Generation dispatch with large-scale photovoltaic systems

by

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SUMMARY

GENERATION DISPATCH WITH LARGE-SCALE PHOTOVOLTAIC (PV) SYSTEMS

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There is a widespread adoption of stability strategies that employ power system voltage, rotor angle and frequency control techniques for dealing with the impacts of large-scale PV systems on sub-transmission and transmission power system networks. However, generation dispatch strategy which is equally vital for solving operational challenges presented by non-conventional sources such as large-scale PV systems remain under-utilized. The list of well-known operational challenges associated with large-scale PV systems include load-following and spinning reserve requirements, load frequency excursions and system stability, amongst others. Generation dispatch is the aspect of control strategy that takes into account the intermittent nature of non-conventional sources and relies on the adjustment of power output from other generating units in the entire generation mix consisting of both non-conventional and conventional sources to maintain balance between generation and load. These entails fulfilling numerous operational requirements such as holding dispatchable sources in the form of both spinning and non-spinning reserve, optimal economic dispatch and unit commitment. Opportunity for further research lies in the application of generation

dispatch strategy to solving some of the operational challenges posed by the integration of the large-scale PV systems in the sub-transmission and transmission system networks.

The role of generation dispatch strategy is to maintain a generation and load balance despite the intermittent nature of large-scale PV systems based on economic dispatch as well as spinning and non-spinning reserves techniques. This can be achieved by employing short and long-term forecast techniques for PV power output and working out the cost effective deployment methods of all the other generating units while taking into account prevailing transmission and operational constraints.

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LIST OF ABBREVIATIONS

AGC	Automatic Generation Control
AVR	Automatic Voltage Regulator
CSP	Concentrated Solar Power
DSM	Demand Side Management
IRENA	International Renewable Energy Agency
PV	Photovoltaic
PCC	Point of Common Coupling
PCS	Power Convention System
POI	Point of Interconnection
RES	Renewable Energy Source
RSI	Renewable Systems Interconnection
STATCOM	Static Synchronous Compensator
SVC	Static VAr Compensator
VRE	Variable Renewable Energy
WECC	Western Electricity Coordinating Council

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CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

1.1.1 Context of the problem

Electrical utilities worldwide adopt innovations, technologies and systems that help safeguard the smooth running of all sub-transmission and transmission networks upon integration of large-scale PV systems. Among the crucial approaches taken are the power system voltage, rotor angle and frequency control techniques. These are common approaches within the power system stability practices. Some power utilities use generation dispatch strategy and the related techniques such as economic dispatch and unit commitment. In this particular context, power system stability techniques involve the control of key parameters such as voltage, rotor angle and frequency in dealing with the disturbance caused by large-scale PV systems. These techniques require additional effort in terms of development and implementation. However, generation dispatch strategy and the related techniques are already at the disposal of the system operator. It is simply a matter of devising suitable implementation approaches. Therefore this research seeks to address the challenges posed by the integration of large-scale PV systems using generation dispatch techniques and associated economic dispatch and unit commitment requirements. The interim focus would be on generation dispatch with large-scale PV systems in sub-transmission and transmission network.

1.1.2 Research gap

Many countries such as Namibia have a powerful solar regime with which modern innovative solar energy technologies can be tapped to provide energy to end users. In developing countries, standalone PV systems are popular off-grid power supply solutions for homes in remote locations [1]. Meanwhile, in most developed countries, grid-connected PV systems feature prominently at low voltage distribution level [2–4]. Various control strategies aimed at limiting the voltage rise as a result of increased local PV power feed-in have been discussed therein. These include PV inverter control strategies as well as a distribution transformer with On-Load Tap Changer (OLTC) and traditional grid reinforcement measures for grid-connected homes.

However, none of these approaches have addressed the challenges of large-scale PV system in transmission and sub-transmission networks. Despite excellent work on themes such as stability techniques, technical mitigation of dealing with large-scale PV systems coupled to high voltage transmission and sub-transmission networks have not been fully explored as a part of sustainable energy options.

Yet, without such an option, a false impression is created that PV systems integration challenges and possible solutions are similar at both low voltage distribution grid and transmission/sub-transmission grid. In addition, generation dispatch and spinning reserve concepts that are mainly applicable to large-scale PV systems are often over-looked.

Research on integration issues has mainly focused on distribution level PV systems [2] and very little attention has been paid to large-scale PV system [5]. With increased deployment of large-scale PV plants, new challenges and solutions need to be explored. This study will remedy this gap in the literature by carrying out a detailed investigation of large-scale PV systems coupled to the transmission and sub-transmission system in the context of uniqueness of large-scale PV systems, grid integration technical concerns, mitigation strategies for widespread deployment of large-scale PV and economic viability to both power utilities and customers.

This study will focus particularly on generation dispatch and the associated economic dispatch mitigation techniques in contrast to stability techniques. Through a close and fine-grained analysis of current large-scale PV mitigation strategies, it shall be demonstrated that in contrast to previous assumptions, in fact generation dispatch and the related economic dispatch can be effective tools in dealing with technical challenges posed by large-scale PV systems coupled to transmission or sub-transmission network. A detailed review of existing generation dispatching techniques with PV systems is carried before presenting the proposed method.

1.2 RESEARCH OBJECTIVE AND QUESTIONS

The main goal of this research is the identification and quantification of impacts of large-scale PV systems deployment in existing conventional electrical networks. Once the impacts have been determined, possible solutions will be investigated further with specific focus on least studied techniques of generation dispatch, economic dispatch and unit commitment. An attempt will also be made to figure out economic factors that may have an influence or might be influenced by these techniques.

The research questions are:

- What are the economic impacts of incorporating large-scale PV in the generation mix of a conventional electric utility?
- What are the roles of generation dispatch strategy and the related economic dispatch methods in solving challenges posed by grid-connected large-scale PV systems?
- What is the optimal economic generation dispatch considering cost and operational constraints?

1.3 APPROACH

The proposed approach entails the following:

- Detailed literature review,
- Energy usage data gathering,
- Case studies of existing large-scale PV systems,
- Experimental simulations using literature and industry data, and
- Modeling.

1.4 RESEARCH GOALS

The objective of this study is to explore the role of generation dispatch strategy and spinning/non-spinning reserve methods in solving challenges posed by grid-connected large-scale PV systems as opposed to the commonly used approaches of power system voltage, rotor angle and frequency control methods. The generation dispatch strategy and spinning reserve methods are similarly considered key solutions as stability control methods in future power system with high penetration of large-scale PV.

1.5 RESEARCH CONTRIBUTION

It is expected that this research will contribute to the on-going search for sustainable energy options and play an important role in shaping the direction of large-scale solar PV systems in light of hindrances presented by grid integration issues and complex regulatory framework. This research is further expected to enhance existing perspective on the generation dispatch and spinning reserve techniques as reliable methods of dealing with large-scale PV systems integration challenges. The expected research output is also expected to come in handy with recent trends of widespread adoption of large-scale PV systems by utilities all over the world.

1.6 RESEARCH OUTPUT

The following journal article was published:

K. Nghitevelekwa, and R. C. Bansal, ‘A review of generation dispatch with large-scale photovoltaic systems’, *Renewable and Sustainable Energy Reviews,* vol. 8, pp. 615-624, 2018.

1.7 OVERVIEW OF STUDY

This dissertation consists of six chapters. The first chapter serves as an introduction on the topic of generation dispatch with large-scale PV systems. This is where the problem statement, research objectives and questions, approach, research goals, research contribution and the overview of the study are outlined. The problem statement spells out the context of the problem as well as the identified research gap.

In Chapter 2 various themes on the literature study of generation dispatch with large-scale PV systems are presented. In Chapter 3 the methods and procedures for the simulations and investigations of generation dispatch with large-scale PV systems are provided. This entails modelling and analysis approaches frequently used in numerous studies involving generation dispatch with large-scale PV systems. In Chapter 4 the results of various simulations conducted to demonstrate the role of generation dispatch in overcoming challenges posed by large-scale grid-connected PV systems are presented. In Chapter 5 a discussion on the interpretation and significance of the research findings pertaining to generation dispatch with large-scale PV systems is presented. In Chapter 6 the conclusion of the study is presented. This includes an evaluation of the outcome and the overview of the main issues surrounding the research on generation dispatch with large-scale PV systems.

CHAPTER 2 LITERATURE STUDY

2.1 CHAPTER OBJECTIVES

This chapter presents an overview of various themes of the literature study concerning the generation dispatch of large-scale PV systems. These range from the technical and economic impacts of large-scale PV systems on the sub-transmission and transmission grid to the applicable solutions thereof. The applications of generation and economic dispatch as a solution to the impacts of grid-integrated large-scale PV systems are discussed in great detail and the key concepts behind these techniques thoroughly described.

In Section 2.2 the first theme on sustainable energy development options was provided. It was found that among major economic activities, electricity and heat production were responsible for about 25 % of all GHGs emissions.

In Section 2.3 a review on the current state of the power industry was provide. It was found that there is an increase in the percentage of RES with respect to the overall global energy mix. In addition, PV energy sources make up about 18 % of the overall RES.

In Section 2.4 an introduction to grid-integrated large-scale PV systems was provided. It was found that flexibility options such as resource forecasting, storage, demand response, dispatchable power and tie-line electricity imports and exports across larger balancing areas can serve as support mechanism in dealing with challenges posed by the intermittent nature of grid-connected large-scale PV systems.

In Section 2.5 the impacts of large-scale PV systems on generation systems and related solutions was discussed. It was found that the severity of impacts and the complexity of related response requirements were directly proportional to the increase in the percentage of share of large-scale PV systems in a particular grid.

In Section 2.6 the impacts of large-scale PV systems on existing power system protection and stability were presented. It was found that the intermittent nature of large-scale PV systems pose challenges to the existing power system protection and stability. Therefore, new requirements on PV design call for the inclusion of a variety of new control and protection functions such as voltage regulation, power curtailment, ramp-rate control, and communication-assisted protection.

In Section 2.7 the impact of variable RESs such as large-scale PV systems on the power system grid code and related solutions were discussed. It was found that effective integration of large-scale PV systems in the grid requires the development and adoption of revised grid codes.

In Section 2.8 the economic impact of large-scale PV systems was discussed. It was found that there a number of factors that have a bearing on the operational cost of the power system integrated with large-scale PV systems. These include hydro availability, generation mix, maintenance schedule, ramping rates, fuel costs, spinning reserve requirements, PV power fluctuations, and geographical diversification.

In Section 2.9 the issue of aiding the integration of large-scale PV systems into the grid using economic dispatch was considered. It was found that flexible supply and demand systems are among options that can be adopted in order to effectively deal with inherent challenges of fluctuating RESs.

In Section 2.10 the integration of large-scale PV systems through generation dispatch was discussed. It was found that there are various options for aiding the integration of large-scale PV systems into the grid through generation dispatch. These include use of pumped-storage hydro plants, complementary hydro-PV operation, geographic dispersion of PV plants to avoid, for instance, simultaneous cloud cover impact and many others.

2.2 SUSTAINABLE ENERGY DEVELOPMENT OPTIONS

Among notable anthropogenic actions that contribute the most to greenhouse gas (GHG) emissions are energy production activities [6]. In terms of key economic sectors, electricity and heat production contribute in total 25 % of all GHG emissions. GHGs are subsequently responsible for global warming, one of the environmental issues linked to climate change. GHGs such as carbon dioxide (CO_2) are emitted during the course of burning fossil fuel and coal for electricity generation, transportation, heating and cooling, and in the process of running many other industrial applications. Energy is required almost in all spheres of life.

In recognition of unprecedented increasing levels of greenhouse gases emissions due to anthropogenic actions, the UNFCCC, also referred to as “The Convention”, was adopted at the Rio Summit in 1992 [7]. The aim of the convention is to prevent dangerous anthropogenic interference with the climate system. The UNFCCC was launched jointly with other two related environmental conventions, namely, the UN Convention on Biological Diversity (UNCBD) and the Convention to Combat Desertification (UNCCD) [8]. The Kyoto Protocol, adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005, is an international agreement linked to the UNFCCC, whose main objective is the reduction of human-induced GHG emissions [9]. This treaty is based on the principle of “common but differentiated responsibilities” in the sense that the heaviest burden of environmental problems is placed on the shoulders of developed nations. The Paris Agreement, adopted in 2015, is aimed at strengthening global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius [10]. All in all, these treaties heeded nations to embrace sustainable development options that would ensure the current generation’s needs are met while ensuring that the future generations would also be able to meet theirs.

In response to continuous calls for nations to adopt sustainable development goals, many countries ratified the UNFCCC treaties. Many other continental, regional and national policies and truces were also adopted in furtherance of sustainable development goals. These include some of the worldwide renewable energy policies such as [11]:

a) The USA's All-of-the-Above Energy Strategy which is aimed at making America energy independent and creating jobs. The key guidelines of this strategy are: reducing dependence on foreign oil, safe and responsible domestic oil and gas production, carbon capture and sequestration technologies, advancing clean energy, energy efficiency and the development of fuel cells,
b) The European Union's Directive 2009/28/EC and of the Council of 23 April 2009, 2030 framework for climate and energy policies and the roadmap for moving towards a low-carbon economy in 2050,
c) Australia's Renewable Energy Target (RET) scheme composed of the Small-scale Renewable Energy Scheme (SRES) and the Large-scale Renewable Energy Target (LRET),
d) Columbia's Program for the Rational and Efficient Use of Energy and the Use of Alternative Energy Sources (PROURE),
e) Chile's National Energy Strategy 2012-2030: rational energy model to face high levels of sustainable economic growth: safe, clean and economical,
f) Thailand's Renewable and Alternative Energy Development Plan 2012-2021 (AEDP 2012-2021),
g) Japan's 2014 Strategic Energy Plan,
h) Saudi Arabia's King Abdullah City for Atomic and Renewable Energy (K.A. CARE),
i) Energy Strategy of the Arab Republic of Egypt, and
j) Tanzania's Strategic Plan 2011/12-2015/16 and the Power System Master Plan 2012 (updated in 2013).

Various governments enacted laws in support of sustainable development objectives. Namibia, for instance, adopted the Renewable Energy Feed-In Tariff (REFIT) Program to encourage investment in renewable energy through Independent Power Producers (IPPs). In addition, the country has also implemented a Renewable Energy Policy that is intended to enhance Renewable Energy development in Namibia. Numerous mechanisms were also institutionalised to enforce compliance.

Despite a strong approval, funding sometimes remains one of the stumbling block in an effort to ensure compliance with environmental conventions. The Global Environment Facility (GEF) serves as a financial mechanism for the UNFCCC as well as other environmental conventions [12]. Among the objectives of the GEF's sustainable development goals, is the need to address climate change through increased funding for the adoption of renewable energy. In addition, the Green Climate Fund (GCF), another financial mechanism for the UNFCCC, was also setup to help developing countries shift towards low carbon, climate resilient development pathways.

As a result, many public entities and numerous private institutions adopted in-house sustainability plans. Some embarked upon the installation of own rooftop grid-connected – hybrid PV systems for the purpose of catering for own daytime electricity consumption needs as well as for reducing own carbon footprint. Where applicable, these installations are done in compliance with net-metering rules that help offset the costs of electricity by offering credit for electricity transmitted into the grid.

2.3 CURRENT STATE OF THE POWER SUPPLY

The second theme of the literature study provides an overview of the current state of the power supply industry. This includes the presentation of the percentage composition of various energy sources in the overall energy mix.

2.3.1 Introduction

Energy plays an important role nationally, regionally and at a global level and makes a significant contribution to the world's economic standing. Electrical power is one vital form of energy and as such it has an important role and is ultimately responsible for determining the world's economic growth. The production of any form of energy is linked to a form of primary input such as fossil fuel for a thermal power plant and natural river flow for hydro power plant. Depending on whether the source of primary input can be replenished naturally, a specific form of energy can either be classified as renewable or non-renewable energy source if the source of primary input cannot be replenished naturally. Based on the bi-products involved in the process of producing a particular form of energy, energy sources can be classified as environmentally friendly if the bi-product is harmless to the environment or environmentally unfriendly if the bi-product has a detrimental effect on the environment. Among the environmental concerns is the need to keep the global temperature rise way below 2 °C relative to pre-industrial levels in line with the 2015 UNFCCC Paris Agreement goals [10]. As a result of dwindling resources and environmental concerns, the world is leaning towards renewable and cleaner form of energy production.

2.3.2 Alternative energy sources

Due to increasing populations, industrial development and deliberate measures taken to ensure universal access to some of the basic services such as electricity, the world is currently faced with the shortage of electrical power. Several options are being considered to address the electrical power supply deficit. Among these, is the continuous search for cleaner and environmentally friendly renewable energy sources (RESs) capable of fulfilling the role of conventional base load power stations [13]. A base load power station is a generation power plant capable of continuous operation and only shutdown subject to maintenance or unforeseen circumstances. This is to help supplement electricity generated from environmentally friendly RESs such as hydro power stations, which are also capable of base load operation mode. The other aim is to substitute or displace use of fossil fuel-based conventional coal-fired power stations and diesel generators as base load power stations. Continuous operation of fossil fuel based power plants is both costly and detrimental to the environmental. This is because of greenhouse gas (GHG) emissions that are associated with climate change. As a result, it is preferable that their use is confined to emergency operation or to bridging out the gap created by the fluctuating nature of variable RES.

Internationally, significant efforts are being made to increase the share of RESs in the generation mix. This is evident in the Renewables 2018 Global Status Report (GSR) that provides insight in the performance of RESs in terms of net additions and overall percentage share of PV with respect to the rest of RESs [14]. One such example is the record deployment of RESs which, in the year 2016, amounted to 32.67% of the global generating capacity net additions. Another example, as illustrated in the Table 2.1, is the fact that solar PV represented about 32.67% of newly installed global power generating capacity in 2017. At the present moment, this brought the share of RESs with respect to non-renewable energy sources to 26.5% of the global generating capacity. In addition, the share of PV with respect to the overall RES generating capacity currently stands at 18.31%. This is a clear indication that "the role of PV power generation is gradually changing from a supplementary energy to an alternative energy resource, with respect to conventional power generation [15]".

Table 2.1: Renewable energy indicators for 2017 [14].

	Units	2016	2017	% increase	% share in 2017	
					Incl. hydro	Excl. hydro
New investment (annual) in renewable power and fuels	Billion USD	274	279.8	2.12%		
Renewable power capacity (including hydro)	GW	2017	2195	8.82%		
Renewable power capacity (excluding hydro)	GW	922	1081	17.25%		
Hydropower capacity	GW	1095	1114	1.74%	50.75%	
Bio-power capacity	GW	114	122	7.02%	5.56%	11.29%
Geothermal power capacity	GW	12.1	12.8	5.79%	0.58%	1.18%
Solar PV capacity	GW	303	402	32.67%	18.31%	37.19%
Concentrating solar thermal power capacity	GW	4.8	4.9	2.08%	0.22%	0.45%
Wind power capacity	GW	487	539	10.68%	24.56%	49.86%
Ocean energy capacity	GW	0.5	0.6	20.00%	0.03%	0.06%

As illustrated in Table 2.1, the world is surely learning towards a cleaner form of renewable energy.

2.4 INTRODUCTION TO GRID-INTEGRATED LARGE-SCALE PV SYSTEMS

Large-scale PV systems are utility-scale PV systems with maximum capacity rating of a few MW to a few hundred MW. They are installed at transmission level voltage system to feed power into the grid like any other generation power plant. In contrast to distribution level PV systems which are usually installed close to the load centres where all the generated energy is consumed, large-scale PV systems are designed to serve large geographical areas.

2.4.1 Variable renewable energy sources

In general, a RES is any form of energy that cannot be depleted. These forms of energy range from hydro, solar, wind and bio-mass. Solar and wind are variable RESs since their generation output varies depending on the prevailing atmospheric conditions. However, the variable RESs are the most abundant forms of energy in comparison to any other form of energy, be it renewable or non-renewable. This is particularly true for solar PV whose primary source is the plentiful solar irradiation from the sun.

Despite being a plentiful form of RES, solar PV’s uptakes are negatively affected by their variable nature which gives credence to the notion that they cannot fulfill the role of a dispatchable generation plant. However, with the deployment of flexibility options such as resource forecasting, storage, demand response, dispatchable power and tie-line electricity imports and exports across larger balancing areas [16, 17], this particular limitation can easily be overcome. Other options include the implementation of DSM initiatives, which are aimed at reducing electricity consumption during peak hours and pumped-storage hydro power plants and CSP systems with storage.

2.4.2 Brief history of grid-integrated PV systems

The history of PV generation is summarised in Table 2.2.

Table 2.2: Summarized history of PV generation.

Date	Historical event	Capacity	Reference
1839	First photovoltaic effect discovery by Edmond Becquerel	N/A	[18]
1954	Development of the first silicon photovoltaic cell with an efficiency of 6% at Bell laboratories.	N/A	[19]
1958	First application of photovoltaic power supply on Vanguard 1, a U.S. satellite launched the same year.	N/A	[20]
1982	The first installation of PV plant built by Atlantic Richfield Oil Company (ARCO) Solar Inc. at Lugo near Hesperia, California.	1 MW_p	[21]
1984	The Carrisa Plains PV Power Plant, also owned and operated by Atlantic Richfield Oil Company (ARCO) Solar Inc. became the world's largest PV central station power plant.	5.2 MW_p	[22]
1985	The first photovoltaic with more than 20% efficiency	N/A	[23]
1989	The first tandem cell with more than 30% efficiency in concentrated sunlight	N/A	[24]
2015	The Tengger Desert Solar Park in Zhongwei, Ningxia China becomes the world's largest PV plant.	1500 MW_p	[25]

Table 2.2 indicates that there is a progressive growth in the capacity of large-scale PV plants.

2.5 THE IMPACTS OF LARGE-SCALE PV SYSTEMS ON GENERATION SYSTEM AND RELATED SOLUTIONS

This theme of literature study investigates the impacts of large-scale PV systems on the transmission grid and the related solutions. The main focus is on the factors that cause the variance in PV generation output and the consequent operational challenges.

2.5.1 Impacts on the supply and demand balance

The increased deployment of grid-connected large-scale PV systems is known to have numerous impacts on the conventional power system. Therefore, despite the strong motivation for alternative RESs such as PV, there has always been a number of limitations to the effective integration of significant amount of PV into the grid [26, 27]. Among these are the imbalance between PV supply and electricity demand, as well as the inflexibility of base load power plants to curtail their power output in the event of increased PV generation output, which results in excess unusable PV power. The suggested solutions include increased system flexibility, dispatchable load and energy storage systems.

The fraction of PV generation to the overall utility generation mix is referred to as the PV penetration level. Different levels of penetration results in different impacts and therefore require different operational measures as presented in Tables 2.3-2.6 [13].

Table 2.3: Impacts of rising shares of variable RES [13].

Share of variable RES	Impacts
10 %	No noticeable impacts
20 %	Small increase in supply variability and uncertainty is noticeable at the systems operations level.
	Limited impact on the operation of individual power plants.
30 %	Growing supply variability and uncertainty has significant impacts at the system operations level.
	Noticeable impact on operations of some power plants.
40 %	Elevated supply variability and uncertainty has major impacts at the systems operations level.
	Noticeable impacts on the operation of virtually all power plants.
>50 %	Structural surplus of VRE generation and seasonal energy imbalances.

Table 2.4: Response requirements to rising shares of variable RES [13].

Share of variable RES	Response requirements
10 %	No additional measures.
20 %	Some adjustments in system operations and grid infrastructure.
30 %	Significant changes to system operations.
	Greater flexibility of supply and demand.
	Some grid reinforcement for voltage and frequency stability.
40 %	Major changes to system operations.
	Significant additional flexibility of supply and demand.
	Significant grid reinforcement for voltage and frequency stability.
>50 %	Additional steps to manage supply and demand imbalances.

Table 2.5: Response summary to rising shares of variable RES [13].

Share of variable RES	**10 %**	**20 %**	**30 %**	**40 %**	**>50 %**
Resource forecasting		✓	✓	✓	✓
Grid operations		✓	✓	✓	✓
Storage			✓	✓	✓
DSM			✓	✓	✓
Grid reinforcement			✓	✓	✓
Sector coupling				✓	✓

Table 2.6: Actions in response to rising shares of variable RES [13].

Share of variable RES	**Response Actions**
10 %	Gathering information about grid conditions and planning, including standards for future growth in VRE.
	Country examples: Indonesia, Mexico and South Africa.
20 %	Establishing a RES forecasting system.
	Introducing improved control technology and operating procedures for efficient scheduling and dispatch of system resources.
	Country examples: Australia, Austria, Belgium, Brazil, Chile, China, India, the Netherlands, New Zealand and Sweden.
30 %	Managing variability through advanced resource forecasting, improved transmission infrastructure and a significantly more dynamic operation of a growing number of dispatchable system resources.
	Co-ordination across control areas with the aid of improved information and control technology, and strengthened transmission interconnections.
	Country examples: Germany, Greece, Italy, Portugal, Spain, the United Kingdom and Uruguay.
40 %	Improving significantly the efficiency and scope of demand response with better information and control technology.
	Deploying significant additional advanced storage on the grid and behind the meter for energy balancing and for voltage and frequency support.
	Country examples: Denmark and Ireland.
>50 %	Sector coupling- electrification of heating, of heating, cooling and transport as a daily, weekly and even seasonal buffer for VRE generation.
	Converting electricity into chemical forms that can be stored (e.g., hydrogen).

When the fraction of generation provided by PV is less than 10 %, there are almost no noticeable impacts and therefore no new requirements. However, as the fraction of PV generation increases towards 50% and slightly beyond, a proportional increase in supply variability and uncertainty becomes evident at the systems operations level. In addition, the impacts on the operation of individual power plants becomes visible. These results in more response requirements. Depending on the level of penetration, the response requirements are, amongst others, resource forecasting, grid operations, storage, DSM, grid reinforcement and sector coupling.

2.5.2 Variation in PV generation output and load-following requirements

Among causes of variability in solar irradiance such as numerous meteorological influences such as temperature, wind speed, cloud cover, atmospheric aerosol levels and humidity level [28], one notable cause of intermittency in PV generation output is the well-known shading effect caused by moving clouds [29, 30]. This is noted to be one of the challenges posed by large-scale grid-connected PV generation which results from sudden change in PV generator output when an entire array is covered or uncovered by a large moving cloud [29]. The resulting operational problem is comparable to the sudden load change in the power system [29]. Similar to load-following requirements, the variance in PV power output results in the need to make adjustments to other generation sources in order to follow PV power output variations [30, 31].

Measures and challenges involved in dealing with this kind of scenario are discussed below. On one hand, the control measures to handle PV generation sudden changes are [29]:

i. Automatic Generation Control (AGC),
ii. regulating conventional generation,
iii. scheduling of more units to regulating duty, and
iv. use of combustion turbines or combined cycle generating units that have very responsive gas or oil firing systems, which make these specific generators easily controllable.

On the other hand the challenges in handling PV generation sudden changes are listed as [29],

i. the ramping rate imbalance - the rate at which the PV generation drops (e.g. MW/min) may be faster than the rate at which the conventional generation is ramped up,
ii. conventional generation entrusted with compensating for lost PV generation may reach peak generation output before attaining desired load-generation balance,
iii. cost of fuel (oil or gas) in combustion generators and the scheduling aspect.

2.5.3 Countering the impacts of shading on PV Systems

An innovative MPPT scheme to counter the negative impact of irradiance and temperature variations on PV power output as a result of partial shading of PV panels has been investigated [32]. It has been noted that the use of numerous optimization methods for design, planning and control for solving various renewable energy problems including solar PV systems has increased [33]. These ranges from determination of best tilt angle of PV modules, identifying the electrical parameters of PV cells and modules as well as sizing of required PV modules prior to installations.

2.5.4 Loss of PV generation due to power system faults and fault ride through capability requirements

Any sudden disconnection of a large-scale PV system from the grid due to power system faults has the potential of disrupting the prevailing load and generation balance. Large-scale PV systems are therefore required to have fault ride through (FRT) capability. The low voltage ride-through (LVRT) capability of the generating unit indicates whether the generating unit can remain connected during short periods of voltage dips and can ride through them, as well as providing current during the voltage dip [34]. On the other hand, the high voltage (HVRT) capability requirement stipulates that PV power plants should remain connected for a short period of time during overvoltage fault conditions [35].

2.6 IMPACTS OF LARGE-SCALE PV SYSTEMS ON EXISTING POWER SYSTEM PROTECTION AND STABILITY

The fifth theme of literature study explores the impacts of large-scale PV systems on power system stability and the related solutions. The emphasis is on the key power system stability parameters such as voltage and frequency and the consequent operational requirements in terms of power system protection.

2.6.1 Impacts on power system protection and the related solutions

In addition to other common large-scale solar PV systems technical challenges such as reverse power-flow, the above-mentioned fluctuations and responses have a direct bearing on power system protection. A number of present control and protection functions as well as proposed control and protection functions for the future large-scale PV systems have been extensively explored [36–38]. Therefore large-scale PV systems are normally equipped with power electronic inverter modules that form up the power conversion systems (PCSs). These PCSs that are responsible for solar energy to electrical energy conversion are equipped with internal and external protection schemes such as fast overcurrent protection and under and overvoltage and frequency stability protection, as well as active anti-island protection schemes which sense when there is grid power outage and immediately stops the PV system from producing power.

As part of future combined efforts to add on the above-mentioned PV control and protection functions, PV inverters will also be expected to provide a variety of new control and protection functions such as voltage regulation, power curtailment, ramp-rate control, and communication-assisted protection [36]. These are aimed at enhancing the interaction of large-scale PV systems with the grid and providing the means for coordinated control and operation through localized or utility-wide supervisory control systems.

2.6.2 Suitable power system protection for PV systems

There are appears to be conflicting requirements in terms of suitable protection for large-scale PV systems. This is with regard to fault ride-through (FRT) capability and anti-islanding. FRT capability is a requirement that calls for intermittent RES to remain connected for short durations during grid faults such voltage dips. On the other hand, the anti-islanding requirements demands for the immediate disconnection of intermittent RES whenever conventional generation sources have tripped due to grid faults.

A review on the impacts of distributed generation (DG) on distribution system protection identified a number of technical challenges in the current industry practices [39]. These are the system stability, DG interface requirements on protection and islanding. One proposed technical solution is the need to review control strategies of inverter-interfaced DGs so that they contribute sufficient fault current for fault detection and isolation. Contrary to current industry practice of anti-islanding, the proposed technical solutions requires grid-integrated DGs, including PV, to have fault-ride through capability which enables the DGs to remain connected during and after fault occurrence. This is essential for improving supply reliability.

2.6.3 Impacts on power system stability and the related solutions

Power system stability is defined as the “ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [40]”. The disturbances are usually in the form of power system faults, load changes and loss of generation that affect key stability parameters such as rotor angle, frequency and voltage. The classification of power system stability in terms of key categories and sub-categories is provided in Figure 2.1.

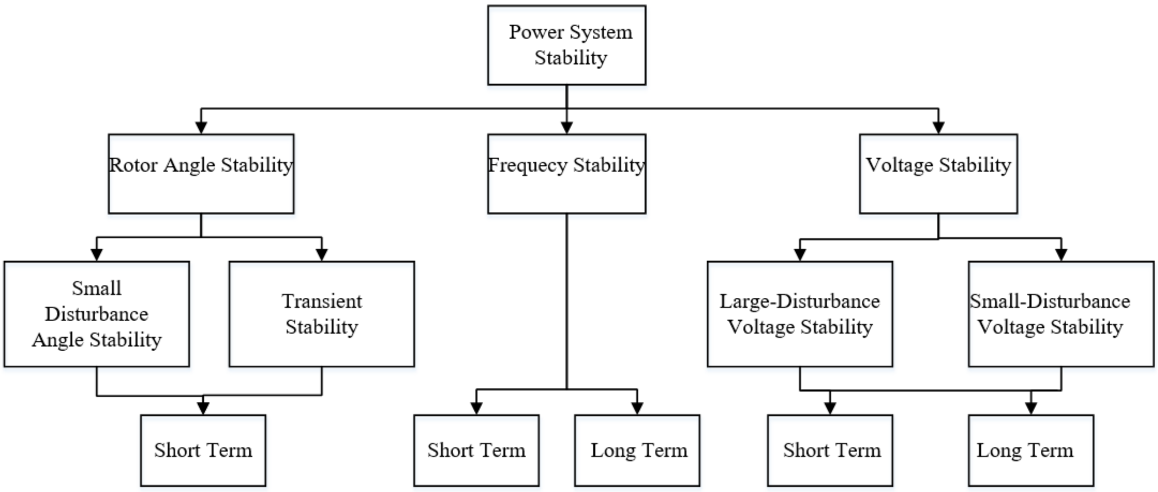

Figure 2.1: Classification of power system stability [40].

Power system stability is further defined and classified [41] in terms of sub-categories as described in the following subsections and in Figures 2.2-2.4.

2.6.3.1 Rotor angle stability

Rotor angle stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism following a disturbance. This is influenced by the ability to maintain and restore equilibrium between electromagnetic torque, which is due to the generator electrical power output, and mechanical torque, which is due to the mechanical power input of the prime mover, of each synchronous machine in the system. Rotor angle instability results in increasing angular swings of some generators leading to their loss of synchronism with other generators.

As depicted in Figure 2.2, rotor angle stability is subdivided further into small-signal and transient stability. Small-disturbance (or small-signal) rotor angle stability is associated with the ability of the power system to maintain synchronism under small disturbances such as variations in loads and generation. The small disturbances are further classified as local and inter-area mode oscillations depending on the scale of occurrence. Local mode oscillations involves small part of the power system, and are usually associated with rotor angle oscillations of a single power plant against the rest of the power system. On the other hand, global (inter-area) mode oscillations are concerned with interactions among large groups of generators and have widespread effects. They involve oscillations of a group of generators in one area swinging against a group of generators in another area. Large-disturbance, commonly referred to as transient stability, is related to the ability of the power system to maintain synchronism when subjected to a severe disturbance, such as short circuits on a transmission line.

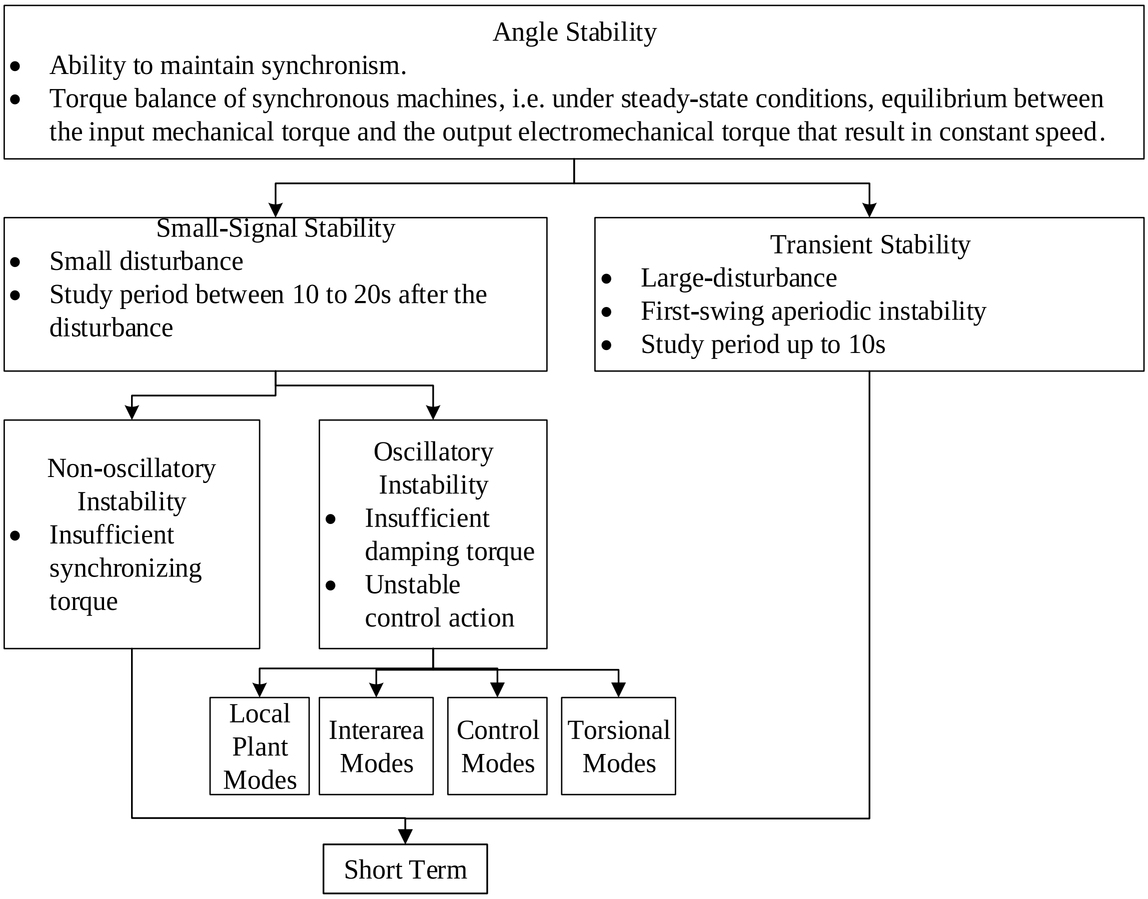

Figure 2.2: Classification of rotor angle stability [41].

2.6.3.2 Frequency stability

Frequency stability is the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. It relies on the ability to maintain and restore equilibrium between system generation and load, with minimum unintentional loss of load. Frequency instability results sustained frequency swings leading to tripping of generating units and/or loads.

As shown in Figure 2.3, frequency stability can be categorised in mid-term and long-term stability.

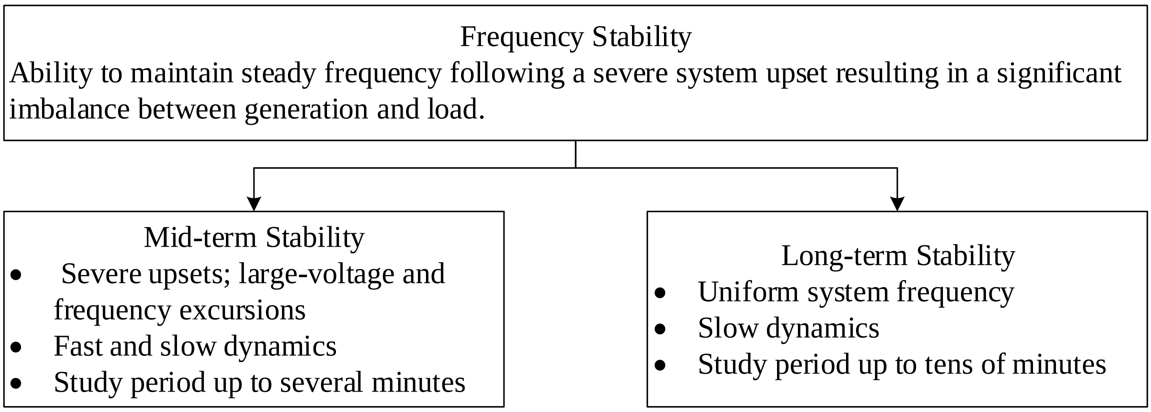

Figure 2.3: Frequency stability [41].

2.6.3.3 Voltage stability

Voltage stability denotes the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It relies on the ability to maintain and restore equilibrium between load demand and load supply from the power system. Voltage instability may lead to a progressive fall or rise of voltages of some buses. These can result in the loss of load in an area, or tripping of transmission lines and other elements by their protective systems leading to cascading outages. These outages and shift in operating conditions that violate field current limit will result in subsequent loss of synchronism of some generators.

As indicated in Figure 2.4, voltage stability is further classified in:

- Large-disturbance voltage stability, which is the system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. This ability is determined by the system and load characteristics, and the interactions of both continuous and discrete controls and protections.
- Small-disturbance voltage stability which is the system's ability to maintain steady voltages when subjected to small perturbations such as incremental

changes in system load. This form of stability is influenced by the characteristics of loads, continuous controls, and discrete controls at a given instant of time.

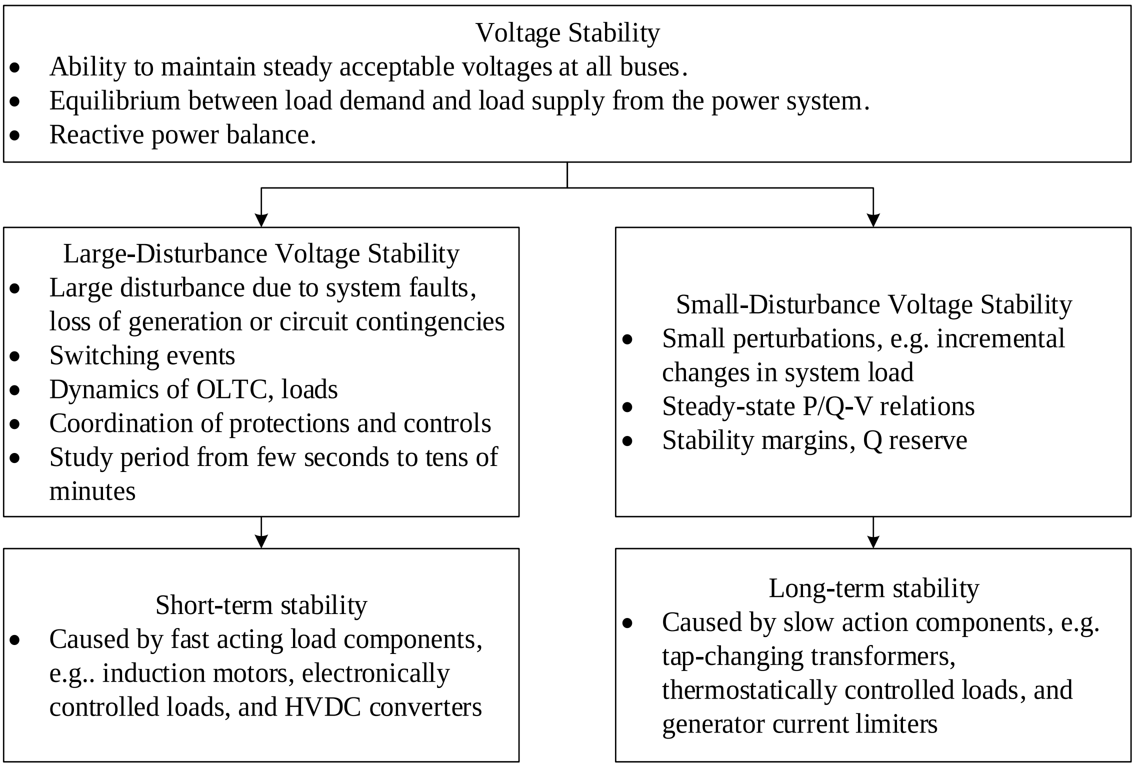

Figure 2.4: Classification of voltage stability [41].

The current consensus is that a transmission system interfaced with significant amounts of PV may respond differently to various system disturbances as opposed to the system without PV. In an effort to validate this specific claim, the research work in [42] investigated the impact of various PV penetration levels on a large test system representing a portion of the western U.S. interconnection. The study took into account steady-state voltages under various PV penetration levels and the impact of reduced inertia on the transient stability, detrimental and beneficial impacts of increased PV penetration both for the steady state and transient stability performance. The analysis results revealed that in terms of utility scale PVs, both steady state and transient stability of the power system are affected by increased PV penetration levels. The amount of PV generation penetration is indirectly proportional to steady state voltage magnitudes. As more PV generation is added, steady state voltage magnitudes drop. On the other hand, overvoltage conditions that are observed to reach a peak of up to +10% in buses are mitigated by switching off shunt capacitors or adjusting the voltages of conventional generators. At about 30 % PV penetration level, reactive power losses tend to decrease. There's also an additional requirement to import reactive power. In terms of transient stability, lack of reactive power support and reduced system inertia lead to potential rotor angle stability problems.

Existing flexible AC transmission system (FACTS) technologies such as static VAR compensators (SVCs) and static synchronous compensators (STATCOMs) deployed in most conventional utility grids can be used to counter the negative effect of voltage instability caused by grid-integrated distributed generators (DGs) such as large-scale PV systems. This has been demonstrated in a study on the impact of large-scale PV penetrations and dynamic VAr placements on voltage stability of the sub-transmission system [43]. Based on the suitable placement of dynamic VAr devices such as SVCs and STATCOMs, it has been found that:

i. With regard to improved system loading, the placement of STATCOM based on short term-VAr as a remedial measure to overcome low voltage ride through (LVRT) problem is found to be more effective than the placement of STATCOM at the weakest bus and at PV generator buses.
ii. In comparison to SVCs, STATCOM is better in improving static voltage stability margin of the system with large-scale PVs.
iii. In terms of the improved voltage stability margin, the placement of SVCs at PV generator buses is a better option compared to placement at weakest bus or placement based on short term dynamic VAr support.

2.6.4 Impacts on the PV inverter design and specifications

Grid connected large-scale PV systems face new requirements in terms of inverter design and specifications [44]. These range from low voltage ride-through (LVRT) and frequency ride through provisions, the requirements for mandatory reactive power generation and real power controls, 0.95 (leading/lagging) power factor, voltage support, and real power ramping and curtailment capability. Other requirements are site level controls at the PCC

(circuit breakers with related protective relaying, measuring, monitoring and metering equipment), communication (SCADA), transfer trip schemes and effective grounding.
LVRT which is linked to voltage and frequency deviations is essential for reliability requirements that discourage the loss of more than one power system element as a result of a single system disturbance. Inverters of large-scale PV systems are therefore required to remain connected for limited durations during large disturbances resulting from adjacent faults. However, internal faults should result in an immediate disconnection of the PV inverter. This possible through anti-islanding mechanism which ensures that the inverter trips immediately for all internal faults to avoid continuous PV power output when the feeder breaker has operated. Failure for anti-islanding to function as desired may necessitate some form of transfer tripping to ensure that the inverter doesn't continue to operate in an islanded mode.

Reactive power generation and absorption requirements are vital for dynamic voltage support functions. This is to help prevent voltage fluctuations as a result of variable power output from PV systems.

Grid connected large-scale PV systems are also required to be in possession of a number of grid support functions [45]. These include reactive power output for the "mitigation of rapid and frequent voltage variations caused by PV power output variations", voltage regulation, disturbance ride-through functions, anti-islanding, alternate measures to prevent islanding such as direct transfer tripping, coordinated voltage regulation by PV the system and feeder etc. In terms of ride-through capability, PV systems are required to possess both high voltage ride through (HVRT) and low voltage ride through (LVRT) capability. In the case of a LVRT, a disturbance sensitivity where the voltage at the PCC is as low as zero volts (e.g. bolted three-phase fault) for duration of up to 200ms is recommended.

In a study involving a 2.3 MW/2.5 MVA, 1500 Vdc PV inverter, the role of inverter rating and inverter type topology with regard to large-scale PV was investigated [46]. In terms of voltage rating, a 1500 Vdc inverter is found be superior to the 1000 Vdc inverter "with regard to lower losses due to the reduction in current, wider MPPT range and higher power density".

With regard to the topology, in comparison to the NPC (double-clamped three-level) inverter, the NPS (T-type three-level) inverter offers the benefits of lower conduction losses that leads to improved efficiency.

The inverters in particular, also provide much needed grid support functions based on stability and reliability functions such as voltage control and regulation, voltage and frequency fault ride-through, reactive and real power control, and frequency response criteria [37]. This is demonstrated in a study of a grid-friendly PV plant composed of numerous smaller PV generators connected to the electrical grid via inverters. The grid-friendly PV plant is made up of a central plant controller and other related interface components such as plant network, point of interconnection measurements, supervisory control and data acquisition human interface machine (SCADA HMI) or substation remote terminal unit (RTU), data acquisition system (DAS) and programmable logic controllers. Through POI measurements, voltage, current and frequency data from individual inverters is made available to the plant controller. At the same time, inverter commands are also transmitted through the network to the inverters. Through these interactions, grid support functions such as automatic voltage regulation, active power curtailment, reactive power injections, and frequency droop control could all be performed.

Another good example of PV inverter involvement in large-scale PV grid-integration solutions is the application of the reactive power injection (RPI) and/or reactive power injection enhanced with active power curtailment (RPI-APC) techniques to solve overvoltage problems in distribution networks integrated with large-scale PV systems [38]. This research work involves the implementation of the RPI algorithm in combination with the RPI-APC algorithm to achieve local voltage regulation. The findings are that the inverter reactive power capability, and by extension, its ability to maintain voltage at the POI within set limits, is enhanced when the RPI technique is used in conjunction with the RPI-APC technique.

In other literature, sources of voltage fluctuations and the related mitigating measures are presented [47]. The main cause of voltage fluctuation is the rapid variation of solar irradiance incident on the solar arrays. Furthermore, this would in turn lead to sudden reductions in generation as a result of undesirable tripping of PV and other generation due to the operation of under voltage relays. As a solution to the above-mentioned voltage fluctuations problem, two voltage control techniques, namely, unity power factor control and automatic voltage control, are considered [48, 49]. However, it's been noted that unity power factor control method is only effective in kW-size generators and not MW-size generators [48].

2.7 THE IMPACTS OF LARGE-SCALE PV SYSTEMS ON THE GRID CODE AND RELATED SOLUTIONS

The integration of large-scale PV to the grid, like all other variable renewable energy (VRE) sources, presents a number of power system operational challenges [50]. Grid codes are therefore considered important for the successful integration of large-scale PV systems in into the grid [50]. In an effort to make this a reality, grid codes are being developed and adapted to include rules governing the adoption of technologies, operational practices and regulations that enable effective integration of VRE sources in the grid.

As shown in Table 2.7, the key aspects of VRE grid connection codes development are: the size of the power system; the interconnection level; voltage levels; distribution and flexibility of load and generation; characteristics of conventional generators; energy policy; energy planning; market size for VRE and operational practices.

Table 2.7: Aspects of grid connection code development **[50]**.

Size of the Power System	**Interconnection level**	**Voltage Levels**
Capacity, generation, consumption and assets.	Strongly connected, weakly interconnected, synchronously independent with or without non-synchronous connections to other power systems, agreements with other countries on services interchange.	Requirements in an extra high voltage transmission system may strongly differ from those in the low voltage distribution system.
Distribution and Flexibility of Load and Generation	**Characteristics of Conventional Generators**	**Energy Policy**
Geographical, point of connection.	Fuel, technology, Operational flexibility.	Incentives for VRE support for grid code compliance.
Energy Planning	**Market size of VRE**	**Operational Practices**
Current and expected future VRE share.	Current and prospect market size may influence the need and enable the use of different technologies and operational practices.	How the system is operated at the moment and operation for the future.

2.7.1 Technical requirements for VRE sources grid code compliance

As it is the case with conventional generation sources, VRE sources are also required to comply with a number of grid code requirements. These include compliance with the set voltage and frequency operation ranges, power quality requirements, reactive and active power control functionalities, fault ride through capabilities, and so on. A brief discussion of VRE grid code requirements is presented in the following sub-subsections [50].

2.7.1.1 Voltage and frequency operation ranges

Electric utilities are required to supply customers with alternating current (AC) voltage of standardised magnitude and frequency. In the case of a disturbance, all generators are required to remain connected within the specified tolerance bands around the nominal values. Typical tolerance bands are ± 10% for voltage and ± 2% for frequency.

Typical requirements are that, outside the given tolerances, the generators must remain connected for a minimum period or disconnect immediately depending on the magnitude of disturbance.

2.7.1.2 Power quality

Power quality is concerned with current and voltage deviations from nominal values with regard to waveform distortions and short-term fluctuations. All generators have an impact on power quality. As part of power quality requirements, there are set limits for emitting voltage disturbances and current for each electrical apparatus connected to the grid. All generators are required to comply with such limits to ensure suitable voltage quality for all consumers.

2.7.1.3 Reactive power capability for voltage control

Typically, power system voltage magnitudes are kept within the nominal value ranges by reactive power in-feed from generators. Conventional power generators possess a wide range of reactive power capability required for this purpose. On the other hand, VRE generators are not necessarily equipped with similar reactive power capability unless explicitly considered during design.

Wide reactive power capability and controllability of VRE generators enable increased penetration of VRE sources into the grid. This is because reactive power can assist in the reduction of voltage rise due to active power injection of DGs. In turn, this permits increased grid-integration of VRE generation without the need for simultaneous costly investment in distribution network reinforcement. In transmission systems, wide reactive power capability assist in averting the need for compulsory operation of conventional generators for the purpose of voltage support. VRE generators such as large-scale PV systems at transmission voltage level are particularly required to provide reactive power during faults in order to support the voltage.

2.7.1.4 Frequency support

Frequency is a universal parameter used in the AC power system. Typical frequency nominal values are 50 Hz and 60 Hz for the 50 Hz and 60 Hz frequency system, respectively. The frequency is kept in narrow ranges of $\pm 2\%$ of the nominal value through the maintenance of load and generation balance at the transmission level. The typical causes of frequency fluctuations are sudden changes in the power system as a result of load loss or power plant disconnection due to a fault, or rapid changes in the power output of VRE generators. The variation in power output of VRE leads to additional spinning reserve requirements to be able to mitigate frequency changes and maintain the load-generation balance.

As part of VRE grid-integration requirements:

- Although VRE generators are not well suited for providing frequency control, they do possess support measures for frequency disturbances.
- VRE generators are required to gradually reduce their power output while remaining connected to the grid during over-frequency fault conditions. Disconnection is only allowed at specified threshold with sufficient margin to the nominal frequency.
- VRE generators are also required to have reduced power output operation mode capability. This is to enable provision of reserve power during under-frequency fault conditions.

Equipping VRE generators with capabilities to meet requirements for power balancing during disturbances minimize the required capacity of conventional generation that must be retained for frequency control.

2.7.1.5 Fault behaviour

Typically, power system faults are events such as line interruptions, short circuits on transformers, cables and overhead lines. The typical high magnitudes of fault currents, which also assist with reliable fault detection, are maintained by power in-feed from generators.

Conventional power generators are capable of injecting the supporting current required for this purpose. VRE generators above a certain minimum size or voltage level are also required to have limited capability of injecting supporting current for fault detection.

Given the increased penetration of large-scale VRE generation into the grid, VRE generators are required to remain connected for brief durations during grid faults. This is to prevent power imbalance. In addition, it has been noted that there are technological limitations in getting VRE generators to provide above nominal currents required for fault detection. As a result, the minimum VRE generator requirements stipulates current contribution limited to nominal current to help support the systems needs in terms of fault detection.

2.7.1.6 Active power gradient limitations

Power injection ramps as a result of fluctuating primary energy are prevalent in power systems integrated with significant amounts of VRE generation. Other causes of ramps include VRE plant start-ups and shutdowns in normal operation and during or after fault incidents, and activation or deactivation of reduced output operation modes. Consequently, these events result in ramping requirements which in turn lead to spinning reserve requirements vital for the prevention of power imbalance. The solution lies in imposing ramping limits on VRE generation thereby reducing the required ramping reserves.

2.7.1.7 Simulation model

It is standard requirement that simulation models of power plants are handed in for analysis and prediction of their behaviour before plant owners are allowed to connect to the grid. The models need to satisfy set requirements and accuracy.

2.7.1.8 Active power management

Power system operation entails generation dispatch actions geared towards the attainment of load and generation balance. This is performed while considering grid stability requirements and transmission capacity limits. For effective operation of power systems containing significant amount of VRE generation, VRE generators are required to provide active power management capabilities. These involve active power reduction during congestion or over-frequency events.

2.7.1.9 Communication

Power system operation requires communication for measurements and sending of commands to various electrical apparatus. With the increased share of VRE generation in the power system, communication interfaces are required for reactive power control and active power management functionalities.

2.7.1.10 Protection

Reliable power system operation depends on strategies to mitigate the impacts of faults and other system disturbances. Besides the requirement for VRE generators to remain connected for short durations during grid faults, another requirement is concerned with the how the protection at the point of common coupling is designed as well as the application of protection settings.

2.7.1.11 Load-following Requirements

VRE generators lack load-following capability and therefore depend on flexible conventional generators to meet this specific requirement. Conventional generators are therefore required to compensate for the difference between the variable renewable power output and consumer demand fast enough to prevent frequency and voltage instability. The variability in VRE generator output can also lead to undesirable sudden changes in the power system’s voltage which can pose a negative effect on some consumers.

2.8 THE ECONOMIC IMPACT OF LARGE-SCALE PV SYSTEMS

The theme of this section is the economic impact of large-scale PV systems. A number of studies dating back to the late 1980s and early 1990s covered the aspect of economic impact of large-scale PV systems on utility costs [51–53]. The research effort in [51] presents a dynamic economic dispatch procedure, which is an optimum commitment technique incorporating hydro, pumped storage and large fossil units for the purpose of maximizing the utilization of customer-owned generation such as PV, while keeping the overall cost down. Parameters that have an impact on the PV energy value, such as PV power profile, variations, seasonal loads, as well as on the optimal schedule generated by the unit commitment algorithm, were also investigated. The main points observed were: PV penetration level beyond 14.45% results in economic dispatch failure; the production cost savings were high for high solar (12%) than for intermittent solar days (7.95%); and the optimal schedule path for each PV penetration level depends on the extent of fluctuations as well on the PV system capacity.

On a similar economic note, other research effort based on simulations attempted to determine the economic impact of the variable energy cost of incorporating large-scale PV systems into the generation mix of various utilities [52]. It is observed that PV penetration has varying impacts on the utility operational cost based on different load and solar days. In contrast to conventional generation plants, it is noted that solar PV systems lacked control needed for varying load conditions. These are the AGC and spinning mechanism that could be used to either reduce the output power when the system load demand has decreased or ramp up the output power to keep up with increasing system demand.

In addition, an all-encompassing five-stage model (yearly generation planning; weekly hydro-thermal coordination; 24-hour unit commitment; production cost, capacity displacement, energy value, and; dispatch emissions post-processor) was also developed to include all issues related to PV such as generation mix, output fluctuations, system load and dispatching practices [53]. It was found that higher hydro availability as well as higher ramping or fast ramping rates enable fast absorption of PV fluctuations, thereby improving PV penetration levels.

A similar model was also designed to determine the degree of penetration of large-scale PV system into the electric utility generation mix [54]. This model consists of three modules, namely, long-term scheduling, short-term scheduling and economic analysis. The functions carried out by the model are hydroelectric dispatch; AGC; tie-line interchange; pumped-storage hydro dispatching, and; spinning reserve constrained economic dispatch. A number of factors were found to have an influence on the economic and operational value of large-scale PV systems. These are hydro availability, generation mix, maintenance schedule, ramping rates, fuel costs, spinning reserve requirements, PV power fluctuations, and geographical diversification. Other parameters that can impact PV penetration level are prevailing weather conditions, daily and seasonal load and solar resource variations, and PV generation control options.

2.9 AIDING LARGE-SCALE PV SYSTEMS GRID-INTEGRATION THROUGH ECONOMIC DISPATCH

Economic dispatch is "the process of allocating generation levels to the generating units in the mix, so that the system load may be supplied entirely and most economically [55]". In the same literature, four categories of economic dispatch have been identified:

i. optimal power flow,
ii. economic dispatch in relation to automatic generation control (AGC),
iii. dynamic dispatch, and
iv. economic dispatch with non-conventional generation sources.

Economic dispatch with non-conventional generation sources refers to economic dispatch activities involving sources such as PV, solar thermal, wind, geothermal, battery, etc. The main focus of this research is the use of economic dispatch to deal with power system operational challenges posed by non-conventional generation sources, particularly, large-scale PV systems.

Similar to other non-conventional generation sources, the intermittent nature of PV output power results in additional operational problems such as load-following, spinning reserve requirements, load frequency excursions, system stability and so on. These specific operational problems cannot be handled effectively by conventional AGC [52, 56, 57].

As part of the mitigation measures aimed at dealing with some of the above-mentioned operational problems, a dynamic rule-based algorithm was developed to aid a utility dispatcher choose optimal unit commitment and dispatch when PV generation is operating [57]. This is achieved through the forecast of PV generation at the beginning of each dispatch interval followed by a series of rule-based PV, thermal, combustion turbines, pumped-storage, hydro generation or imports through inter-connected tie-lines dispatch actions aimed at achieving the generation-load balance condition.

The outlined actions involve monitoring the initial response of committable sources of generation, such as thermal, in dealing with small to medium PV generation fluctuations. For instance, once the response limits of thermal generators is reached, non-committable sources of generation such as combustion turbines, pumped-storage, hydro or imports through inter-connected tie-lines are called into action to correct the mismatches in the generation and load demand.

In addition, in order to deal with increased share of renewables in isolated and weak interconnected power systems, a software control system has also been proposed that conducts both load and generation forecasts [58]. This control system, formally referred to as MORE CARE, is also aimed at aiding the operators in carrying successful generation dispatch. It also consists of the usual modules associated with other dispatch techniques, namely unit commitment and economic dispatch. However, what makes the MORE CARE control system unique is the online security system module that is responsible for issuing preventive and corrective guidance in case of predicted disturbances. The disturbances referred to here are the frequency excursions as well as under voltage and overvoltage conditions that can lead to generator trips as a result of relay operations.

Furthermore, from recent literature, with higher penetration of PV generation resulting in the displacement of some of the conventional generators, another consideration is the displacement or rescheduling of the remaining conventional generators which becomes one of the critical factors of power system operation. This was demonstrated in a study of a large system with a mixed combination of various generation sources that is part of the U.S. Western Electricity Coordinating Council (WECC) where the concept for an optimal

dispatch ratio (ODR) was developed [59]. The ODR is the optimal dispatch or displacement ratio of the conventional generators that lead to reliable system operation.
This project first demonstrated the need for an ODR, followed by the evaluation of the displace/dispatch ratio (DR) of the conventional generators while more PV generation is being added to the system. The DR is defined as the ratio of power generation [megawatts (MW)] removed from the generation pool versus the generation (MW) that is simply re-dispatched [59].

It is concluded that for a 40% PV penetration level, the ODR that yields the optimal performance is 75%. This means that for every 100 MW of PV addition to the system, 25 MW of generation is compensated by removing conventional units and 75 MW of generation is compensated re-dispatching in-service conventional units [59].

Most of the economic dispatch techniques as presented above are concerned with finding an optimal penetration level of a specific intermittent renewable energy resource (RES) such as PV in relation to conventional energy resources. However, a study conducted in Denmark attempted to ascertain the optimal combination of different intermittent RES (PV, wind and wave power) productions units in the electricity supply mix [60]. In the case of large-scale integration of intermittent RES, the optimal combination investigations also take into consideration other measures such as flexible systems. The overall finding points to the need to have flexible supply and demand systems in order to effectively deal with inherent challenges of fluctuating RESs.

2.10 LARGE-SCALE PV SYSTEMS GRID-INTEGRATION THROUGH GENERATION DISPATCH

This theme of literature study explores various options for aiding the integration of large-scale PV systems into the grid through generation dispatch. These include use of storage facilities such as battery systems and pumped-storage hydro plants; controllable direct current (DC) converters and more flexible conventional generation with faster ramping rates and lower minimum loading levels; better reactive power compensation and a Flexible

Alternating Current Transmission System (FACTS); as well as better weather forecasting to predict the VRE generation levels [50], amongst, others. The emphasis is on the key power system stability parameters such as voltage and frequency and the consequent operational requirements in terms of power system protection.

2.10.1 Flexible production power plants

Conventional power plants such as hydro and thermal that normally play the role of base-load, intermediate or peak-load generation sources are now subjected to new requirements for the purpose of accommodating grid-integrated fluctuating RES such as PV [61, 62]. The new requirements are in the form of the need for these power plants to possess the ability to rapidly adjust their outputs in accordance with the supply and demand variations.

Spinning reserves, are a form of extra generating reserve that most hydro and thermal power plants possess when they are intentionally run at less than full capacity [63]. This is the energy reserve that can be used to fill the shortfall created by any sudden drop in PV generation output.

Flexibility requirements are also extended to the RESs whereby PV or wind power plants are required to possess the ability to curtail their power output whenever supply exceeds demand.

Effective control of conventional power plants can be ensured with the use of remote communication systems that would enable commands to be sent from the control centre.

2.10.2 Dispatch strategy and spinning reserve

Numerous generation dispatch techniques are discussed in the literature. For the purpose of aiding increased PV penetration in the power system, the variable nature of generation sources is compensated by the following generation dispatch techniques [64], namely, AGC, day-ahead generation scheduling settlement, and adjustment of several generation sources.

Dispatch strategy is the aspect of control strategy that pertains to the adjustment of output power from other generation units to maintain a generation and load balance [65]. Meanwhile, economic dispatch entails control strategies geared towards the short-term determination of the optimal output of a number of generation units, to meet the system load, at the lowest possible cost, subject to transmission and operational constraints [55, 66].

The spinning reserve is the kind of operating reserve that refers to the extra generating capacity available by increasing the power output of generators that are already connected to the power system. In contrast, non-spinning reserve refers to the extra generating capacity that is not connected to the power system but can be brought online within a short period of time.

As a part of the renewable systems interconnection (RSI) study launched by the U.S. Department of Energy, a detailed reliability and performance analysis was carried out on the transmission systems to determine the impact of high PV penetration [67]. The aim is to address renewable energy grid-integration issues in general, as well as PV systems integration in particular. It was found that for high PV penetration, it is required to maintain strict performance requirement for PV units in order to maintain similar reliability and performance. In addition, the dispatch and conventional unit commitment criterion is found to have a major influence on the system behaviour.

The impacts of large-scale PV system on the power system operations results in numerous variations on various parameters. These range from variations in PV generation power output in response to variation in irradiance and other varying environmental factors such as wind speed and temperature [68]. In response to the aforementioned issues, a novel probabilistic power flow (PPF) algorithm considering the conventional generation dispatch which can balance the variations of PV generation resources is proposed. This in turn leads to voltage fluctuations. In the end, there are also variations in frequency and rotor angle as a result of conventional generation response through corrective techniques such as generation dispatch and spinning reserve [29, 68, 69].

2.10.3 Demand dispatch

Besides the load following generation plants that help fulfill load following requirements, demand dispatch is also anticipated to play a complementary role in dealing with increased penetration of intermittent renewable energy resources such as large-scale PV systems [70]. This is a method in which generator outputs are adjusted and some loads are switched on or off to achieve generation – load balance as demand for electricity fluctuates. Widespread modern communication infrastructure such as internet is prerequisite to a successful demand dispatch technique.

Another approach for aiding the integration of large-scale PV into the grid is the complementary demand-supply matching [71, 72]. The purpose of demand-supply matching is to make sure that the timing of electricity generation corresponds to consumer electricity demand [71]. The precision of matching is dependent upon realistic supply and demand profiles, which are obtained through measurement, load profiling and load simulation [71].

In the case of PV, the effectiveness of demand-supply matching can also be enhanced with the use of storage systems such as batteries and back-up generation systems such as diesel generators [71]. Batteries can be used to store excess energy produced during peak periods when consumption is low and back-up generation systems can be dispatched during periods of low generation and high demand.

As part of the renewable energy integration requirements, probabilistic load forecasting (PLF) plays an important role for the planning and operation of power systems [73]. PLF is a branch of load forecasting based on two perspectives. The first perspective is the application side where PLF serve as inputs to decision making process. The second perspective is on the technical and development side where PLF is used in the search of improved forecast quality.

2.10.4 Complementary hydro-PV operation

The complementary hydro-PV power plant is a type of hybrid energy source consisting of hydro-power and PV power sources used together in a complementary operation mode. Longyangxia hydro-PV plant consisting of 850 MW PV arrays and 1280 MW hydropower units situated in north-western China is one of the popular case studies in this regard [74, 75]. The key aim is the attainment of improved PV power quality as well as aiding the integration of large-scale PV in the power system [75]. The improvement in PV power quality is accomplished through tracking and compensation of random and intermittent PV power output using promptly-adjustable hydropower units.

The other benefits lies in the ability to offset costly storage and spinning reserve requirements [75]. There are also economic spinoffs based on local harnessing and deployment of complementary hydro-PV schemes in regions that are plentifully blessed with both hydro and solar energy.

2.10.5 Averaging effect / diversity factor

Other possible solutions to the challenges of sudden changes in PV output as a result of abrupt clouds cover lies in the averaging effect and wide-area geographic diversity factor concepts. In terms of shading effect caused by moving clouds, large-scale PV systems in transmission and sub-transmission are not severely affected as opposed to PV systems at distribution level. This is because large-scale PV systems are usually installed in a vast area [76], and the resulting drop in PV output is minimized by the averaging effect. On the other hand, the output of a PV module in distribution level systems can severely be reduced to below 50%. This is of course in contrast to PV arrays installed across a vast area where the averaging effect minimizes the impact of this phenomenon on the PV generation output [5].

Geographic dispersion of PV facilities is another way of preventing PV generation variability as a result of cloud cover. A study funded by the U.S. Department of Energy investigated the role of wide-area geographic diversity factor in relation to cloud-induced short-term variability of solar power output [77]. It is noted that taking into account the potential role of diversity factor can greatly minimize the impact of short-term variability on the combined PV power output. In addition, the geographic diversity factor also holds the potential to reduce the resources and costs required to accommodate and manage the variability, respectively. The aforementioned additional resources and costs are directly associated with the system operator's reliance on the following resources and methods to maintain generation and load demand balance:

i. requirements to hold dispatchable resources in reserve in the form of spinning and non-spinning reserves,
ii. economic dispatch or load-following requirements, and
iii. unit commitment requirements.

This specific study also questions the conclusions of earlier studies that were mostly based on scaled PV plant data. One popular conclusion is that "the economic value of PV is significantly reduced at increasing levels of PV penetration due to the additional need for reserves". The other conclusion is that "the high variability of PV and the limited ramp rates of conventional generation limit the feasible penetration of PV". It was concluded that "the degree to which PV increases the demand for resources to balance the net load therefore depends on the amount of smoothing offered by geographic diversity". A similar study aimed at determining what the actual barriers to the adoption of intermittent renewable energy resources attained a similar conclusion [78].

2.11 CHAPTER SUMMARY

In this chapter an overview of the body of science covering the research on large-scale photovoltaic (PV) was provided. These ranges from the concepts of sustainable energy development to the current state of the power supply industry. An in-depth discussion on grid-integrated large-scale PV systems and their inherent intermittency characteristic was also provided. Grid-integrated large-scale PV systems have an impact on various power systems aspects such as conventional generation systems, existing power system protection, grid codes, generation dispatch and spinning reserve requirements and economic dispatch.

The enabling flexibility options to deal with operational challenges caused by the variable nature of RES such as large-scale PV systems were also outlined.

CHAPTER 3 METHODS AND PROCEDURES FOR THE INVESTIGATION OF GENERATION DISPATCH WITH LARGE-SCALE PV SYSTEMS

3.1 CHAPTER OBJECTIVES

This chapter presents the proposed approach concerning the generation dispatch with large-scale PV systems. As depicted in Figure 3.1, these entail generation and economic dispatch with non-conventional generation sources, as well as economic dispatch in relation to AGC. The technical and economic impacts of large-scale PV systems on the sub-transmission and transmission grid to the applicable solutions thereof are also assessed. The application of generation and economic dispatch as a solution to the impacts of grid-integrated large-scale PV systems is evaluated. Finally, through the observation of the transmission system dynamics, the overall transmission performance is observed.

In Section 3.2 a brief summary of large-scale PV impacts and associated requirements was presented. These entail discussions on the impacts of large-scale PV systems and the aspect of generation dispatch as a possible solution. It was found that unit commitment and voltage regulation aspects were considered more relevant for simulations.

In Section 3.3 the theme on the formulation of the generation dispatch research problem was introduced. The aspects of formulating the generation dispatch problem considering large-scale PV plants were presented.

In Section 3.4 the theme on the development of the generation dispatch model was introduced. The aspects of modelling and performance evaluation of generation dispatch with large-scale PV plants were presented.

In Section 3.5 the methods and procedures for determining the impacts of grid-connected large-scale PV systems on the power system grid were outlined. Related solutions in terms of generation dispatch and spinning reserve that take into account the impacts of large-scale PV systems while also considering other aspects such as transmission line constraints are presented.

In Section 3.6 the benchmark power systems and the related data used in the simulations of generation dispatch with large-scale PV systems were presented. The test system was modified to introduce renewable energy generation in the form of large-scale PV plants.

In Section 3.7 the methods and procedures used in the simulations of generation dispatch with large-scale PV systems on typical utility benchmark networks such as the IEEE-14 are presented.

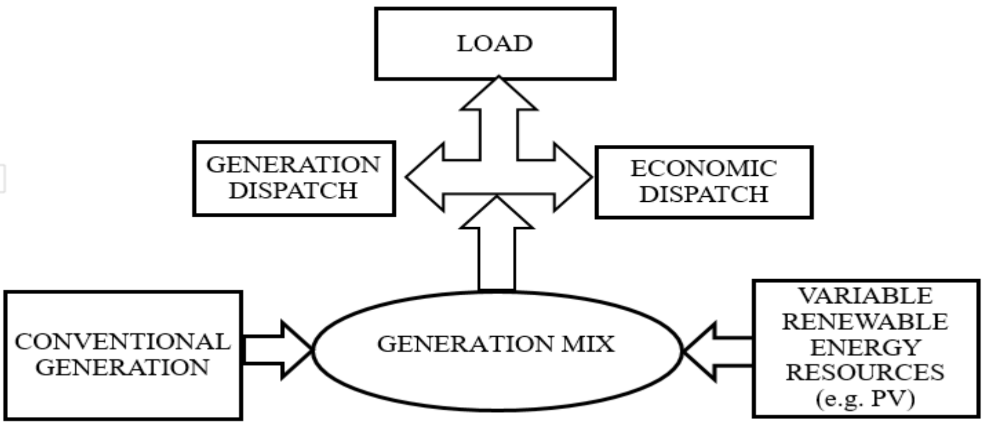

Figure 3.1: The proposed generation dispatch with large-scale PV systems.

3.2 APPROACH TO THE DEVELOPMENT OF A GENERATION DISPATCH WITH LARGE LARGE-SCALE PV SYSTEMS

The choice of methods and procedures for this research is informed by what is considered to be the major impacts and observations of increased PV penetration on modern power system grid. As per the research questions and objectives, this will entail determining the economic impacts of incorporating large-scale PV in the generation mix consisting of conventional electric utility; determining the roles of generation dispatch strategy and the related economic dispatch methods in solving challenges posed by grid-connected large-scale PV systems and working out an optimal economic generation dispatch considering cost and operational constraints. Another consideration is to focus on the least used approaches in order to the address the prevailing research gap. A brief summary of large-scale PV impacts and associated requirements is presented in the following sub-subsections [79].

3.2.1 Main observations associated with system aspects with increased penetration of PV

As stated in various literatures, the impacts of increased penetration of large-scale PV systems leads to numerous requirements in terms of unit commitment strategy, the remaining conventional generation, system reliability and stability. The impacts and the associated requirements are [80–84]:

A. Unit commitment strategy has a significant impact on system performance at high PV penetration levels:
   i) System inertia and frequency regulation capabilities are reduced as conventional generation is de-commissioned.
   ii) Thermal units could operate at less efficient load levels
   iii) Reactive power support in the transmission system is reduced as conventional generation is de-commissioned.
   iv) Dynamic stability of the system can be affected.

B. Considerable dispatch flexibility of conventional generation is required to accommodate high-penetration PV.

C. With substantial PV penetration that is compliant with IEEE 1547, there is a considerable reduction in system reliability caused by extensive loss of PV generation during transmission faults.

D. PV generation could provide primary frequency control for frequency excursions above nominal without significantly reducing the energy production.

E. Anti-islanding schemes of PV can affect the oscillatory stability of the bulk power system.

3.2.2 The main observations on PV potential performance

In terms of previous studies, the following are some of the main observations on PV potential performance [85–88]:

A. The low-voltage ride-through capability of PV would reduce the negative impact on system reliability of high-penetration PV.

B. Even if the PV stays connected during and after a system fault, voltage sags are prone to cause prolonged PV power output reductions.

3.2.3 Other aspects of PV integration considered relevant for simulations

Most of the simulations work [89–91] focused on system performance after electrical faults and power imbalances caused by generation trips. The following are other simulations considered relevant:

A. The commitment of fewer regulating units to accommodate PV generation increases the requirements of load-following reserve in the system and for individual units [92–94]. Additionally, the variability of PV generation may also increase load-following requirements.

B. The implementation of voltage control [95–99] on individual PV systems is challenging. There is potential for undesirable interactions between PV systems connected to the same feeder and phase and between PV systems and other voltage-regulating devices.

3.3 FORMULATION OF THE GENERATION DISPATCH WITH LARGE-SCALE PV SYSTEMS PROPLEM

The application of generation dispatch techniques in dealing with the impacts of large-scale PV systems on sub-transmission and transmission power system networks has a two-fold objective:

1) To maintain a generation and load balance despite the intermittent nature of large-scale PV systems based on economic dispatch as well as spinning and non-spinning reserves techniques.
2) To enable the power systems to operate efficiently while taking into account prevailing transmission and operational constraints. The list of well-known operational challenges associated with large-scale PV systems include load-following and spinning reserve requirements, load frequency excursions and system stability, amongst others.

The problem formulation follows guidelines presented in various existing literature [100, 101].

3.3.1 The economic dispatch considering system constraints

The generation dispatch problem formulation presented in this subsection is based on approaches that did not take into account the impact of large-scale PV in transmission systems [100].

3.3.1.1 Economic dispatch based on cost constraints only

The economic dispatch of the electric power system is formulated as an optimization problem expressed using the equation presented in (3.1):

$$z_1 = \min \quad c(x_0) \tag{3.1}$$

The optimization problem is subject to system operating constraints such as power flow and generator operating limits which are expressed as a set in the equation presented in (3.2):

$$A_0(x_0) \geq b_0 \tag{3.2}$$

where the variables x_0 represents the operating decisions such as the generation level in each bus and b_0 represents the system operating constraints.

3.3.1.2 Economic dispatch considering both cost and technical constraints

Once system disturbances are taken into account, the operating point x_0 should be feasible for all configurations. The dispatch problem expressed in equation (3.1) therefore becomes:

$$z_2 = \min \quad c(x_0) \tag{3.3}$$

subject to system operating constraints which are expressed as a set in the equation presented in (3.4):

$$\left.\begin{array}{l} A_0(x_0) \geq b_0 \\ A_i(x_0) \geq b_i \quad i = 1,2,\ldots,M \end{array}\right\} \tag{3.4}$$

where M is a list of possible contingencies / disturbances such as line and / or generator outages. The set of system operating constraints for the ith post-disturbance configuration is represented by $A_i(x_i) \geq b_i$ for all $i = 1,2,\ldots,M$.

3.3.2 The proposed generation dispatch problem formulation

The proposed generation dispatch problem is based on approaches that consider the impact of large-scale PV systems in electrical network [101]. Besides cost, many technical constraints such as real power, reactive power and voltage limits are considered. Key parameters:

- The scheduling period considered is 1 hour (60 minutes),
- The scheduling period is divided into N_{int} of 5 to 15 minutes scheduling intervals ($T = 1,2,\ldots,N_{\text{int}}$), and
- N_{int} is subdivided into N_{sub} of 1 minute sub-intervals ($t = 1,2,\ldots,N_{sub}$).

The proposed generation dispatch of the electric power system containing intermittent renewable energy sources is formulated as an optimization problem aimed at minimizing cost in each scheduling interval $'T'$ expressed using the equation presented in (3.5):

$$\min \sum_{t=1}^{N_{sub}} \sum_{i=1}^{N_G} C_{Gi}(P_{Gi,t}) \tag{3.5}$$

The optimization problem is subject to system operating constraints such as power flow and generator operating limits which are presented in the following equations:

3.3.2.1 Generation limits

The generation limits in each interval t are expressed as follows:

$$\min[P_{Gi}^{\min}, P_{Gi,t-1} - R_{Gi,t}^{down}] \leq P_{Gi,t} \leq \min[P_{Gi}^{\max}, P_{Gi,t-1} + R_{Gi,t}^{up}] \tag{3.6}$$

Where $P_{Gi}^{\min}$ and $P_{Gi}^{\max}$ are the minimum and maximum limits of active power at each i^{th} bus, respectively.

3.3.2.2 Constraints on voltage magnitude

The constraints on voltage magnitudes are expressed as:

$$V_{Gi}^{\min} \leq V_{Gi,t} \leq V_{Gi}^{\max} \tag{3.7}$$

where $V_{Gi}^{\min}$ and $V_{Gi}^{\max}$ are the voltage magnitude minimum and maximum limits at each i^{th} bus, respectively, and $V_{Gi,t}$ is the voltage magnitude at subinterval t.

3.3.2.3 Constraints on reactive power

The reactive power generation $Q_{Gi,t}$ in sub-interval t is governed by the following expression:

$$Q_{Gi}^{\min} \leq Q_{Gi,t} \leq Q_{Gi}^{\max} \tag{3.8}$$

where $Q_{Gi}^{\min}$ and $Q_{Gi}^{\max}$ are the minimum and maximum reactive power magnitude limits at each i^{th} bus, respectively.

3.3.2.4 Line flow constraints

The active power flow P_{ij}^{t} through each line is limited by:

$$-P_{ij}^{\max} \leq P_{ij}^{t} \leq P_{ij}^{\max} \tag{3.9}$$

where $P_{ij}^{\max}$ is the maximum power limit of each line between buses i and j.

3.3.2.5 Fluctuations in generation in each interval

The amount of generation changes required in each interval $'t'$ is expressed as:

$$\Delta P_{Gi,t} = PF_i[\Delta P_{Solar} + \Delta P_{Load}] \tag{3.10}$$

where $\Delta P_{Gi,t}$, ΔP_{Solar} and ΔP_{Load} are the variations in overall generation, solar generation and load demand, respectively, and PF_i is the participation factor generation units.

3.4 PROCEDURES ON THE DEVELOPMENT OF A GENERATION DISPATCH MODEL

Among the recommended future research areas [79], “the development of a unit commitment and dispatch strategy for conventional units in systems with high-penetration PV”, is considered the most responsive to the objectives of this research effort. Borrowing on other recommended research areas such as [26, 102–106] also add great value:

- The improvement of the understanding and provision of the guidelines to quantify the performance and economic impact of PV penetration on regulation and load-following requirements, and
- The development of methodologies for estimating the required flexibility of the generation assets to meet regulation and load-following requirements; in particular, the requirements for generating units to ramp production up or down and to stop and start,
- Provision of guidelines on quantifying the value in terms of performance and the economic benefits of potentially mitigating measures of PV power variability (modifications of control zone constraints, flexible conventional generation, centralized and local energy storage, forecast, etc.);

A typical utility network such as the IEEE 14-bus system is utilized. A few large-scale PV plant models are added at strategic locations. The entire generation mix is considered. Models of other conventional generation plants as well as those of storage systems are also added.

3.4.1 Modelling generation dispatch with large-scale grid-connected PV systems with conventional generation sources

In line with the literature presented in the following sections, a generation dispatch model that takes into account the impacts of large-scale PV systems is then presented. As described in [68], the nonlinear model of transmission system is expressed using nonlinear equations presented in (3.11):

$$\begin{aligned} y &= g(x) \\ z &= h(x) \end{aligned} \tag{3.11}$$

where y is the vector of active and reactive power injections, x is the vector of bus voltage magnitudes and phases, z is the vector of line flow active and reactive powers, g is the power injection function and h is the line flow function.

The linear model is obtained by linearizing (3.11) around the operating point, and is expressed in (3.12), as follows:

$$\begin{aligned} \Delta x &= G^{-1}\Delta y = K\Delta y \\ \Delta z &= H\Delta x = HK\Delta y = L\Delta y \end{aligned} \tag{3.12}$$

where:

- G and H are the Jacobian matrices of g and h at the operating point, respectively, and,
- K and L are the sensitivity matrices of Δx and Δz, respectively.

The first part of the linear model of power system representing the linear model of the power injection in (3.12) is further expanded as illustrated in (3.13):

$$\begin{pmatrix} \Delta\delta \\ \Delta|V| \end{pmatrix} = K\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} = \left(K_{P_L}, K_{P_{PV}}, K_{P_{gen}}, K_Q\right)\begin{pmatrix} \Delta P_L \\ \Delta P_{PV} \\ \Delta P_{gen} \\ \Delta Q \end{pmatrix} \tag{3.13}$$

Substituting (3.16) into (3.13) results in (3.14):

$$\begin{pmatrix}\Delta\delta \\ \Delta|V|\end{pmatrix} = \underbrace{\left[K_{P_L}\left(K_{P_{PV}}, K_{Pgen}, K_{P_{gen}}T\right), K_Q\right]}_{K_{amend}} \begin{pmatrix}\Delta P_L \\ \Delta P_{PV} \\ \Delta Q\end{pmatrix} \tag{3.14}$$

The K and L matrices are revised to become K_{amend} and $L_{amend} = HK_{amend}$, respectively. As a result, the power system linear model in (3.11) is also revised as follows in (3.15):

$$\begin{aligned}\Delta x &= K_{amend}\Delta y \\ \Delta z &= HK_{amend}\Delta y = L_{amend}\Delta y\end{aligned} \tag{3.15}$$

The linear model of the power generation dispatch operations considering the power system uncertainties is represented by (3.16):

$$\Delta P_{gen} = T\Delta P_{PV} \tag{3.16}$$

where ΔP_{gen} is the uncertainty variable of the conventional sources P_{gen} in the overall generation mix and ΔP_{PV} is the uncertainty variable of the intermittent PV generated power P_{PV}. The sensitivity matrix of conventional generation is represented by T. The elements T_{ij} of T represents the change in the ith generator for a corresponding unity change jth in PV generation.

The model presented in (3.16) illustrates how generation sources balance the changes caused by the intermittency of PV generation sources. It is further demonstrated that the variations of conventional sources are the functions of variations of PV generations sources and the chosen generation dispatch strategy.

3.5 METHODS AND PROCEDURES FOR STUDYING THE IMPACTS OF GRID-CONNECTED LARGE-SCALE PV SYSTEMS AND RELATED SOLUTIONS

In line with the literature [107–113] presented in the following sections, methods and procedures for determining the impacts of grid-connected large-scale PV systems on the power system grid are outlined. Related solutions in terms of generation dispatch and spinning reserve that take into account the impacts of large-scale PV systems while also considering other aspects such as transmission line constraints are presented. The use of software tools such as MATLAB / Simulink and DigSILENT, amongst others, for simulations are also outlined.

3.5.1 Methods for comparative response evaluation of the impact of grid-connected PV systems and spinning reserve requirements

The introduction of large-scale PV systems into the grid has an impact on the load-following and spinning reserve requirements. Studies have been conducted to determine load-following and spinning reserve requirements for power systems interfaced with large-scale PV systems. In one of the investigations, a simple method for estimating the load-following and spinning reserve requirements for power systems interfaced with large-scale PV systems is presented [107]. This entails a comparative analysis in terms of costs of load-following and spinning reserve requirements in a power system with VREs in comparison to the base case of a normal power system without VREs.

Frequency stability is one form of power system stability that is affected by sudden and prolonged imbalance between generation output and load demand. In the case of RESs such a large-scale PV systems, generation output can vary as a result of variation in solar irradiance and other atmospheric parameters such as temperature.

As opposed to traditional stability strategies used to maintain frequency stability, an algorithm that employs spinning reserve techniques as a form of frequency control mechanism is proposed [109]. The approach defines an appropriate energy storage system (ESS) and load shedding scheme to cater for positive and negative spinning reserve requirements, respectively. A comparative frequency response investigation in terms of inertia and load model effect among synchronous generators with different inertia constants and the inertia-less PV plant is carried out. Furthermore, the use of ESS and load shedding scheme as corrective measures for frequency instability are implemented.

The power system network used in the study is the three-machine, nine-bus WECC test system. Simulations are carried encompassing such key functionalities such as:

- Observing frequency behavior during 30 % PV penetration level for PV plant and synchronous machines with different inertia constants,
- Measuring the time of frequency fall from nominal to lowest acceptable frequency level during 10 to 30 % overload at 30 % PV penetration level, and
- The use of BESS in parallel with a PV system to restore frequency to acceptable limits after a severe overload.

Besides power system stability issues, other key aspects of the power system that are impacted by large-scale PV systems are security and reliability. A secure power system is one that maintains the flow of electricity from generation sources to customers during small or large, local or widespread disturbances. Similarly, a reliable power system is one that performs as expected under all planned and unplanned events. In light of increasing large-scale PV penetration levels into the grid, the use of spinning reserve techniques is inevitable. Contrary to the traditional straight-forward approach of ensuring the continuity of supply from firm and dispatch-able conventional generation sources, modern tools are required when it comes to RESs with varying and intermittent power output. Typically, for the PV system without any form of storage, the power output rises gradually from the time of sun rise and peaks at midday as illustrated in Figure 3.2. Thereafter, the power output decreases gradually until it reaches zero output at the time of sunset.

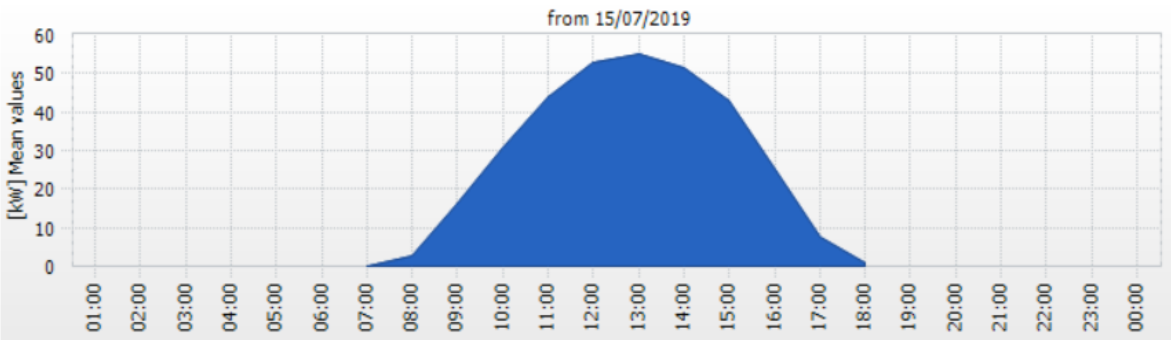

Figure 3.2: Typical roof-top PV plant generation output [kW] vs. time [hour] daily pattern.

The power output from the large-scale PV system is given by (3.17):

$$P_{PV} = \eta SI[1-0.05(t_0-25)] \tag{3.17}$$

where η = conversion efficiency (%)

S = array area (m^2)

I = solar irradiation (kW/m^2)

t_0 = outside air temperature ($^{\circ}C$)

Solar radiation and outside air temperature, like many other weather parameters, can be forecasted thereby offering a glimpse of future PV generation output behaviour. However, despite advancement in the short and long-term forecasting techniques, errors remain inevitable. As a result, the actual PV generation output at a particular time does not always match the PV generation output projected earlier on, resulting in a PV output predicted error [114] presented in (3.18).

$$Er_t^{PV} = P_t^{PV} - P_t^{f,PV}, \forall t \in \Omega^t \tag{3.18}$$

where:

Er_t^{PV} = prediction error,

P_t^{PV} = actual power output of the PV array, and

$P_t^{f,PV}$ = forecasted power output of the PV array.

In the end, it is the Er_t^{PV} prediction error that gives rise to expected energy not supplied (EENS) as far as the PV generation output is concerned. EENS represents a shortfall from the predicted to the actual output of the PV generation system. This can be given by (3.19).

$$PV_{EENS} = PV_{predicted\_energy\_output} - PV_{actual\_energy\_output} \tag{3.19}$$

Besides PV, the outage possibility of any of the CGSs can also lead to EENS. This can be represented by the following formula:

$$CGS_{EENS} = CGS_{predicted\_energy\_output} - CGS_{actual\_energy\_output} \tag{3.20}$$

Sometimes CGS is forced into outage due to transmission line constraints and other unforeseen circumstances. Subsequently, the overall EENS can be represented by the formula given in (3.21).

$$EENS = PV_{EENS} + CGS_{EENS} \tag{3.21}$$

The EENS have an impact on spinning reserve requirements. These include:

- Under-estimation of the required spinning reserve, which may lead to failure to meet the spinning reserve requirements of the power system, or
- Over-estimation of the required spinning reserve as a result of efforts to provide contingency measures. This may lead to costly CGSs being deployed at reduced capacity, which in any case, is still an expensive exercise.

Therefore, there is a need for an optimal trade-off to be made between the cost of providing adequate spinning reserve and the cost of EENS.

In order to deal with this type of variation, the use of a novel spinning reserve requirement optimization model is demonstrated on the IEEE reliability test system (RTS-96) [110]. The purpose is to evaluate the impact of large-scale PV systems unpredictability on the power system reserve allocation by using the benefit/cost analysis to control the costs of generation operation and the cost of expected energy not supplied (EENS). The model makes the use of PV generation output forecast error to work out optimal spinning reserve requirements for the power system that serves as input to the reserve-constrained unit commitment. A comparative benefit/cost analysis of the model employing PV forecast error in relation to the one not considering PV forecast error and the one making use of precise forecast is performed. The impact of PV forecast error on EENS is also analyzed.

Furthermore, in order to evaluate the impact of PV penetration level on the required capacity of spinning reserves, a comparative analysis considering PV generation with and without forecast error is conducted. As illustrated in (3.22), the PV penetration level, denoted by PL_{PV} is a fraction of the PV generation capacity, denoted by $P_{PV,capacity}$ over the total power system generation mix, denoted by P_{system} .

$$PL_{PV} = \left(\frac{P_{PV,capacity}}{P_{system}} \right) 100\% \tag{3.22}$$

The daily average scheduled spinning reserve (ASR), which is given in (3.23) and is directly proportional to the increase in PV penetration level.

$$ASR = \frac{1}{24} \sum_{t \in \Omega^t} r_t^{req} \tag{3.23}$$

where r_t^{req}, denotes the required spinning reserve.

It is demonstrated that with PV forecast error, the overall generation cost decline in comparison to the scenario without PV forecast. It is shown that increased PV penetration levels lead to higher spinning reserve requirements.

3.5.2 Methods for studying the dynamic voltage impact of large-scale PV plants on the utility grid's stability

Dynamic stability analysis entails system performance response analysis under continuous small disturbances. Numerous methods exist for studying both steady and dynamic voltage stability. One such method is the dynamic stability analysis, which has been used on a standard IEEE 30-bus system to study the impact of a large-scale PV system on voltage stability using the ETAP software [112]. In this instance, the disturbance considered in the simulation studies is load switching both as a small disturbance (9 ms) and a large disturbance (2 – 8 s).

Using simulations, a comparative analysis under normal and load switching scenarios (small and large disturbances) is performed while observing:

a) Voltage terminal across the PV bus at bus 12 and bus 26 (weakest bus);
b) Electrical power output of generator 1 and 2;
c) Power angle of generator 1 and 2;
d) Terminal current of generator 1 and 2;
e) Reactive power of generator 1 and 2;

Bus 26 is considered the weakest bus since it is only interconnected by a single transmission line with the rest of the system and it is therefore responsible for voltage collapse.

Under normal situation, no load switching is performed. The small disturbance is introduced by switching off the load at bus no. 5 for a short period of 9 ms. A noticeable disturbance is observed in the generator electrical power. The positive impact of large-scale PV in minimizing the change in voltage and current values, improving voltage stability and contribution to reactive power control is also observed. On the other hand, the large disturbance is introduced by switching off the large load at bus no. 5 for a period of 2 to 8 seconds. The main observations are on the large-scale PV system’s contribution to improved power system operation, reduced rotor angle and voltage instability, which leads to minimal generator outages.

Dynamic voltage stability is modelled by differential equations and a set of algebraic equations. In the end, voltage stability is estimated by calculating the voltages and generator angles using the standard Newton-Raphson method for power flow analysis. The process entails two iterations for the standard system and eight iterations for the system with large-scale PV.

3.5.3 Methods for studying the impact of large-scale PV systems on the utility grid’s transient stability

Transient stability analysis entails system performance response analysis to determine the system’s ability to restore the load angle to steady state following the clearance of a disturbance. A standard IEEE 30-bus system has been used to study the impact of a large-scale PV system on transient stability using the ETAP software [113]. The large-scale PV system is connected at bus no. 13 with penetration level ranging from 135 MW to 154 MW. Bus no. 13 is one of the medium voltage level buses. Buses no. 26, 29 and 30 are the weakest buses responsible for voltage collapse. In this instance, the disturbances considered (one at a time) in the simulation studies are the addition of the large-scale PV system to the standard IEEE 30-bus system, the disconnection of the second largest synchronous generator (G2) and the application of the single line to ground fault at bus no. 26.

Using simulations, a comparative analysis on the impact of a large-scale PV system on the standard IEEE 30-bus system is performed while observing:

i. the terminal voltage on buses no. 26, 29, 30 and on PV bus when PV is connected;
ii. the voltage angles on buses no. 26, 29, 30 and on PV bus when PV is connected
iii. the output electrical power on generator no. 1 and 2;
iv. the terminal current on generator no. 1 and 2;

The simulations are done in the following sequence:

A. Standard IEEE 30-bus system without large-scale PV

Firstly, the standard IEEE 30-bus system without the large-scale PV connected is simulated to check that the system is stable and all generators are in synchronization with the system.

B. Standard IEEE 30-bus system with large-scale PV bus no. 13

In the second instance, the large-scale PV system is introduced to a stable IEEE 30-bus system. The bus voltages and the variations of the buses' angles of the generators no. 1 and 2 are observed. It is also observed that the generator terminal voltage and current turn out to be more constant, an indication of improved rotor speed stability. This is attributed to the difference between the mechanical input power P_m and electrical output power P_e. On the overall the IEEE 30-bus system with large-scale PV is considered more stable as compared to the system without PV.

C. Standard IEEE 30-bus system with large-scale PV bus no. 13 and disconnection of a 40 MW generator

The purpose of this simulation is to test the large-scale PV system's capability to cope with the sudden loss of significant synchronous generation. The expected response is for the large-scale PV to commence with power export into the grid to compensate for partial loss of generation. The PV system's generation capacity was then ramped to 154 MW while at the same time disconnecting one of the synchronous generators with the 40 MW from the system. It can be observed from the variations in output electrical power and terminal current of generator no. 1 and 2 that generator no. 1 losses its stability in response to the disconnection of the generator no. 2. However, the system regained its transient stability quickly because the remaining generators and the PV could meet the load supply demand.

D. Standard IEEE 30-bus system with large-scale PV bus no. 13 and single line to ground fault at bus no. 26

The purpose of this simulation is to test the IEEE 30-bus system's capability to maintain stability when subjected to a single line to ground fault in the presence of large-scale PV generation. The expected response is for the large-scale PV and other conventional generators to exercise fault ride-though capability and remain connected in short periods of grid fault. The fault was introduced at time 2 seconds for a short duration of 0.2 seconds. The system's response to this disturbance can be observed from the variations in bus voltage, bus voltage angle, output electrical power and terminal current of generator no. 1 and 2 during for the entire fault duration. It is obvious that the system losses its stability during the fault duration. However, the system regains its transient stability immediately after fault clearance.

3.5.4 Methods for determining the required spinning reserve in power systems with large-scale PV systems

Unit commitment with spinning reserve is one of the key requirements in ensuring the load and generation balance in systems interfaced with large-scale PV systems. Numerous methods for optimal scheduling of spinning reserve have been explored in the literature

[115–117]. Adequate spinning reserves are essential for managing unforeseen disturbances such as generation output forecasting errors associated with RESs such as PV and wind turbines [117], unscheduled conventional generator outages and major load forecasting errors without resorting to load shedding [115]. The main approaches adopted in this regard are either deterministic or probabilistic spinning reserve requirement (SRR) assessment. In of these approaches, a probabilistic reliability assessment is employed in short-term scheduling to work out an appropriate SRR [115]. In another approach, a probabilistic reliability assessment is also employed in short-term scheduling to allocate appropriate spinning reserve based on the well-being model [116]. What these approaches have in common is the demonstration of the effect of forecast error and outage replacement rate (ORR) uncertainties on the tradeoff between the cost of SRR and the cost of EENS.

3.6 BENCHMARK SYSTEMS FOR THE SIMULATION OF GENERATION DISPATCH WITH LARGE-SCALE PV SYSTEMS

This section presents the benchmark power systems and the related data used in the simulations of generation dispatch with large-scale PV systems. A typical utility benchmark networks such as the IEEE 14-bus system is considered. The test system is modified to introduce renewable energy generation in the form of large-scale PV plants. The main aim is to investigate how generation dispatch can be employed as a stability technique to handle the impact of large-scale PV systems on the grid. The proposed remedial measures to deal with the impacts of grid-connected PV systems are also tested.

3.6.1 The IEEE 14 Bus System

The IEEE 14 Bus System represents a portion of the American Electric Power System (in the Midwestern US) as of February, 1962. A much-Xeroxed paper version of the data was kindly provided by Iraj Dabbagchi of AEP and entered in IEEE Common Data Format by Rich Christie at the University of Washington in August 1993 [118]. It consists of 14 buses, 5 generators, and 11 loads.

Figure 3.3 shows the single line diagram of IEEE-14 bus system. Like other IEEE bus systems, this system is widely used by researchers to investigate new ideas and concepts.

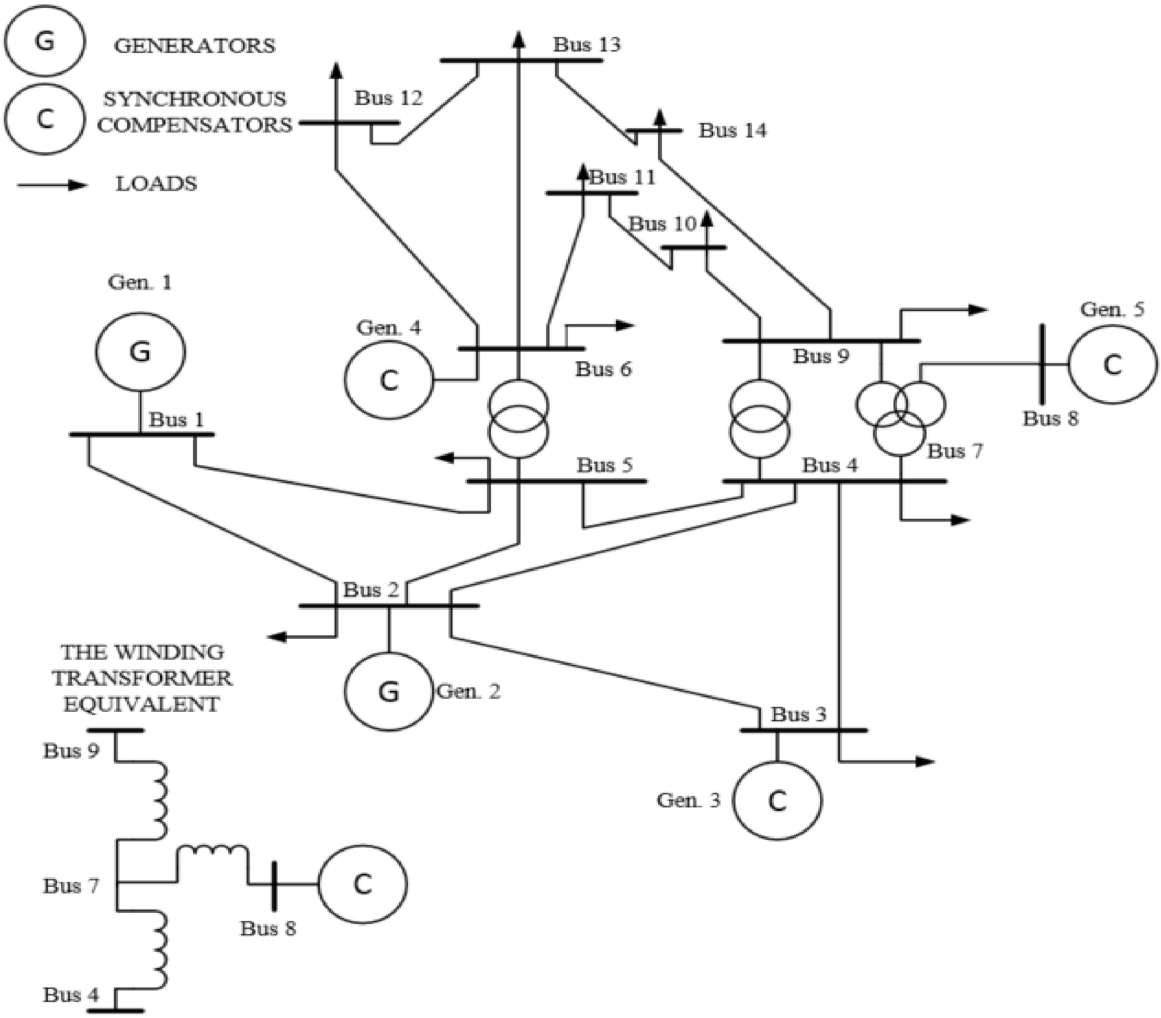

Figure 3.3: IEEE 14-bus test system [118].

The system data for generators, loads, lines, transformers, AVRs, PSSs and TGs, where appropriate, is drawn from various sources [119] including the benchmark implementation in [120].

3.6.1.1 Generator parameters

All generators are modelled as 6th order synchronous machines except generator 1 which is modelled as a 5th order synchronous machine. All generators are also equipped with IEEE

Type-2 exciters. Generator 1 is also equipped with a PSS. Generators 1 and 2 are equipped with turbine governors.

The generator parameters are governed by the following formula given in (3.14):

$$N_s = \frac{120f}{P} \tag{3.24}$$

where N_s is the speed in rotations per minute (rpm),

f is the frequency of power supply, and

P is the number of poles in the machine.

3.6.1.2 Transmission line parameters

The transmission line parameters are governed by the following equations:

$$X_C = \frac{1}{2\pi fC} \tag{3.25}$$

$$G = \frac{1}{R} \tag{3.26}$$

$$B_L = \frac{1}{2\pi fL} \tag{3.27}$$

$$B_C = 2\pi fC \tag{3.28}$$

$$Y = \frac{1}{Z} = \sqrt{G^2 + B^2} \tag{3.29}$$

$$Z = R + jX \tag{3.30}$$

$$X_L = 2\pi fL \tag{3.31}$$

where Z is the impedance in ohms (Ω),

R is the resistance in ohms (Ω),

j is the imaginary unit

X is the reactance is ohms (Ω),

Y is admittance (measured in Siemens),

X_L Inductive reactance (measured in ohms),

X_C Capacitive reactance,

f is the frequency in Hz,

L is the inductance in Henry (H), and

C is the capacitance in farads (F).

3.7 METHODS AND PROCEDURES FOR THE SIMULATION OF GENERATION DISPATCH WITH LARGE-SCALE PV SYSTEMS ON IEEE BUS SYSTEMS

This section presents the methods and procedures used in the simulations of generation dispatch with large-scale PV systems on a typical utility benchmark network, the IEEE-14. As opposed to practical systems, literature based test systems are preferred due to [121]:

i. Confidentiality associated with practical systems,
ii. Poor documentation of static and dynamic data from practical systems,
iii. Challenges associated with calculations of various scenarios due to large amount of data,
iv. Unavailability of software tools capable of handling large sets of data,
v. Minimal or lack of generic results from practical systems,

A few large-scale PV plant models are added at strategic locations. The entire generation mix is taken into account. Models of other unconventional generation plants as well as those of storage systems are also placed at strategic points in the system. In line with the literature presented in the following sections, a generation dispatch model that takes into account the impacts of large-scale PV systems is developed.

3.7.1 Simulations on the IEEE 14 Bus System

3.7.1.1 Methods for analysing the impact of large-scale PV plants on the utility grid's stability

Power system stability is one of the power system characteristics that are affected by large-scale PV plants. This is mainly due to the intermittent, unpredictable and static nature of PV plants. On the issue of intermittency, this means the generation output of a PV plant is dependent upon atmospheric factors such as irradiance and temperature. With regard to unpredictability, this means there is no certainty as to what the actual output of a PV plant would be from time to time. The intermittent and unpredictable nature of PV systems can have an effect on both voltage and frequency stability. And lastly, the lack of rotational parts in PV systems as opposed to the rotating prime movers and turbines in synchronous conventional generators or the rotational parts in wind plants renders PV systems to be inertia less. The lack of inertia means, following a disturbance, PV plants do not participate in the restoration of power system equilibrium associated with power-angle relationships. This has an impact on rotor angle stability.

In order to determine the impacts of a large-scale PV system on voltage and frequency stability as well on the general power quality, an investigation similar to what was done in [111] was carried on a standard IEEE 14-bus system using the MATLAB based Power System Analysis Tool (PSAT). The following simulation steps were followed:

A. Modelling of the PV plant

A 50 MW PV plant with reference voltage of 1.045 p.u. is added to bus 13. This was chosen because it is furthest from the slack bus, which is typical of real world scenarios where PV farms are located in remote locations such as deserts. The PV plant, which is operated at 100 % efficiency, is run in the constant power and constant voltage (PV) control mode.

B. Initial static simulation

The first step entails the running of the initial static simulation and finding the bus voltages using the Newton-Raphson iterative method on a reference base case system without PV being connected. Thereafter, similar simulations are repeated after adding the 50 MW PV plant to Bus 13 and three breakers at different locations.

Upon the performance of first simulation, which is a simple steady-state power flow analysis for both the base and PV connected system, a comparative analysis is carried out focusing on:

i. Voltages of buses 4, 5 and 14;
ii. Real and reactive power generated at bus 13;
iii. Phase angles of all buses;
iv. Real and reactive power generator or absorbed at the slack bus (bus 1);
v. Real and reactive power generator or absorbed at all buses in the system;

C. Power Quality

The possible impacts of large-scale PV systems on power quality is investigated in terms of power system voltage, rotor angle and frequency stability following a disturbance. The disturbances considered are the operations for breaker 1 (located between buses 5 and 6), breaker 2 (located between buses 4 and 9) and breaker 3 (located between buses 4 and 7).

The power quality is tested by opening the breakers for 5s between 20s and 25s in different combinations and carrying out simulations with and without the PV generator for comparative analysis. A comparative analysis is carried on the base case and the PV connected case focusing on voltages on load buses 9 to 14 that are farther away from main generation and near the solar park. The aim to investigate the role of PV in the provision of voltage support when the breaker is open and assistance with stabilization immediately after closure.

D. Voltage Stability

Voltage stability is tested by studying the power system's performance following a three-phase fault. With the PV generator still at bus 13, a 20 MW, 13.8 kV, 0.5 seconds three-phase to ground fault is applied at bus 14 for both the base system and PV connected system case. The fault size approximately matches the maximum power available at bus 14 in the static analysis, thereby providing the worst case scenario in terms of voltage stability. Bus 14 is chosen because it has the lowest reactive power reserves, which makes it ideal to test the resilience of a power system with PV generator.

A comparative analysis is carried on the base and the PV connected case focusing on all bus voltages, with special emphasis on bus 14. The first aim is to investigate the role of PV in mitigating the impact of faults on bus voltages. The second aim is study the recovery trends of system voltages with respect to timeframes following fault clearance.

E. Frequency Stability

In the first stage, frequency stability is investigated by studying the impact of increased penetration of large-scale PV systems on the system load bus frequencies. This is performed by comparative analysis of the load bus frequencies on the base system, the system with the 50 MW PV plant and the system with the 60 MW PV plant. The purpose is to determine the appropriate PV penetration level in relation to the total generation mix at which the system still remains stable.

In the second stage, frequency stability is investigated by simulating a 20 MW, 13.8 kV, 0.5 seconds three-phase to ground fault at bus 14 for the base system and the PV connected system. A comparative analysis of the load bus frequencies is carried out to investigate the role of inertia provided by synchronous generators in the restoration of system stability following a fault.

3.8 CHAPTER SUMMARY

In this chapter an overview of the proposed methods and procedures concerning the aspect of generation dispatch with large-scale PV systems was presented. The methods and procedures for the determination of the impacts of large-scale PV systems on the grid were introduced. The research problem was also formulated. Subsequently, associated modelling, simulation and performance evaluation techniques of generation dispatch with large-scale PV plants were also provided. Typical simulation methods employed for power system stability studies on benchmark networks such as the IEEE-14 bus system were outlined.

CHAPTER 4 RESULTS ON SIMULATION STUDIES WITH LARGE-SCALE PV SYSTEMS

4.1 CHAPTER OBJECTIVES

The main aim of this chapter is to present the results of all simulations and experiments conducted to demonstrate the role of generation dispatch in overcoming challenges posed by increased penetration of large-scale PV systems in sub-transmission and transmission systems. The simulations and the accompanying results presented in this chapter are conducted to evaluate the performance of generation dispatch based on the IEEE 14 Bus Test System shown in Figure 4.1. The system data for the system buses, generators and transmission lines is presented in Appendix A. The IEEE 14 Bus Test System implementation in [122] is modified to introduce renewable energy generation in the form of large-scale PV plants.

The main aim is to verify some of previous research studies conducted on the impact of large-scale PV systems on the grid. The results from the proposed remedial measures to deal with the impacts of grid-connected PV systems are also presented.

In Section 4.2 an overview of the power modelling, design and analysis was presented. The power system methods of power flow (PF), continuation power flow (CPF) and time domain (TD) analysis used in the testing and evaluation of the power system were also presented.

In Section 4.3 the performance of the IEEE 14-bus system base case model was evaluated without introducing any system disturbances before the integration of large-scale PV systems into the grid. The base case power system was found to be to be stable.

In Section 4.4 the performance of the IEEE 14-bus system model was again tested upon the integration of large-scale PV systems into the grid without introducing any disturbances. The power system was still found to be stable following the integration of the large-scale PV system.

In Section 4.5 a comparative analysis of the power systems' response to power system disturbances was performed on both the base case system and the system integrated with large-scale PV systems. Based on power quality and stability analysis results, it was found that the presence of large-scale PV systems results in improved power quality and stability.

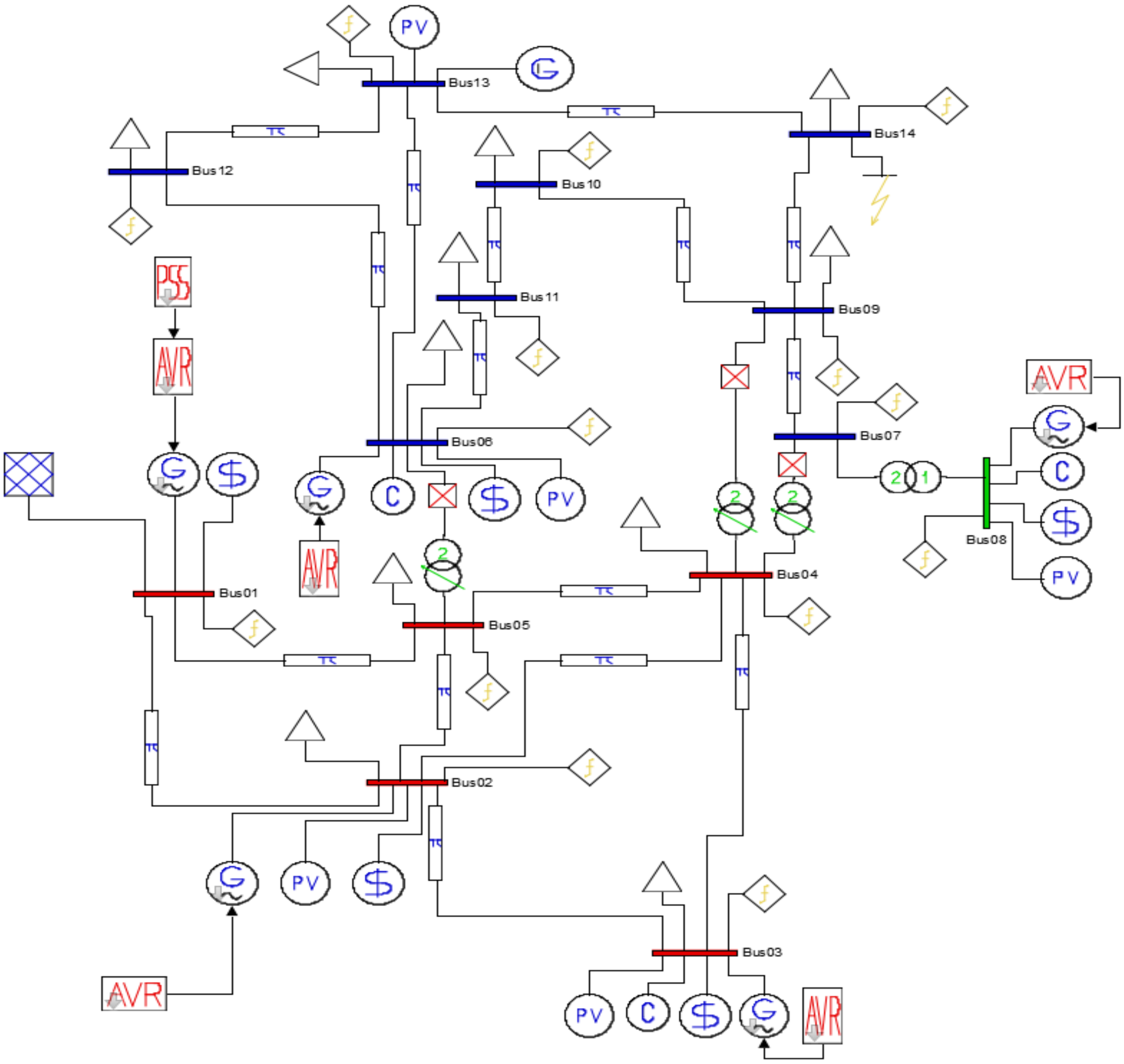

Figure 4.1: PSAT model of the IEEE 14-Bus System.

4.2 POWER SYSTEM ANALYSIS AND DESIGN

4.2.1 The Power System Analysis Toolbox (PSAT)

The design of the IEEE 14-bus system and subsequent power system analysis are carried out using the MATLAB based Power System Analysis Toolbox (PSAT) [121], a free and open source software. The analysis is conducted using the power flow analysis methods such as power flow (PF), continuation power flow (CPF) and time domain (TD) analysis that are based on a full Jacobian matrix [123]. These analysis are performed at different stages such as planning, operation, control and economic dispatch.

4.2.1.1 The power system model

The simulations are conducted on a power system model which is represented by a set of non-linear differential algebraic equations expressed in (4.1):

$$\begin{aligned} \dot{x} &= f(x, y, p) \\ 0 &= g(x, y, p) \end{aligned} \tag{4.1}$$

where x are the state variables $x \in \Re^n$; y are the algebraic variables $y \in \Re^m$; p are the independent variables $p \in \Re^l$; f are the differential equations $f : \Re^n \times \Re^m \times \Re^l \mapsto \Re^n$; and g are the differential equations $g : \Re^m \times \Re^m \times \Re^l \mapsto \Re^m$; Equation (4.1) is used in all PSAT algorithms such as PF, CPF, OPF, small signal stability analysis and TD simulation.

The algebraic equations g is the sum of all active and reactive power injections at buses and is expressed using (4.2):

$$g(x, y, p) = \begin{bmatrix} g_p \\ g_p \end{bmatrix} = \begin{bmatrix} g_{pm} \\ g_{pm} \end{bmatrix} - \sum_{c \in C_m} \begin{bmatrix} g_{pc} \\ g_{qc} \end{bmatrix} \qquad \forall m \in \mathcal{M} \tag{4.2}$$

where:

- g_{pm} and g_{qm} are the power flows in the transmission lines,
- $\mathcal{M}$ is the set of network buses,
- C_m are the set of components connected at bus m.
- $\begin{bmatrix} g_{pc} \\ g_{qc} \end{bmatrix}$ are the power injections of components connected at bus m.

Equations (4.3) are the PSAT component-oriented independent set of non-linear differential-algebraic equations which are expressed as follows:

$$\begin{aligned} \dot{x} &= f_c(x_c, y_c, p_c) \\ P_c &= g_{pc}(x_c, y_c, p_c) \\ Q_c &= g_{qc}(x_c, y_c, p_c) \end{aligned} \tag{4.3}$$

where x_c are the component state variables, y_c are the algebraic variables (i.e. voltage magnitudes V and phase θ at the buses to which components are connected) and p_c are the independent variables. The differential equations f in equation 16 are built concatenating f_c of all components. Equation (4.3) together with Jacobian matrices are defined in a function which is used for both static and dynamic analysis. In addition, a component containing data, parameters and the interconnection to the grid is defined by means of structure.

4.2.1.2 The power flow analysis

Power system stability is one of the power system characteristics that is affected by large-scale PV plants. The power flow problem is derived from (4.1), as follows:

$$\begin{aligned} 0 &= f(x, y, p) \\ 0 &= g(x, y, p) \end{aligned} \tag{4.4}$$

where first time derivative $\dot{x}$ is set to zero.

The purpose of PF analysis using the Newton Raphson method, which is the first step undertaken under normal operating conditions, is to:

i. determine voltage magnitude and angle values, generated real and reactive power as well as the load real and reactive power at all fourteen (14) buses of the interconnected network,
ii. determine the real and reactive power flows across all eleven (11) transmission lines of the interconnected network,
iii. provide limit violation information with regard to voltage, current, real power, reactive power and apparent power at all buses and across all transmission lines,
iv. determine the total generation, load capacities and losses of the entire interconnected network.

This aids with the investigation of the current state of the stable network before commencing with the simulation of various control, operation and generation dispatch scenarios.

The power flow or load-flow analysis is a numerical analysis performed to determine the steady-state behaviour of the interconnected power system. In this study, power flow analysis serves as the base point of reference for both the base case and the system integrated with large-scale PV systems. This means before any system disturbances are introduced either to the base case test system or the system integrated with large-scale PV, power flow analysis is performed to determine the status of various power system parameters such as voltage magnitude and angles, real and reactive power at buses and in transmission lines.

The comparative PF analysis is also performed for the base case network without large-scale PV systems versus the one with large-scale PV systems.

The power flow results in PSAT are displayed using the GUI or the selected report format (HTML, Excel, ASCII and Latex).

4.2.1.3 The continuation power flow analysis

In terms of the overall voltage stability analysis, the CPF is used to determine the generator reactive power and voltage limits as well as the flow limits of transmission lines of the interconnected power system [123]. In PSAT, the CPF method is made up of the predictor step which is found by the computation of the tangent vector and the corrector step which is acquired either by local parameterization or perpendicular intersection [123]. The CPF analysis solves the Jacobian matrix to determine the maximum loading of transmission lines based on a specific loading scenario. This is done through successive solutions by computing the voltage profile as a function of loading parameter λ_c up to the collapse point where the Jacobian matrix becomes singular. The details steps in solving the Jacobian matrix are provided in [124]. From its inception, the original purpose of the CPF analysis is to determine the approximate steady-state voltage stability limit (critical point) of the interconnected network starting from some base load through a series of continuum power flow solutions [125].

The CPF problem is formulated as illustrated in (4.5):

$$\begin{aligned} 0 &= f(x, y, \lambda) \\ 0 &= g(x, y, \lambda) \end{aligned} \tag{4.5}$$

where $\lambda \in \Re$ is the loading parameter used to vary base case generator power P_{Go} and load powers (P_{Lo} and Q_{Lo}). This is performed as shown in (4.6):

$$\begin{aligned} P_G &= (\lambda + \gamma k_G) P_{G_0} \\ [P_{L,} Q_L] &= \lambda [P_{L_0,} Q_{L_0}] \end{aligned} \tag{4.6}$$

Similar to PF, the CPF flow results in PSAT can also be displayed using the GUI or the selected report format (HTML, Excel, ASCII and Latex). The GUI for plotting CPF results in PSAT is used to produce nose curve graphs for different contingencies in the interconnected network. The nose curve graphs are used to display voltage as a function of loading parameter λ_c of transmission lines.

In this study, the continuation power flow analysis also serves as the base point of reference for both the base case and the system integrated with large-scale PV systems. A comparative CPF analysis is also performed for contingencies in the base case network without large-scale PV systems versus the one with large-scale PV systems.

4.2.1.4 The time domain analysis

Power system stability is one of the power system characteristics that are affected by large-scale PV plants. The time domain analysis, together with small signal analysis, is part of dynamic analysis. Time domain analysis is used for the simulation of disturbances such as faults and breaker operations. These are the most common perturbations for transient stability analysis. The TD simulation results in PSAT are plotted as a function of time using the GUI.

In this study, the key results obtained using time domain analysis includes:

a) rotor speed and angle as a function of time for the five generators,
b) active and reactive power profiles as a function of time for the five generators,
c) voltage magnitude and angle profiles for the 14 buses.

A comparative analysis is also performed for the base case network without large-scale PV systems versus the one with large-scale PV systems. This entails:

a) Static time domain analysis where no system disturbances are involved for the base case network without large-scale PV systems versus the one with large-scale PV systems, and

b) Dynamic time domain analysis where for instance, faults and breaker operations, are simulated for the base case network without large-scale PV systems versus the one with large-scale PV systems.

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PSAT's graphical user interface from which PF, CPF and TD functionalities are assessed is presented in Figure 4.2.

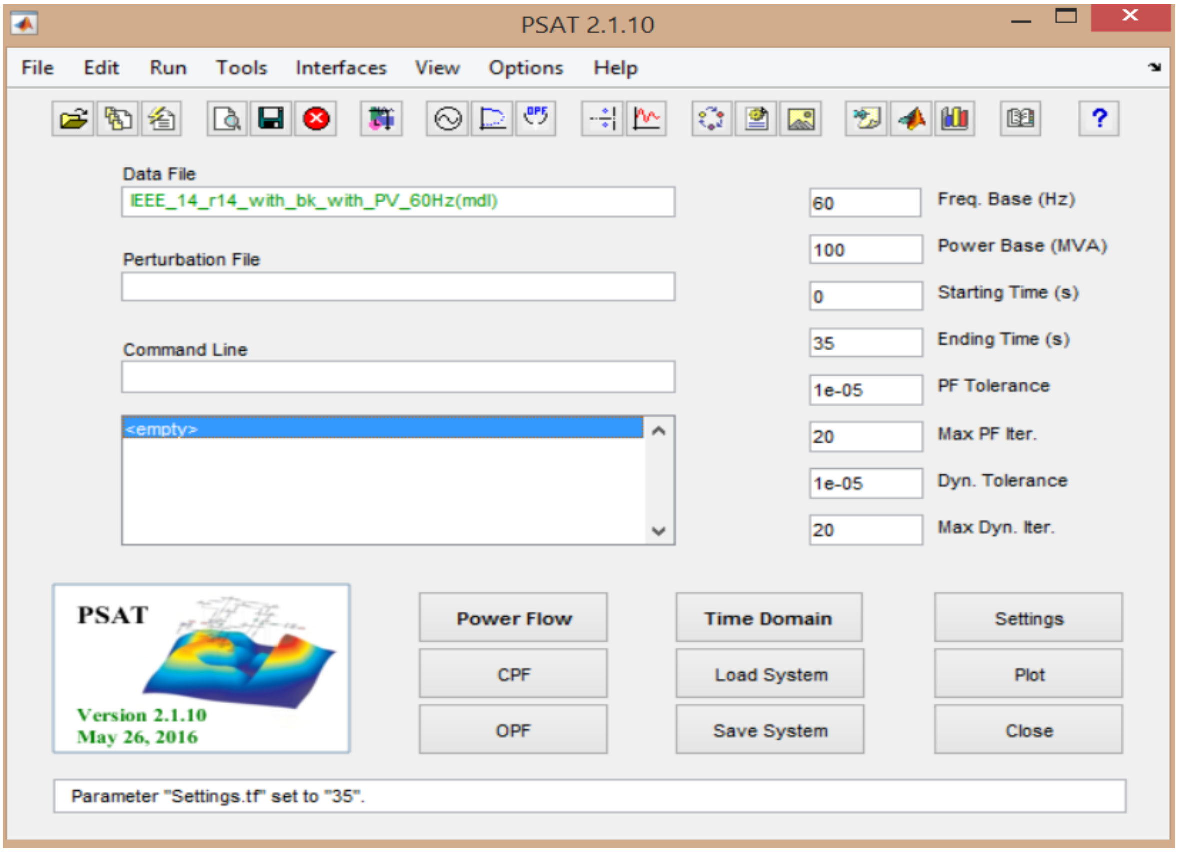


Figure 4.2: PSAT's GUI.

4.2.2 The Power System Design using PSAT

In addition to the GUI, PSAT has a SIMULINK based library that provides a user-friendly tool for network design. The single line diagram PSAT model of the IEEE 14-bus system shown in Figure 4.1 has been designed using this SIMULINK based library. The library is shown in Figure 4.3.

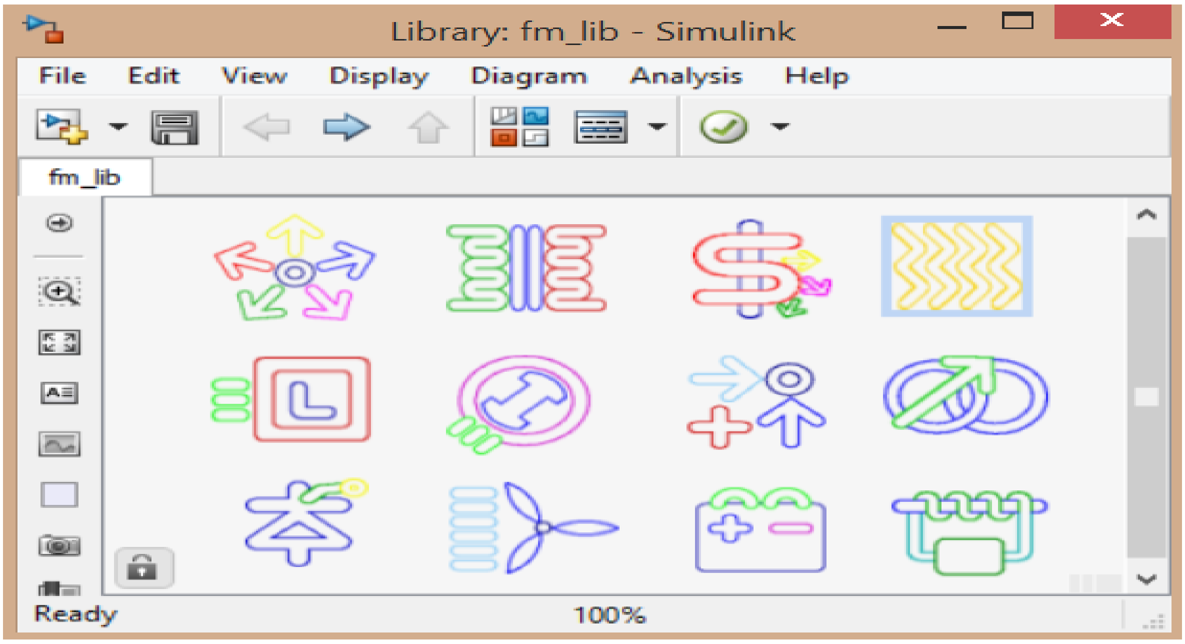


Figure 4.3: The Simulink based library.

The library contains various static and dynamic models [122, 123]. As shown in Figure 4.3, the first row (from left to right) consists of buses and connections, static components and devices, OPF and CPF data and faults and breakers. The second row (from left to right) consists of loads, machines, controls and regulating transformers. The third row (from left to right) consists of FACTS, wind turbines, other models and measurements.

4.2.3 The Power System Analysis Reports

4.2.3.1 The GUI power flow results

The GUI report shown in Figure 4.4 displays the power system's bus names and their corresponding voltage magnitude and angles as well as their real and reactive power magnitudes. Using the buttons on top of the parameter list, the voltage magnitude and angle profiles as well as the real and reactive power profiles are also plotted with respect to their corresponding bus names. The voltage and power parameters can either be plotted in per unit values or in absolute values as shown in Figure 4.4.

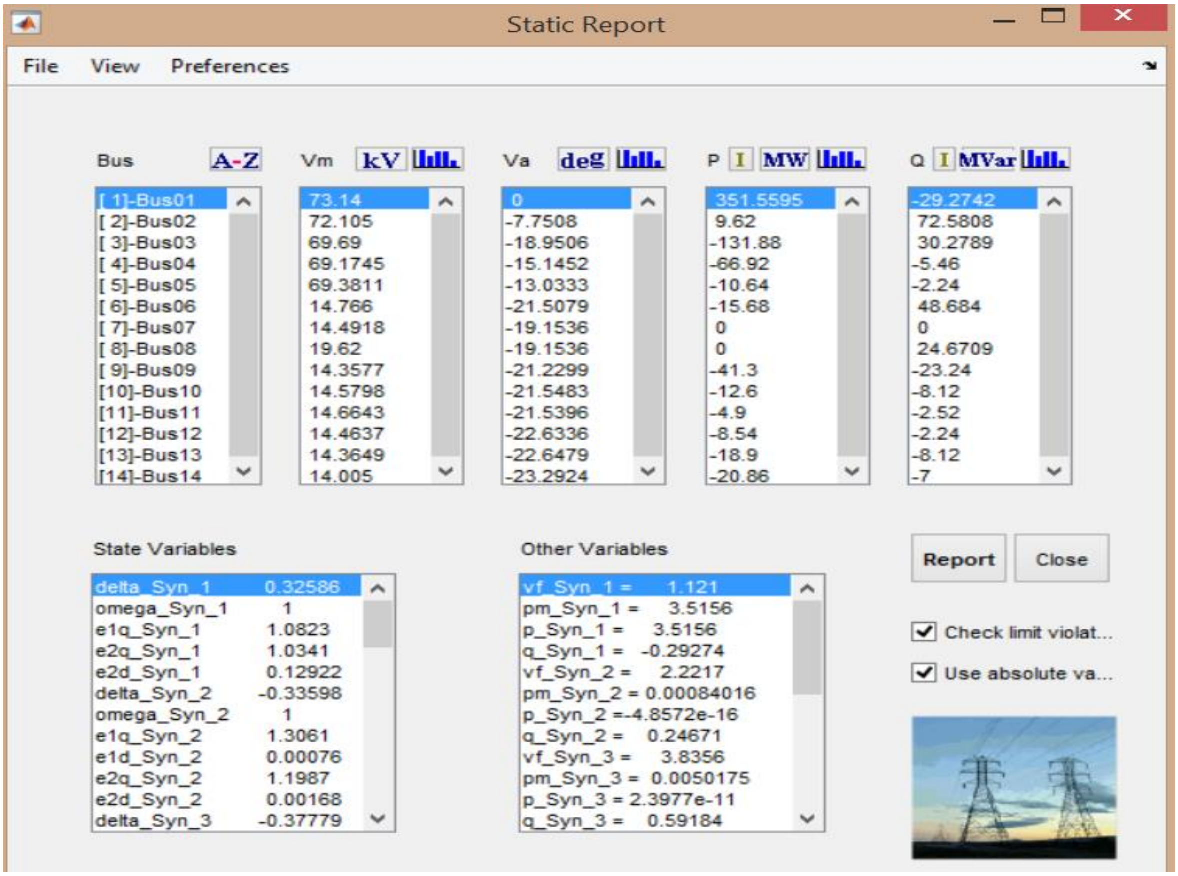


Figure 4.4: The GUI for displaying power flow results.

4.2.3.2 The selected report format

The key results obtained from the selected format are the:

A. Network statistics

The network statistics displays the number of buses, lines, transformers, generators and loads in the interconnected network.

B. Solution statistics

The solution statistics table provides the number of iterations, maximum P mismatch and maximum Q mismatch.

C. Power flow results

The power flow results table displays the bus names and their corresponding voltage magnitude and angle values, generated real and reactive power as well as the load real and reactive power. It also provides information on the maximum limit violations with respect any of the aforementioned parameters.

D. State variables

The state variables are all other algebraic variables such as generator field voltages, AVR field voltages, etc.

E. Other algebraic variables

These are the voltage magnitudes V and phases θ at the network buses.

F. Transmission line flows

The transmission line flow results table displays real and reactive power flows as well as the load real and reactive power losses in all transmission lines of the interconnected network.

G. Global summary report

The global summary report displays the total generation, load and losses in terms of real and reactive power.

H. Limit violation statistics

The limit violations statistics checks whether all voltages, current, real power, reactive power and apparent power flows at various places in the interconnected network are within the set limits. The total numbers of limit violation occurrences are also displayed whenever something to the contrary occurs.

4.3 THE BASE CASE IEEE 14-BUS TEST SYSTEM PERFORMANCE

The first step is to test the satisfactory performance of the IEEE 14-bus system base case model before the integration of large-scale PV systems into the grid. This is done using PSAT to perform several power system analysis such as PF, CPF and TD analysis on the IEEE 14-bus system. The results are presented in Tables 4.1-4.3 and in Figures 4.5-4.8. The active power, reactive power and voltage values are given on the system of 100 MVA and 60 Hz base. Based on the results presented below, the power system is found to be stable.

4.3.1 Static load flow simulation results on the IEEE 14-Bus System base case

This subsection presents the static power (load) flow simulation results.

4.3.1.1 Statistics and global summary report

The GUI report shown in Tables 4.1-4.3 present the network statistics, solution statistics and the global summary report, respectively.

Table 4.1: Network statistics.

Buses	14
Lines	16
Transformers	4
Generators	5
Loads	11

Table 4.2 presents PSAT's computational performance in terms of the number of iterations undertaken to conclude simulations and the minimum convergence error. The real and active power mismatch parameters are an indication of accuracy between input and computed network data. A low convergence error as shown in this table is an indication of high accuracy network performance level.

Table 4.2: Solution statistics.

Number of Iterations	4
Maximum P mismatch [MW]	8.61×10^{-10}
Maximum Q mismatch [MVAr]	6.03×10^{-09}
Power rate [MVA]	100

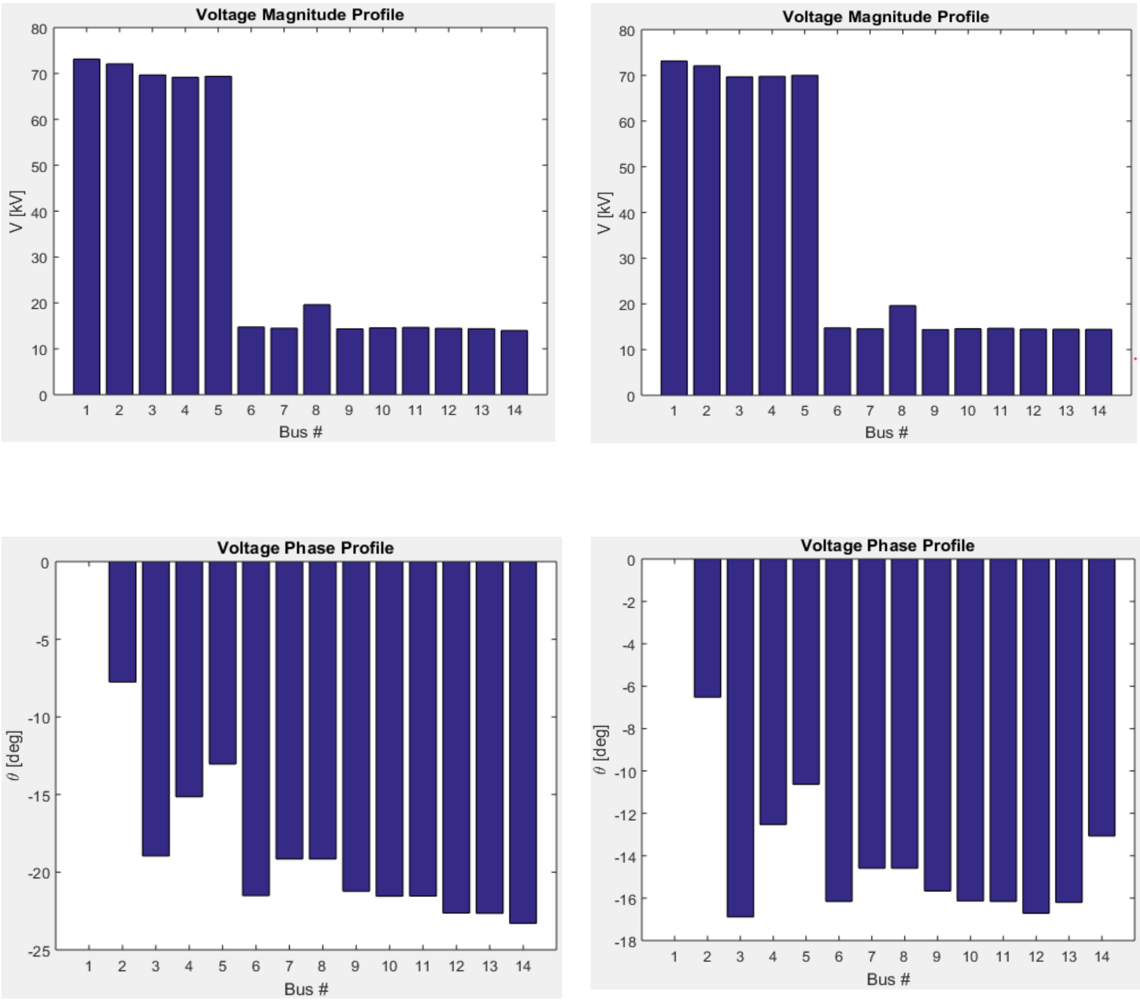
Table 4.3 presents the real and reactive power profiles in terms of total generation, load demand and network losses following a simulation of the base case network. The summation of total load demand and total losses adds up to total generation available in the IEEE-14 bus system.

Table 4.3: Global summary report.

Power	**Total Generation**	**Total Load**	**Total Losses**
Real power [MW]	391.56	362.6	28.96
Reactive power [MVAr]	201.82	113.82	88.00

4.3.1.2 Voltage magnitude and phase profiles

The GUI report shown in Figure 4.5 present the comparative analysis of the voltage magnitude and phase profiles for the 14-buses on the IEEE-14 bus system without and with PV connected at bus 14.



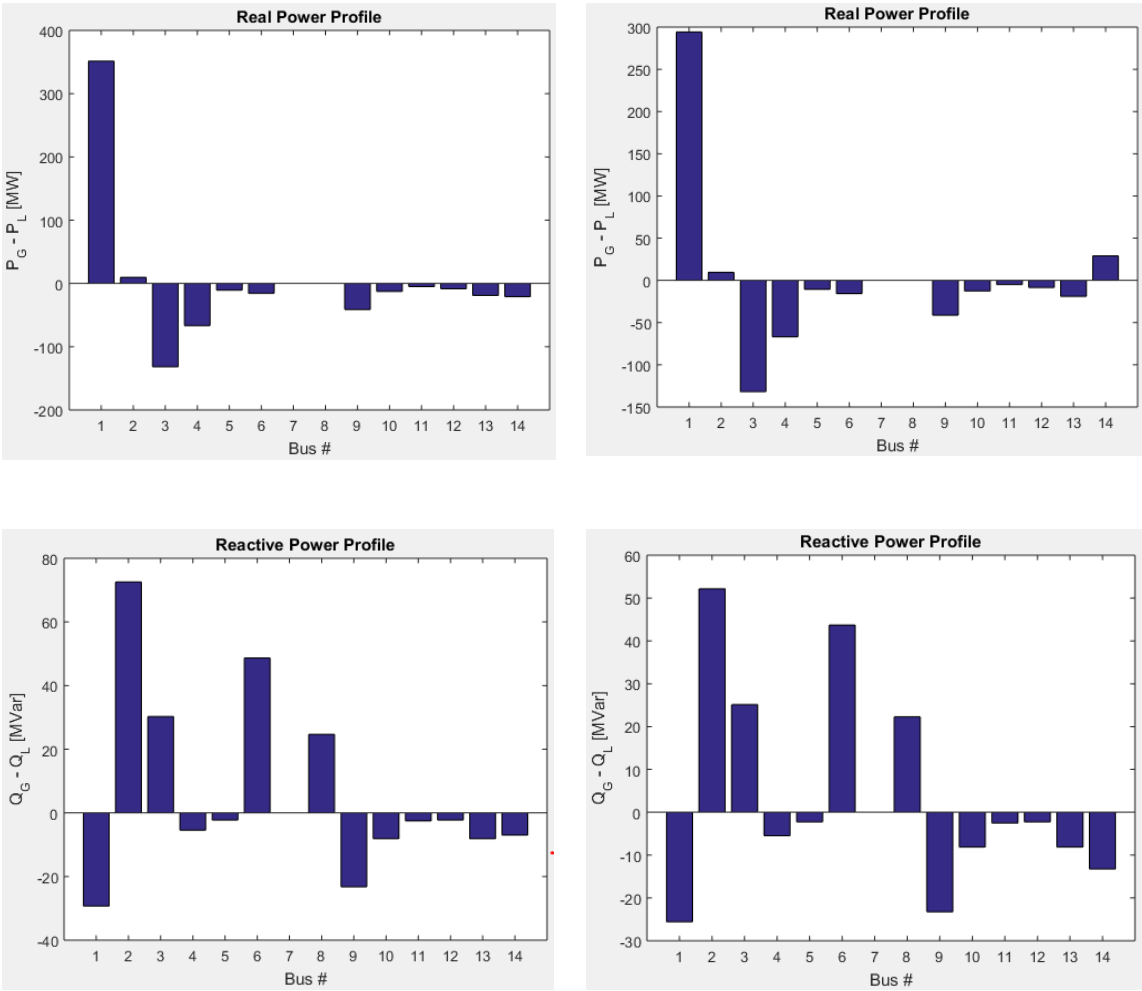
(a) (b)

Figure 4.5: Voltage magnitude and phase profile plot of the IEEE 14-Bus System.
(a) System without PV. (b) System with PV.

It can be observed that the presence of the large-scale PV system on bus 14 results in an increase in voltage phase angle of all buses.

4.3.1.3 Real and reactive power profiles

Figure 4.6 presents the comparative analysis of the real and reactive power profiles for the 14-buses on the IEEE-14 bus system without and with PV connected at bus 14.



(a) (b)

Figure 4.6: Real and reactive power profile plot of the IEEE 14-Bus System.
(a) System without PV. (b) System with PV.

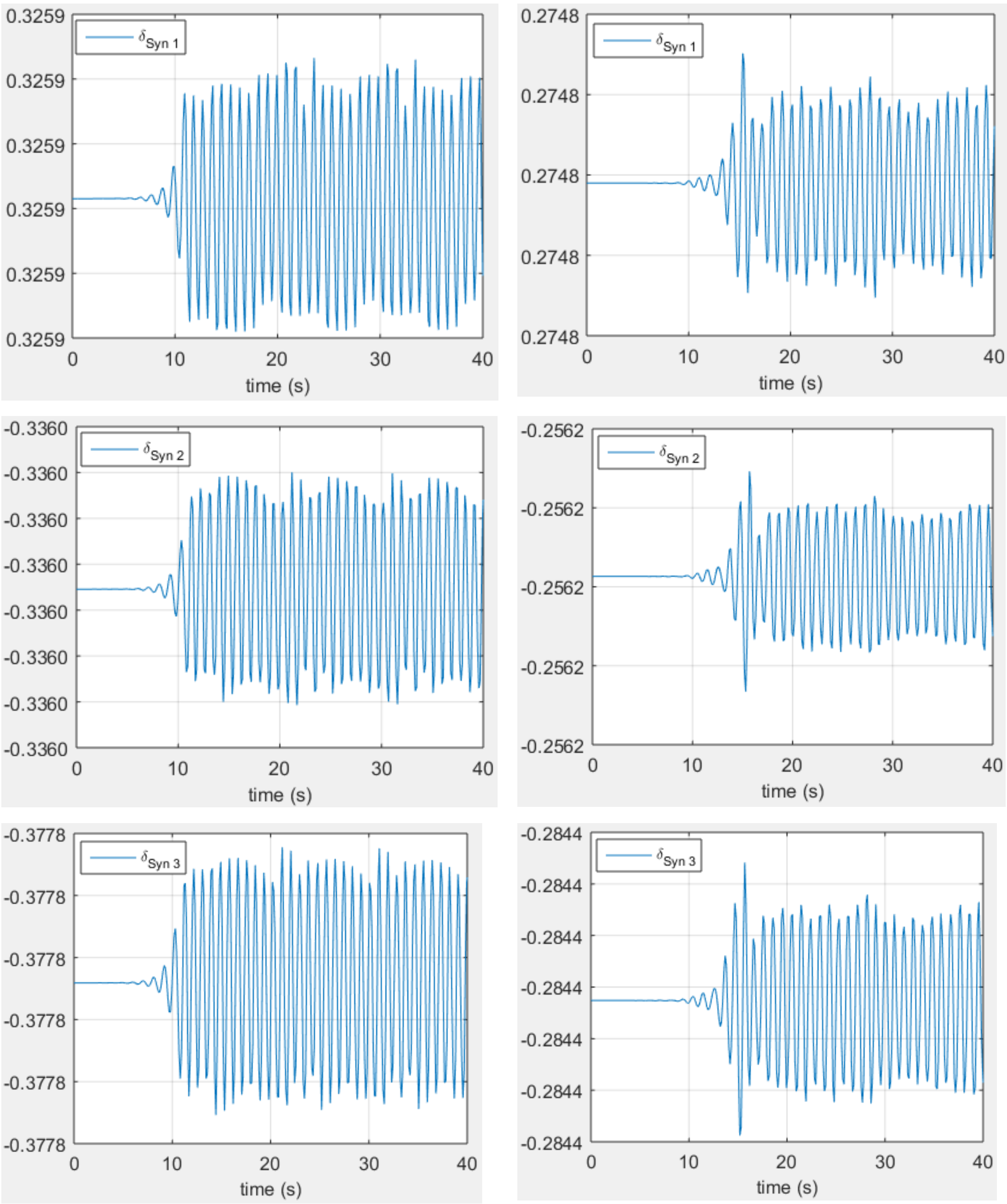
The only noticeable difference in the power profiles of systems without PV and system with PV is that bus 14 now supplies about 30 MW while there also a noticeable increase in the reactive power it absorbs as illustrated in Figure 4.6 (b). This reactive power is injected into the grid from the PV inverter.

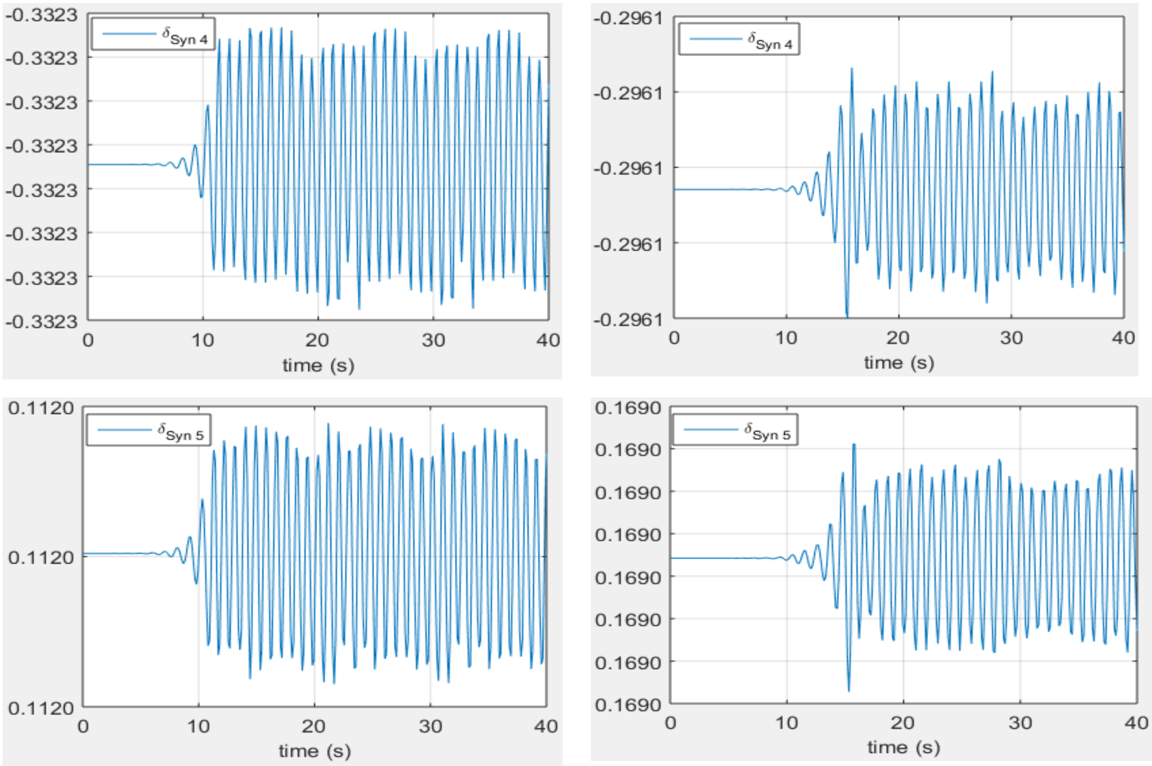
4.3.2 Dynamic flow studies on the IEEE 14-Bus System base case

This subsection presents the dynamic load flow simulation results. In this case dynamic simulation was performed without introducing any system events.

4.3.2.1 Rotor angle of generating units

Figure 4.7 presents the comparative analysis of the rotor speed profiles as a function of time for the 5 synchronous machines on the IEEE-14 bus system without and with PV connected at bus 14.





(a) (b)

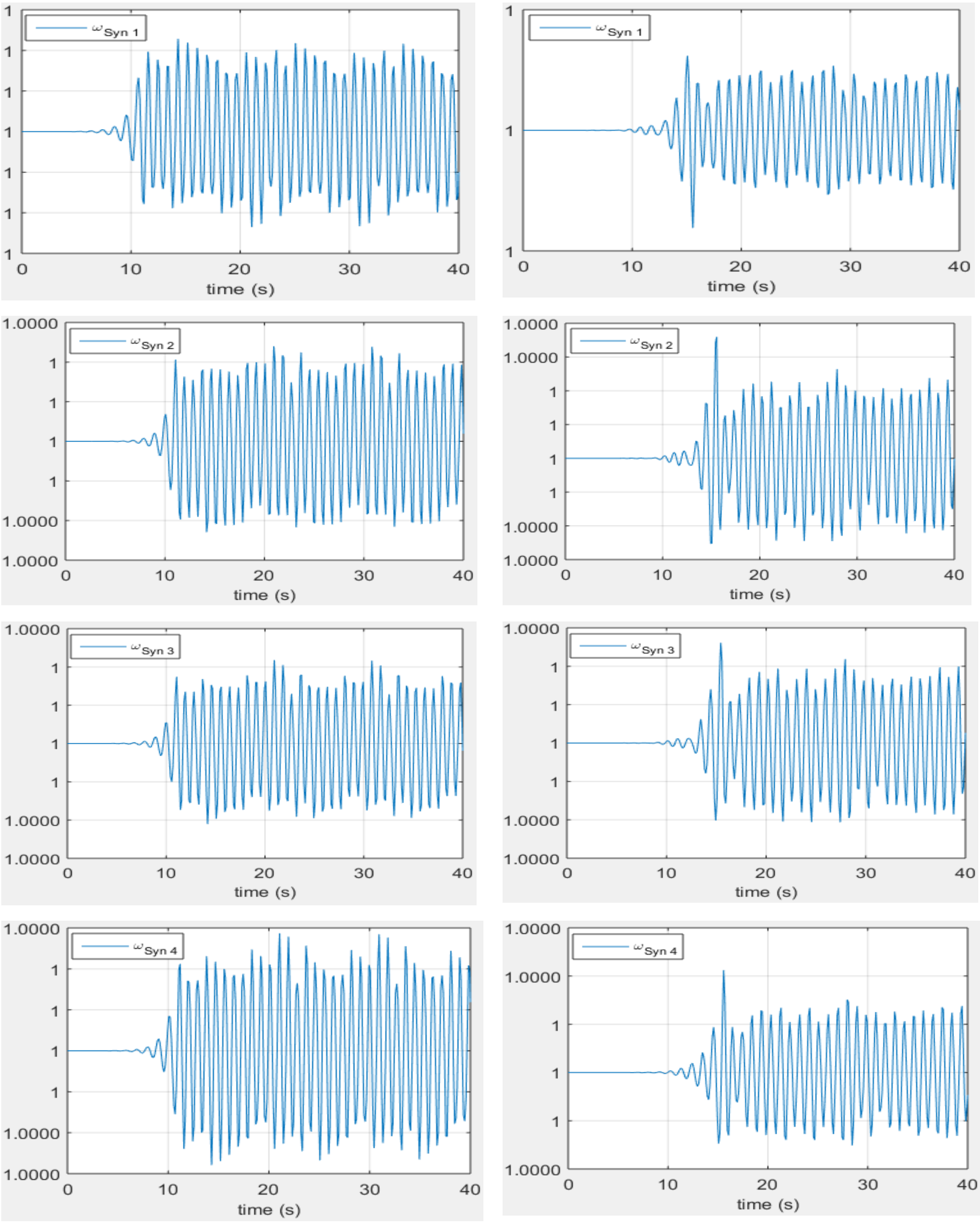
Figure 4.7: Rotor angle versus time plot of the IEEE-14 bus system without and with PV.

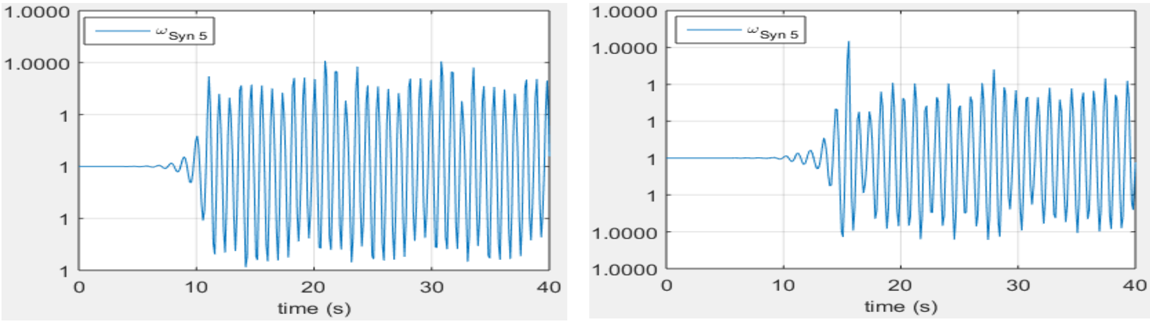
(a) δ versus time plot: system without PV (b) δ versus time plot: system with PV

The only noticeable difference is that the rotor angle oscillations start earlier, just before 10 s, for the system without PV as illustrated in Figure 4.7 (a). This is an indication that large-scale PV plants enhance the transient behaviour of the transmission system.

4.3.2.2 Rotor speed of generating units

Figure 4.8 presents the comparative analysis of the rotor angle profiles as a function of time for the 5 synchronous machines on the IEEE-14 bus system without and with PV connected at bus 14.


ωSyn 1
time (s)
ωSyn 1
time (s)
ωSyn 2
time (s)
ωSyn 2
time (s)
ωSyn 3
time (s)
ωSyn 3
time (s)
ωSyn 4
time (s)
ωSyn 4
time (s)



(a) (b)

Figure 4.8: Rotor speed versus time plot of the IEEE-14 bus system without and with PV. (a) ω versus time plot: system without PV. (b) ω versus time plot: system with PV.

The only noticeable difference is that the rotor speed oscillations start earlier, just before 10 s, for the system without PV as illustrated in Figure 4.8 (a). This is again an indication that large-scale PV plants enhance the transient behaviour of the transmission system.

4.4 IMPACT OF LARGE SCALE PV SYSTEMS ON THE IEEE 14-BUS TEST SYSTEM PERFORMANCE

The second step is to test the satisfactory performance of the IEEE 14-bus system model upon the integration of large-scale PV systems into the grid. A 50 MW PV plant is connected at bus 14 as suggested in [111]. No system disturbances are introduced at this stage. Using PSAT, the same power system analysis performed for the base case such as PF, CPF and TD analysis on the IEEE 14-bus system are repeated. The results are presented in Tables 4.4-4.6 and in the Figures 4.9-4.45. The active power, reactive power and voltage values are given on the system of 100 MVA and 60 Hz base. Based on the results presented below, the power system is still found to be stable following the integration of the large-scale PV system.

4.4.1 Static load flow studies on the IEEE 14-Bus System with PV connected

This subsection presents the static load flow simulation results.

4.4.1.1 Statistics and global summary report

Tables 4.4 and 4.5 present solution statistics and the global summary report, respectively. The network statistics results remain the same as in Table 4.1.

Table 4.4 presents PSAT's computational performance in terms of the number of iterations undertaken to conclude simulations and the minimum convergence error. The real and active power mismatch parameters are an indication of accuracy between input and computed network data. A low convergence error as shown in this table is an indication of high accuracy network performance level.

Table 4.4: Solution statistics.

Number of Iterations	4
Maximum P mismatch [MW]	8.49×10^{-10}
Maximum Q mismatch [MVAr]	4.05×10^{-09}
Power rate [MVA]	100

Table 4.5 presents the real and reactive power profiles in terms of total generation, load demand and network losses. The summation of total load demand and total losses adds up to total generation available in the IEEE-14 bus system with the 50 MW PV plant connected at bus 13.

Table 4.5: Global summary report.

Power	Total Generation	Total Load	Total Losses
Real power [MW]	385.72	362.6	23.12
Reactive power [MVAr]	172.62	113.82	58.8

4.4.1.2 Power flow results with PV connected

Table 4.6 presents the voltage, generator and the load profiles for the 14-buses on the IEEE-14 bus system with the 50 MW PV plant connected at bus 13.

Table 4.6: Power Flow Results with PV connected.

Bus	V [kV]	Phase [rad]	P_{gen} [MW]	Q_{gen} [MVAr]	P_{load} [MW]	Q_{load} [MVAr]
Bus01	73.14	0	294.7682	-25.5987	0	0
Bus02	72.105	-0.11412	40	70.88223	30.38	17.78
Bus03	69.69	-0.29572	3.09E-12	52.3808	131.88	26.6
Bus04	69.70487	-0.21981	-8.7E-10	1.13E-09	66.92	5.46
Bus05	69.99695	-0.18521	4.4E-10	3.87E-09	10.64	2.24
Bus06	14.766	-0.27222	1.46E-09	66.98575	15.68	10.5
Bus07	14.51173	-0.26166	3.73E-10	5.8E-10	0	0
Bus08	19.62	-0.26166	-4.6E-14	23.77726	0	0
Bus09	14.32584	-0.28356	4.85E-10	1E-09	41.3	23.24
Bus10	14.56604	-0.27801	4.28E-10	1.9E-10	12.6	8.12
Bus11	14.65637	-0.27535	3.01E-10	-2.7E-12	4.9	2.52
Bus12	14.42366	-0.26918	1.75E-13	2.2E-13	8.54	2.24
Bus13	14.421	-0.24564	50	-21.2388	18.9	8.12
Bus14	14.00617	-0.29219	1.8E-10	2.51E-11	20.86	7

4.5 IMPACT OF LARGE SCALE PV SYSTEMS ON THE IEEE 14-BUS TEST SYSTEM FOLLOWING DISTURBANCES

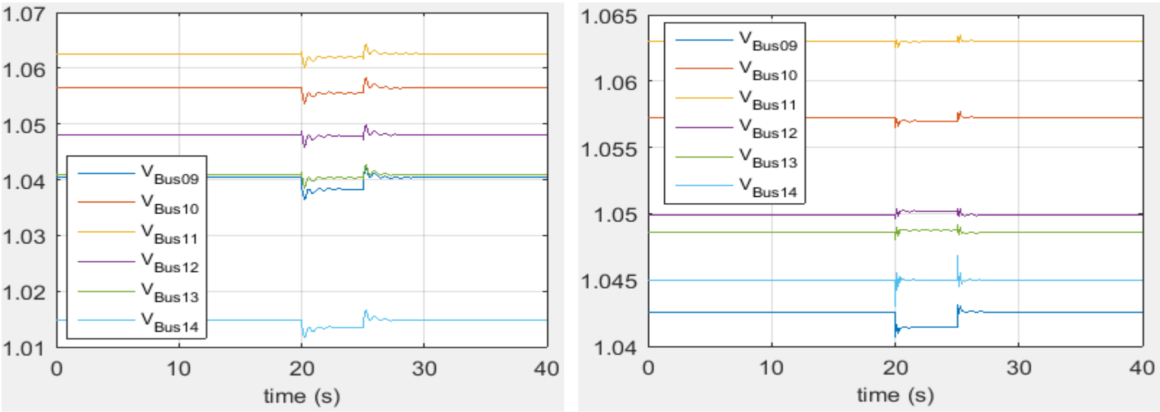
The third step is to test the performance of the IEEE 14-bus system following disturbances. This is done using PF, CPF and TD analysis for both the base case system and the system integrated with large-scale PV plants. The results are presented as follows.

4.5.1 Power quality simulations

The results presented in this section are for power quality investigations in terms of power system voltage, rotor angle and frequency stability following a disturbance. The disturbances considered are the operations for breaker 1 (located between buses 5 and 6), breaker 2 (located between buses 4 and 9) and breaker 3 (located between buses 4 and 7).

4.5.1.1 Bus voltage magnitude profiles

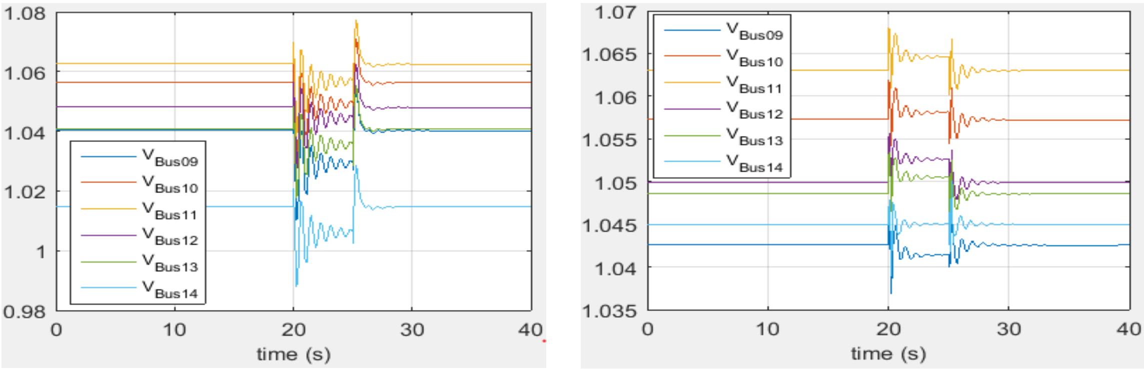
The results presented in this sub-section in Figures 4.9-4.11 are for power quality investigation in terms of power system voltage in a system without large-scale PV plants and with a large-scale PV plant connected at bus 14.



(a) (b)

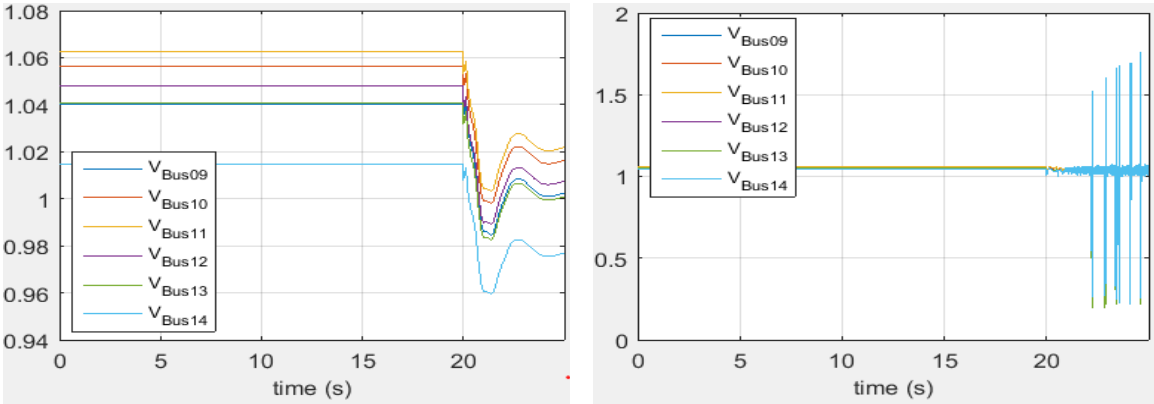
Figure 4.9: Bus voltages (p.u.) when breaker 1 is activated.

(a) Breaker 1 activated without PV. (b) Breaker 1 activated with PV.



(a) (b)

Figure 4.10: Bus voltages (p.u.) when breaker 1 and 2 are activated.
(a) Breaker 1 and 2 activated without PV. (b) Breaker 1 and 2 activated with PV.



(a) (b)

Figure 4.11: Bus voltages (p.u.) when breaker 1, 2 and 3 are activated.
(a) Breaker 1, 2 and 3 activated without PV. (b) Breaker 1, 2 and 3 activated with PV.

As illustrated in Figures 4.9 (a)-4.11(a), the voltage levels in the system without large-scale PV plants dropped significantly when the breaker is opened followed by prolonged oscillations when the breaker is re-closed. The system without large-scale PV plants also takes much longer to attain stability.

On the other hand, with large-scale PV systems connected, only a slight drop in voltage levels could be noticed when the breaker is opened and very minimal oscillations can be observed after the breaker is reclosed. The system takes much quicker to re-gain stability. This is illustrated in Figures 4.9 (b)-4.11(b).

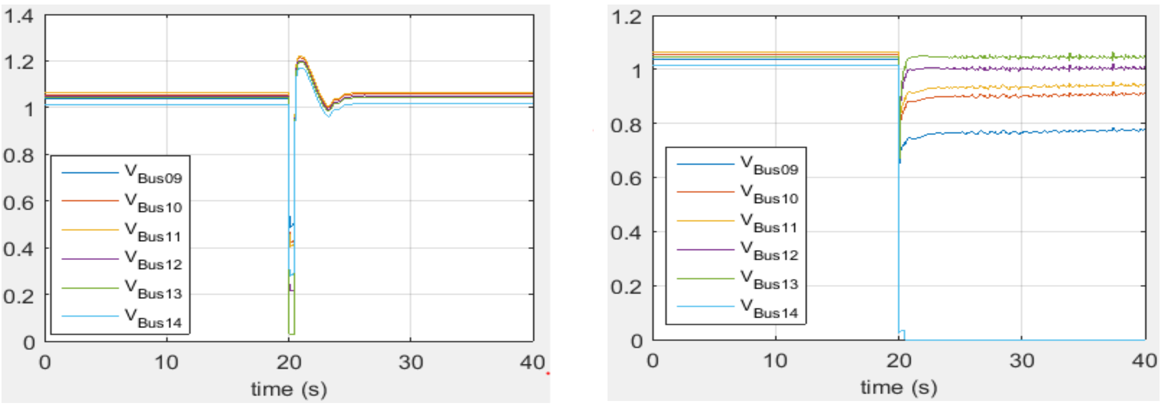
In the case of opening three breakers, simulation is stopped at t = 25 s due to singularity as shown in Figure 4.11. The network also becomes divided into two islanded networks with:

- sub-network 1 consisting of 5 buses and 3 generators, and
- sub-network 2 consisting of 9 buses and 2 generators.

4.5.2 Voltage stability simulations

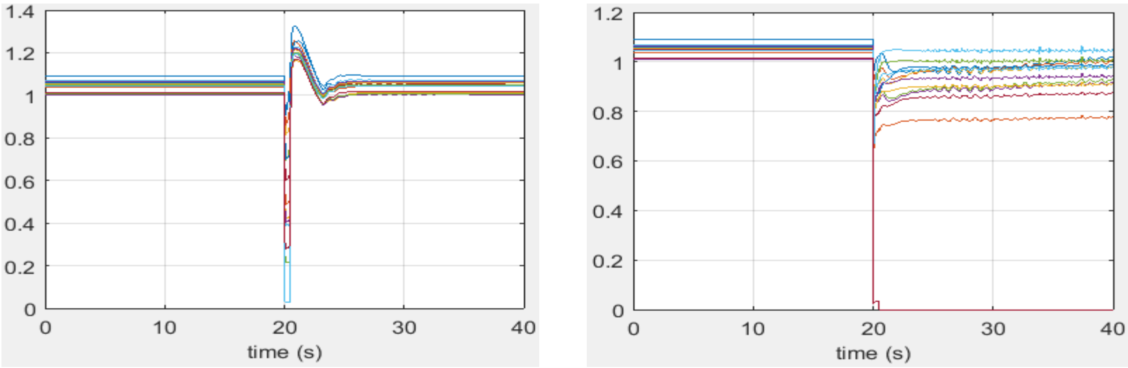
4.5.2.1 Fault contingency simulations

In this subsection, the simulation results in Figure 4.12 are presented to demonstrate the performance of the system following a 20 MW, 13.8 kV, 0.5 s three phase to ground fault on bus 13. The fault is introduced at t = 20 s and lasts for a period of 5 s before it is cleared at t = 25 s. As illustrated in Figures 4.12 (a) and 4.13 (b), the system without PV recovers promptly from the voltage collapse situation following this three phase fault. However, as shown in Figure 4.12 (b), this three phase fault has a severe impact on a system with a PV plant. The oscillations that follow the post-fault clearance are an indication of the system's failure to regain stability.



(a) (b)

Figure 4.12: Bus voltages (p.u.) during a three phase fault.
(a) Without PV. (b) With PV in PV mode.

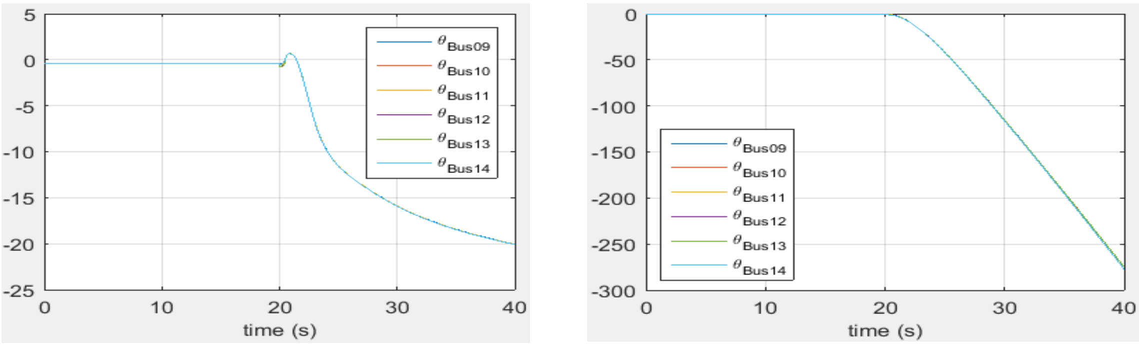


(a) (b)

Figure 4.13: All 14 bus voltages (p.u.) during a three phase fault.

(a) without PV. (b) with PV.

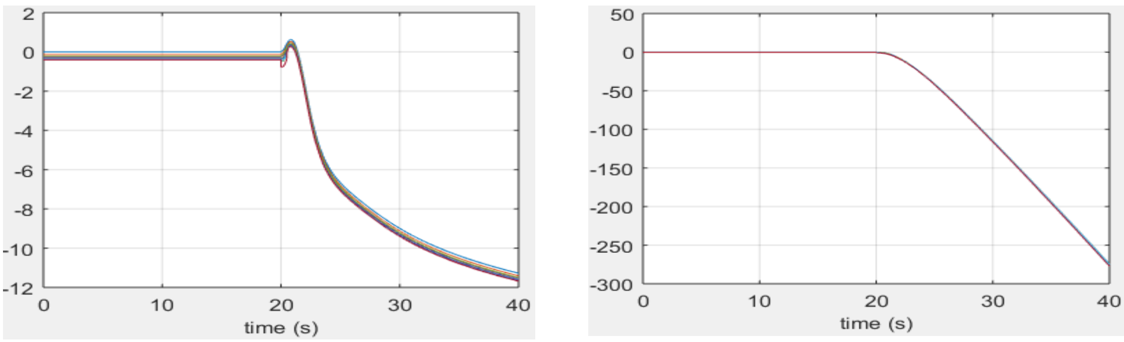
The bus angles plot illustrated in Figures 4.14 and 4.15 show that the system without PV attempts recovery following a fault but the impact it is still clear that the impact is still worse in the system with PV.



(a) (b)

Figure 4.14: Bus angles (in radians) during a three phase fault.

(a) without PV. (b) with PV.



(a) (b)

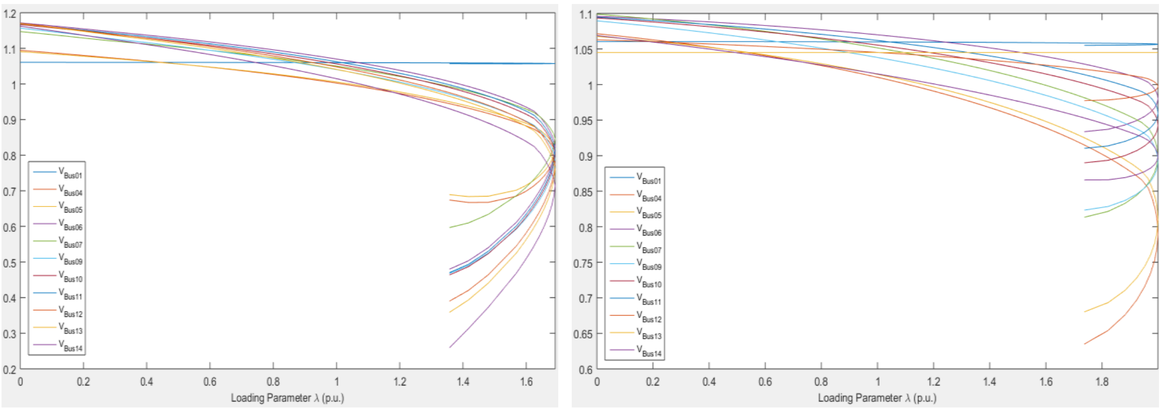
Figure 4.15: All bus angles (in radians) during a three phase fault.

(a) without PV. (b) with PV.

4.5.2.2 Line outage contingency simulations

The results presented in this section are for voltage stability investigation following a line outage contingency. The contingencies considered are the operations for breaker 1 (outage of line 5-6), breaker 2 (outage of line 4-9) and breaker 3 (outage of line 4-7).

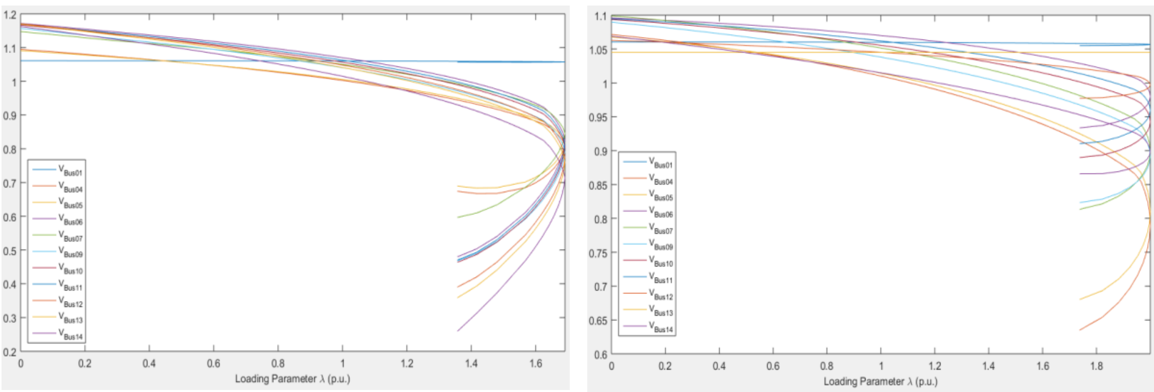
For the systems without PV, the maximum loading parameter is 1.6913 for CPF completed in 2.3635 s. On the other hand, for the systems with PV, the maximum loading parameter is 1.9995 for CPF completed in 2.6126 s. Figures 4.16 (a)-4.19 (a) shows that the system with PV possesses a higher loading margin in comparison to the one without PV.



(a) (b)

Figure 4.16: Voltage profile (p.u.) – normal condition without and with PV.

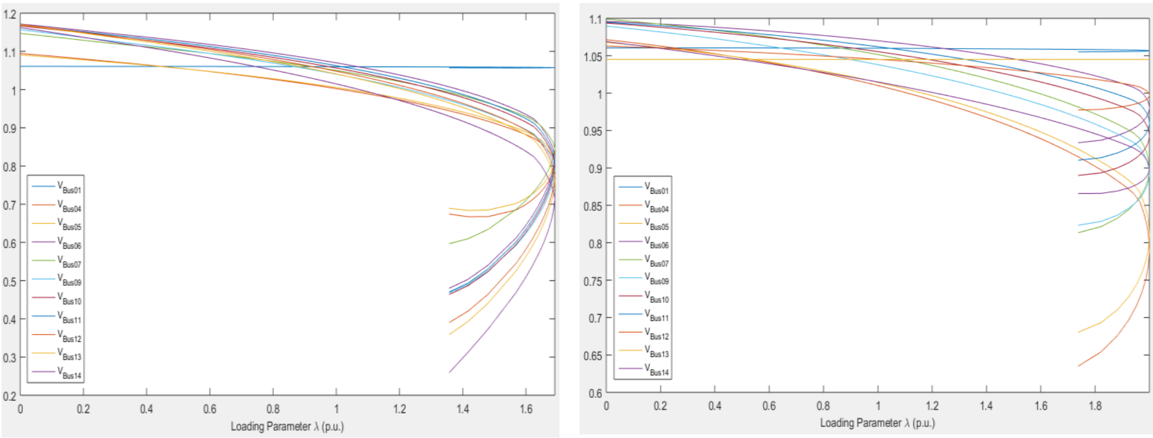
(a) Normal condition without PV. (b) Normal condition with PV.



(a) (b)

Figure 4.17: Voltage profile (p.u.) – breaker 1 operated.

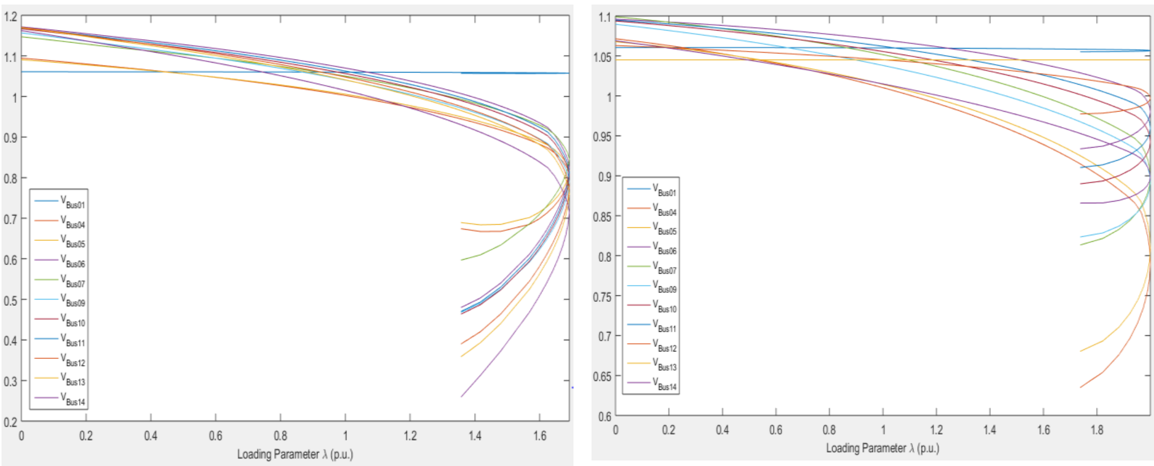
(a) Breaker 1 operated without PV. (b) Breaker 1 operated with PV.



(a) (b)

Figure 4.18: Voltage profile (p.u.) – breaker 1 and 2 operated.

(a) Breaker 1 and 2 operated without PV. (b) Breaker 1 and 2 operated with PV.



(a) (b)

Figure 4.19: Voltage profile (p.u.) – breaker 1, 2 and 3 operated with PV.

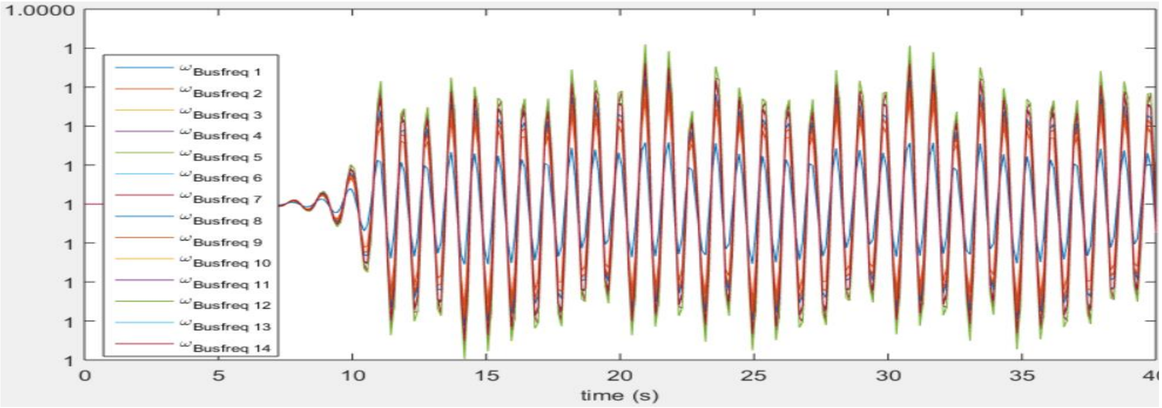
(a) Breaker 1, 2 and 3 operated without PV. (b) Breaker 1, 2 and 3 operated with PV.

4.5.3 Frequency stability simulations

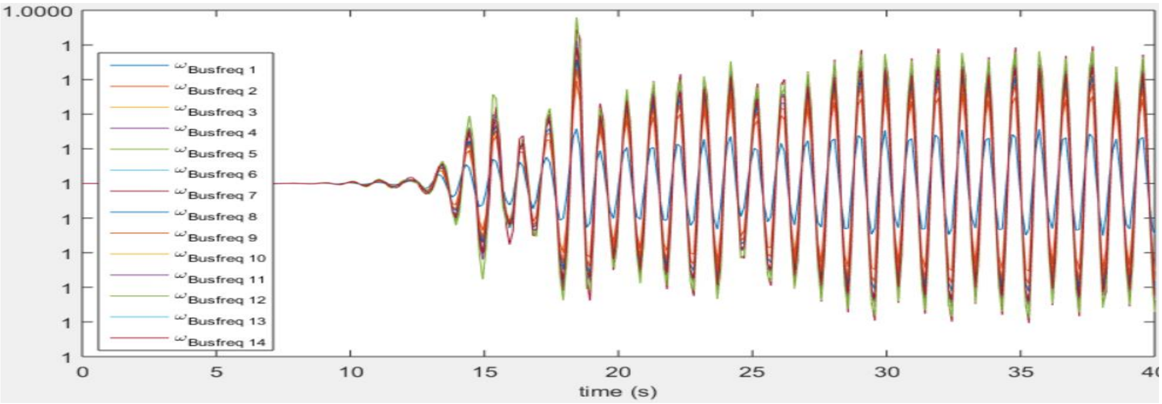
4.5.3.1 Impact of increased penetration of large-scale PV systems on system's frequency

The simulations presented in this subsection are a demonstration of the impact that increased penetration of large-scale PV systems has on the system's frequency. As illustrated in Figure

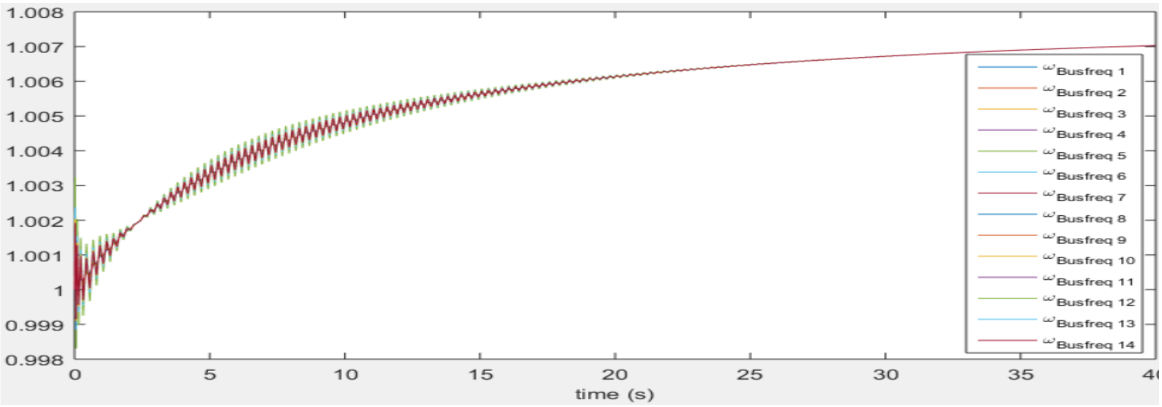
4.20 (b), the systems still remain stable when a 50 MW PV plant is added at bus 13. Figure 4.20 (c) illustrates that increasing the capacity of the PV plant to 60 MW leads to frequency instability.



(a)



(b)



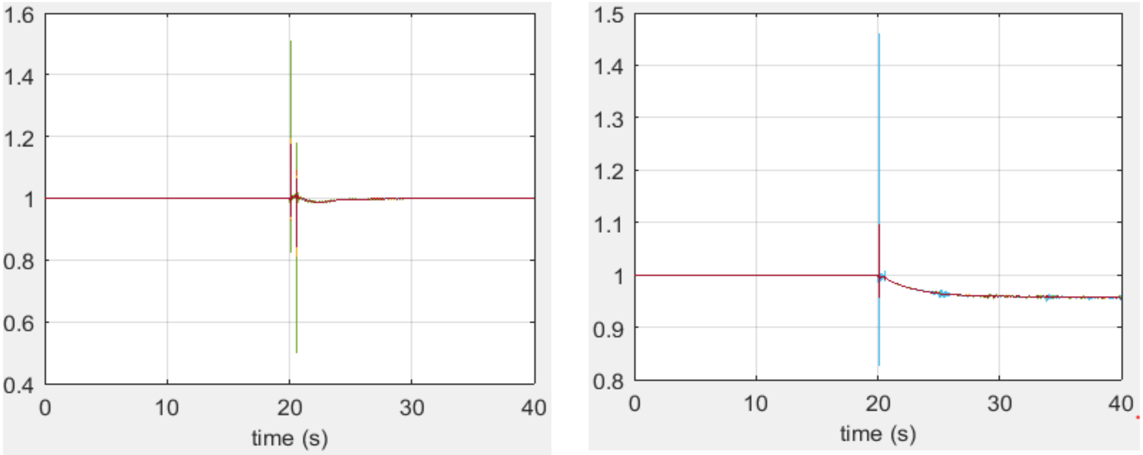
(c)

Figure 4.20: Bus frequencies (in Hz) in the IEEE-14 bus system.

(a) without PV. (b) with a 50 MW PV plant. (c) with a 60 MW PV.

4.5.3.2 Impact of large-scale PV system on frequency following a fault

The simulation results in Figure 4.21 are presented to demonstrate the response of the base and the system with large-scale PV to a 20 MW, 13.8 kV, 0.5 s three phase to ground fault on bus 14. The fault is introduced at t = 20 s and lasts for a period of 5 s before it is cleared at t = 25 s. As illustrated in Figure 4.21 (a), the base system recovers quickly from the frequency instability following this three phase fault. However, as shown in Figure 4.21 (b), this three phase fault has a severe impact on a system with a PV plant. The oscillations that follow the post-fault clearance are an indication of the system's failure to regain stability.



(a) (b)

Figure 4.21: Bus frequencies (in Hz) during a three phase fault.
(a) without PV. (b) with PV.

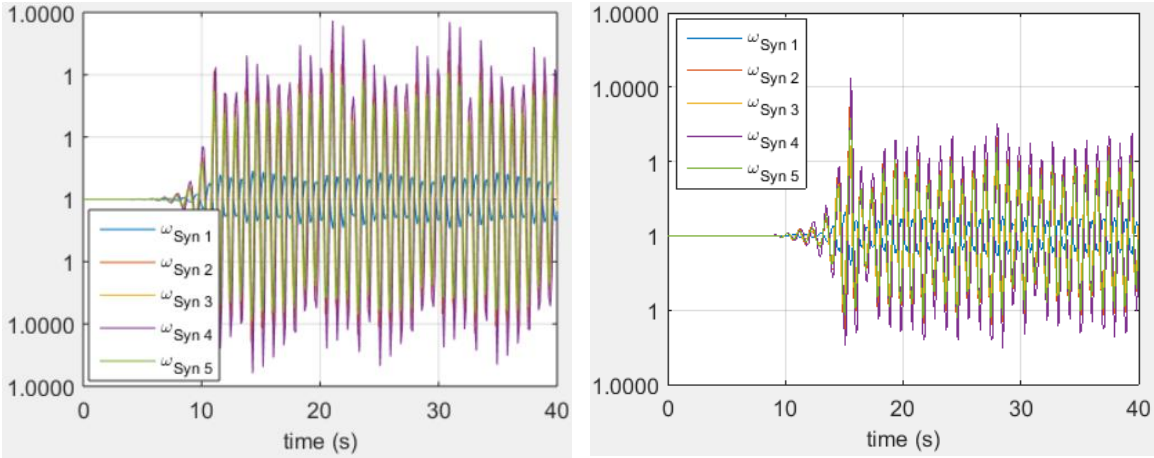
4.5.4 Rotor angle simulations

The results presented in this section are for rotor angle stability investigation following a contingency. The contingencies considered are disturbances in the system due to transmission line outage as a result of breaker operations and faults. The breaker operations to be simulated are for breaker 1 (outage of line 5-6), breaker 2 (outage of line 4-9) and breaker 3 (outage of line 4-7). A 20 MW, 13.8 kV, 0.5 s three phase to ground fault is simulated on bus 14.

4.5.4.1 Case 1 – Simulations without any contingencies

Time domain simulations are performed with and without introducing any large-scale PV systems in the grid. The system is observed to be stable for both scenarios.

Figure 4.22 shows the rotor speed profiles as a function of time for the 5 synchronous machines.

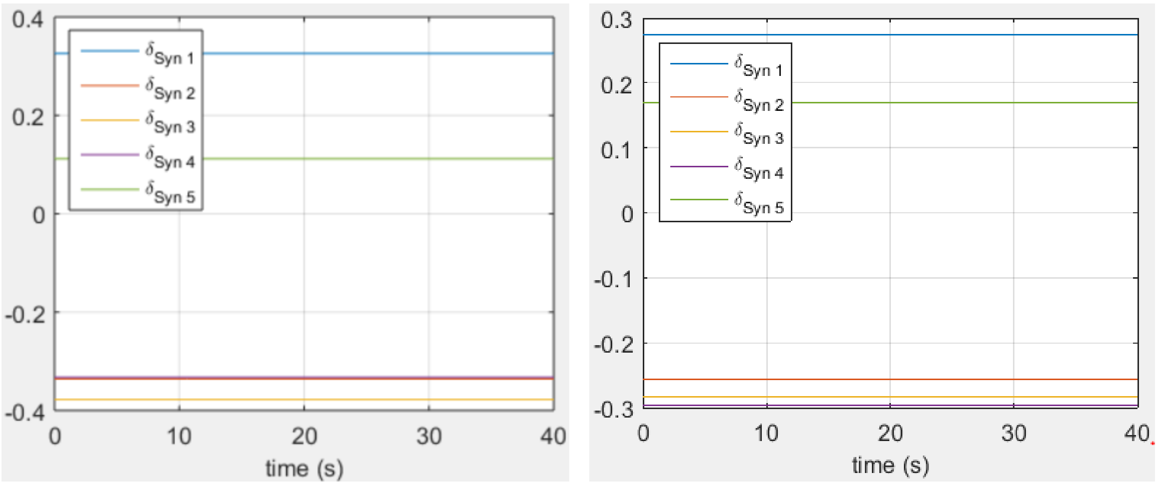


(a) (b)

Figure 4.22: ω (in percent per unit) versus time plot.

(a) without PV. (b) with PV.

Figure 4.23 shows the rotor angle profiles as a function of time for the 5 synchronous machines.



(a) (b)

Figure 4.23: δ (in radians) versus time plot.

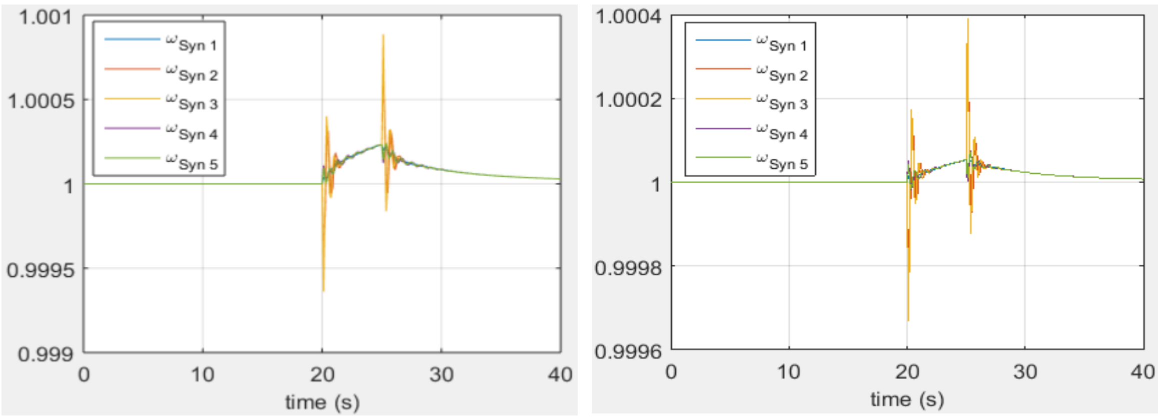
(a) without PV. (b) with PV.

When a large-scale 50 MW plant is connected at bus 13, the system is still observed to be stable. Figure 4.22 (b) shows the rotor speed profiles as a function of time for the 5 synchronous machines in a system integrated with large-scale PV systems. Figure 4.23 (b) shows the rotor angle profiles as a function of time for the 5 synchronous machines in a system integrated with large-scale PV systems.

4.5.4.2 Case 2 – Simulation with breaker operation contingency

In this instance, breaker operations are simulated are for breaker 1 (outage of line 5-6), breaker 2 (outage of line 4-9) and breaker 3 (outage of line 4-7) for base case system and the system with large-scale PV plants.

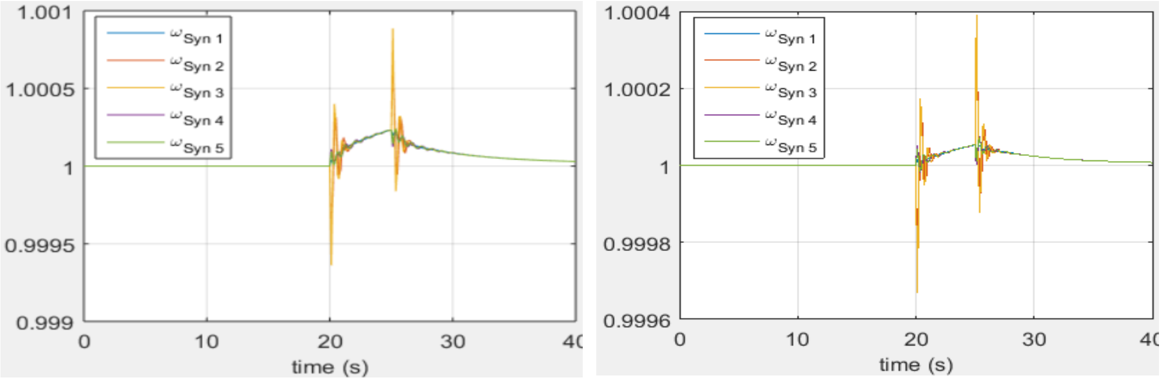
Based on rotor speed simulation results illustrated in Figures 4.24-4.28, it clear that the system with a large-scale PV system has better chance of regaining stability following a breaker operation contingency.



(a) (b)

Figure 4.24: ω (rad/s) versus time plot – Breaker 1 operated.

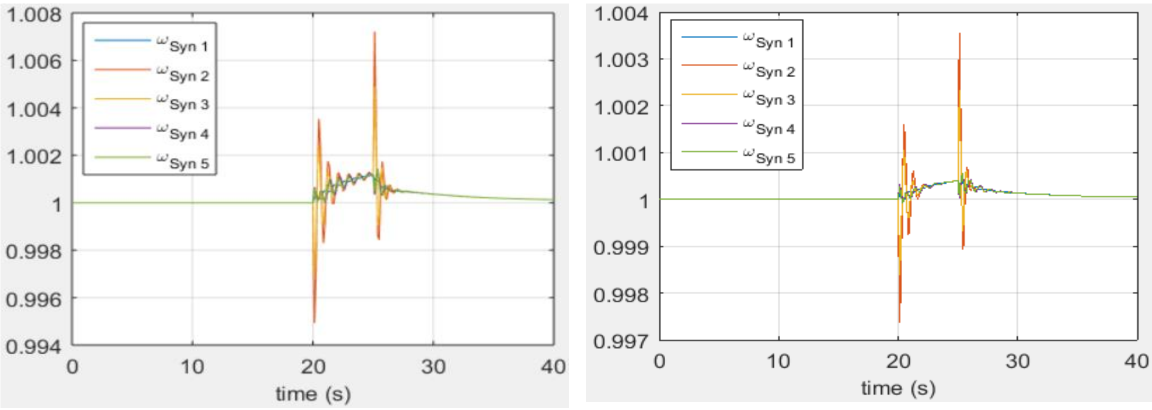
(a) without PV. (b) with PV.



(a) (b)

Figure 4.25: ω (rad/s) versus time plot – Breaker 2 operated.

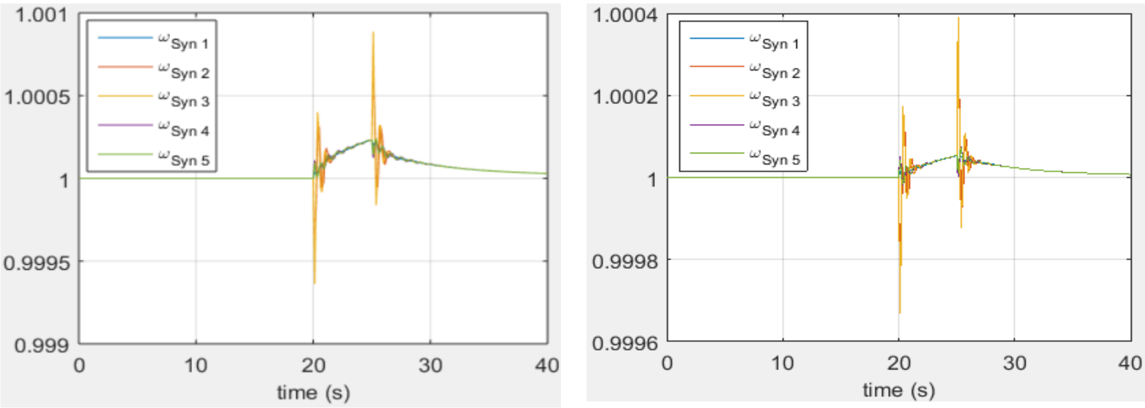
(a) without PV. (b) with PV



(a) (b)

Figure 4.26: ω (rad/s) versus time plot – Breaker 1 and 2 operated.

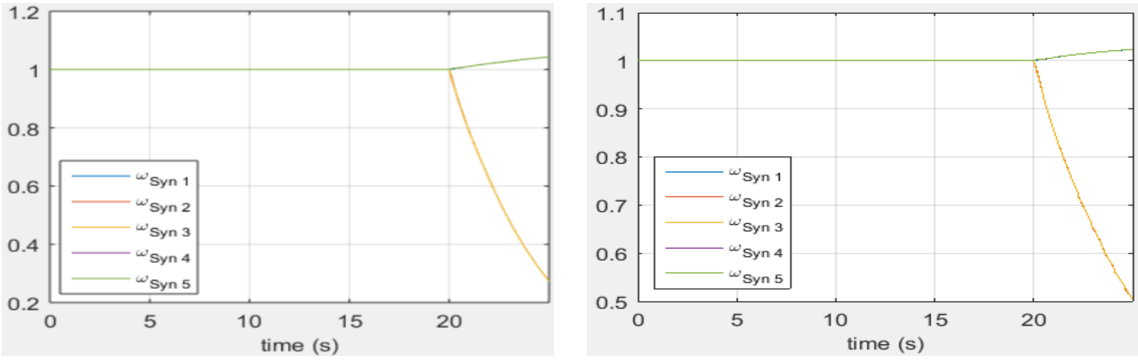
(a) without PV. (b) with PV.



(a) (b)

Figure 4.27: ω (rad/s) versus time plot – Breaker 3 operated.

(a) without PV. (b) with PV.

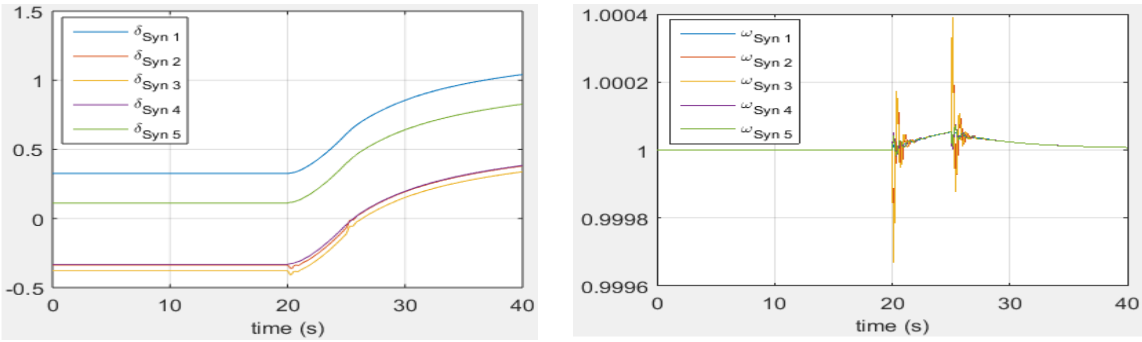


(a) (b)

Figure 4.28: ω (rad/s) versus time plot – Breaker 1, 2 and 3 operated.

(a) without PV. (b) with PV.

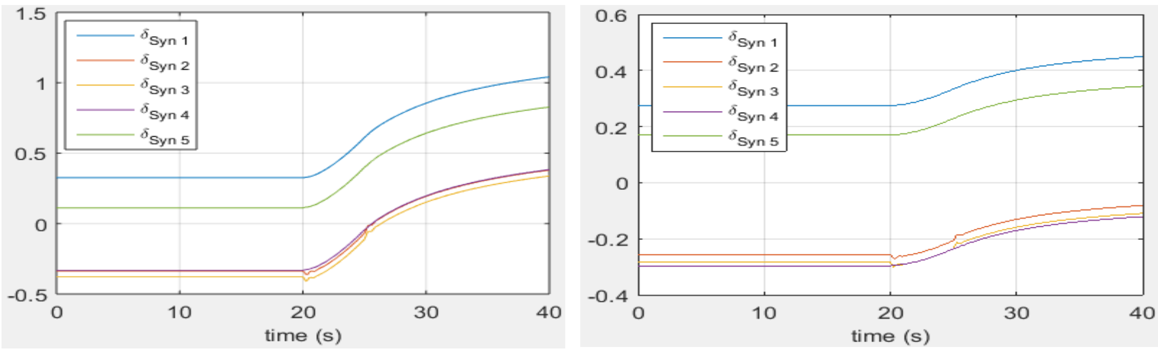
Figures 4.29-4.33 present the rotor angle response to breaker operation contingency. Although synchronism is not regained in both scenarios, it is clear that the severity of this transient disturbance is worse in a system without large-scale PV systems.



(a) (b)

Figure 4.29: δ (in radians) versus time plot – Breaker 1 operated.

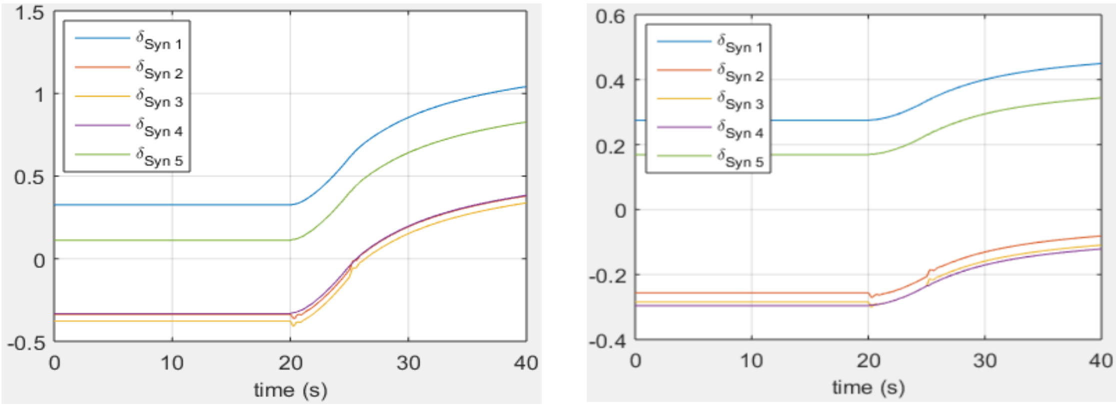
(a) without PV. (b) with PV



(a) (b)

Figure 4.30: δ (in radians) versus time plot – Breaker 2 operated.

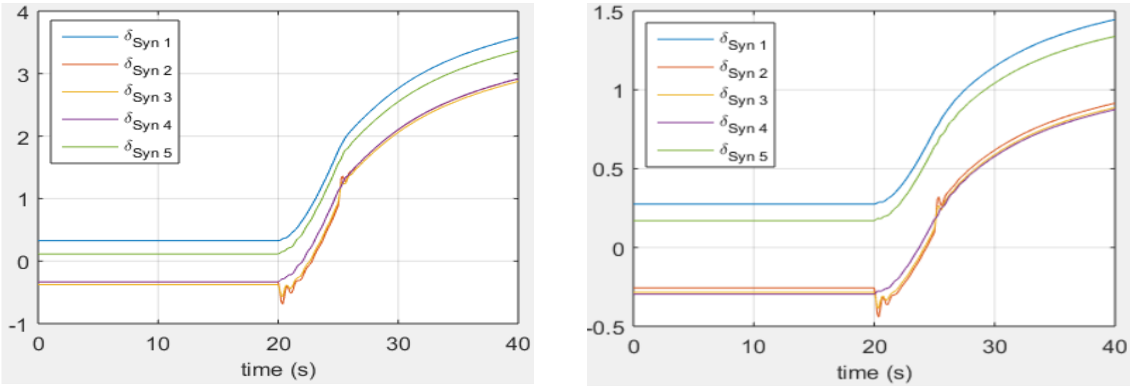
(a) without PV. (b) with PV.



(a) (b)

Figure 4.31: δ (in radians) versus time plot – Breaker 3 operated.

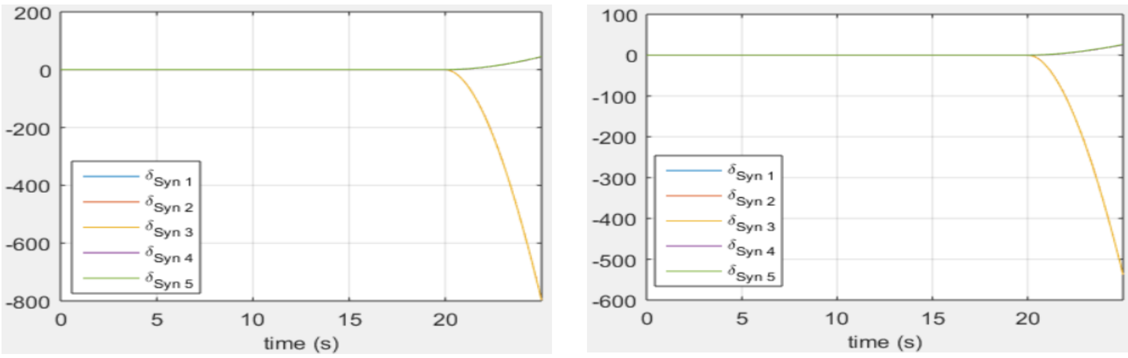
(a) without PV. (b) with PV.



(a) (b)

Figure 4.32: δ (in radians) versus time plot – Breaker 1 and 2 operated.

(a) without PV. (b) with PV.



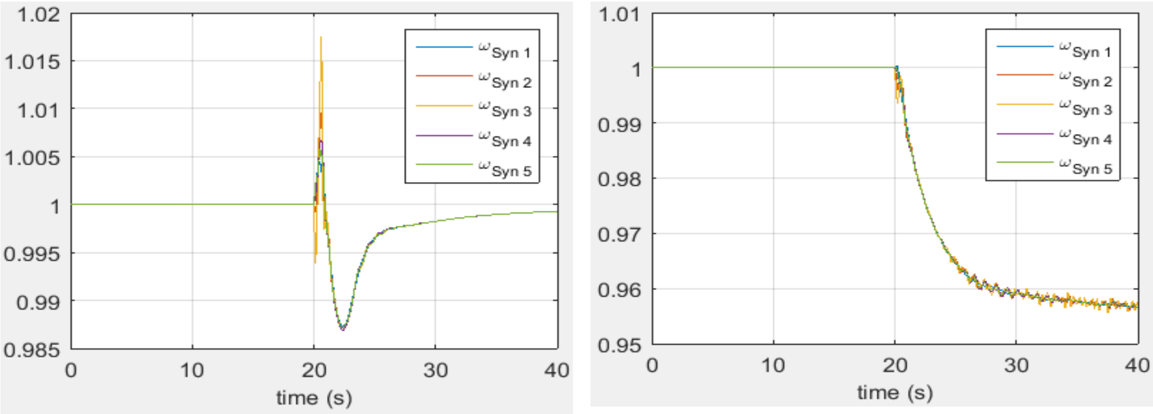
(a) (b)

Figure 4.33: δ (in radians) versus time plot – Breaker 1, 2 and 3 operated.

(a) without PV. (b) with PV.

4.5.4.3 Case 3 – Simulation with fault condition contingency at bus 14

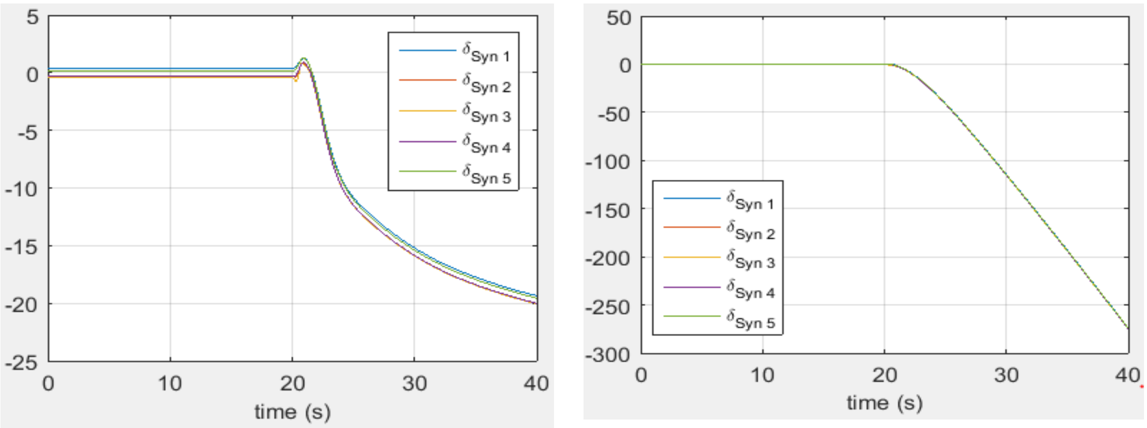
A 20 MW, 13.8 kV, 0.5 s three phase to ground fault is simulated on bus 14. Figures 4.34 and 4.35 present the rotor speed and angle response to the fault contingency, respectively. The system without large-scale PV systems responds better to a fault in terms of restoring the rotor speed and angle to the nominal value. On the other hand, the system with a large-scale PV connected at bus 13 completely loses synchronism.



(a) (a)

Figure 4.34: ω (rad/s) versus time plot – fault at bus 14.

(a) without PV. (b) with PV.



(a) (b)

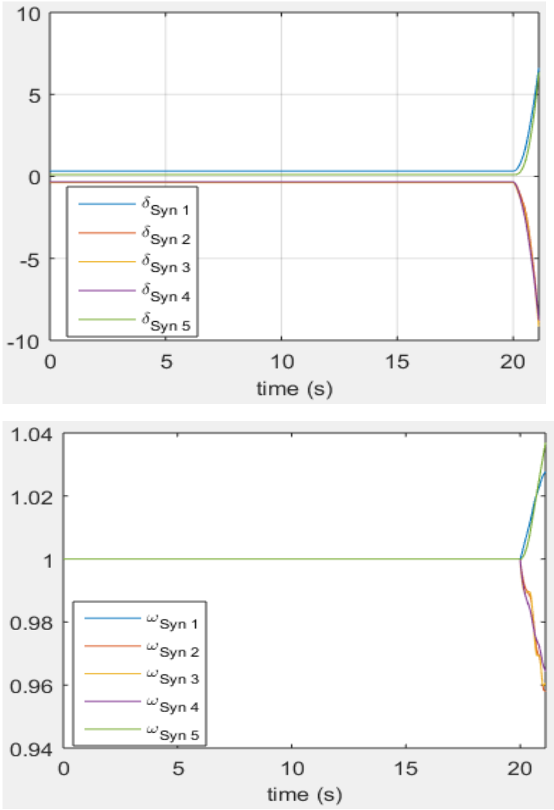
Figure 4.35: δ (in radians) versus time plot - fault at bus 14.

(a) without PV. (b) with PV.

Although synchronism is not regained in both scenarios, it is clear from Figure 4.35 that the severity of this transient disturbance is worse in a system without large-scale PV systems.

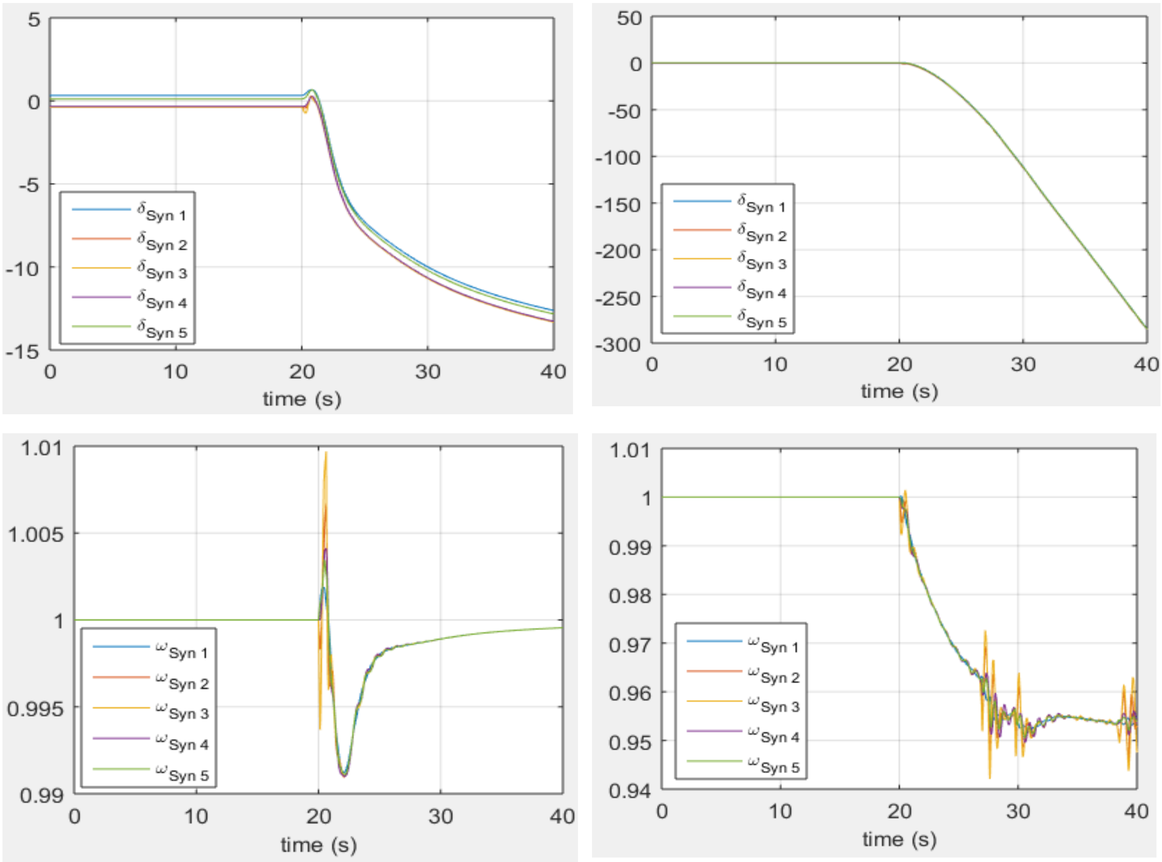
4.5.4.4 Case 4 - Simulation with fault condition contingency at bus 2 and 12

Figures 4.36 and 4.37 present the comparative analysis of the rotor angle and speed profiles following a fault for the 14-buses on the IEEE-14 bus system without and with PV connected at bus 14.



(a) (b)

Figure 4.36: Rotor angle (radians) and speed (rad/s) for fault at bus 2.
(a) without PV. (b) with PV.



(a) (b)

Figure 4.37: Rotor angle (in radians) and speed (rad/s) for fault at bus 12.
(a) without PV. (b) with PV.

It is again obvious from Figures 4.36 and 4.37 that the system with large-scale PV responds poorly to fault contingencies simulated on various buses.

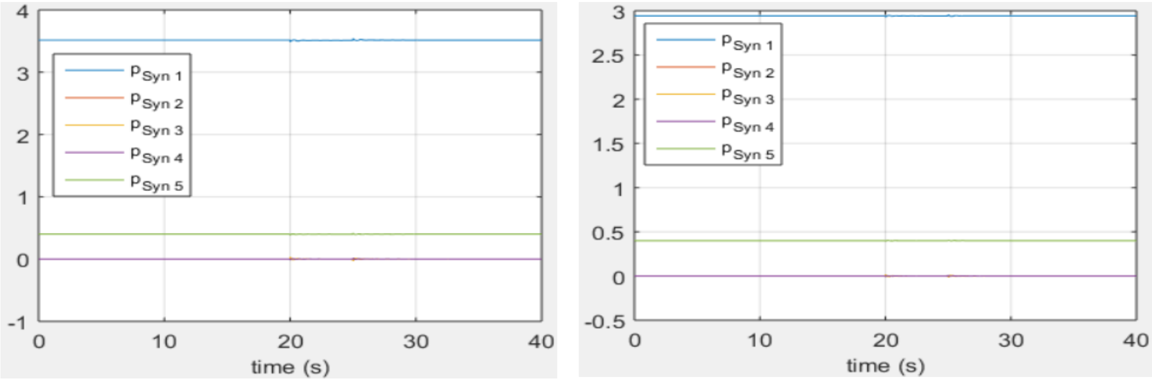
4.5.5 Impact of system contingencies on the generator power output

The results presented in this section are for the investigations of generator power output response to power system contingencies. The contingencies considered are disturbances in the system due to transmission line outage as a result of breaker operations and faults.

4.5.5.1 Real and reactive power output profiles following breaker operation

The breaker operations to be simulated are for breaker 1 (outage of line 5-6), breaker 2 (outage of line 4-9) and breaker 3 (outage of line 4-7). The results as illustrated in Figures

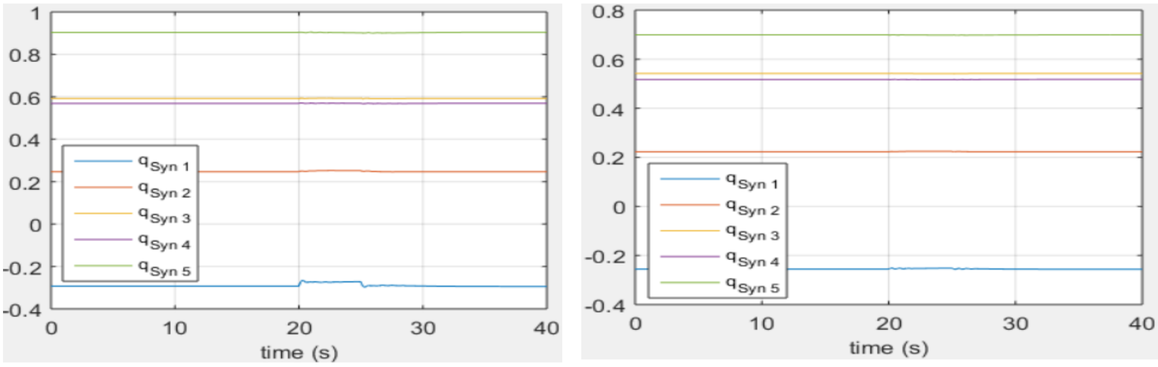
4.38-4.43 indicate that breaker operations results in negligible drop of the generator power output.



(a) (b)

Figure 4.38: Real power (p.u.) versus time plot – Breaker 1 operated.

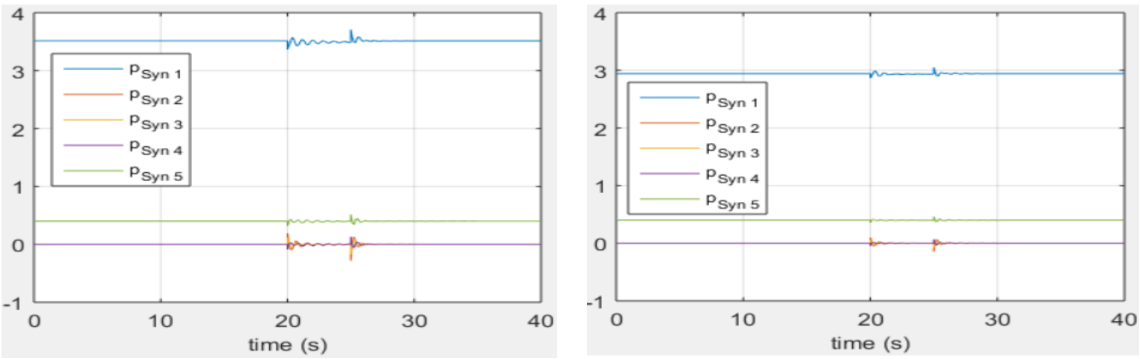
(a) without PV. (b) with PV.



(a) (b)

Figure 4.39: Reactive power (p.u) versus time plot – Breaker 1 operated.

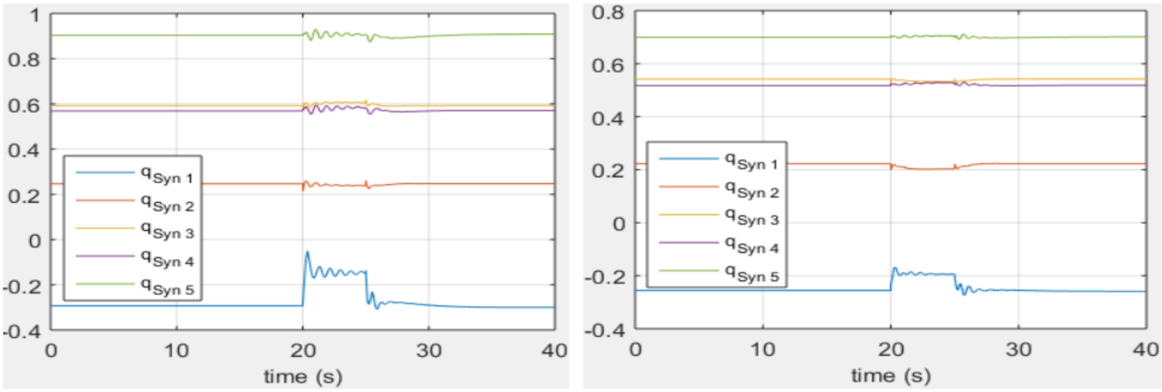
(a) without PV. (b) with PV.



(a) (b)

Figure 4.40: Real power (p.u.) versus time plot – Breaker 1 and 2 operated.

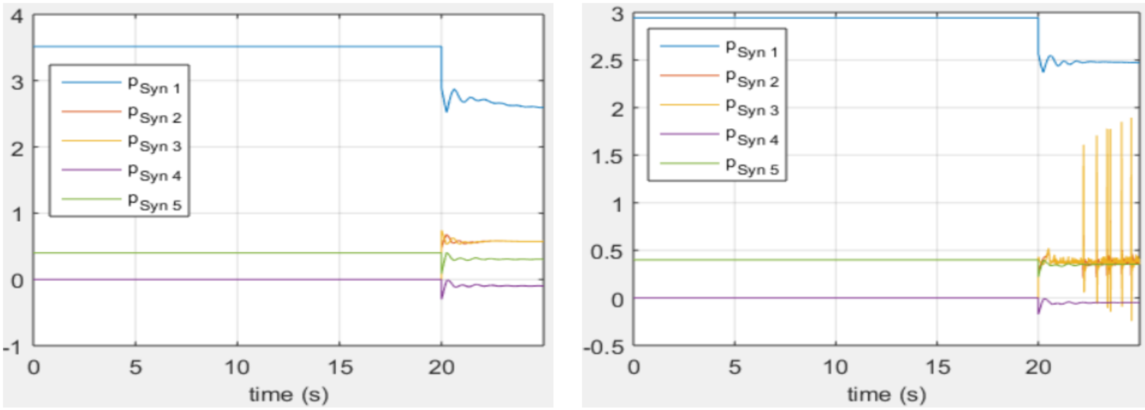
(a) without PV. (b) with PV.



(a) (b)

Figure 4.41: Reactive power (p.u.) versus time plot – Breaker 1 and 2 operated.

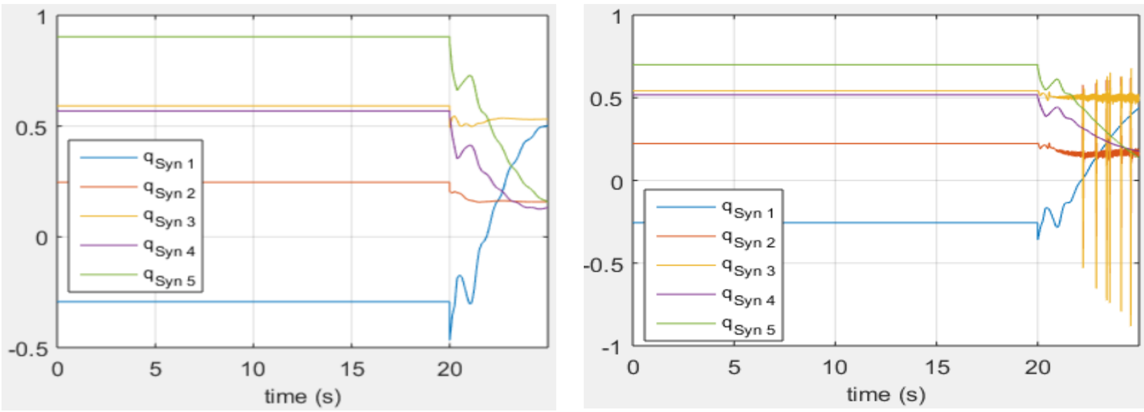
(a) without PV. (b) with PV.



(a) (b)

Figure 4.42: Real power (p.u.) versus time plot – Breaker 1, 2 and 3 operated.

(a) without PV. (b) with PV.



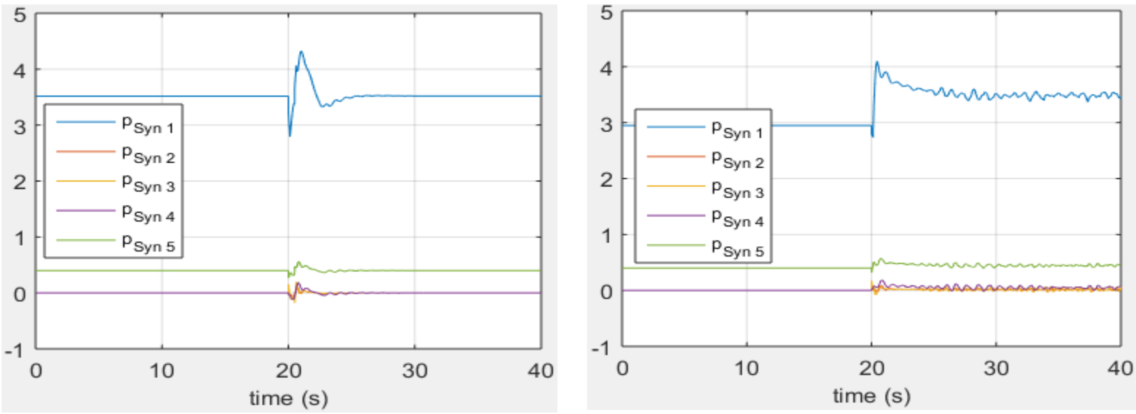
(a) (b)

Figure 4.43: Reactive power (p.u.) versus time plot – Breaker 1, 2 and 3 operated.

(a) without PV. (b) with PV.

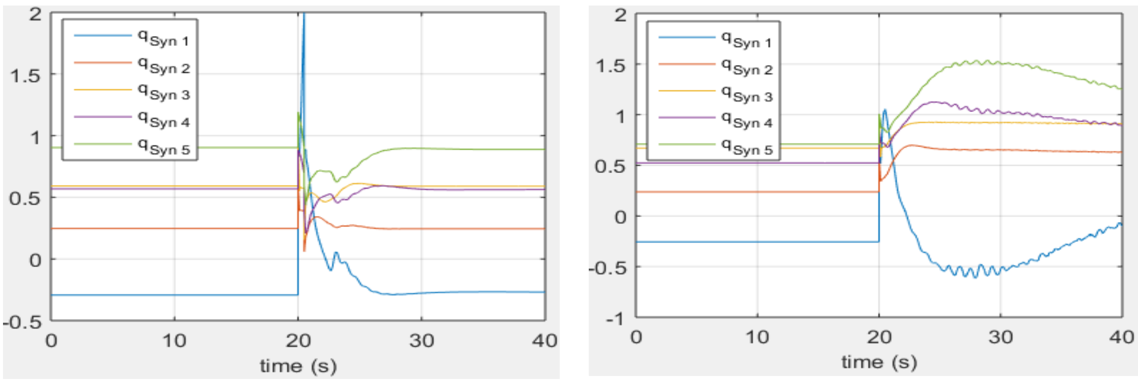
4.5.5.2 Real and reactive power output profiles following a fault

A 20 MW, 13.8 kV, 0.5 s three phase to ground fault is simulated on bus 14. As depicted in Figures 4.44 and 4.45, it is observed that the system without large-scale PV systems responds better to fault contingencies in terms of power output fluctuations following fault clearance.



(a) (b)

Figure 4.44: Real power (p.u.) versus time plot - fault at bus 14.
(a) without PV. (b) with PV.



(a) (b)

Figure 4.45: Reactive power (p.u.) versus time plot - fault at bus 14.
(a) without PV. (b) with PV.

4.6 CHAPTER SUMMARY

In this chapter the results of all simulations and experiments conducted to demonstrate the role of generation dispatch in overcoming challenges posed by increased penetration of large-scale photovoltaic (PV) systems in sub-transmission and transmission systems were presented.

The Power System Analysis Toolbox (PSAT) model of the IEEE 14-bus system was also introduced. An overview of the power system modelling, design and analysis in PSAT was presented. The power system methods of power flow (PF), continuation power flow (CPF) and time domain (TD) analysis used in the testing and evaluation of the power system network were also presented. The performance of the IEEE 14-bus system base case model was evaluated without introducing any system disturbances before the integration of large-scale PV systems into the grid (base case) and after the integration of large-scale PV systems into the grid without introducing any disturbances. A comparative analysis of the power systems' response to power system disturbances was performed on both the base case system and the system integrated with large-scale PV systems.

CHAPTER 5 DISCUSSION

5.1 CHAPTER OBJECTIVES

This chapter provides an interpretation and description of the significance of the research findings in light of what was already known about the role of generation dispatch with large-scale PV systems in solving power system stability problems. In consideration of the new findings, the discussion also present new explanations on the understanding and insights about generation dispatch strategy and spinning/non-spinning reserve methods in solving challenges posed by grid-connected large-scale PV systems as opposed to the commonly used approaches of power system voltage, rotor angle and frequency control methods.

Furthermore, an in-depth analysis is carried out on the experimental results from various simulations conducted to test the concept of generation dispatch with large-scale PV systems. These range from comparative analysis of the research findings and findings from existing literature on the technical and economic impacts of large-scale PV systems on the sub-transmission and transmission grid to the applicable solutions thereof. The application of generation and economic dispatch as a solution to the impacts of grid-integrated large-scale PV systems are analysed in detail and the key concepts behind these techniques described.

In Section 5.2 the research problem and major findings were presented. It was found that generation dispatch strategy and spinning reserve techniques were equally effective in overcoming challenges posed by grid-integrated large-scale PV systems.

In Section 5.3 the meaning and importance of key findings were provided. It was found that the presence of large-scale PV systems in the grid offers improved system performance in terms of power systems' swift return to stability following a disturbance.

In Section 5.4 the relationship between these research findings and other similar studies was presented. It was found that the research findings compares very well to similar studies conducted in the past.

In Section 5.5 the alternative explanation of the study findings was provided. It was noted that large-scale PV systems can also serve the role of existing flexible AC transmission system (FACTS) technologies such as static VAR compensators (SVCs) and static synchronous compensators (STATCOMs) deployed in most conventional utility grids.

In Section 5.6 the limitations of the research study was presented. Lack of synthetic power system case studies was noted as one of the limitations.

5.2 RESEARCH PROBLEM AND MAJOR FINDINGS

The objective of this study is to explore the role of generation dispatch strategy and spinning / non-spinning reserve methods in solving challenges posed by grid-connected large-scale PV systems as opposed to the commonly used approaches of power system voltage, rotor angle and frequency control methods. The investigations covered issues associated with the inherent intermittent nature of PV output power which results in additional operational challenges such as load-following requirements, spinning reserve requirements, load frequency excursions and system stability. A detailed performance evaluation of generation dispatch with large-scale PV systems was carried out based on the IEEE 14-bus test system using the MATLAB based Power System Analysis Toolbox (PSAT). This was done by modifying the IEEE 14-bus system to introduce large-scale PV systems at strategic points.

An analysis was then conducted using the power flow analysis methods such as PF, CPF and TD analysis to gain an understanding of the influence that large-scale PV systems have on sub-transmission and transmission networks. Comparative analysis was conducted on the base case system with zero PV penetration and the IEEE 14-bus system with large-scale PV systems. The key findings is that large-scale PV systems improve the resilience of the power system to regain stability quicker and faster following disturbances such as faults and breaker operations.

5.3 THE MEANING AND IMPORTANCE OF KEY FINDINGS

The positive influence of large-scale PV systems with regard to the power system swift return to stability following a disturbance would stand out as one of the key findings of this research. In the end this would make up for the intermittency and inertia-less characteristics, the commonly cited drawbacks of PV systems.

5.4 RELATING THE FINDINGS TO SIMILAR STUDIES

The outcomes of this research relate very well to other findings in other studies, particularly those concerned with increased penetration of large-scale PV systems in sub-transmission and transmission level. However, the bulk of the existing literature focused on specific elements of power system stability such as frequency, small signal, voltage stability etc. and not on the overall application of generation dispatch as means of handling power system stability issues.

5.5 ALTERNATIVE EXPLAINATIONS OF THE STUDY FINDINGS

It has been found that large-scale PV systems can also play the role of dynamic VAr devices such as SVCs and STATCOMs in terms of contributing to improved system loading and voltage stability margin. In addition, large-scale PV systems can also serve as a remedial measure to overcome low voltage ride through (LVRT) problem.

5.6 LIMITATIONS OF THE RESEARCH STUDY

Lack of synthetic case studies is one of the limitations of this research. This is due to the confidentiality issues associated with the data of most power utilities. Another limitation is the inability of PSAT to model the behavior of large-scale PV plants in relation to temperature and irradiance variability. In addition, PSAT has a number of limitations in terms of time domain simulations as observed in another research study [126]. These are the inability to handle multiple islands when the network splits as observed in case of simultaneous operation of three circuit breakers and not being able to simulate generator contingencies.

5.7 CHAPTER SUMMARY

In this chapter a discussion on the significance of the research findings in light of what was already known about the role of generation dispatch with large-scale PV systems in solving power system stability problems was provided. The research problem and major findings were outlined. Subsequently, the meaning and importance of key findings were also provided. The relationship between these research findings and other similar studies was explored. The alternative explanation of the study findings was presented. Lastly, the limitations of the research study were presented.

CHAPTER 6 CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 CHAPTER OBJECTIVES

The objective of this chapter is to evaluate the outcome and contribution of this research work and state the main issues around the research findings.

In Section 6.2 the summarized outcome of the research findings was provided. It was found that, of all power system stability parameters, power system frequency was the worst affected by increased penetration of large-scale PV systems in the grid.

In Section 6.3 the summarized contribution of the research findings. It was found that there is a limit as far as the uptake of large-scale PV systems is concerned. Although some challenges might not be obvious during normal system operations, these can become evident during power system contingencies.

In Section 6.4 recommendations were made. It was suggested that strategic placement of large-scale PV systems and observance of appropriate penetration level are among the practical options that should be considered to minimize undesired impacts of large-scale PV systems.

In Section 6.5 suggestions for further research were presented. It was noted that further research should be conducted on synthetic power systems as opposed to the outdated literature power systems. This is due to the fact that the power system has evolved over the years.

6.2 SUMMARIZED OUTCOME

This research explores the use of generation dispatch strategy in dealing with the impacts of large-scale PV systems on sub-transmission and transmission power system networks as opposed to stability strategies that employ power system voltage, rotor angle and frequency control.

Using static power flow analysis, continuation power flow analysis and time domain analysis, a detailed investigation was carried to study the impact of large-scale PV systems on the power systems' voltage, rotor angle and frequency stability. In addition, a comparative analysis on the system without any PV systems and the one with large-scale PV system was also conducted to determine the influence of large-scale PV systems on the power system's response to power system disturbances such as faults and breaker operations. The findings are summarized in the following subsections.

6.2.1 Voltage stability

The system with large-scale PV system responds better to breaker operations. This is due to voltage support that the PV system continues to provide during breaker operation. However, during faults, the system with large-scale PV system takes longer to regain stability following fault clearance. It was also demonstrated that systems integrated with large-scale PV systems possess higher loading margins.

6.2.2 Rotor angle stability

The severity of transient disturbance as a result of both breaker operation and faults is worse in a system with large-scale PV systems. As a result, there is a noticeable increase in rotor angle amplitude and a slower return to steady state following a disturbance. This results in complete loss of synchronism.

6.2.3 Frequency stability

The system with large-scale PV systems performs poorly in terms of frequency stability following a fault. The noticeable impact is the longer delay in re-gaining stability. In addition, it was also demonstrated that excessive penetration of large-scale PV systems into the grid results in frequency instability.

6.2.4 Real and reactive power magnitudes

The system with large-scale PV systems performs better in terms of sustaining the real and reactive power magnitudes close to nominal values during a system fault and breaker operation contingencies. This is due to the fact the large-scale PV systems possess no inertia and are therefore less prone to large transient disturbances. As a result, their power output is less affected by system disturbances.

6.3 CONTRIBUTION

This research undertaking sought to investigate the role of generation dispatch in dealing with challenges posed by increasing levels of intermittent generation sources at sub-transmission and transmission levels. These entailed detailed investigations to determine the economic impacts, the role of generation dispatch and figuring out the optimal economic generation dispatch strategy considering cost and operational constraints. The findings to these pertinent questions are summarized in the following subsections:

6.3.1 Economic impacts

The ever increasing demand for environmentally friendly forms of energy such as solar photovoltaic have an economic impact on the operations of modern power systems. These include investment in required flexibility options to support increased uptake of intermittent RES such as large-scale PV systems.

6.3.2 Role of generation dispatch

Historically, generation dispatch was mainly aimed at cost minimization. The operational constraints posed by the intermittent nature of PV systems results in additional role that an effective generation dispatch strategy is required to play. In this study, it was demonstrated how generation dispatch can also be used to solve challenges posed by the impacts of large-scale PV systems on the transmission grid.

6.3.3 Optimal economic dispatch

In this study it was determined that there is a limit beyond which further integration of large-scale PV systems can lead to serious operational problems. These challenges mainly come to during system contingencies such as faults and breaker operations.

6.4 RECOMMENDATIONS

A well designed power system that places emphasis on placing large-scale PV systems at strategic locations would enable effective use of generation dispatch in dealing with the impact of large-scale PV systems. In addition, working out the appropriate penetration level of large-scale PV systems would also assist in minimizing their negative impacts on sub-transmission and transmission systems.

6.5 SUGGESTIONS FOR FURTHER RESEARCH

In light of all the challenges that large-scale PV systems pose to the sub-transmission and transmission systems, generation dispatch strategy remains equally vital in solving operational challenges. It is obvious from the simulations conducted that the intermittent nature of solar PV power is one of the operational challenges large-scale PV systems pose to the conventional power system. The challenges come in a form of new requirements such as the need for spinning and non-spinning reserves, load following mechanisms and unit commitment. A generation mix consisting of a variety of sources in the form of hydro-electric, pumped-storage hydro, combustion turbines, tie-line interconnections, amongst others, is the answer to the afore-mentioned requirements. Every utility would need a custom-made generation dispatch technique to be able to accommodate non-conventional sources such as large-scale PV systems. However, there is a need to develop a generic generation dispatch technique to accommodate large-scale PV systems.

In future studies, the test systems can also include more synthetic test systems as opposed to literature IEEE test systems. This is due to the fact that the power systems have evolved more compared to power systems from the 1960s. The recent increased uptake of large-scale PV systems in transmission networks worldwide need to be assessed. Future research studies should also include more real-time simulations to help cater for the intermittent aspects of PV systems as a result of temperature and irradiance variability. In addition, future studies should also focus on the role of PV system inverters in addressing power system stability challenges.

6.6 CHAPTER SUMMARY

In this chapter the research outcome was evaluated and contribution of this research work outlined. The main issues around the research findings were also discussed. In addition, recommendations and suggestions with regard to further research were also presented. These include the suggestion for further research to be conducted on synthetic power systems as opposed to literature power systems such as the IEEE-14 benchmark system used in this research work.

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ADDENDUM A POWER SYSTEM DATA AND OTHER PARAMETERS

A.1 THE IEEE-14 BUS SYSTEM

This section presents the data of the IEEE 14-Bus System used in this research work. All the data is taken from [120].

A.1.1 The bus data

The bus data of the IEEE 14-Bus System is presented in Tables A.1 and A.2.

Table A.1: Generator AVR parameter connotations.

P_g	Real power generated
Q_g	Reactive power generated
Q_{min}	Minimum generated reactive power
Q_{max}	Maximum generated reactive power
P_d	Real load power
Q_d	Reactive load power
V (kV)	Rated voltage
V_m **(pu)**	Voltage magnitude in per unit
V_a **(pu)**	Voltage phase angle in per unit
V_{max} **(pu)**	Maximum voltage in per unit
V_{min} **(pu)**	Minimum voltage in per unit

Table A.2: Bus data for the IEEE 14-Bus System [120].

Bus no.	Type	Generation data				Load data		V (kV)	V_m (pu)	V_a (pu)	V_{max} (pu)	V_{min} (pu)
		P_g (pu)	Q_g (pu)	Q_{min} (pu)	Q_{max} (pu)	P_d (pu)	Q_d (pu)					
1	2	2.32	-0.17	10	-10	0	0	69	1.06	0	1.06	0.94
2	1	0.4	-0.4	0.5	-0.42	0.217	0.127	69	1.045	-4.98	1.06	0.94
3	2	0	0	0.4	0	0.942	0.19	69	1.01	-12.72	1.06	0.94
4	3	0	0	0	0	0.478	0	69	1.019	-10.33	1.06	0.94
5	3	0	0	0	0	0.076	0.016	69	1.02	-8.78	1.06	0.94
6	2	0	0	0.24	-0.06	0.112	0.075	13.8	1.07	-14.22	1.06	0.94
7	3	0	0	0	0	0	0	13.8	1.062	-13.37	1.06	0.94
8	2	0	0	0.24	-0.06	0	0	18	1.09	-13.36	1.06	0.94
9	3	0	0	0	0	0.295	0.166	13.8	1.056	-14.94	1.06	0.94
10	3	0	0	0	0	0.09	0.058	13.8	1.051	-15.1	1.06	0.94
11	3	0	0	0	0	0.035	0.018	13.8	1.057	-14.79	1.06	0.94
12	3	0	0	0	0	0.061	0.016	13.8	1.055	-15.07	1.06	0.94
13	3	0	0	0	0	0.135	0.058	13.8	1.05	-15.16	1.06	0.94
14	3	0	0	0	0	0.149	0.05	13.8	1.036	-16.04	1.06	0.94

Buses are normally classified as slack/swing buses, generation/machine buses and load buses. Table A.3 provides a classification of different types of buses on the IEEE 14-Bus System.

Table A.3: Types of buses on the IEEE 14-Bus System [120].

Bus ref	**Bus Type**	**Specified quantities**	**Unknown quantities**
1	Slack/Swing bus	$\|V\|, \delta$	P, Q
2	Generation/Machine bus (PV bus)	$P, \|V\|$	Q, δ
3	Load bus (PQ bus)	P, Q	$\|V\|, \delta$

A.1.2 Transmission line data

The data for the transmission lines is given in Tables A.4.

Table A.4: Transmission line data for the IEEE 14-bus system [120].

From Bus No.	To Bus No.	R (p.u.)	X (p.u.)	B (p.u.)	Ratio	Angle	Status	ang_{min}	ang_{max}
1	2	0.01938	0.05917	0.0528	0	0	1	-360	360
1	5	0.05403	0.22304	0.0492	0	0	1	-360	360
2	3	0.04699	0.19797	0.0438	0	0	1	-360	360
2	4	0.05811	0.17632	0.034	0	0	1	-360	360
2	5	0.05695	0.17388	0.0346	0	0	1	-360	360
3	4	0.06701	0.17103	0.0128	0	0	1	-360	360
4	5	0.01335	0.04211	0	0	0	1	-360	360
4	7	0	0.20912	0	0.978	0	1	-360	360
4	9	0	0.55618	0	0.969	0	1	-360	360
5	6	0	0.25202	0	0.932	0	1	-360	360
6	11	0.09498	0.1989	0	0	0	1	-360	360
6	12	0.12291	0.25581	0	0	0	1	-360	360
6	13	0.06615	0.13027	0	0	0	1	-360	360
7	8	0	0.17615	0	0	0	1	-360	360
7	9	0	0.11001	0	0	0	1	-360	360
9	10	0.03181	0.0845	0	0	0	1	-360	360
9	14	0.12711	0.27038	0	0	0	1	-360	360
10	11	0.08205	0.19207	0	0	0	1	-360	360
12	13	0.22092	0.19988	0	0	0	1	-360	360
13	14	0.17093	0.34802	0	0	0	1	-360	360

A.1.3 The generation data

Tables A.5 and A.6 presents the generation data for the IEEE 14-Bus System.

Table A.5: Generator data for the IEEE 14-Bus System [120].

Bus No.	**P_g (MW)**	**Q_g (MVAr)**	**Q_{max}**	**Q_{min}**	**V_g**	**Base (MVA)**	**Status**	**P_{max}**	**P_{min}**
1	232.4	-16.9	10	0	1.06	100	1	332.4	0
2	40	42.4	50	-40	1.045	100	1	140	0
3	0	23.4	40	0	1.01	100	1	100	0
6	0	12.2	24	-6	1.07	100	1	100	0
8	0	17.4	24	-6	1.09	100	1	100	0

Table A.6: Generator capacity and cost coefficients data for the IEEE 14-bus system [120].

Generator No.	$\boldsymbol{P_i^{min}}$ **(MW)**	$\boldsymbol{P_i^{max}}$ **(MW)**	$\boldsymbol{a_i}$ $(\$/(\boldsymbol{MWhr})^2)$	$\boldsymbol{b_i}$ $(\$/\boldsymbol{MWhr})$	$\boldsymbol{c_i}$ $(\$/\boldsymbol{hr})$
$\boldsymbol{G_1}$	10	160	0.005	2.450	105.000
$\boldsymbol{G_2}$	20	80	0.005	3.510	44.100
$\boldsymbol{G_3}$	20	50	0.005	3.890	40.600

A.1.4 The dynamic data

This subsection presents the dynamic data of the generators which includes generator dynamic data, AVR data and PSS data. Tables A.8, A.10 and A.12 present the generator dynamic data, AVR data and PSS data, respectively.

Table A.7: Generator parameter connotations for the IEEE 14-bus system [120].

Base MVA	**100 for all Generators**
x_1 (pu)	Leakage reactance
r_a (pu)	Resistance
x_d (pu)	d-axis synchronous reactance
x_d' (pu)	d-axis transient reactance
x_d'' (pu)	d-axis subtransient reactance
T_{d0}' (sec)	d-axis open-circuit time constant
T_{d0}'' (sec)	d-axis open-circuit subtransient time constant
x_q (pu)	q-axis synchronous reactance
x_q' (pu)	q-axis transient reactance
x_q'' (pu)	q-axis subtransient reactance
T_{q0}' (sec)	q-axis open-circuit time constant
T_{q0}'' (sec)	q-axis open circuit subtransient time constant %
H (sec)	inertia constant
d_0 (pu)	damping coefficient = 0 for all Generators
d_1 (pu)	damping coefficient = 0 for all Generators

Table A.8: Generator Parameters for the IEEE 14-Bus System [120].

Gen. Bus No.	**1**	**2**	**3**	**4**	**5**
MVA	615	60	60	25	25
x_1 (pu)	0.2396	0.00	0.00	0.134	0.134
r_a (pu)	0.00	0.0031	0.0031	0.0014	0.0041
x_d (pu)	0.8979	1.05	1.05	1.25	1.25
$x_d^{'}$ (pu)	0.2995	0.1850	0.1850	0.232	0.232
$x_d^{''}$ (pu)	0.23	0.13	0.13	0.12	0.12
$T_{do}^{'}$	7.4	6.1	6.1	4.75	4.75
$T_{do}^{''}$	0.03	0.04	0.04	0.06	0.06
x_q (pu)	0.646	0.98	0.98	1.22	1.22
$x_q^{'}$ (pu)	0.646	0.36	0.36	0.715	0.715
$x_q^{''}$ (pu)	0.4	0.13	0.13	0.12	0.12
$T_{qo}^{'}$	0.00	0.3	0.3	1.5	1.5
$T_{qo}^{''}$	0.033	0.099	0.099	0.21	0.21
H	5.148	6.54	6.54	5.06	5.06
D	2	2	2	2	2

Some of the generators in the IEEE 14-bus system are equipped with AVRs as defined in Tables and as illustrated in Figure A.1.

Table A.9: Generator AVR parameter connotations.

T_R	Low pass filter time constant (s)
K_A	Regulator gain
T_A	Regulator time constant (s)
T_B	Lead-lag compensator time constant (s)
T_C	Lead-lag compensator time constant (s)
V_{set_point}	Terminal voltage (p.u.)
$E_{fd,Max}$	Upper limit for regulator output
$E_{fd,Min}$	Lower limit for regulator output

Table A.10: Generator AVR data for the IEEE 14-Bus System [120].

Gen. No.	**1**	**2**	**3**	**4**	**5**
Model	1	1	1	1	1
v_r^{max}**(pu)**	9.9	2.05	1.7	2.2	2.2
v_r^{min}**(pu)**	0	0	0	1.0	1.0
K_a**(pu/pu)**	200	20	20	20	20
T_a**(s)**	0.02	0.02	0.02	0.02	0.02
K_f**(s pu/pu)**	0.0012	0.001	0.001	0.001	0.001
T_f**(s)**	1.0	1.0	1.0	1.0	1.0
K_e**(pu)**	1.0	1.0	1.0	1.0	1.0
T_e**(s)**	0.19	1.98	1.98	0.7	0.7
K_r**(s)**	0.001	0.001	0.001	0.001	0.001
A_e	0.0006	0.0006	0.0006	0.0006	0.0006
B_e**(1/pu)**	0.9	0.9	0.9	0.9	0.9

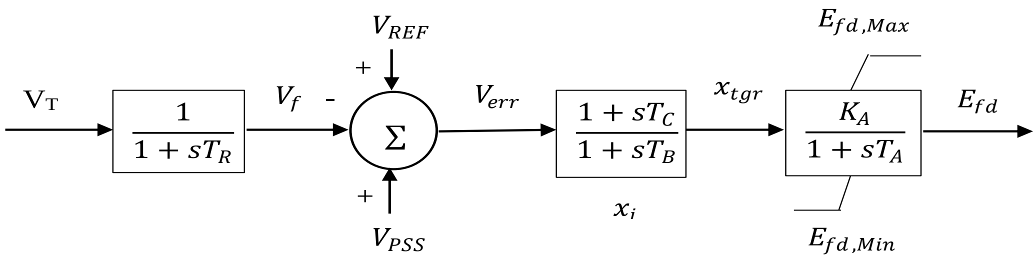

Figure A.1: Bock diagram of the AVR model.

The generator AVR parameters are defined by the following equations:

$$\dot{V}_f = \frac{1}{T_R}\left(V_T - V_f\right) \tag{A.1}$$

$$\dot{E}_{fd} = \frac{1}{T_A}\left(K_A x_{tgr} - E_{fd}\right) \tag{A.2}$$

$$\dot{x}_i = x_{err} - x_{tgr} \tag{A.3}$$

$$\dot{V}_{REF} = \begin{cases} 0, t > 0 \\ V_T - V_{setpoint}, t < 0 \end{cases} \tag{A.4}$$

$$0 = V_T^2 - (V_r^2 + V_i^2) \tag{A.5}$$

$$0 = T_{Bx_{tgr}} - T_{Cx_{err}} - x_i \tag{A.6}$$

$$0 = x_{err} - (V_{REF} + V_{PSS} - V_f) \tag{A.7}$$

$$0 = E_{fd} - E_{fd} \tag{A.8}$$

$$Upper\ Limit\ Detector < 0 \begin{cases} 0 = Upper\ Limit\ Switch - 1 \\ 0 = Upper\ Limit\ Detector - E_{fd} - E_{fd,Max} \end{cases} \tag{A.9}$$

$$Upper\ Limit\ Detector > 0 \begin{cases} 0 = Upper\ Limit\ Switch \\ 0 = Uppwer\ Limit\ Detector - (K_{Ax_{tgr}} - E_{fd}) \end{cases} \tag{A.10}$$

$$Lower\ Limit\ Detector > 0 \begin{cases} 0 = Lower\ Limit\ Switch - 1 \\ 0 = Lower\ Limit\ Detector - E_{fd} - E_{fd,Min} \end{cases} \quad (A.11)$$

$$Lower\ Limit\ Detector < \begin{cases} 0 = Lower\ Limit\ Switch \\ 0 = Lower\ Limit\ Switch - (K_{Ax_{tgr}} - E_{fd}) \end{cases} \quad (A.12)$$

Some of the generators in the IEEE 14-bus system are equipped with PSSs as defined in Tables A.11 and A.12 and as illustrated in Figure A.2.

Table A.11: Generator PSS parameter connotations **[120]**.

K	Global gain
f_L	Frequency of low frequency band (Hz)
K_L	Gain of low frequency band
f_I	Frequency of intermediate frequency band (Hz)
K_I	Gain of intermediate frequency band
f_H	Frequency of high frequency band (Hz)
K_H	Gain of high frequency band

Table A.12: PSS data for the IEEE 14-Bus System **[120]**.

AVR no.	K_w (pu/pu)	T_w (s)	T_1 (s)	T_2 (s)	T_3 (s)	T_4 (s)	v_s^{max}	v_s^{min}
1	5	10	0.28	0.02	0.28	0.02	0.1	-0.1

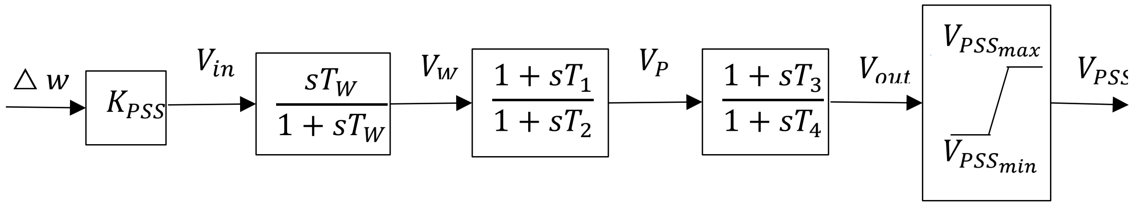

Figure A.2: Bock diagram of the PSS model.

The generator PSS parameters are defined by the following equations:

$$\dot{x}_w = \frac{V_w}{T_W} \tag{A.13}$$

$$\dot{x}_p = V_W - V_P \tag{A.14}$$

$$\dot{x}_Q = V_P - V_{out} \tag{A.15}$$

$$0 = wK_{PSS} - V_w - x_w \tag{A.16}$$

$$0 = V_P T_2 - V_W T_1 - x_P \tag{A.17}$$

$$0 = V_{out} T_4 - V_P T_3 - x_Q \tag{A.18}$$

$$0 = x_{PSS,Max} - V_{out} - (V_{PSS,Max} - V_{out}) \tag{A.19}$$

$$0 = V_{out} - x_{PSS,Min} - (V_{out} - V_{PSS,Min}) \tag{A.20}$$

$$0 = \begin{cases} V_{PSS} - x_{PSS,Max}, & \text{when } (V_{PSS,Max} - V_{out}) < 0 \\ V_{PSS} - x_{PSS,Min}, & \text{when } (V_{out} - V_{PSS,Min}) < 0 \\ V_{PSS} - V_{out}, & \text{otherwise} \end{cases} \tag{A.21}$$