Faculty of Engineering

ANALYSIS OF THE GRID FOLLOWING OPERATION DURING FAULT CONDITION

Chai Mui Keak

Bachelor of Engineering (Hons)

Electrical and Electronics Engineering

2023

UNIVERSITI MALAYSIA SARAWAK

Grade: ____________

Please tick (√)

Final Year Project Report	√
Masters	
PhD	

DECLARATION OF ORIGINAL WORK

This declaration is made on the 4th day of JULY 2023.

Student's Declaration:

I CHAI MUI KEAK, 69302, FACULTY OF ENGINEERING hereby declare that the work entitled ANALYSIS OF THE GRID FOLLOWING OPERATION DURING FAULT CONDITION is my original work. I have not copied from any other students' work or from any other sources except where due reference or acknowledgement is made explicitly in the text, nor has any part been written for me by another person.

04/07/2023 Chai Mui Keak (69302)

Date submitted Name of the student (Matric No.)

Supervisor's Declaration:

I AHMED M. A. HAIDAR hereby certifies that the work entitled ANALYSIS OF THE GRID FOLLOWING OPERATION DURING FAULT CONDITION was prepared by the above named student, and was submitted to the "FACULTY" as a * partial/full fulfillment for the conferment of BACHELOR OF ENGINEERING, ELECTRICAL AND ELECTRONIC ENGINEERING WITH HONOURS, and the aforementioned work, to the best of my knowledge, is the said student's work.

Received for examination by: Ahmed M.A. Haidar Date: 04/07/2023

(Name of the supervisor)

I declare that Project/Thesis is classified as (Please tick (√)):

☐ **CONFIDENTIAL** (Contains confidential information under the Official Secret Act 1972)*****
☐ **RESTRICTED** (Contains restricted information as specified by the organisation where research was done)*****
☑ **OPEN ACCESS**

Validation of Project/Thesis

I therefore duly affirm with free consent and willingly declare that this said Project/Thesis shall be placed officially in the Centre for Academic Information Services with the abiding interest and rights as follows:

- This Project/Thesis is the sole legal property of Universiti Malaysia Sarawak (UNIMAS).
- The Centre for Academic Information Services has the lawful right to make copies for the purpose of academic and research only and not for other purpose.
- The Centre for Academic Information Services has the lawful right to digitalise the content for the Local Content Database.
- The Centre for Academic Information Services has the lawful right to make copies of the Project/Thesis for academic exchange between Higher Learning Institute.
- No dispute or any claim shall arise from the student itself neither third party on this Project/Thesis once it becomes the sole property of UNIMAS.
- This Project/Thesis or any material, data and information related to it shall not be distributed, published or disclosed to any party by the student except with UNIMAS permission.

Student signature signature ____________________ (04/07/2023)

Supervisor signature: AMAH __________ Date: 04/07/2023

Current Address:

Lot 6116, Taman Fah Tah, Batu 3 1/2, Jalan Matang, 93050 Kuching, Sarawak

Notes: * If the Project/Thesis is **CONFIDENTIAL** or **RESTRICTED**, please attach together as annexure a letter from the organisation with the period and reasons of confidentiality and restriction.

[The instrument is duly prepared by The Centre for Academic Information Services]

ANALYSIS OF THE GRID FOLLOWING OPERATION DURING FAULT CONDITION

CHAI MUI KEAK

A dissertation submitted in partial fulfilment
of the requirement for the degree of
Bachelor of Electrical and Electronics
Engineering with Honours

Faculty of Engineering

Universiti Malaysia Sarawak

2023

ACKNOWLEDGEMENT

First and foremost, I would like to express my special thanks of gratitude to my supervisor, Associate Professor Dr Ahmed Mohamed Ahmed Haidar and the course coordinator, Ir Dr Abadi bin Chanik @ Azhar for their invaluable suggestions and endless support throughout this final year project (FYP).

Besides that, I would also like to give sincere appreciation to the Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS) for the guidance during FYP period.

Finally, millions of thanks are dedicated to my family, classmates, and every individual who supported me directly or indirectly in this project. Their cooperation in giving ideas or encouraging comments really helps me in improving my project.

ABSTRACT

The renewable energy system is usually connected to the distribution network which lacks the regulating and monitoring devices compared to the transmission network. In such cases, it is not easy to maintain stable operation of power grid during fault condition. The grid following (GFL) control is able to provide optimal power regulation in a solar PV system, but the deviation of grid impedance leads to a reduction of system's stability. The main objective of this work is to analyse the behavior of grid following inverter during fault condition, in order to measure its control response in real time. A grid-connected solar PV system had been designed using MATLAB environment. In this system, PQ control is used to support the stable operation of the power grid. The system is validated experimentally using available facilities at the power laboratory. The result showed that the system can be controlled using GFL mechanism during the abnormal condition. Here, the optimum control of the injected current at 200 A, with respect to the grid voltage and frequency at the point of common coupling have been achieved.

ABSTRAK

Sistem tenaga boleh diperbaharui biasanya disambungkan ke rangkaian pengedaran yang tidak mempunyai peranti pengawal selia dan pemantauan berbanding dengan rangkaian penghantaran. Dalam kes sedemikian, bukan mudah untuk mengekalkan operasi stabil grid kuasa semasa keadaan kerosakan. Kawalan grid berikut (GFL) mampu menyediakan peraturan kuasa yang optimum dalam sistem PV solar, tetapi sisihan impedans grid membawa kepada pengurangan kestabilan sistem. Objektif utama kerja ini adalah untuk menganalisis kelakuan penyongsang mengikut grid semasa keadaan kerosakan, untuk mengukur tindak balas kawalannya dalam masa nyata. Sistem PV solar bersambung grid akan direka bentuk menggunakan persekitaran MATLAB. Dalam sistem ini, kawalan PQ digunakan untuk menyokong operasi stabil grid kuasa. Sistem ini akan disahkan secara eksperimen menggunakan kemudahan yang ada di makmal kuasa. Keputusan menunjukkan bahawa sistem boleh dikawal menggunakan mekanisme GFL semasa keadaaan tidak normal. Di sini, kawalan optimum arus yang disuntik pada 200 A, berkenaan dengan voltan grid dan kekerapan pada titik gandingan biasa telah dicapai.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

LIST OF ABBREVIATIONS

ASEAN	-	Association of Southeast Asian Nations
CVC	-	Current Vector Control
DC	-	Direct Current
GCPV	-	Grid Connected Photovoltaic system
GFL	-	Grid-following
GFM	-	Grid-forming
IGBT	-	Insulated Gate Bipolar Transistor
MPPT	-	Maximum Power Point Tracking
OGPV	-	Off-grid Photovoltaic system
PCC	-	Point of Common Coupling
PI	-	Proportional-Integral
PLL	-	Phase Locked Loop
PV	-	Photovoltaic
PWM	-	Pulse Width Modulation
RMS	-	Root Mean Square
STC	-	Standard Test Condition
VSC	-	Voltage Source Converter

CHAPTER 1

INTRODUCTION

1.1 Background

A microgrid is defined as an aggregation of electrical loads and alternate power sources. The microgrid can always function regardless of whether it is connected to the larger grid or smaller grid. According to previous research [1], it stated that the definition of microgrid says nothing about the size of the distributed energy resources or the type of technology that should be used.

Nowadays, most of the ASEAN Member States (AMS) are continuously developing their microgrids. This is mainly because the population and industrial growth causes the rapid rise in energy demand. Malaysia has microgrids in Banggi Island, Tanjung Labian, Bario, Kema and Tanjung Batu Laut [2] in Figure 1.1. However, since these microgrids usually rely heavily on diesel gensets, so it would be better to integrate them into the hybrid systems. The existing microgrids can be combined with a renewable source such as solar panels, in which also leads to the increase in reliability of the microgrids and the long-term cost saving of the renewable energy source.

Figure 1.1: Microgrid in Banggi Island (Sabah, Malaysia) [2]

In the previous ten (10) years, the inverter-based technologies were only limited to grid-following (GFL) control. In a GFL topology, the grid provides voltage and frequency measurements to the inverters, while the power plant controller provides the active and reactive power setpoints (in Figure 1.2). The GFL inverter also acts as a controllable current source with respect to the change in the frequency and grid voltage [3].

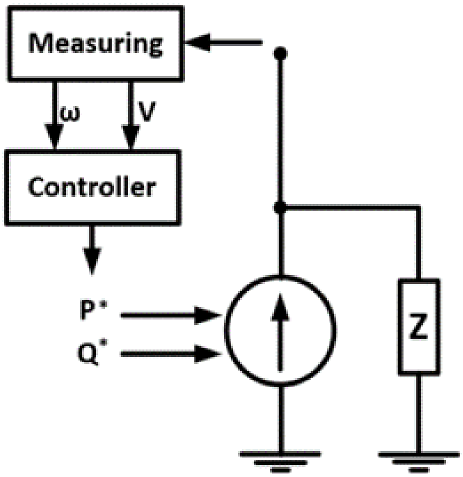

Figure 1.2: Configuration of the GFL inverter [3]

However, the grid strength cannot be further strengthened by the GFL inverter. The grid condition should always be monitored so that the power system can operate at optimum performance levels. But there will be a delay in the operation of the GFL inverter as a result of dependency on the control system. Thus, an additional synchronous condenser is needed at the point of common coupling (PCC) to compensate for the insufficient inertia.

1.2 Problem Statement

The GFL inverter can regulate the output power by controlling the injected current with respect to the grid voltage and frequency at the PCC. Improved control schemes are necessary for the operation of the inverters to ensure the stability of the power system. The appropriate control scheme must be selected wisely to achieve high power quality under strong system conditions.

The typical control strategy of GFL mode is the current vector control (CVC) based on the phase-locked loop (PLL). It can ensure maximum efficiency in a PV system, but the large fluctuation of grid impedance will lead to a reduction of stability. It is mainly because there is a coupling relationship between the CVC and the grid via PLL.

In real-time implementation, the grid code outlines the guidelines for the operation of the power system network. The regulations are also adjusted to the circumstances of the power system according to the grid code. As a result, it is crucial to examine the behavior of the GFL inverter during fault conditions as a fundamental part of grid code.

1.3 Objectives

The objectives of this project are:

1. To study the operation of grid following inverter
2. To evaluate the behavior of grid following inverter during the fault condition
3. To implement the grid following control in real time

Chapter 2

LITERATURE REVIEW

2.1 Overview

Based on the related studies in this project, many countries have utilized the renewable energies to reduce environmental issues such as the emission of carbon dioxide. The solar PV system is one of the best options for new electricity generation. In real life, most of the existing grid-tie inverters will operate as grid-following (GFL) sources. However, the complex control in these inverters increases the case of instability of the system during fault condition.

2.2 Related Studies

In reference [4], the status of the microgrid connected system in different locations of Sarawak is demonstrated. The current need for electrification in Sarawak is provided for further analysis. The comparison between the proposed approach and the most existing works is also being demonstrated. It showcases the computational techniques and the employment of simulation software. In this case study, the performance of different hybrid microgrid configurations in Long San Village, Sarawak is being evaluated. As for the construction of the hybrid microgrid, the solar PV array is modelled by taking into consideration the temperature and solar irradiance. For this case, the battery characteristics are also vital since it includes the datasheet about the discharge rate and its efficiency. The discharge rate can be measured in term of State of Charge (SOC) and Depth of Discharge (DOD). SOC is the percentage of available charge with respect to its full capacity, while DOD is the battery content that has been consumed. Moving on to the next part, another issue in a microgrid would be the voltage control during the normal and abnormal conditions. When a fault occurs in the system, it causes a severe disturbance such as voltage sag and instability in microgrids. Hence, the steady-state and transient behaviors of the system are analysed. From the operational analysis using PSCAD, the authors declared that it is necessary to distribute the loads around the sources equally, in order to reduce power shortage issue.

From [5], a hybrid maximum power point tracking (MPPT) technique is proposed for PV systems to extract the maximum power. In general, MPPT is an algorithm that is included in charger controllers under certain conditions such as Partial Shading Conditions (PSCs). Usually, an MPPT device will be inserted between the PV arrays and the loads. In the conventional model, the perturb and observe (P&O) method is widely used. However, it is only effective in tracking the MPPS within the system with uniform irradiance distribution. Hence, the artificial neural network (ANN) is applied to solve this issue since it can simulate the complex non-linear relationship between the input and output. In short, the proposed method is a combination of an ANN-based technique with the P&O algorithm. In this paper, the hybrid MPPT method is outlined for two (2) different scenarios, with and without irradiance sensors. The first model uses the irradiance sensors to provides the inputs to ANN classifier, while the second implementation applies the measured value at specific point corresponding to the I-V curve caused by shading. Temperature and irradiance are two (2) common factor which can affect the MPP region. However, the temperature is assumed to be constant for these two (2) scenarios because the temperature difference between the PV modules is relatively small. Based on the simulation and experimental analysis, the researchers proved that the proposed hybrid MPPT method can efficiently track the global MPP under various shading patterns. This MPPT technique also provides better tracking performance since the system response time is less than 2 seconds.

The authors stated that the presence of PV systems is increased to provide power for different types of loads [6]. In this case, the PV systems are capable to supply the energy for remote loads, whereas the grid-connected system is applied to provide power for local loads. This research paper also considers many possible impacts of grid-connected PV system on distribution systems, such as inrush current, overvoltage, output power fluctuation and harmonic. To carry out this study, the meteorological data of Kuala Lumpur (within 1 year) are collected from Malaysian Meteorological Department (MMD). The relevant simulation is then carried on a 16 bus test system with an embedded grid-connected PV system using MATLAB Simulink. The effects of variable weather conditions (sunny and cloudy) on the performance of the PV modules are being investigated. To be conclude, the active power produced by PV system causes power quality issues such as voltage flicker and the affected equipment(s) could be damaged.

About [7], the capability of a Digital Signal Processor (DSP) for power electronics applications is being tested. The Delfino TMS320F28379D (also known as F28379D Launch Pad) is implemented in this solution. Pulse Width Modulation (PWM) technique is applied to regulate the power supplied from the source side. For this case, the Code Composer Studio (CCS) of Texas Instrument is used as the main software package to write the programme or code. The results show that the microcontroller used can effectively produce different type of PWM signal curve for the inverter control, such as the square wave and triangular wave.

In reference [8], the authors proposed a closed-loop design of the grid inverter using the TMS320F28335 development board. This DSP board will be applied to generate the ePWM signal and this step can be done by the configuration using MATLAB Simulink. An external 5V power supply is supplied to the development board. The produced signal is then used to drive the gate driver of the Insulated Gate Bipolar Transistor (IGBT). The Code Composer Studio by Texas Instrument is also being used to compile the simulation model in the MATLAB environment into C programming language. In order to have voltage control at the optimum level, a closed-loop algorithm will only allow the generation of the pulse signal when the magnitude of the carrier voltage is greater than the reference voltage.

In reference [9], the performance of power electronics appliances had been tested in real-time with the aid of the F28379D Launch Pad. A block diagram for DC-DC converters is proposed to achieve an optimal performance in voltage control. The proposed approach uses a single feedback loop from the output voltage side. The controller is used to reduce the error gap between the reference voltage and the output voltage. The output from the controller is then compared with the carrier signal to generate the gate switching signal. As the amplitude of the controller output is higher than the amplitude of the carrier signal, it will generate a gate signal for operation of the power electronic converters. For hardware implementation, two (2) LAUNCHXL-F28379D development kits are used. The first one is applied to generate the analog output signal through Digital-to-Analog Converter (DAC) pins, while the command from the controller will be received by Analog-to-Digital Converter (ADC) pins of the second development kits. This platform is commonly known as Controller-Hardware-in-the-Loop. The output results verify the feasibility of proposed implementation without using any expensive Hardware-in-the-Loop systems.

According to [10], the efficiency of the PV panel is mainly affected by two (2) major factors, which are solar cell temperature and solar irradiance. The mathematical modelling is also implemented using MATLAB environment. Based on the study, the increase in solar cell temperature will decrease the power generated by the cell. Meanwhile, an increase in solar radiation causes an increase in power generation. The performance of different types of photovoltaic cells are also being evaluated in terms of power-voltage characteristics. The standard test condition is applied in this study, whereas the irradiance and cell temperature are set as 1000 W/m^2 and 25 °C respectively. Among different PV technologies, the result shows that the monocrystalline solar cells have highest efficiency.

In reference [11], a comparison between the GFL and grid forming (GFM) control is proposed for a high inverter penetration power system. Most of the commercial PV inverters function as GFL sources. In order to achieve optimal current control, the real and reactive output power is controlled based on frequency and voltage. GFL sources also applied the phase-locked loop (PLL) to measure the voltage angle of the grid, thereby regulating the output power. For the GFM control, the real and reactive power will be measured, then the magnitudes of frequency and voltage are obtained for the voltage control. In terms of the impact of inverter penetration level, the increase in the penetration level will lead to a better-damped response and less oscillatory fluctuation in peak frequency magnitudes for GFM inverters. In the case of GFL inverters, the increase in penetration level results in underdamped response and greater peak frequency excursions. This most probably will cause the nuisance tripping of the load and inverter.

Regarding [12], the GFL inverter is modelled to achieve a stable operation in the distribution network. In the first part of this model, the difference between the nominal inverter voltage and RMS voltage is compared in a voltage supply block. The quadrature current is obtained and being driven to the current limiter. For the second part, the direct current will also be driven to the current limiter block and it is considered as a constant value since the dynamics of the dc-link is neglected. As the output, the current limiter will drive the reference direct current and reference quadrature current by considering the maximum current produced by the inverter within the safety range.

As mentioned in [13], renewable energy resources can easily connect to the grid through a GFL. A maximum power point tracking (MPPT) algorithm is applied to maximize the power generated. A voltage source converter (VSC) control system is also constructed for GFL based on the Park transformation. The park transform block is used to converts the time-domain elements (abc reference frame) of a three-phase system to direct, quadrature and zero components (dq0 reference frame). Meanwhile, a PLL will be used to measure the phase angle of the grid. This kind of control system has high dependency to the pre-existing grid. Thus, the active and reactive power will not vary even if there is variation between the grid voltage and frequency caused by a transient situation. To resolve this issue, a droops control is implemented to achieve high stability in tracking the reference values of the active and reactive power. This is mainly because the power flow of the droop control has a high sensitivity to the fluctuation of grid frequency and voltage. The current control loop is also being implemented to obtain the error value by comparing the difference between the referenced current and the measured current. After that, it goes through a PI controller, which generates the references magnitude of the output direct and quadrature voltage. The saturation unit is also added to protect against overcurrent case during fault condition. The main limitation of the GFL is that it cannot restart the grid operation after a blackout or sudden nuisance shutdown. This leads to its limited capability in an islanded system. Hence, GFL only can be present in a grid-connected mode with proper measurements of voltage and frequency.

From [14], the stability of PQ-controlled GFL inverters had been studied. In the GFL inverter, the grid voltages and currents will be measured and converted to the dq0-frame. The park transform (abc to dq0) block is used to preserve the direct, quadrature and zero components from the abc reference frame of the three-phase system. The zero component is always equal to zero for a balanced system. The measured voltages and currents at the point of common coupling (PCC) are applied as the input of the PQ controller. There are two (2) cascaded loops to control both active power, P and reactive power, Q. In the last stage, the output from the PQ controller is used to generate the reference signal for the PWM signal and support the operation of the associated inverter. The inverter performs like a current source and assists in supporting the grid voltage through reactive power compensation. The results show that the low power levels in the grid and variation in filter parameters will lead to the inverter’s instabilities.

As stated in [15], the usage of renewable energy resources can be integrated into a power system with the aid of the GFL inverters. The reactive power – frequency (Q-w) droop control and phase-locked loop (PLL) will be used in the inverters. This kind of droop control is applied to share power from the inverter to the grid, whereas the PLL establishes a relationship between the frequency and grid voltage, whereby it measures the phase angle of voltage by controlling the quadrature voltage to zero using a proportional-integral (PI) controller. In terms of extreme operation, the PLL grid-following inverter is stable when it is connected to an ideal voltage source, and unstable when it is connected to an ideal current source. Weak grid strength also leads to instability of the inverter. In short, the GFL inverter is voltage-following and current-forming.

In reference to [16], the performance of the GFL inverters during an unbalanced fault is being studied. The control architectures of the GFL inverter consist of the power control loop, measurement of voltage and current, Park Transformation block and a current-reference saturation limiter. The limiter is installed between the current control loop and the power control loop to limit the output current within a specific range. The IEEE 14-bus network is modelled using MATLAB environment. The case considered for this study is that the GFL controls at some buses operate in unstable condition. The results show that there is a drastic drop in positive sequence voltage and rise in negative sequence voltage during the fault condition. The decrease in positive sequence voltage is caused by the injection of purely balanced currents. Meanwhile, the increase in current required to feed the unbalanced fault is the main reason for the imbalance of the negative sequence voltage in the GFL inverter. This clearly exhibits voltage unbalance during the line-to-line faults (unbalanced faults). The excursion of peak current is detected by the current limiter after the fault. This study can be a good source to benchmark the fault behavior of the GFL inverters for the future work.

From [17], the GFL control is used to achieve optimal power performance. The authors proposed the modelling of a GFL converter with grid-supporting mode. The GFL control is applied to adjust the injected power with reference to the grid voltage at the point of common coupling (PCC). The GFL converter also regulates the amplitude and phase of the injected current in order to control the active and reactive power independently. For this case, a three-phase phase-locked loop (PLL) can be used to synchronize on a set of variable frequencies of the grid voltage, then generate the instantaneous magnitude of the reference voltage and reference current. Since the grid voltage is regulated by the injection of reactive power, thus the result shows that the GFL unit would also exhibit a higher apparent power.

In reference [18], the transient stability of the GFL inverter is being analysed. Three (3) types of system configurations are proposed for this study. In the first configuration, the GFL inverter is connected to an infinite bus with a single three-phase line and a three-phase fault is applied in between the line for a certain timeframe. The second and third configuration involves the connection of two (2) parallel three-phase lines. For the second configuration, one of the parallel lines is disconnected for a specific time range. As for the third configuration, a three-phase fault will be applied to one of the two parallel lines before it is disconnected for a certain period. Several cases are considered and the system is examined in time-domain simulations using MATLAB environment. In the first case, a single-line three-phase fault is applied in the single-line configuration. For this system based on a GFL inverter, there is a deviation from the equilibrium point in the strong grid during the fault. As the impedance of the grid increases, the deviation also increases which contributes to the instability of the system in the weak grid. As for the second case, there will be no equilibrium point in the system when one of the lines are disconnected. The system become unstable and does not return to the equilibrium point even after the line is reconnected. For the third case, while a three-phase fault is applied in two-line configuration, the GFL inverter has higher tendency to approach equilibrium points. The results also show that the disconnection of the line after the fault contributes to the system's instability in the faster manner. In short, the faults will have more severe impacts on GFL inverters in weak grid conditions.

From [19], the grid code for the capability of GCPV is reviewed and an improved control strategy is proposed to enhance the performance of the solar PV system during the fault. There are different requirements from some countries such as Canada and Germany to disconnect the inverter from the power system as the grid voltage drop below the set levels. When a fault is applied to the grid, the system should be able to withstand the voltage imbalance or rapid voltage drop within a specified time frame. To prevent the nuisance shutdown of the inverter, the circuit should be connected back immediately when a fault occurs due to an overcurrent case. This can balance the power flow by continuous generation of active and reactive power to support the grid operation. The result shows that the inverter can remain connected to the system even when there is a