element3	U3 300V	I3 30A
Element4	U4 1000V	I4 30A

Figure 60 Experimental result of 3rd harmonic value addition

Figure 59 depicts the experimental result in the only 3rd harmonic order value adding of the distorted grid voltage system. The total output power (P_{output}) 4978.1W and the both PV simulations (P_{input}) 5225.4W. the both-sides power capacity is certified the inverter efficiency by the both power calculation, equivalent to 95% of operational system. PCC voltage magnitude varies a bit 220.33V of the basic voltage 220V, the current value falls down a little bit, 22.66A comparing with the ideal grid application in 100% power, I_{PCC} 23A. More addition, the active power (S) 4978.6 KVA and reactive power (Q) 0.06 Kvar are located in good level. Otherwise, the THD current goes up to quite a high value 3.14%, which could absorb the unsmooth current flow pathway and the ripple current waveform as shown in figure 60, but this rank does not yet exceed over the power regulation of the grid code in Cambodia and this case will be permitted to continue for power transaction. Whereas, the only 3rd harmonic order value is illustrated in the chart of harmonic spectrum in figure 61.

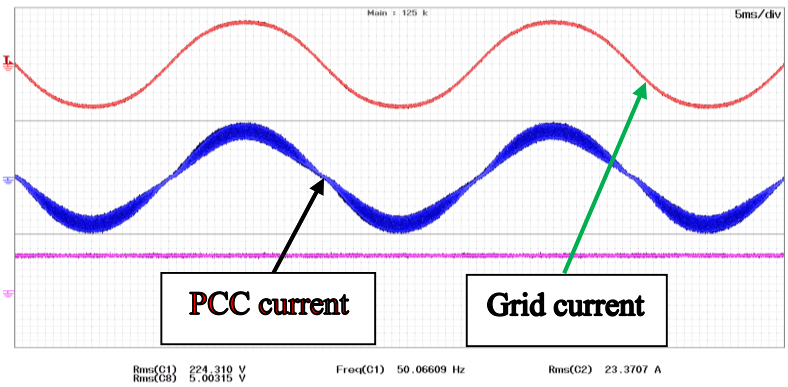


Figure 61 Grid current and PCC current waveform

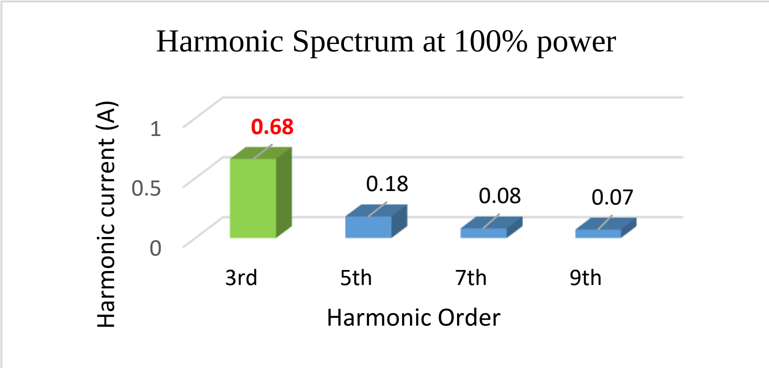
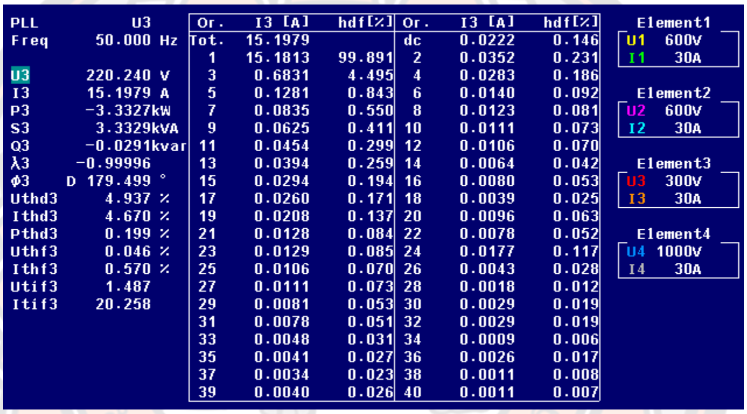


Figure 62 The 3rd harmonic order value

The only 3rd harmonic order value addition for 66% Power



Or.	I3 [A]	hdf[%]	Or.	I3 [A]	hdf[%]
Tot.	15.1979		dc	0.0222	0.146
1	15.1813	99.891	2	0.0352	0.231
3	0.6831	4.495	4	0.0283	0.186
5	0.1281	0.843	6	0.0140	0.092
7	0.0835	0.550	8	0.0123	0.081
9	0.0625	0.411	10	0.0111	0.073
11	0.0454	0.299	12	0.0106	0.070
13	0.0394	0.259	14	0.0064	0.042
15	0.0294	0.194	16	0.0080	0.053
17	0.0260	0.171	18	0.0039	0.025
19	0.0208	0.137	20	0.0096	0.063
21	0.0128	0.084	22	0.0078	0.052
23	0.0129	0.085	24	0.0177	0.117
25	0.0106	0.070	26	0.0043	0.028
27	0.0111	0.073	28	0.0018	0.012
29	0.0081	0.053	30	0.0029	0.019
31	0.0078	0.051	32	0.0029	0.019
33	0.0048	0.031	34	0.0009	0.006
35	0.0041	0.027	36	0.0026	0.017
37	0.0034	0.023	38	0.0011	0.008
39	0.0040	0.026	40	0.0011	0.007

Figure 63 Experimental Result of 3rd harmonic order magnitude

Figure 61 depicts the experimental result of the only 3rd harmonic order magnitude insertion in 66% power of the distorted grid voltage system. These results express the PCC voltage increases up a little bit 220.24V of the foundational voltage for a single phase (220V), the current value is 15.19A by comparing with the experiment in 66% power of the ideal grid voltage system (I_{ideal})15A. The inverter performance is enhanced and the efficiency gets equal to 96% by the technical calculation between the total output power (P_{output}) 3332.7W and the total input power (P_{input}) 3443.3W. the active power (S) 3332.7 KVA and the reactive power (Q) 0.02 Kvar, these values reach to the good rank for the grid system. By the way, the total harmonic distortion of current (THD) goes to a high value 4.67% and this value nearly locates in the warning level of power regulation which THD effects could draw the distorted grid system and the unsmooth-ripple current flow, thus the 3rd harmonic order addition value comprises the low grade 0.68% as shown in figure 64.

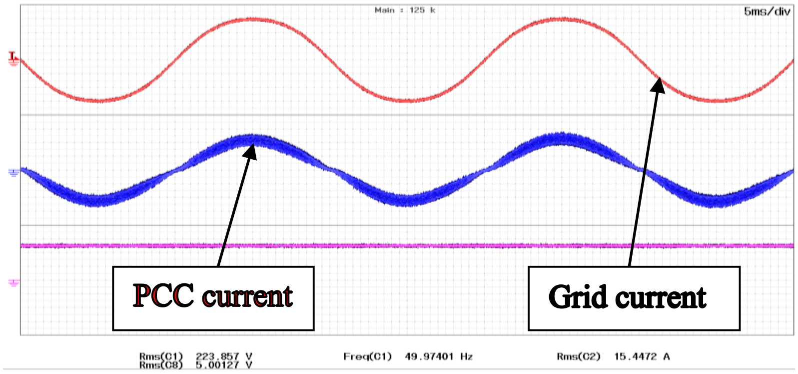


Figure 64 Grid current and PCC current waveform

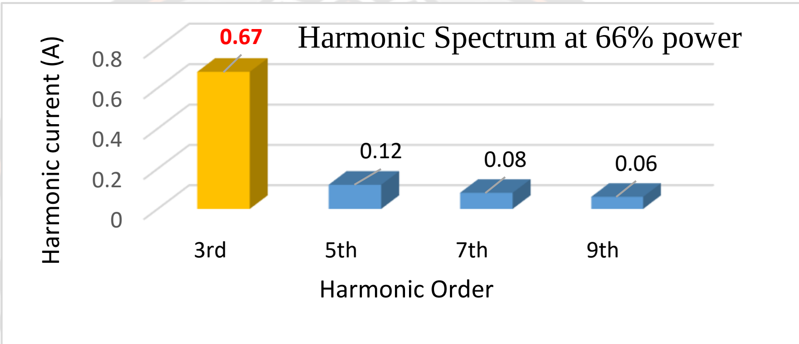
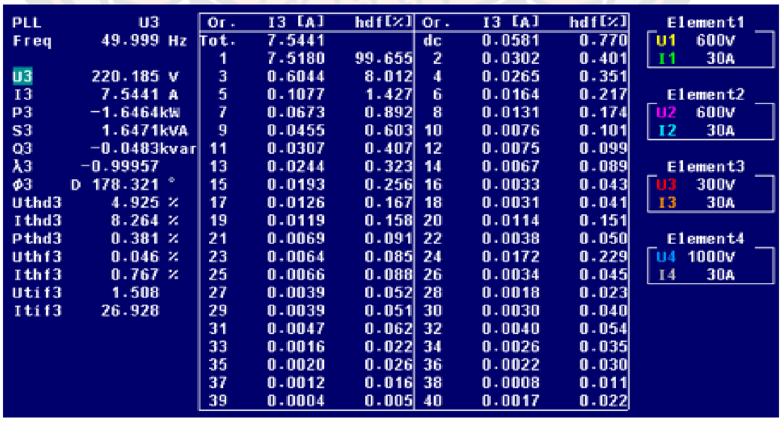


Figure 65 The 3rd harmonic order value

The only 3rd harmonic order value addition for 33% Power



PLL	U3
Freq	49.999 Hz
U3	220.185 V
I3	7.5441 A
P3	−1.6464kW
S3	1.6471kVA
Q3	−0.0483kvar
λ3	−0.99957
φ3	D 178.321 °
Uthd3	4.925 %
Ithd3	8.264 %
Pthd3	0.381 %
Uthf3	0.046 %
Ithf3	0.767 %
Utif3	1.508
Itif3	26.928

Or.	I3 [A]	hdf[%]	Or.	I3 [A]	hdf[%]
Tot.	7.5441		dc	0.0581	0.770
1	7.5180	99.655	2	0.0302	0.401
3	0.6044	8.012	4	0.0265	0.351
5	0.1077	1.427	6	0.0164	0.217
7	0.0673	0.892	8	0.0131	0.174
9	0.0455	0.603	10	0.0076	0.101
11	0.0307	0.407	12	0.0075	0.099
13	0.0244	0.323	14	0.0067	0.089
15	0.0193	0.256	16	0.0033	0.043
17	0.0126	0.167	18	0.0031	0.041
19	0.0119	0.158	20	0.0114	0.151
21	0.0069	0.091	22	0.0038	0.050
23	0.0064	0.085	24	0.0172	0.229
25	0.0066	0.088	26	0.0034	0.045
27	0.0039	0.052	28	0.0018	0.023
29	0.0039	0.051	30	0.0030	0.040
31	0.0047	0.062	32	0.0040	0.054
33	0.0016	0.022	34	0.0026	0.035
35	0.0020	0.026	36	0.0022	0.030
37	0.0012	0.016	38	0.0008	0.011
39	0.0004	0.005	40	0.0017	0.022

Element	U	I
Element1	U1 600V	I1 30A
Element2	U2 600V	I2 30A
Element3	U3 300V	I3 30A
Element4	U4 1000V	I4 30A

Figure 66 Experimental result of 3rd order harmonic value addition

Figure 65 demonstrates the experimental result in 33% power with the only 3rd harmonic order value addition. These certify the total harmonic distortion of the current (THD) consists of the highest expansion 8.26% and the maximum magnitude exceeds over the limitation of power regulation in Cambodia which passed by EAC <5% and THD effect could lead extremely distorted grid system until the power transmission shall be stopped as shown in figure 66. The PCC voltage deviates a little bit 220.18V of the basic voltage 220V, frequency is 99.99 Hz and the PCC current comprises of 7.54A. Judiciously, the inverter performance is good and the efficiency stands on 96% of the grid system with the calculation between P_{output} 1646.4W and P_{input} 1705.4W, furthermore, the active power (S) and the reactive power (Q) keep in good level for this grid system. The 3rd harmonic order value is 0.59% as illustrated in the chart of the harmonic spectrum in figure 67.

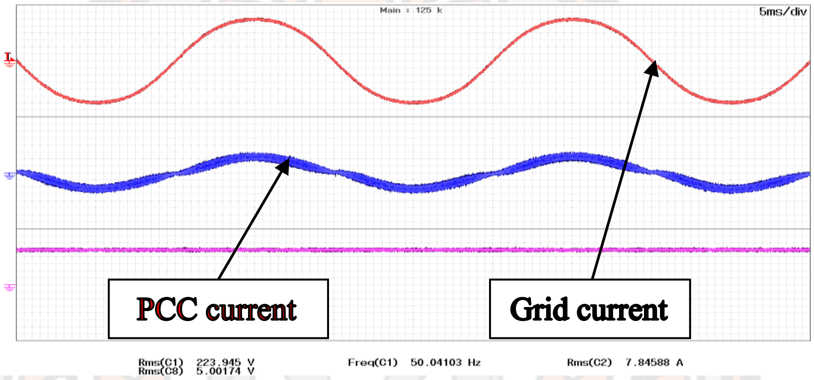


Figure 67 Grid current and PCC current waveform

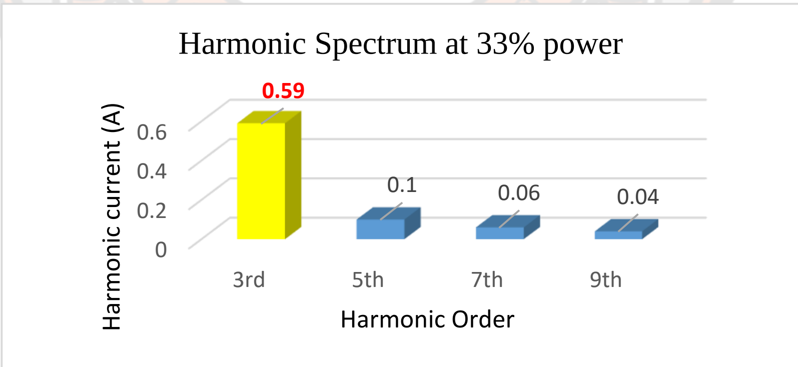


Figure 68 The 3rd harmonic order value

Table 23 The comparison of the 3rd harmonic order value adding

Name	33% power	66% power	100% power	Units
V_{PCC}	220.18	220.24	220.33	Volt
Frequency	49.99	50	49.99	Hertz
I_{PCC}	7.54	15.19	22.66	Ampere
$P_{PCC\ total}$	1.6464	3.3327	4.9781	KW
Active power (S)	1.6491	3.3329	4.9786	KVA
Reactive power (Q)	0.04	0.02	0.06	Kvar
Power factor (PF)	0.99	0.99	0.99	-
3^{rd} Harmonic value	**0.66**	**0.67**	**0.68**	Percent(%)
THD current	**8.26**	**4.67**	**3.14**	Percent(%)
Inverter efficiency	96	96	95	Percent(%)

Table 22 depicts the operating power comparison in the 3^{rd} harmonic order value adding of a distorted grid voltage system. The PCC output power in 100% falls down about 22W of 5 Kw capacity and the inverter efficiency is received 95% by P_{output} and P_{input} calculation, comparing with the inverter efficiency in 66% and 33% power is equivalent to 96%, and decreases down about 1%. The PCC current of 100% power decreases a bit about 0.1A of the total current 22.72A, whereas, the frequency is constant (50 Hz), if comparing with the experiment in 66% and 33% power are equivalent to 49.99 Hz of basic frequency. All PCC voltages fluctuate a little bit from 0.18V to 0.33V, judiciously, the power system transparency is considered as a good operating grid system depending on the characteristics of the active power (S), reactive power (Q) and power factor (PF) stay in good level.

More addition, the 3^{rd} harmonic order value is considered as a good rank and in the constant amounts, moreover, THD current magnitude in 100% power expands to 8.26% of the operating system, and this amplitude is an overvalue for power regulation principle of grid code in Cambodia <5% of max THD current, as totally mentioned, when a high THD value shall not be allowed to transfer power or the grid system shall be disconnected. Otherwise, the THD value in 66% and 33% powers go up to high levels, but these values do not exceed over the power regulation of grid code in Cambodia as shown in table 22. The THD magnitude in 66% power is 4.67% and 33% power is 3.14%, so these harmonic effects could absorb the unsmooth current flow pathway and very distorted-ripple current waveform in the grid system.

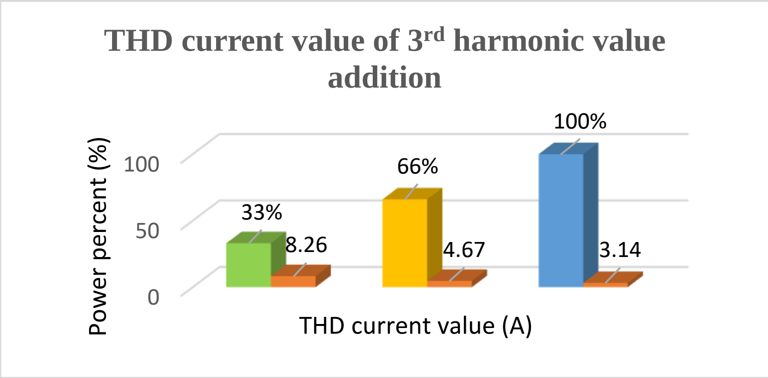


Figure 69 Ppower (%) and THD current of 3rd harmonic value add

The Weak Grid System (WGS)

This simulated system implementation of the weak grid will be demonstrated the operational network of PV simulator linked to solar inverter with 5 KW power capacity and the grid simulator with voltage 220V/50Hz which is connected in series with the impedance components. in those, the impedance components comprise of the inductive reactance (X_L) for the primary experiment and the inductive reactance (X_L) and resistive elements for secondary experiment. The values of the inductive reactance are diverse, primarily, three inductive reactance compensation comprise of 0.477 Ohm of each element and the another exists of 0.318 Ohm. The mathematical calculation for total amplitude of inductive reactance elements X_L, (0.477 x 3) + 0.318 equal to 1.749 Ohm. Additionally, the technical experiment is applied properly with the power adjustment as three stages like the previous states to find out the grid system transparency and the correction. The power fluctuation is the main status which lead the decreasing or increasing THD current magnitude, the current deviation and the grid voltage fluctuation. Else, the grid simulator is connected in series with the inductive reactance (X_L) or coupled with the inductive reactance (X_L) and the resistive elements (R) shall consist of the voltage variation (ΔV) and the grid frequency fluctuation (Δf) and the inverter efficiency. More addition, the weak grid system is expressed the inverter performance efficiency and the harmonic distortion effects of the entire system.

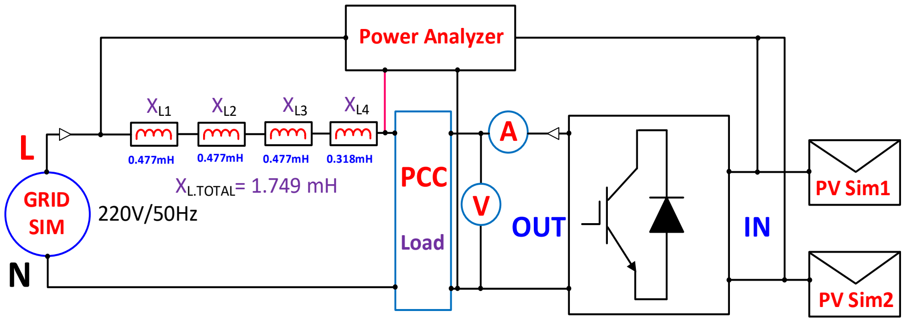


Figure 70 Experimental process of Weak Grid System (X_L)

The Experimental Result of the Weak Grid System (X_L)

The 100% Power Experiment of the Weak Grid System (XL)

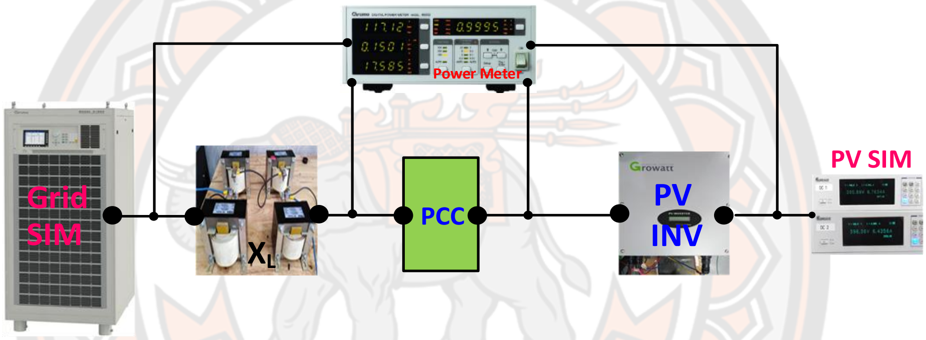
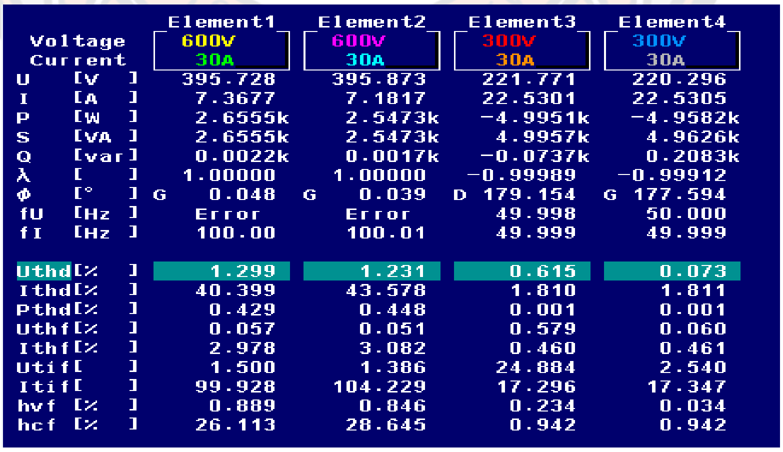


Figure 71 Applying system of Impedance Grid (XL)



		Element1	Element2	Element3	Element4
Voltage		600V	600V	300V	300V
Current		30A	30A	30A	30A
U	[V]	395.728	395.873	221.771	220.296
I	[A]	7.3677	7.1817	22.5301	22.5305
P	[W]	2.6555k	2.5473k	-4.9951k	-4.9582k
S	[VA]	2.6555k	2.5473k	4.9957k	4.9626k
Q	[var]	0.0022k	0.0017k	-0.0737k	0.2083k
λ	[ ]	1.00000	1.00000	-0.99989	-0.99912
φ	[°]	G 0.048	G 0.039	D 179.154	G 177.594
fU	[Hz]	Error	Error	49.998	50.000
fI	[Hz]	100.00	100.01	49.999	49.999
Uthd	[%]	1.299	1.231	0.615	0.073
Ithd	[%]	40.399	43.578	1.810	1.811
Pthd	[%]	0.429	0.448	0.001	0.001
Uthf	[%]	0.057	0.051	0.579	0.060
Ithf	[%]	2.978	3.082	0.460	0.461
Utif	[ ]	1.500	1.386	24.884	2.540
Itif	[ ]	99.928	104.229	17.296	17.347
hvf	[%]	0.889	0.846	0.234	0.034
hcf	[%]	26.113	28.645	0.942	0.942

Figure 72. shows experimental result of the Weak Grid System (XL)

Figure 71 clarifies the simulated experimental result of the 100% power of the weak grid system (X_L) and the total value of the inductive reactance is 1.749 Ohm.

The experimental results are depicted by power analyser and oscilloscope waveform. Therefore, the results are illustrated PCC voltage (V_{PCC}) consists of 221.77V of the grid voltage 220.29V, therefore the voltage variation (ΔV) is equal to 1.48V and the 1.48 value is equivalent to 0.67%, in this case, the grid system is possible to operate normally with following the power regulation principle of grid code in Cambodia (EAC), is the low voltage fluctuation (ΔV) -10% and +6% and I_{PCC} value is 22.53A, if this magnitude is compared with the previous experimental results in 100% power adjustment to decrease less a bit than the harmonic order value insertion I_{PCC} is 23A, the only 3rd harmonic order value I_{PCC} is 22.66A of the ideal grid and I_{PCC} of the distorted grid voltage is 22.67A. The total output power (P_{output}) is 4995.1W and the total input power (P_{input}) is 5228.4W, therefore the inverter efficiency is received 95% by technical calculation. The active power (S) 4.9957KVA and reactive power (Q) 0.07Kvar where these amplitudes stand on the good level. The operational frequency is 49.99 Hz with a little deviation of the basic frequency 50 Hz.

$$\Delta V\,(\%) = V_{PCC} - V_g \qquad \text{(Eg.4.6)}$$

$$\Delta f\,(\%) = f_{PCC} - f_g \qquad \text{(Eg.4.7)}$$

The total harmonic distortion of current (THD) is 1.8% which locates in a good value and harmonic effects could lead a little bit waveform distortion and a little grid distortion, actually the grid system can naturally apply.

$$\begin{aligned} Z &= \sqrt{R^2 + X_L^2}\ (\Omega) \\ X_L &= 2\pi L f \end{aligned} \qquad \text{(Eg.4.8)}$$

L	- Length of wire (m)
f	- Frequency (50 or 60 Hz)
X_L	- Inductive element (Ohm)
π (pi)	- a numeric constant of 3.142

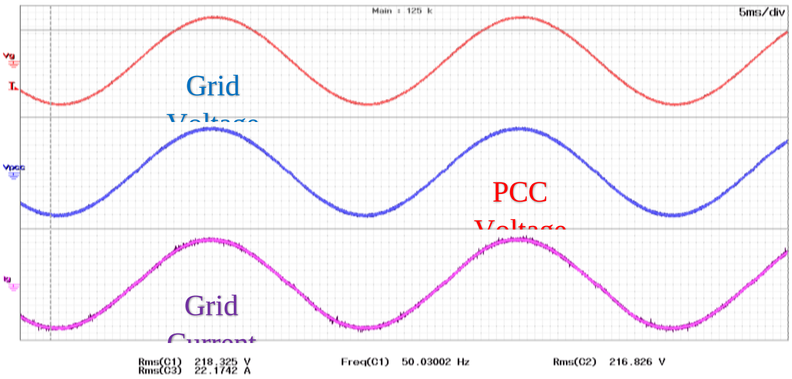


Figure 73 Waveform of V_G, V_{PCC} and I_G

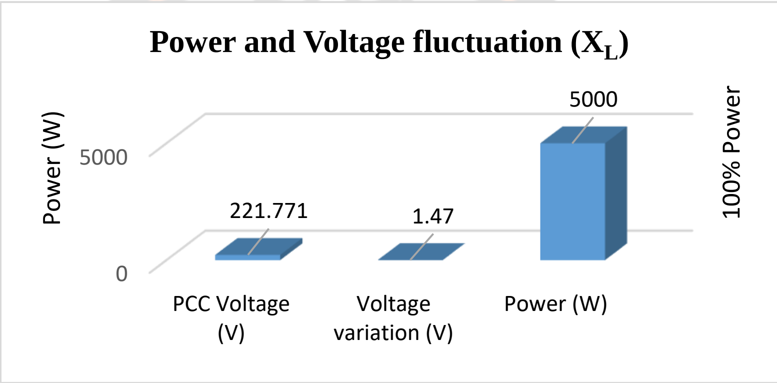
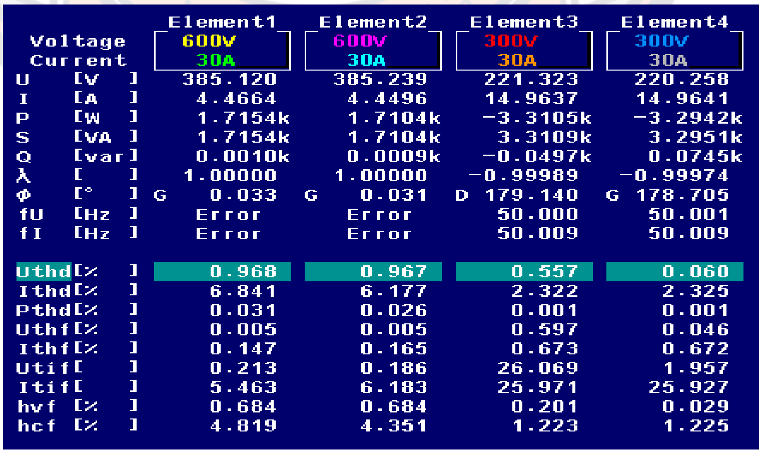


Figure 74 The voltage deviation and power

The 66% Power Experiment of the Weak Grid System (XL)



Voltage / Current		Element1 600V 30A	Element2 600V 30A	Element3 300V 30A	Element4 300V 30A
U	[V]	385.120	385.239	221.323	220.258
I	[A]	4.4664	4.4496	14.9637	14.9641
P	[W]	1.7154k	1.7104k	−3.3105k	−3.2942k
S	[VA]	1.7154k	1.7104k	3.3109k	3.2951k
Q	[var]	0.0010k	0.0009k	−0.0497k	0.0745k
λ	[ ]	1.00000	1.00000	−0.99989	−0.99974
Φ	[°]	G 0.033	G 0.031	D 179.140	G 178.705
fU	[Hz]	Error	Error	50.000	50.001
fI	[Hz]	Error	Error	50.009	50.009
Uthd	[%]	0.968	0.967	0.557	0.060
Ithd	[%]	6.841	6.177	2.322	2.325
Pthd	[%]	0.031	0.026	0.001	0.001
Uthf	[%]	0.005	0.005	0.597	0.046
Ithf	[%]	0.147	0.165	0.673	0.672
Utif	[ ]	0.213	0.186	26.069	1.957
Itif	[ ]	5.463	6.183	25.971	25.927
hvf	[%]	0.684	0.684	0.201	0.029
hcf	[%]	4.819	4.351	1.223	1.225

Figure 75 Experimental result of the Weak Grid System (XL)

Figure 73 expresses the experimental result of The 66% power adjustment of the weak grid system (XL) and the PCC output power (P_{output}) is 3310.5KW and the total input power (P_{input}), hence the inverter efficiency is given 96% by both power calculations. The reactive power amplitude (Q) is 0.05 Kvar and active power value (S) 3310.9KVA, referring to these magnitudes keep in a good level for a normal operation. The PCC voltage is 221.32V, increases a little bit around 1.07V, be equivalent to 0.48% of a grid voltage 220.25V, this voltage magnitude allows the grid system to apply naturally by depending on the power regulation of grid code in Cambodia which is passed by EAC -10% and -6% and the frequency is constant 50Hz, furthermore, the current value is 14.96A, this certifies that it is a less decrement value than the ideal grid 15A and the distorted grid voltage system for harmonic order value adding 15.14A and the only 3rd harmonic order value 15.19A in 66% power.

$$\Delta V = V_{PCC} - V_g \, (\mathrm{V})$$
$$\Delta V = 221.32V - 220.25V \qquad \text{(Eq.4.9)}$$
$$Hence, \Delta V = 1.07V$$

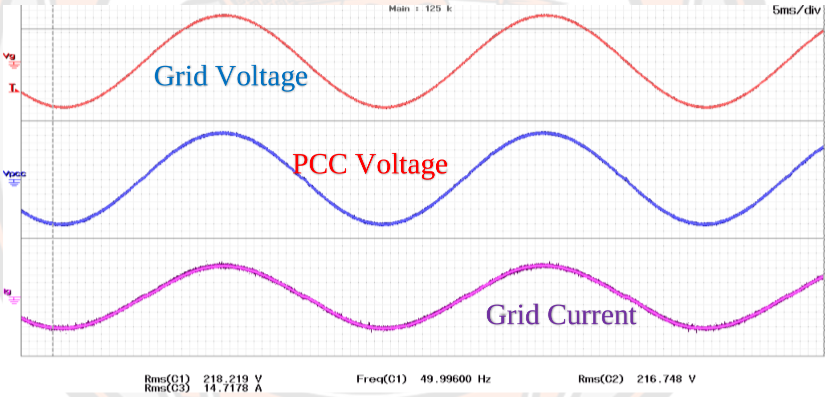


Figure 76 Waveform of V_G, V_{PCC} and I_G

Figure 75 demonstrates the grid voltage waveform (V_g), the point of common coupling voltage (V_{pcc}) and PCC current waveform (I_{pcc}). The total harmonic distortion of current (THD) comprises of 2.32% and referring to I_{pcc} waveform, the grid system is considered the grid operation can apply simply, but harmonic effects could lead the quite much current flow distortion, otherwise THD value does not yet exceed over the power regulation of grid code in Cambodia.

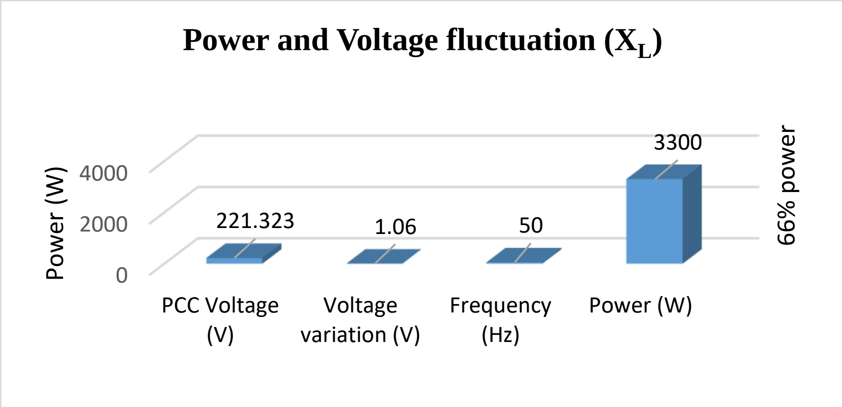
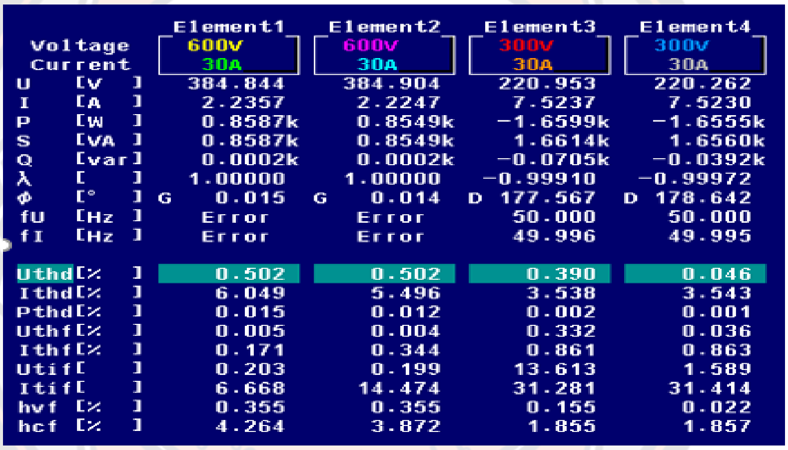


Figure 77 The voltage deviation and power

The 33% Power Experiment of the Weak Grid System (XL)



Voltage / Current		Element1 600V 30A	Element2 600V 30A	Element3 300V 30A	Element4 300V 30A
U	[V]	384.844	384.904	220.953	220.262
I	[A]	2.2357	2.2247	7.5237	7.5230
P	[W]	0.8587k	0.8549k	-1.6599k	-1.6555k
S	[VA]	0.8587k	0.8549k	1.6614k	1.6560k
Q	[var]	0.0002k	0.0002k	-0.0705k	-0.0392k
λ	[ ]	1.00000	1.00000	-0.99910	-0.99972
Φ	[°]	G 0.015	G 0.014	D 177.567	D 178.642
fU	[Hz]	Error	Error	50.000	50.000
fI	[Hz]	Error	Error	49.996	49.995
Uthd	[%]	0.502	0.502	0.390	0.046
Ithd	[%]	6.049	5.496	3.538	3.543
Pthd	[%]	0.015	0.012	0.002	0.001
Uthf	[%]	0.005	0.004	0.332	0.036
Ithf	[%]	0.171	0.344	0.861	0.863
Utif	[ ]	0.203	0.199	13.613	1.589
Itif	[ ]	6.668	14.474	31.281	31.414
hvf	[%]	0.355	0.355	0.155	0.022
hcf	[%]	4.264	3.872	1.855	1.857

Figure 78 Proves experimental result of the Weak Grid System (XL)

Figure 77 demonstrates the experimental result in 33% power of the weak grid system (X_L). the total output power (P_{output}) at the point of common coupling is 1659.9W and the input power (P_{input}) 1705.4W. the both power certifications is shown the inverter operating performance is good and the efficiency (η_{INV}) is received 97% of this system by a calculated principle. Additionally, the PCC voltage magnitude 220.95 deviates about 0.69V, be equivalent to 0.31% of the grid voltage and this value is considered as the normal operating grid system with referring to low voltage fluctuation (-10% and +6%) of power regulation in Cambodia and the current value is 7.52A. The active power (S) value 1.6614KVA is observed in good operating range and reactive power (Q) amplitude 0.07Kvar keeps in good level of a grid system.

More addition, the total harmonic distortion of current (THD) increases up to quite higher order value 3.53% comparing with THD value in 66% power, 2.32% and in 100% power,1.81%, despite, this magnitude is located in higher level, but It does not yet exceed over from the power regulation of the grid code (<5%) in Cambodia which passed by the Electricity Authority of Cambodia (EAC) and judiciously the harmonic effect could draw the influent current flow pathway, the ripple current waveform and the distorted grid system.

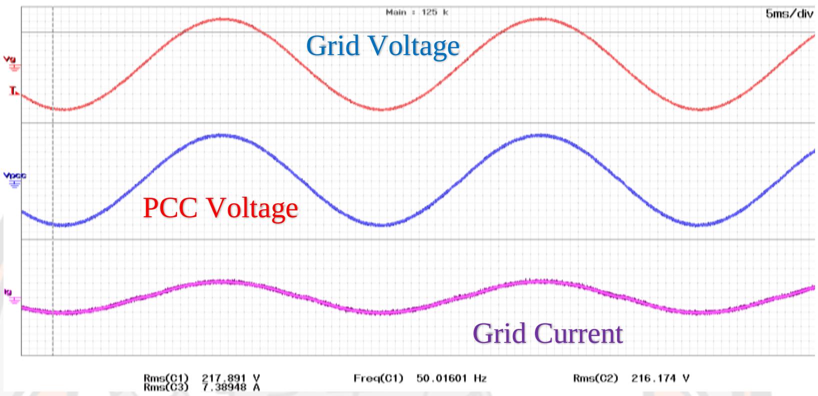


Figure 79 Waveform of V_G, V_{PCC} and I_G

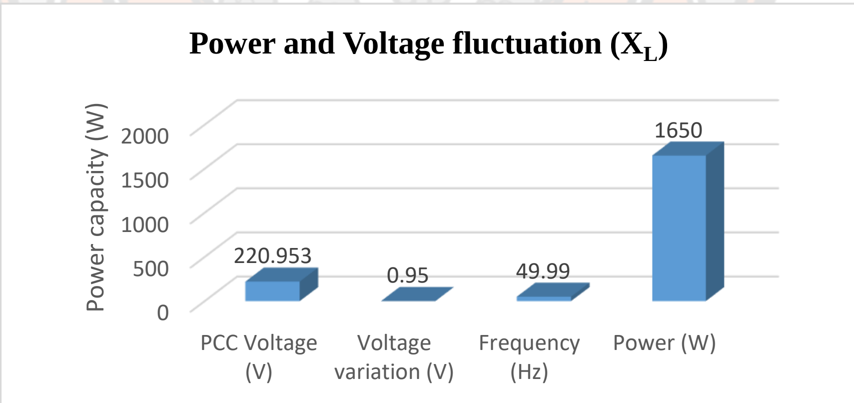


Figure 80 The voltage deviation and power

Table 24 Result comparison of the Weak Grid System (XL)

Name	33% power	66% power	100% power	Units
PCC Voltage (V_{PCC})	220.95	221.32	221.77	Volt
Grid Voltage (Vg)	220.26	220.25	220.29	Volt
Voltage Variation (ΔV)	0.69	1.07	1.48	Volt
Frequency (f)	49.99	50	49.99	Hertz
PCC Current (I_{PCC})	7.52	14.96	22.53	Ampere

Table 24 (cont.)

Name	33% power	66% power	100% power	Units
P_{OUTPUT} (P)	1.6599	3.3105	4.9951	KW
Active power (S)	1.6614	3.3109	4.9957	KVA
Reactive power (Q)	0.07	0.04	0.07	Kvar
Power factor (PF)	0.99	0.99	0.99	-
THD Current	3.53	2.32	1.81	Percent
Inverter efficiency	97	96	95	

Table 23 depicts the result comparisons of the experimental application for a weak grid system connected with the inductive reactance (X_L). The PCC output power in 100% falls down about 5W of 5 Kw capacity and the inverter efficiencies are received 95%, 96% and 97% linked to table 23 by P_{output} and P_{input} calculation, comparing with the inverter efficiencies in table 22 of the 3rd harmonic order value in the distorted grid voltage system are equivalent to 95% and 96%, consequently, these inverter efficiencies are considered as similar values and located in quite good ranks. The PCC current values of the weak grid system (XL) as shown in table 23 to be compared with the current value in a grid system of the 3rd harmonic order value in the distorted grid voltage system are equivalent to 22.66%,15.19% and 7.54%, thus, the current magnitudes of the weak grid system (XL) decrease in 0.23% maximum value, but frequency values in the weak grid system as shown in table 23 to be compared with the 3rd harmonic order value in the distorted grid voltage system are same value and can be considered as constant level. All PCC voltages of a weak grid system (X_L) are higher than PCC voltage magnitudes of the 3rd harmonic order value around 1.0A as shown in this table 22. Judiciously, the both system transparencies reflected as a good operating grid system depending on the characteristics of the active power (S), reactive power (Q) and power factor (PF) keep in good level.

More addition, the 3rd harmonic order value in the distorted grid voltage system are equivalent to 3.14%, 4.67% and 8.26% are higher than 1.33%, 2.35% and 4.73% of each THD current magnitude in a weak grid system (X_L), these issues cause high percentage rate of harmonic order values. The power regulation principle in Cambodia is limited the max THD current is not larger than <5%, as totally mentioned, when a high THD value shall not be allowed to transfer power or the grid system shall be disconnected. Otherwise, these harmonic effects could absorb the unsmooth current flow pathway and quite a distorted-ripple current waveform in the grid system.

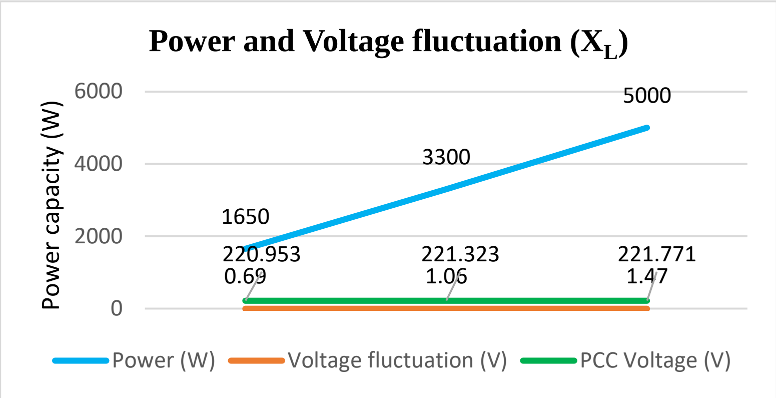


Figure 81 Result Comparison of Weak Grid System (X_L)

The Experimental Result of Weak Grid System (XL and R)

The simulated experiment will be demonstrated the applying process of a weak grid system (grid impedance) and a single phase grid simulator is connected in series with four inductive reactance units (X_L) and overall inductive components (X_L) are united in series to the three resistive elements (R) as shown in figure 81. As mentioned, three inductive reactance(X_L) comprise of 0.477Ω in each unit and another one exists of 0.318 Ω. Whereas, the overall resistive elements are calculated in the mathematical equations, the value of voltage variation (ΔV) is taken to divide with the PCC current value of the grid system is 0.87Ω. The total X_L amplitude is taken 0.477Ω to multiply 3 and plus 0.318Ω equal to 1.749 Ω. The total impedance value is 2.619Ω. Additionally, the technical experiment is applied appropriately with the power changes as three stages, 100%, 66% and 33% power. The operating process of a weak grid system shall be analysed logically the PCC voltage, the inverter efficiency, the voltage fluctuation (ΔV) and THD current value of the entire system, the grid voltage control and the PCC current magnitude.

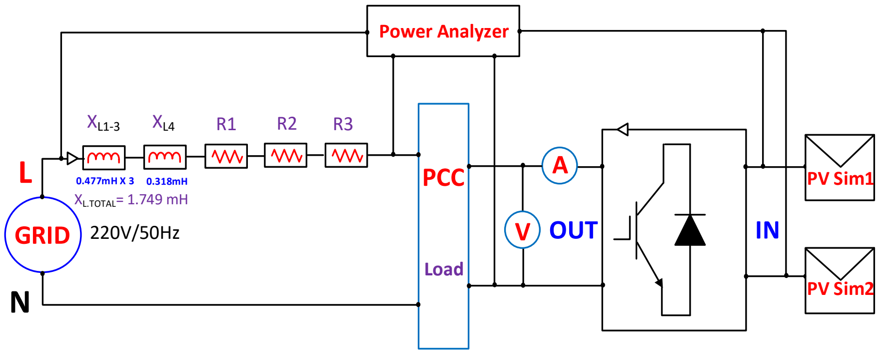


Figure 82 Experimental process with Impendent Grid (X_L), (X_R)

$$R = \Delta V / I \, (\Omega) \qquad \text{(Eg.4.10)}$$

The 100% Power Experiment of the Weak Grid System (X_L) and (R)

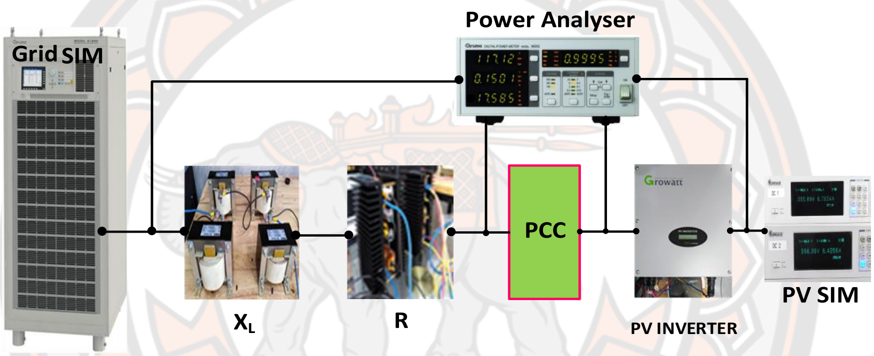


Figure 83 Operating process passed Impendent Grid (X_L, R)

		Element1	Element2	Element3	Element4
Voltage		600V	600V	300V	300V
Current		30A	30A	30A	30A
U	[V]	395.810	395.922	238.114	220.322
I	[A]	7.3604	7.1631	20.9960	20.9959
P	[W]	2.6489k	2.5347k	−4.9986k	−4.6199k
S	[VA]	2.6489k	2.5347k	4.9987k	4.6251k
Q	[var]	0.0020k	0.0013k	−0.0257k	0.2207k
λ	[ ]	1.00000	1.00000	−0.99999	−0.99886
Φ	[°]	G 0.043	G 0.030	D 179.705	G 177.265
fU	[Hz]	Error	Error	50.000	50.000
fI	[Hz]	99.991	99.990	49.997	49.998
Uthd	[%]	1.323	1.252	0.585	0.057
Ithd	[%]	40.746	44.021	1.789	1.791
Pthd	[%]	0.427	0.453	0.003	0.001
Uthf	[%]	0.057	0.050	0.575	0.040
Ithf	[%]	2.954	3.029	0.500	0.501
Utif	[ ]	1.500	1.359	24.698	1.673
Itif	[ ]	98.898	101.810	19.093	19.108
hvf	[%]	0.902	0.858	0.220	0.026
hcf	[%]	26.147	28.810	0.921	0.921

Figure 84 The experimental result of weak grid (X_L, R)

Figure 79 demonstrates the experiment result of the weak grid system (X_L and R) in 100% power which is focused on the power system control which is penetrated to PV inverter simulation. The total input power (P_{input}) is given by the both-two PV simulation 5228.4W and the total output power (P_{output}) is 4998.6W, the characteristic observation is identified the inverter operation efficiency is good, equivalent to 95% by the mathematical calculation of both side powers. Actually, PCC current value 20.99A (I_{PCC}) drops down a round 2.0 A, if comparing to the mentioned results in chapter IV for 100% power experiment. This factor is found that because of the high impedance value for current flow disturbance. Otherwise, PCC voltage value increases up to 238.11V of the foundational voltage 220V, this value is considered as overvoltage range, hence, the protection equipment will be disconnected from the normal operating system. Otherwise, this voltage fluctuation (ΔV) exceeds over power regulation certification of grid code in Cambodia which Electrical Authority of Cambodia (EAC) is passed the law for power transmission system, therefore, in the case, -10% and +6% low voltage variation is equal to 198V and 233.2V of normal operating system in power transmission, and the voltage deviation (ΔV) is certified in the highest amplitude a round 8.23% by the calculation for the operating system. when a grid-connected inverter produces ac current, the impedance from the grid and inverter output-circuit conductors causes an increase in voltage at the inverter relative to the utility voltage. This phenomenon is commonly referred to as voltage rise and, whereas, the THD current 1.78% is still located in quite a good status, but the harmonic value effects could absorb the unsmooth current flow and ripple current waveform in the grid system.

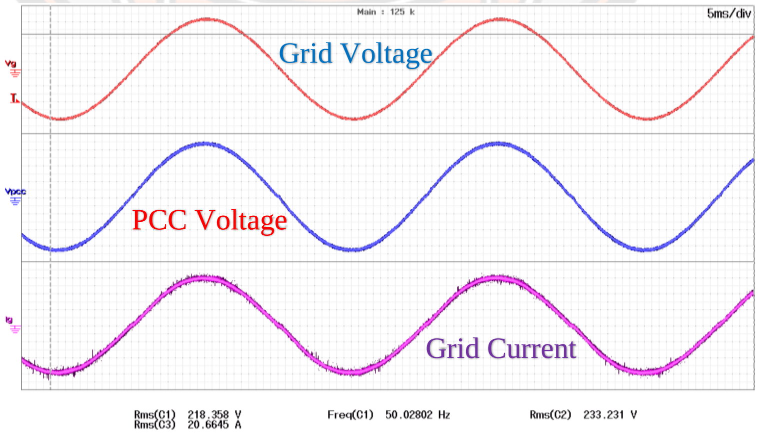


Figure 85 Waveform of V_G, V_{PCC} and I_G passed X_L R

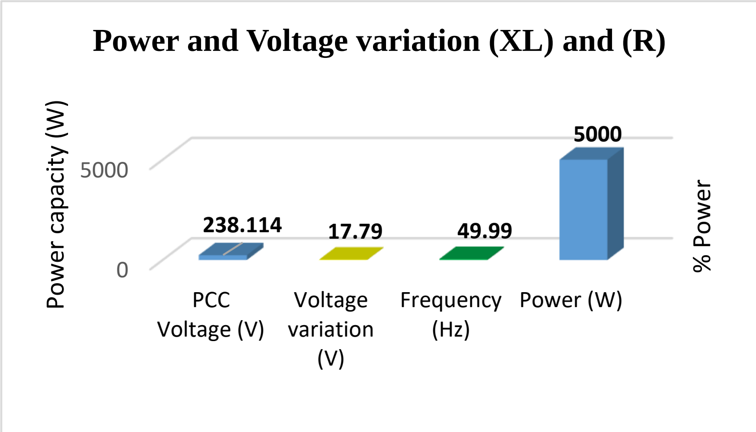
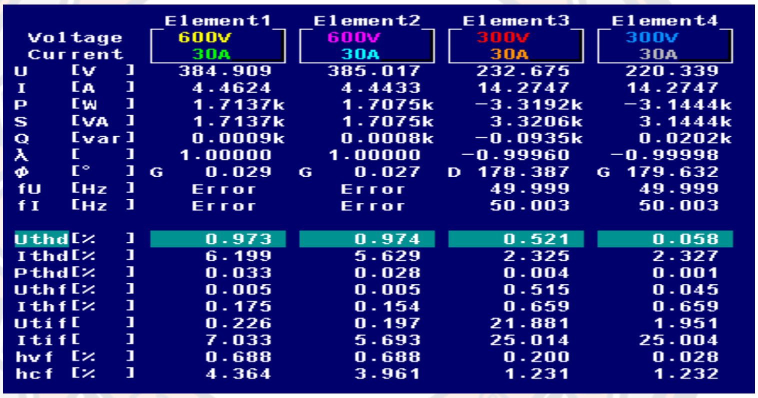


Figure 86 The voltage deviation and power

The 66 % Power Experiment of the Weak Grid System (X_L) and (R)



Voltage Current	Element1 600V 30A	Element2 600V 30A	Element3 300V 30A	Element4 300V 30A
U [V]	384.909	385.017	232.675	220.339
I [A]	4.4624	4.4433	14.2747	14.2747
P [W]	1.7137k	1.7075k	−3.3192k	−3.1444k
S [VA]	1.7137k	1.7075k	3.3206k	3.1444k
Q [var]	0.0009k	0.0008k	−0.0935k	0.0202k
λ [ ]	1.00000	1.00000	−0.99960	−0.99998
φ [°]	G 0.029	G 0.027	D 178.387	G 179.632
fU [Hz]	Error	Error	49.999	49.999
fI [Hz]	Error	Error	50.003	50.003
Uthd[%]	0.973	0.974	0.521	0.058
Ithd[%]	6.199	5.629	2.325	2.327
Pthd[%]	0.033	0.028	0.004	0.001
Uthf[%]	0.005	0.005	0.515	0.045
Ithf[%]	0.175	0.154	0.659	0.659
Utif[ ]	0.226	0.197	21.881	1.951
Itif[ ]	7.033	5.693	25.014	25.004
hvf [%]	0.688	0.688	0.200	0.028
hcf [%]	4.364	3.961	1.231	1.232

Figure 87 The experimental result of weak grid (X_L, R)

Figure 86 illustrates the experimental result of 66% power in the weak grid (X_L and R). The inverter operating performance is good by the mathematic calculation of the total output power (P_{output}) 3319.2W and total input power (P_{input}) 3443.3W, therefore, the inverter efficiency is equal to 96% of the operating system. The active power (S) 3320.6 KVA and reactive (Q) 0.09 Kvar stand in good level for this operating system. the PCC current value comprise of 14.27A, decreases a little bit about 1A of 66% power systems. The PCC voltage magnitude grows up to 232.67V of basic voltage 220V, particularly the value locates in the higher level than the voltage in the inductive reactance system (221.32V) is equal to 11.35V, equivalent to 5.15% of 66% power. Particularly, the voltage fluctuation (ΔV) is equal to 5.75% for a weak grid system. The power transmission of the low voltage system is allowed to apply naturally in the fluctuated value -10% and +6% of a simple system. PCC voltage amplitude is not considered as the overvoltage value by referring to the power regulation of grid code which passed Electricity Authority of Cambodia (EAC).

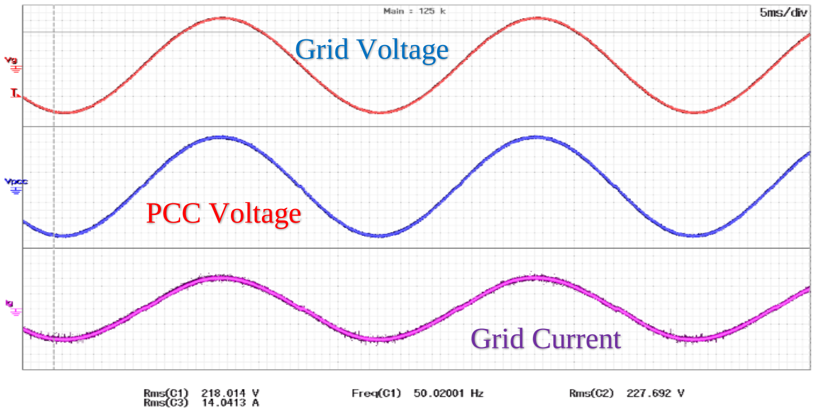


Figure 88 Waveform of V_G, V_{PCC} and I_G passed X_L X_R

whereas, figure 87 shows PCC current waveform in progress with a pink signal which reflects the current flow is not quite a good because of the total harmonic distortion of current (THD) expand to 2.32%, comparing to the grid system which is connected with only inductive reactance (X_L) of 66% power to be equal together, but this value could lead the unsmooth current flow and the quite ripple waveform as shown in 87.

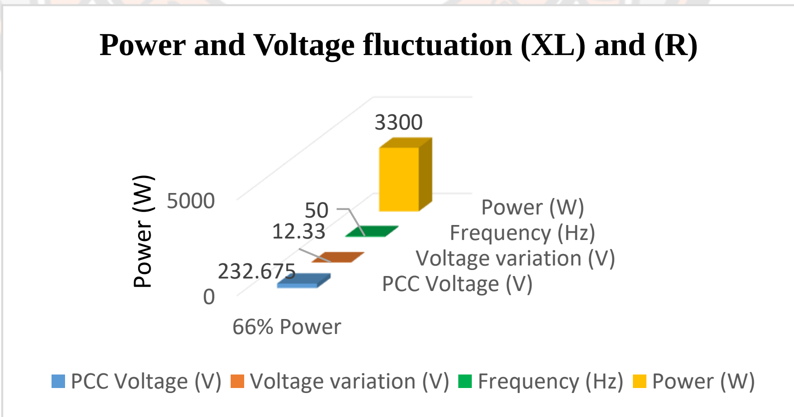
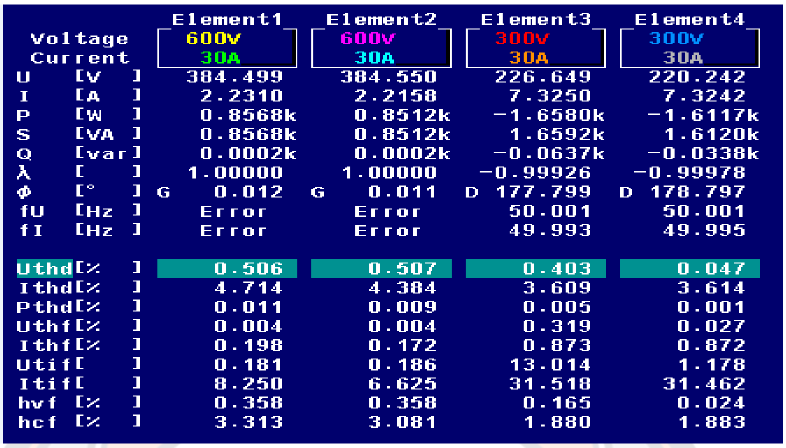


Figure 89 The voltage deviation and power

The 33% Power Experiment of the Weak Grid System (X_L) and (R)



		Element1	Element2	Element3	Element4
Voltage		600V	600V	300V	300V
Current		30A	30A	30A	30A
U	[V]	384.499	384.550	226.649	220.242
I	[A]	2.2310	2.2158	7.3250	7.3242
P	[W]	0.8568k	0.8512k	−1.6580k	−1.6117k
S	[VA]	0.8568k	0.8512k	1.6592k	1.6120k
Q	[var]	0.0002k	0.0002k	−0.0637k	−0.0338k
λ	[ ]	1.00000	1.00000	−0.99926	−0.99978
Φ	[°]	G 0.012	G 0.011	D 177.799	D 178.797
fU	[Hz]	Error	Error	50.001	50.001
fI	[Hz]	Error	Error	49.993	49.995
Uthd	[%]	0.506	0.507	0.403	0.047
Ithd	[%]	4.714	4.384	3.609	3.614
Pthd	[%]	0.011	0.009	0.005	0.001
Uthf	[%]	0.004	0.004	0.319	0.027
Ithf	[%]	0.198	0.172	0.873	0.872
Utif	[ ]	0.181	0.186	13.014	1.178
Itif	[ ]	8.250	6.625	31.518	31.462
hvf	[%]	0.358	0.358	0.165	0.024
hcf	[%]	3.313	3.081	1.880	1.883

Figure 90 The experimental result of weak grid (X_L, R)

Figure 87 depicts the experimental value in 33% power of the weak grid (X_L and R) system. These results are verified the operating power quality is good, and total output power (P_{output}) comprises of 1658W and the total input power (P_{input}) consists of 1705.4W, therefore, the inverter efficiency (η_{INV}) is accepted 97% by the equational calculation. The active power (S) 1659.2 KVA is certified in good operation and the reactive power (Q) exists of 0.06 Kvar, this amount is located in good level for the grid system. The THD current value spreads up to the high level 3.60%, this value will be allowed for a continuous power transmission which is operating because the value 3.60% does not yet exceed over the power regulation of grid code which passed by EAC <5%, The THD current value of the normal operating system is not allowed bigger than 5% by AEC. Customarily, during the total harmonic distortion of current value increased in high degree, its effects can draw the grid strength or can interrupt the current flow pathway in power transition system.

Judiciously the harmonic effects could foment the unsmooth current flow pathway and the quite ripple-distorted current waveform of the system as shown in figure 90 with a pink waveform.

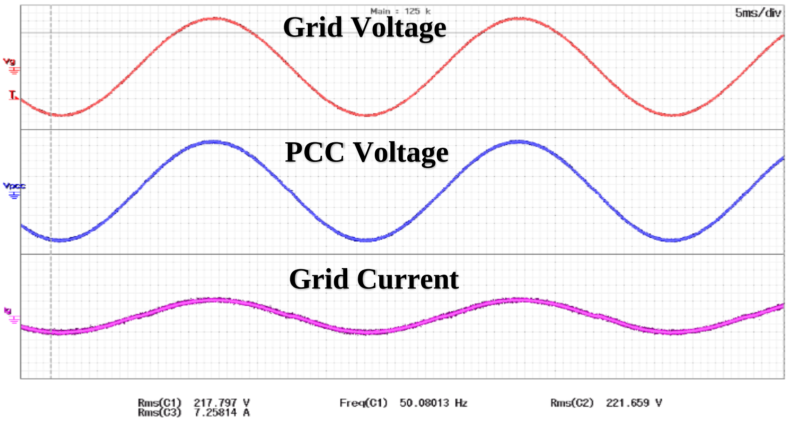


Figure 91 Waveform of V_G, V_{PCC} and I_G passed X_L R

Figure 90 depicts the waveform of PCC voltage value (V_{pcc}) and the grid voltage (V_{grid}). The PCC voltage value goes up to 226.64V, and the grid voltage value spreads up a bit 220.24V of basic voltage (220V), hence, the voltage deviation (ΔV) increase up to 6.40V around 3% of the operating grid system. The 3% voltage fluctuation (ΔV) does not exceed over the power regulation determination of the low variation voltage in Cambodia which passed by EAC, mainly, as depicted the maximum and minimum voltage variation (ΔV) are -10% and +6% of the low voltage.

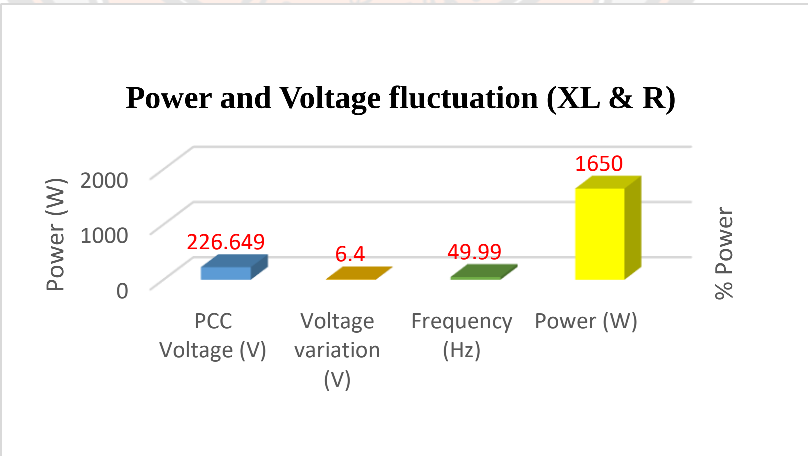


Figure 92 The voltage deviation and power

Table 25 The experimental result of weak grid (X_L&R)

Name	33% power	66% power	100% power	Units
PCC Voltage (V_{PCC})	226.64	232.67	238.11	Volt
Grid Voltage (Vg)	220.24	220.33	220.32	Volt
Voltage fluctuation (ΔV)	6.40	12.34	17.79	Volt
Frequency (f)	49.99	50.00	49.99	Hertz
Power factor (pf)	0.99	0.99	0.99	-
PCC Current (I_{PCC})	7.32	14.27	20.99	Ampere
Total output power (P_{out})	1658	3319.2	4998.6	Watts
Active power (S)	1.6592	3.3206	4.9987	KVA
Reactive power (Q)	0.06	0.0935	0.02	Kvar
THD Current	3.60	2.32	1.78	Percent
Inverter efficiency	97	96	95	

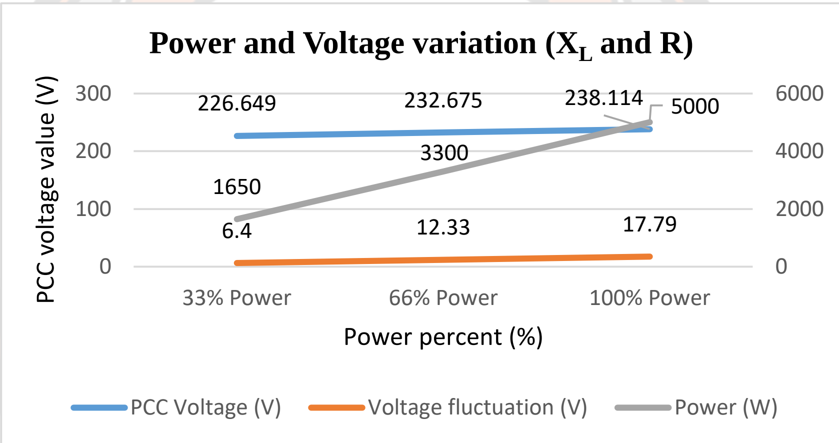


Figure 93 Result Comparison of Weak Grid System (X_L, R)

CHAPTER V

CONCLUSION AND RECOMMENDATIONS

Conclusion

A Single-Phase Grid-connected PV Inverter Performance under a weak grid conditions for Cambodia is shown the power control of a weak grid, the distorted grid voltage system and the harmonic effect control and the inverter efficiency.

As depicted in chapter IV, the grid simulator side is associated in series with inductive reactance (X_L) and the resistive components (R) synchronized with PV simulator and penetrated power to the point of common coupling (PCC). The operational characteristics of ideal grid system referring to the results are notified that the whole power systems are in good progress, but THD current value increased over the average magnitude (<1%), THD values of ideal grid system are 2.19%, 2.14% and 3.41% for 3-stage power adjustments, logically these THD expansion values are quite high and the harmonic effects could attract the influent current flow and the distorted current waveforms, moreover, the inverter performances are articulated that efficiency is 97% for 100% power and 96% for 66% and 33% power adjustments.

The distorted grid voltage systems certified that power systems are excellent, the max PCC voltage increased a little bit around 0.33V of basic voltage and the active and reactive power are located in quite good level, in power capacity verification, inverter performances are quite good and the efficiencies given 95% in 100% power and 96% in 66% and 33% power. Furthermore, the magnitudes of the 3rd harmonic, 5th harmonic, 7th harmonic and 9th and the only 3rd harmonics stand on good levels, these views could cause the excellent power quality, voltage and current stability. Despite of the good power system, the THD current value in 33% power systems expand highly to 8.88%, this could cause the large percent insertion of harmonic values and this exceeds over max total order harmonic value of power regulation in Cambodia which passed by EAC <5% of the operating system. When THD value exceeds over the limitation of power regulation, hence, the applying system will be disconnected suddenly or will not be allowed to transfer power in the grid system. Although, THD current values in 66% and 33% power do not exceed over the power regulation, but the harmonic effects will draw extremely ripple current flow and distorted current waveforms of the operating systems.

The performance characteristics of a weak grid system in series connections with inductive reactance (X_L) verified that the power system is in good operation and the inverter efficiencies is 95% in 100% power, 96% in 66% power and 97% in 33% power. Furthermore, the max PCC voltage expands to 221.77V of basic voltage, and max PCC current value is 22.67A of 23A, thus, a little current decrement cause impedance value effects in the system. The THD current values of a weak grid are observed these magnitudes exceed the average 1.81%, 2.32% and 3.53% and THD effects could lead the ripple current and distorted current waveforms.

The weak grid system in series connections with inductive reactance (X_L) and resistive (R) certified that a power quality system is in good operating situation and judiciously the inverter performance efficiencies are offered 95% in 100% power, 96% in 66% power and 97% in 33% power by P_{output} and P_{input} calculation. The max PCC voltage value (ΔV) spreads up to 238.11V of a grid voltage 220.32V about 8%.

The low voltage fluctuation of power regulation in Cambodia is limited for the customary operating system from -10% and +6% by EAC. This ΔV value is in exceeding level, therefore, the grid system will be tripped automatically by protection devices. The max PCC current comprises of 20.99A of 23A, hence this value decreases about 2A of the operating system, this causes the impedance effect expansion (X_L and R). Otherwise, The THD current values of a weak grid are observed these magnitudes exceed the average, 1.78%, 2.32% and 3.60% and THD effects could draw the unsmooth current flow, the ripple current and distorted current waveforms.

In conclusion, a single-phase grid-connected PV inverter performance under a weak grid conditions verified that the ideal grid system could be operated normally, but THD values expand higher than average magnitude and the distorted grid voltage system could not be operated because THD value very high, although, power systems locate in good performance. A weak grid system (X_L) could be operated simply, but THD values increase quite high over the average THD magnitudes and a weak grid system (X_L and R) is not able to be operated naturally because the voltage deviation exceeds over the power regulation and not only, THD values are in quit high ranks and the inverter efficiencies of overall experiment applications are fair good.

Limitations

This study has some limitations. First, when the experiments occur, the distance, secondly, the conductor sizes and conductor lengths are not measured which the impedance value is not definite in the grid system.

Recommendations

- It is recommended that the Ministry of Mine and Energy uses the single-phase grid-connected PV inverter performance under a weak grid condition to install or apply widely in households in Cambodia.
- Future researcher should measure the distance between the grid foundation and PV inverter, calculate the conductor size and length for installations or experiments because the electric wires have internal impedance values.
- In future study , the experimental result of a weak grid system should be compared with an existed-weak grid data which have be installed in households or others to make the weak grid transparency sure for recommendation practice.

REFERENCES

1]	Cambodia, N.I.o.S., *Population Projection of Cambodia 3013-2023.* . February 2017.
[2]	VDB, L., *Cambodia-Power-Update-April-2018.* 2018.
[3]	Goswami, R.M.a.D.Y., *Photovoltaics Fundamentals, Technology and Application. 2007.* 2007.
[4]	AGENCY, I.E., *PV Systems for Rural Health Facilities in Developing Areas* 2014.
[5]	V.Birunda Mary, D.I.W.C., Dr.G.Themozhi, *3-Switch Single-Phase Inverter for PV System.* 2017.
[6]	Dudley, B., *BP Statistical Review of World Energy full report.* June 2019.
[7]	Jana, J.S., Hiranmay Das Bhattacharya, Konika, *A review of inverter topologies for single-phase grid-connected photovoltaic systems.* Renewable and Sustainable Energy Reviews, 2017. **72**: p. 1256-1270.
[8]	SUNTRACE, *Solar Market Brief Cambodia.* 2018.
[9]	Zhang, D.A., Ruichi Wu, Thomas, *Effect of voltage unbalance and distortion on the loss characteristics of three-phase cage induction motor.* IET Electric Power Applications, 2018. **12**(2): p. 264-270.
[10]	Bindner, H., *Power Control for Wind Turbines in Weak Grids.* 1999.
[11]	Khazaei, J.I., Peter Asrari, Arash Shafaye, A. B. Piyasinghe, Lakshan, *Review of HVDC control in weak AC grids.* Electric Power Systems Research, 2018. **162**: p. 194-206.
[12]	Chhim, C.K., Nipon Suriwong, Tawat, *Techno-Economic Analysis of PV Battery Charging Station in Kampot, Cambodia.* Journal of Clean Energy Technologies, 2014. **2**(4): p. 369-373.
[13]	Sarraf, M.R., B. Saidur, R. Ping, H. W. Rahim, N. A., *Renewable energy policies for sustainable development in Cambodia.* Renewable and Sustainable Energy Reviews, 2013. **22**: p. 223-229.
[14]	Franklin, D.E., *Solar Photovoltaic (PV) System Components.* May 2018.
[15]	Fritz, W., *Validation of Solar PV Inverter Harmonics Behaviour at Different Power Levels in a Test Network.* 2019.
[16]	Klingler, A.-L., *The effect of electric vehicles and heat pumps on the market potential of PV + battery systems.* Energy, 2018. **161**: p. 1064-1073.
[17]	Salas, V.S., W. Salas, R. A., *Overview of the off-grid photovoltaic diesel batteries systems with AC loads.* Applied Energy, 2015. **157**: p. 195-216.
[18]	Arghavani, H.P., Mitra, *Unbalanced current-based tariff.* CIRED - Open Access Proceedings Journal, 2017. **2017**(1): p. 883-887.
[19]	Saadeh, O.R., Rabi Bani Melhem, Muath, *New effective PV battery charging algorithms.* Solar Energy, 2018. **166**: p. 509-518.
[20]	21, I.S.C.C., *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces.* 15 February 2018.
[21]	Corporation, T.E.D.S., *DC-AC Inverter Circuit.* 2018-07-26.
[22]	Remus Teodorescu, M.L.a.P.R., *GRID CONVERTERS FOR PHOTOVOLTAIC AND WIND POWER SYSTEMS.* 2011
[23]	Scarabelot, L.T.R., Carlos R. Rampinelli, Giuliano A., *A relative power-based*

adaptive hybrid model for DC/AC average inverter efficiency of photovoltaics systems. Renewable and Sustainable Energy Reviews, 2018. **92**: p. 470-477.

[24] Vázquez, N.L., Joaquín Vaquero, *Inverters.* 2018: p. 289-338.

[25] Ahmad Ale Ahmad, S.M., IEEE, Adib Abrishamifar, Member, IEEE, Mohammad Farzi, IRIEE. , *A New Design Procedure for Output LC Filter of Single Phase Inverters.* 29 April 2010.

[26] Hanif, M.B., M. Gaughan, K., *Understanding the operation of a Z-source inverter for photovoltaic application with a design example.* IET Power Electronics, 2011. **4**(3): p. 278.

[27] Jim Doucet , D.E., Jeremy Shaw, *DC/AC Pure Sine Wave Inverter.* 2006-2007.

[28] Ahmad Firdaus Ahmad Zaidia Sazali Yaacobd , R.M., Ahmad Mujahid Ahmad Zaidic , Nur Hidayah Ahmad Zaidie, *Development of Microcontroller-Based Inverter Control Circuit for Residential Wind Generator Application.* December 2011.

[29] Ruan, X.W., Xuehua Pan, DonghuanYang, Dongsheng Li, Weiwei Bao, Chenlei, *Design of LCL Filter.* 2018: p. 31-61.

[30] Xavier, L.S.C., Allan F. Pereira, Heverton A., *Ancillary services provided by photovoltaic inverters: Single and three phase control strategies.* Computers & Electrical Engineering, 2018. **70**: p. 102-121.

[31] Darshni M.Shukla, B.P., *Comparison-of-Space-Vector-and-Carrier-Based-Pulse-Width-Modulation-Technique-for-Three-Level-Inverter*. July-2017.

[32] Saleh, M.A., S. K. Moin Kalam, Akhtar Abu-Rub, Haitham, *Carrier-based pulse width modulation technique for a three-to-five phase matrix converter for supplying five-phase two-motor drives.* International Journal of Engineering, Science and Technology, 2011. **2**(10).

[33] Athari, H.N., Mehdi Ataei, Mohammad, *Review and Classification of Control Systems in Grid-tied Inverters.* Renewable and Sustainable Energy Reviews, 2017. **72**: p. 1167-1176.

[34] Ms.Greeshma S1, M.J.P., *Grid Connected Self-Synchronized Inverter.* 2017.

[35] Chander, A.H.K., Lalit, *Design of a Synchronous Reference Frame Controller for Single Phase Standalone Photovoltaic Inverter.* 2017: p. 1-6.

[36] Ciobotaru, M.T., R. Blaabjerg, F., *Control of single-stage single-phase PV inverter.* 2005: p. 10 pp.-P.10.

[37] Hassaine, L.O., E. Quintero, J. Salas, V., *Overview of power inverter topologies and control structures for grid connected photovoltaic systems.* Renewable and Sustainable Energy Reviews, 2014. **30**: p. 796-807.

[38] de Aguiar, E.L., et al., *Distributed Renewable Power Sources in Weak Grids - Analysis and Control.* 2016.

[39] ASWAD ADIB1, S.M., IEEE), BEHROOZ MIRAFZAL 1, (Senior Member, IEEE), XIONGFEI WANG2, (Senior Member, IEEE), AND FREDE BLAABJERG 2, (Fellow, IEEE) *On Stability of Voltage Source Inverters in Weak Grids.* January 2018

[40] Im, J.-H., S.-H. Song, and S. Kang, *Analysis and Compensation of PCC Voltage Variations caused by Wind Turbine Power Fluctuations.* Journal of Power Electronics, 201. **13**(5): p. 854-860.

[41] Ji-Hoon 1m, S.-H.S., *Calculation and compensation of PCC voltage variation using a grid connected inverter of a wind turbine in a weak grid.* October 2009.

[42] Brian K. Perera*, P.C.a.S.P., *Point of common coupling (PCC) voltage control of a grid-connected solar photovoltaic (PV) system.* 2013.

[43] Chatterjee, A. and K.B. Mohanty, *Current control strategies for single phase grid integrated inverters for photovoltaic applications-a review.* Renewable and Sustainable Energy Reviews, 2018. **92**: p. 554-569.

[44] (EAC), E.A.o.C., *ELECTRIC POWER TECHNICAL STANDARDS OF THE KINGDOM OF CAMBODIA.* July 16, 2004.

[45] Vai, V., *Planning of low voltage distribution system with integration of PV sources and storage means: Case of power system of Cambodia.* 9 Jan 2018.

[46] Yuan-KangWu, M., IEEE, Jhih-Hao Lin, and Huei-Jeng Lin, *Standards and Guidelines for Grid-Connected Photovoltaic Generation system.* 4, JULY/AUGUST 2017.

[47] Committee, E.T.G.C.a.T.E.D.N., *Solar Energy Plants Grid Connection Code.* March 2017.

[48] Soeren Baekhoej Kjaer, M., IEEE, John K. Pedersen, Senior Member, IEEE, and Frede Blaabjerg, Fellow, IEEE, *A Review of Single-Phase Grid-Connected Inverters for PV module.* 5, SEPTEMBER/OCTOBER 2005

[49] CAMBODIA, E.A.O., *On General Conditions For Connecting Solar Generation Sources To The Electricity Supply System Of National Grid Or To Electrical System Of A Consumer Connected To The Electricity Supply System Of National Grid.* January 26, 2018.

[50] R. Teodorescu, L.M.a.R., P, *Photovoltaic Inverter Structure," in Grid Converters for Photovoltaic and Wind Powers.* . 2010

[51] Tsegay Hailu, L.M., *voltage stiff to voltage weak DC distribution grid : Opportunities and Challenges.* 2016.