Grid Interaction Performance Evaluation of BIPV and Analysis with Energy Storage on Distributed Network Power Management
Aimie Nazmin Azmi

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Doctoral Dissertation for the degree Philosophiae Doctor (PhD) at the Faculty of Engineering and Science, specialization in Renewable Energy

University of Agder
Faculty of Engineering & Science
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Nostalgia is like a grammar lesson. You find the present tense and the past perfect....'

In the name of Allah, most Gracious and most Merciful,

For Arwah Abah, and Mama

Your love, support and belief in me, gave me strength.

And always being there for me,

And being the best parents ever.

For family members,

For being the best brothers, sister, and in-laws

For your well wishes and prayers

For my other half (God knows who)

For not being here. Just yet.

And for everyone who has touched my life

I dedicate this to all of you.
Abstract

This research focuses on analysis of photovoltaic (PV) based active generator in microgrid and its utilization in not only for operational planning of the power system but also for instantaneous power flow management in the smart grid environment. The application of this system is part of a solution on handling a large scale deployment of grid connected distributed generators, especially PV system. By implementing the PV based active generator, it will be very flexible able to manage the power delivery from the active generator sources (e.g. PV system, energy storage technologies, active power conditioning devices). In Southern Norway, a smart village Skarpnes is developed for ZEBs. These ZEBs have Building Integrated Photovoltaic (BIPV) system. The energy efficient housing development should consider that a building should produce the same amount of electrical energy as its annual requirements (i.e. ZEB). In future, ZEBs are going to play a significant role in the upcoming smart grid development due to their contribution on the on-site electrical generation, energy storage, demand side management etc. In this work the main objective is to evaluate the usefulness of ZEBs for load matching with BIPV generation profiles and grid interaction analysis. Impact of BIPV system has been investigated on the distributed network power flow as well as on protection and protective relays analysis. Furthermore, techno-economic analysis of BIPV system is presented which will be useful to the utility for developing new business models as well as demand side management (DSM) strategies and for decentralized energy storage. The real operational results of a year are analyzed for annual energy balance with on-site BIPV generation and local load. This work provides quantitative analysis of various grid interaction parameters suitable to describe energy performance of the BIPV. The load matching and grid interaction parameters are calculated for a house to find relationship of BIPV generation and building load. The loss of load probability is analyzed for fulfilling the local load at desired reliability level. Results of this work are going to be useful for developing DSM strategies and energy storage as well as import/export energy to the grid. This work will be beneficial for future planning of the distributed network when the BIPV penetrations are going to increase.
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1 Introduction

This dissertation will cover the photovoltaic (PV) based active generator. The system comprises of a PV system, battery storage, and power electronics power converter devices. The purpose of this project is to analyze PV based active generator in micro-grid and its utilization in operational planning of the power system in a smart grid environment. In order to integrate micro-grid level power management system (EMS) with the centralized EMS, several functions may need proper consideration such as photovoltaic (PV) energy availability, local load consumption and local energy storage availability.

A future smart grid power system network will serve as a dynamic network for bi-directional power flows, linking widely distributed small capacity renewable energy systems (e.g. PV) at consumer level, distribution networks and centralized higher-capacity power generators. It will facilitate active participation of customer choice for energy production and demand management, and will provide real-time information on the performance and optimal operation of the power system network. Many challenges lay ahead in achieving the smart grid network vision. The integration of intermittent renewable energy and other efficient distributed energy resources into existing and future electricity networks represents significant technical and economic challenges. The widespread development of such systems requires a thorough analysis of all technical and commercial aspects of renewable energy sources and other decentralized generation units in the distribution network [1]. A Smart Grid research and technology development effort has to harmonize with expansion of the power system infrastructure, the information and communications infrastructure with modern actuators, and integration of new...
monitoring and control applications. These developments are forcing to redesign the power system operation and control [2, 3]. To facilitate higher penetration integration of intermittent renewable energy sources, the EMS of renewable energy sources need to be based on active generator approach.

At present, most of the world-wide grid connected PV systems are operating at maximum power points and not contributing effectively towards the energy management in the power system network [4]. Many studies have been made on techno-economic optimum sizing of standalone (off-grid) PV system [1, 5, 6]. Unless properly managed and controlled, large scale deployment of grid connected PV generators may create problems such as voltage fluctuations, frequency deviations, power quality in the power system network, change in fault currents and protections settings etc. These problems are becoming critical for maintaining the power system stability and control. A solution to some of these problems is the unique concept of PV based active generator. Active generators will be very flexible and able to manage the power delivery as used to be in conventional generator system. This active generator includes the PV array with combination of energy storage technologies and proper power conditioning devices. Figure 1 in the next chapter shows the block diagram of PV based active generator. It is essential to develop unique configurations of the PV based active generator, for delivering the required power in the micro-grid network.

The PV array output is nature dependent and therefore the PV power output predictability is important for operational planning of the micro-grid as well as for centralized generators. PV array output forecasting as well as load forecasting is critical for EMS. The PV power predictions can be adapted more and more accurately by means of predictive models [7]. Markov chain method, artificial neural network, autoregressive and a few more mathematical models are forecasting models used nowadays. The forecasting methodology is required to be incorporated in the EMS in order to make sure that the loop of energy supply will be ongoing and the system stability should be maintained within the prescribed power system network limits.

In power system network, power quality is very important. Due to PV power output fluctuations, there are some chances for power quality disturbances e.g. voltage transients due to intermittency, harmonics, active and reactive power management, power delivery angles etc. In the conventional grid connected PV generators, hybrid filters are used to improve the power quality
Higher penetrations of distributed generators may create different possibilities of faults, not only in the micro-grid network but at the higher voltage power system network as well. Fault detection and the isolation mechanism are very important for the power system operation. It is needed to analyze the fault protection system for example fault current levels, relay settings and fault clearing time in the micro-grid environment by considering the PV based active generators [8-10]. The grid may be disconnected during fault or any unwanted events and abnormal conditions at the micro-grid network, thus islanding effect may occur in micro-grid. It will create many problems for grid operation and safety issues. In such type of situations, micro-grid EMS has to be intelligent for effectively managing the power flows within the micro-grid by considering not only voltage and frequency fluctuations but also taking into accounts the safety by using different protection standards [11, 12]. These standards are used to make sure that the PV based active generator grid connections are safe and not going to harm either equipment or personnel. By using these protection standards, the utilities company can envisage the impact of the control strategies of the connection, which includes the performance of voltage deviations, power quality and harmonics.

This research is focusing on the implementations of EMS for a PV based active generator that is connected at micro-grid level in a smart grid environment. In order to integrate micro grid level EMS with the centralized EMS, several functions such as of PV output, local load profile and local energy storage availability may need proper consideration for upgrading the centralized EMS as well as developing new business models for the utility. In this project, the concept of the PV based active generator, the building integrated PV (BIPV) system performance, the grid interaction indicators, operational planning of PV based active generator, and fault analysis in distributed generators are being studied.

1.1 Objectives and Scope

This research focuses on analysis of PV based active generator in microgrid and its utilization in operational planning of the power system in smart grid environment. Impact of PV based active generator is investigated on the distributed network protection and protective relays. Development of energy efficient housing is progressing around the world and most of these houses will
be integrated with PV system. In this work, the real operational results of a BIPV house are analyzed for annual energy balance and to provide quantitative analysis of various grid interaction parameters. Furthermore, techno-economic analysis of BIPV system is presented which will be useful to the utility for developing new business models as well as demand side management (DSM) strategies and for decentralized energy storage. Based on these, the research is divided in following topics:

1) **PV based active generator fundamental**

   This active generator has the capacity to support frequency control and instantaneous power balance. The grid operator adjusts the power dispatch of generators according to power demand fluctuations. PV based active generators can be used as load following generators in the same manner as other power dispatch generators. This new type of distribution system, based on active generator(s), needs new innovative management and operation strategies for increasing the penetration of intermittent renewable energy systems. The considered PV based active generator has three units, i.e., PV array, battery storage and super capacitor. For this research work, the management and operation approaches of PV based active generators are discussed.

2) **Local power management system for PV based active generation for micro-grid management**

   The proposed architecture of the PV based active generator which can meet the load demand while compensating the intermittent nature of the PV power generation is executed by using a random aggregated load from 30 houses. This is to control the active and reactive power demand of a set of AC loads connected with the grid connected PV based active generator with respect to the voltage and frequency stability.

3) **Application of PV based active generator**

   An example of PV based active generator application will be presented. Skarpnes smart house is an example on how the PV based active generator act in a common environment. However, the application on battery storage is still in a trial mode, where there is still lack of information. This project is a pilot project of a ZEB. The energy required in this project will be partially supplied from the PV arrays on the rooftops. It is connected to conventional grid and has a capability of exporting surplus energy
especially in summer. The mismatch loads and generation is calculated to determine the condition of the project.

4) Fault analysis in micro-grid network with PV based active generator

There will be few major issues regarding the protection in the micro-grid network with higher penetration of distributed generators. Fault currents in a micro-grid network are not similar to faults in a conventional grid system. In micro-grid network, there are limitations on protection system due to the islanding operation mode. Also the fault clearing time is important for micro-grid stability and operation. In this work, the fault analysis of the PV based active generators in the micro-grid network will be analyzed with the power flow analysis and protective device behavior.

1.2 Thesis Outline

Chapter 1
This chapter consists of a brief introduction of the thesis and the objectives are presented.

Chapter 2
The introduction and definition of PV based active generator as the main idea of this thesis is presented. Literature review and state of the art on how PV based active generator might change the distributed generators in conventional grid is reported.

Chapter 3
In this chapter, the architecture of a PV based active generator which can provide active and reactive power while maintaining the frequency and the voltage stability with grid constraints is presented. With the proposed architecture, the load demand to the grid is reduced and the power flow is managed using a hierarchical approach with stateflow analysis and droop characteristics.

Chapter 4
The application of PV based active generator is presented here. The main concept of the active generator has been executed in the Skarpnes smart house ZEB. The definition of ZEB for this particular project and the data from one of the house has been selected to be examined and discussed.
Chapter 5
With a penetration of PV in DG, what are the effects of the power flow, voltage and how the protective device will act in a case of fault? This will be answered in chapter 5. A simulation using PowerFactory Digsilent ® is used to see the effect.

Chapter 6
Chapter 6 summarizes the inputs from this work and recommends further investigation that can be done based on this work.

1.3 List of Publications


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(Appendix B, Page: 150)
Chapter 2

2 Photovoltaic Based Active Generator\textsuperscript{1}

At present, most of the world-wide grid connected PV systems are operating at maximum power points and not contributing effectively towards the energy management in the power system network [4]. There are many studies on techno-economic optimum sizing of standalone (off-grid) PV system [5, 13-16]. Unless properly managed and controlled, large scale deployment of grid connected PV generators may create problems; voltage fluctuations, frequency deviations, power quality problems in the power system network, changes in fault currents and protections settings, and congestion in distributed network. These problems are becoming critical for maintaining the power system stability and control. A solution to these problems is the concept of active generator. The active generators will be very flexible and able to manage the power delivery as used to be in conventional generator system. This active generator includes the PV array with combination of energy storage technologies and proper power conditioning devices.

2.1 Introduction

PV array output is nature dependent and therefore the PV power output predictability is important for operational planning of the micro-grid as well as centralized generators. The PV array output forecasting as well as load forecasting is critical for energy management system (EMS). PV power predictions can be adapted more and more accurately by means of predictive models [7]. Markov chain method, artificial neural network, autoregressive and a few more mathematical models are forecasting models used nowadays. The

\textsuperscript{1} Modified from the paper published and presented in a peer reviewed conference. IEEE International Symposium on Advanced Topics in Electrical Engineering (ATEE 2015), Bucharest, Romania. DOI: 10.1109/ATEE.2015.7133914, Pp 812-815, 2015
forecasting methodology is required to incorporate in EMS in order to make sure that the loop of energy supply would be on-going and the system stability should be maintained within the prescribed power system network limits.

In power system network, the power quality is significant. Due to PV power output fluctuations; there are some chances for power quality disturbances e.g. voltage transients due to intermittency, harmonics, active and reactive power management, power delivery angles etc. In conventional grid connected PV generators, hybrid filters are used to improve the power quality [8]. But for multiple PV based active generators (e.g. group of buildings with BIPV), the power quality issues require more analysis. It seems like analyses on fault protection system is needed due to there will be some unknown situations that might occur and interrupting the power flow on the grid and reducing the efficiency of the grid performance.

The higher penetrations of distributed generators are going to create different possibilities of the faults not only in the micro-grid network but at higher voltage power system network. Fault detection and isolation mechanism is compulsory for power system operation. It is needed to analyses the fault protection system for instance: fault current levels, relay settings and fault clearing time in the micro-grid environment by considering the existence of PV based active generators [9]. During fault or any unwanted events and abnormal conditions at the micro-grid network, the grid may be disconnected, and islanding effect may occur in micro-grid. It will create many problems towards the grid operation and safety issues. In such situations, micro-grid EMS has to be intelligent for effectively managing the power flows within the micro-grid by considering not only voltage and frequency fluctuations but also taking into accounts the safety by using different protection standards [11, 17]. These standards are used to make sure that the PV based active generator and grid connections are safe and not going to harm either equipment or personnel. By using these protection standards, the utilities company can envisage the impact of the control strategies of the connection; which includes the performance of voltage deviations, power quality and harmonics.

2.2 Overview of PV based Active Generator

PV based active generator is a systems that comprise of PV array with a battery storage system with a capacity of storing energy for a long and short term for local usage [18]. From this definition, it can be conclude that this system will be able to generate, store and release energy as long as the electricity
is needed. This can be done with a proper hierarchical monitoring and energy management system. Figure 2.1 shows exactly the system [3].

Power management is crucial to control the whole energy flow in the PV based active generator. As discussed in [19], the author put an emphasize on the power management algorithm on the active PV station with a battery storage. Four hierarchical positions have been introduced and each level has its own task, as shown in Figure 2.2. These PV based active generator is expected to offers a new flexibilities to the consumer and operator and will be a new dimension of generating electricity through clean energy. This system will be operated in a microgrid environment and will have a lot more parameters that need to be considered.
The author stated that the main disadvantage for this system is the stochastic output for solar radiation and the output energy is really dependent on the weather. In order to solve this problem the PV based active generator is introduced by the author. This basic concept of PV based active generator is then discussed in the next paper which is discussed further on the application of PV based active generator and the dimension in the environmental and economical point of view [18, 20].

The system is connected to the battery storage and or supercapacitors and which is then is coupled with choppers and connected to the existing grid (microgrid). With the combination of battery and supercapacitors, it will increase the system efficiency as the battery will be able to store and release energy gradually, while supercapacitor effectively acts as storage device with very high power density. For a complete PV active based generator, a set of battery bank connected in a combination series-parallel in order to provide desired power to the system. The additional supercapacitor will provide a fast response energy storage device that can reduce the effect of short term fluctuations of PV output and will enhance the whole system [21].

The combination of battery storage and supercapacitor will be able to smooth the output from the PV array since it will be fluctuate. For a renewable energy application, the battery storage system will be operated under the partial state of charge duty (PSOC) [22]. In this condition, the battery or supercapacitors will be partially discharge at all time, in order to make sure the system will be able to absorb or discharging power to the grid as it is needed [23]. To charge the supercapacitor, a few methods as discussed in [24] can be used. In this reference, the writers are discussing on the supercapacitor charging efficiency of PV system. Based on simulation that has been done, constant power charging mode is better for charging supercapacitor in PV environment.
However, it is not proven that it will be suit to the microgrid environment yet. For a dynamic equation of supercapacitor, can be seen as;

\[
\frac{C_e \partial V_e}{\omega \partial t} = \frac{1}{R_e}\left[(\frac{1 - d}{d})V_{dc} - V_e\right]
\]

(2.1)

Where:

- \(C_e\) = capacitance value
- \(R_e\) = series resistance of supercapacitor
- \(V_e\) = supercapacitor voltage
- \(d\) = duty cycle.

The duty cycle implemented in the system is proportional and integration controller (PI).

### 2.3 PV Based Active Generator in Microgrid Environment

Microgrid is a system that operates at low voltage and has a few distributed energy resources (PV, wind, geothermal etc.) With proper energy management and systematic supervision microgrid can be a new dimension of generating and transmitting energy to the load. PV based active generator can be integrated into microgrid and it has been done in Kytnos Island and Mannheim-Wallstadt [18]. It needs a good supervision from the utility operator to make sure it will well operate. Energy supervision for the whole system is compulsory and in [25], the author has divided the system into two different parts: (i) central energy management of the microgrid and (ii) supervision for the active generator. On the microgrid side, the operator needs to manage the energy between source and load. This will includes the active and reactive power, frequency regulation, voltage fluctuations and etc.

From [25] and [20] the author has initiate a strategic framework of executing PV based active generator in a smart grid environment with more consideration and rules. Both have been considered on the long term energy management and short term power balancing this duration of time in monitoring the EMS in smart grid environment is presented in Figure 2.3. In [20] the same approach has been used and the optimization on the environmental and economic criteria has been develop. It is based on 24 hours of PV prediction. The author in [18] describes on the long term operational planning for energy management of a microgrid. In this paper, the author presented a microgrid
system with a source from a three gas turbines and PV based active generator. The microgrid central energy management system (MCEMS) is executed. This system has a different task and parameters such as dealing with the environmental effect, forecasting energy, power prediction, and deal with the power market. Based on all these crucial parameters the microgrid system can be organized properly and the output of the system will be much more efficient and clean.

![Figure 2.1 Timing classifications for EMS][20]

### 2.4 Battery Storage and Supercapacitor (Storage System)

Battery storage sizing is very important. There are 3 main parameters that need to be considering for every installation of battery storage system. The depth of discharge (DOD), state of charge (SOC), state of health (SOH), battery capacity, maximum battery charge and discharge power and the utility rating type [26]. Battery storage systems are being progressively used in distributed renewable energy generation nowadays. With the existence of supercapacitors, the effectiveness of the storage system will be much more reliable to be used in the near future. With the combination of battery and supercapacitors, it will increase the system efficiency as the battery will be able to store and release energy gradually, while supercapacitor effectively acts as storage device with very high power density. For a complete PV active based generator, a set of battery bank connected in a combination series-parallel in order to provide desired power to the system. The additional supercapacitor will provide a fast...
response energy storage device that can reduce the effect of short term fluctuations of PV output and will enhance the whole system [21].

Basically the total produced power from the system is a total power generated from the PV, battery and supercapacitor.

\[ P_T = P_{PV} + P_B + P_{SC} \]  \hspace{1cm} (2.2)

Where;
\[ P_T \] : Total power
\[ P_{PV} \] : PV power
\[ P_B \] : Battery power
\[ P_{SC} \] : Supercapacitor power

There are a lot of research has been done for the battery storage system for PV generator. The battery dynamic equation can be represents as [27];

\[ \frac{dE_B}{dt} = P_B(t) \]  \hspace{1cm} (2.3)

Where \( E_B \) represent the amount of electricity stored at \( t \) time and \( P_B \) is the charging or discharging rate. This should be integrating with the supercapacitor to make sure that both of this storage system can be used and compatible to each other. In [25] the author focus on using the optimal use of batteries. There are several relevant resources regarding the optimization of batteries for PV. The author from [28] has proposed a battery model specifically useful for the stand-alone photovoltaic applications. Seven different levels of working zone and zone conditions has been proposed; saturation zone, overcharge zone, charge zone, changing from charge to discharge or vice versa, discharge zone, over discharge and exhaustion. As can be seen in Figure 2.4, the working condition is depends on the voltage and current that went through the battery. This is a sample of a 2V battery.