A Solar Photo-Voltaic and Battery Integrated Microgrid Test System Performance Analysis

Phani Kumar K.S.V[1], S.Venkateshwarlu[2]
[1,2]Dept of EEE, CVR college of Engineering, Hyderabad, India
Email: phani5016@gmail.com, svip123@gmail.com

Abstract— **Power crisis has been a matter of major concern with losses in the transmission adding to the woes. The former can be overcome by replacing the conventional energy sources (CES) with the renewable energy sources (RES). And the latter problem can be dealt by using Microgrid technology which is taking boom. This paper deals with the integration of renewable energy sources with the Microgrid technology considering the standard IEEE Fourteen bus system as reference. The entire system is simulated, operation is analyzed and the final results have been published.**

Index terms—**Microgrid, IEEE Fourteen bus system, RES, PV array**

I. INTRODUCTION

The energy sources used for the present power generation are getting exhausted day by day. So, the usage of renewable energy sources would be of great importance. Also, the available transmission and distribution efficiency of 16.45% in AP is not up to the mark.

A small energy system capable of generating power within a defined boundary integrated with variable Distributed Energy Resources (DERs) called Microgrid (as stated in IEEE Std 1547.4-2011 [1]) seems to be a perfect solution for overcoming these problems. Some of the resources that can be integrated with microgrid are solar energy (using the photo voltaic systems), wind energy and bio-mass energy, etc. Depending on the availability of the source and the cost of production of power the choice of selection of a distributed source is made for the power generation. There are two catalysts boosting the renewable energy integration into the grid. Firstly, the cost of power production is decreasing as the investment cost per KW of production is decreasing as bulk manufacturing is happening and many players have come into the market competing for the ever increasing customer base.

Much of the research is being done in operating a microgrid in two modes i.e., grid connected mode, islanding mode [2]. Based on the measurement and information systems, there can be two modes of control, i.e., Centralized and distributed modes [3] complying with IEC61850 standards. It provides service reliability and reduces the cost of energy encouraging the usage of eco-friendly renewable energy resources. The simulation of microgrids has been traditionally done in system level and component level. The system level simulation yields results that can be used in the stability, reliability and power quality analysis. The simulation results are further compared to the grid standards and the choice of controlling action is chosen accordingly. The concept of net metering has brought many security issues into light and the Indian Electricity act 2003 highlights the rules for grid connectivity and the sale of electricity in section 86 (1) (e) [4]. In India, the policies, initiatives, subsidies, research and development are significant for the growth of solar photovoltaic power generation for roof-top off-grid, net-metered rooftop and concentrated solar power. The solar map of India also proves the extensive availability of solar energy [5].

From 1859, many chemical combinations of rechargeable lead-acid batteries were developed and ever since then they have been used for energy storage. Though Sony has made lithium-ion batteries commercially available from 1991, the market has not responded so well in India. Some pilot projects like Sendai Substation Lithium Ion Battery Pilot Project [6] is under construction in Japan for 30 min duration at rated power, with a capacity of 20 MWh and maximum output of 40 MW.

The presence of a storage system enhances the reliability of the system but poses many security threats and controlling the system. Battery Management is also another area that has been researched about and shall be included in the later work as an extension to this paper work.

The rest of the paper is organized as following sections:

1) Objective: This section briefs about the objective of the paper.
2) System structure: This section presents the structure of the system which has been considered in this paper and the details pertaining to it.
3) Solar Energy: This part provides the brief idea of the working of solar cells.
4) PV modelling: This part presents the equivalent circuit of a PV cell and the related equations.
5) Inverters: This topic deals with the basic types of inverters and the inverter which is being considered in this paper (Cascaded H-bridge type).
6) Solar grid interfacing: This topic deals with the challenges faced in the interconnection of Distributed Electric Production resources with the utility grid and the international standard governing them.
7) Simulation: The results of simulation have been presented in this section.
8) The interferences made from the results have been summarized in this section.

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II. OBJECTIVE

This paper deals with testing of the feasibility of implementing the DERs in a microgrid system and to study the performance of the system, considering the standard IEEE fourteen bus system as reference. Solar Energy is taken as the source of renewable energy and the conventional synchronous generators are replaced with solar arrays coupled with a cascaded H-bridge inverter. The main objective is to obtain the voltage at load bus and verify it with the existing standard.

III. SYSTEM STRUCTURE

The test system (Fig.1) which has been considered consists of:

a) Fourteen buses
b) Two solar power generators in buses 1 and 2.
c) Three synchronous compensators to provide reactive power compensation in buses 3, 6 and 8.
d) loads in buses 2, 3, 4, 5, 6, 9, 10, 11, 12, 13 and 14

The line and bus data have been provided in the appendix.

IV. SOLAR ENERGY

Solar energy is one of the abundantly available renewable sources on earth. Due to its no-polluting nature, it is being used in major applications involving energy generation. The best way to harness this solar energy would be through the photovoltaic cells. They convert solar energy into DC electricity, which can be used for various purposes. A photovoltaic (PV) cell consists of a P-N unction. Whenever light falls on a PV cell, if the incident energy is greater than or equal to the bonding energy of the electron, then an electron hole pair is generated. The electron which is majority charge carrier (in case of N- layer) passes through the connected load and meets the hole which has crossed the junction. In this way, the circuit is completed and electricity is generated. The general formula used to estimate the output electricity of photo voltaic system is given by

$$E=A*t*r*H*PR \quad (1)$$

Where, E= energy (KWh)
A=total area of the solar panel,

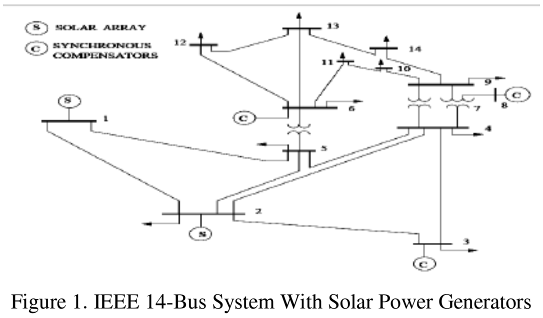

Figure 1. IEEE 14-Bus System With Solar Power Generators

r = yield of the solar panel,
H=annual average solar radiation on fitted panels,
PR=performance ratio (coefficient of losses)

V. MODELLING OF SOURCES

A. PV Module

The solar cell can be considered as a type of p-n junction diode. Unlike a conventional diode, the electron-hole (e-h) pair in a solar cell is formed by photovoltaic effect. The e-h pairs are separated by the electric field existing across the junction and are driven through the external load by the junction potential.

The solar cell can be considered as a current source. The current supplied by the solar cell gets divided as the load current and the leakage current. Thus, the losses can be accounted by considering two resistances: series and shunt. The reverse saturation current also adds to these losses. Considering the above factors into account, the equivalent circuit of the solar cell can be drawn as shown in Fig. 2 below.

The output terminal current can be given by the equation (2)

$$I = I_{ph} - I_D - I_{sh} \quad (2)$$

Where, I is the load current
I_{ph} is the total light generated current
I_D is the diode current
I_{sh} is the shunt leakage current

In an ideal solar cell, R_s=0 and R_{sh}=∞.

Small changes in shunt resistance will not have much effect on the efficiency but, small changes in the series resistance can cause the PV output to reduce significantly.

The load current of the solar cell is given by the expression (3)

$$I = I_{ph}-I_{os}\ \{\exp\ [qU_{oc}/AKT]-1\}-(U_{oc}/R_{sh}) \quad (3)$$

Where,
I_{ph} = total light generated current (A)
I = cell output current (A)
I_{os} = cell reverse saturation current. (A)
q = electron charge=1.6*10^19 Coulombs.
A = ideality factor of p-n junction.
K = Bolzmann constant.
T = cell temperature [^{o}C].
R_{sh} = shunt resistance. (Ohms)
U_{oc} = terminal voltage of the cell (V)

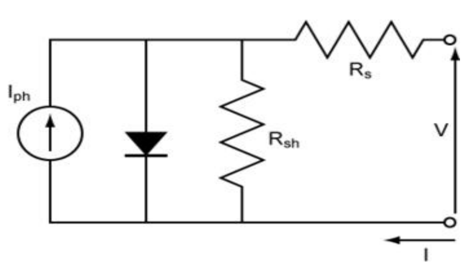

Figure 2. Equivalent Circuit of PV cell

B. Battery Module

A typical model of lead acid battery can be understood in two equations,(4,5) corresponding to the charging and discharging models. The flow of current while charging is considered to be negative for charging and positive for discharging. The models can be written, with reference to the MATLAB as:

Discharge model (i* > 0)

$$f_1(it,i^*,i,Exp) = E_0 - K\cdot\frac{Q}{Q-it}\cdot i^* - K\cdot\frac{Q}{Q-it}\cdot it + \text{Laplace}^{-1}\left(\frac{Exp(s)}{Sel(s)}\cdot 0\right) \quad (4)$$

Charge Model (i* < 0)

$$f_2(it,i^*,i,Exp) = E_0 - K\cdot\frac{Q}{it+0.1\cdot Q}\cdot i^* - K\cdot\frac{Q}{Q-it}\cdot it + \text{Laplace}^{-1}\left(\frac{Exp(s)}{Sel(s)}\cdot\frac{1}{s}\right) \quad (5)$$

Where,

E_{Batt} = Nonlinear voltage (V)
E_0 = Constant voltage (V)
Exp(s) = Exponential zone dynamics (V)
Sel(s) = Represents the battery mode. Sel(s) = 0 during battery discharge, Sel(s) = 1 during battery charging.
K = Polarization constant (Ah^{-1})
i* = Low frequency current dynamics (A)
i = Battery current (A)
it = Extracted capacity (Ah)
Q = Maximum battery capacity (Ah)
A = Exponential voltage (V)
B = Exponential capacity $(Ah)^{-1}$

VI. INVERTER

Inverters are the devices which convert DC voltage to AC voltage. There are two basic types of inverters: grid interactive inverters and standalone inverters. Grid interactive type inverters are supplied with voltage and frequency by the grid itself and they cannot operate without the supply from the grid. Standalone inverters can operate without a grid and can serve as a back-up for the renewable generation.

The topology used here is a three-phase cascaded multi-level inverter (without battery balance). It basically consists of series connected modules consisting of a H-bridge. Single phase version of the topology is shown in the Fig. 3.

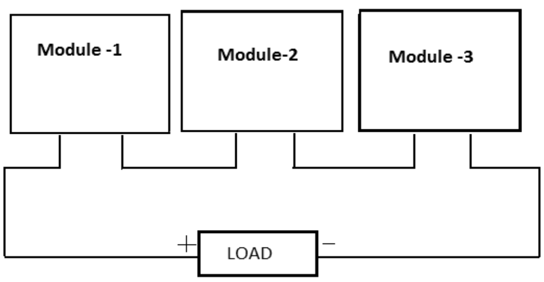

Figure 3. Block Diagram Of Cascaded H-Bridge Inverter

To get a sinusoidal wave, the switching sequence is appropriately controlled. With a single H-bridge inverter, we get three levels (two non-zero levels and a zero level) in the output waveform. To make the waveform more sinusoidal in nature, we cascade more number of H-bridge inverters, which increases the non-zero levels obtained in the output waveform. In this paper, solar array is considered as the isolated dc source that the topology demands. The switching frequency used here is the fundamental frequency so that the switching losses are reduced while the Total Harmonic Distortion (THD) is observed not to be deviating from the standards to be maintained at the Point of Common Coupling (PCC).

VII. SOLAR GRID INTERFACING

The power quality of a solar panel is affected by various parameters including irradiation, PV modules, inverters, etc. A small change in the irradiance level and cloud cover or shading effects play a vital role for low-voltage distribution grids with high penetration of photo-voltage, as presented in [2].

These voltage fluctuations can cause the disconnection of inverters from the grid. Also, in the long run, the performance efficiency of the grid-connected PV systems reduces due to the source variation and inverter performance [3].

Therefore, attention has to be given to the voltage and power profiles.

The general block diagram of a single-phase or three-phase PV system is as shown in the Fig. 4. The PV array can be a single panel or a series and parallel combination of various PV modules. The PV systems can also be used in centralized and decentralized modes and the summary of advantages and disadvantages of these topologies are discussed in [4].

The major factors to be considered while designing the inverter are the injection of harmonics due to the usage of inverter, irradiance and the shading effects [5-6]. In this paper, the cascaded H-bridge inverter is being used.

There are a number of technical challenges associated with the parallel connection of distributed electric production resources with the utility grid which include frequency and voltage regulation, disconnection and reconnection rules during the disturbances in the grid, islanding operation and faults minimization when connected to grid.

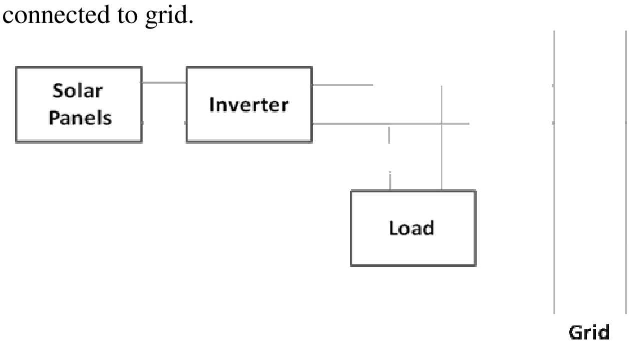

Figure 4. General Structure Of Grid-Connected PV System

A. International Standards:

According to IEEE standards, Electric Power Stations (EPS) refer to the Utility Grids while Distributed

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Resources (DRs) include mini-grid systems. Utility interconnection of electric distributed resources is specified by standards as mentioned in table 1 as:

TABLE 1. STANDARDS FOR MICROGRID

IEEE 1547	The guidance related to the operating island systems in various modes is provided [7]
IEC	Microgrid and their safety concerns are addressed.

In India, 'smart grid forum's working group #9 on renewable and microgrids' is developing standards for the integration of renewable-based microgrids with the main grid.

India's Central Electric Authority released a set of standards for distributed generation resources connectivity [8] in 2012.

VIII. RESULTS

The generator of the fourteen bus system has been replaced by a unit consisting of three solar arrays per module per phase. The properties of them can be listed as

Module type : Canadian solar CS5P-220M
No. of cells per module : 96
No of series connected modules per string: 1
No of parallel strings : 1
Module specifications under STC
Voc : 59.2 V
Isc : 5.09 A
Vmp : 48.3 V
Imp : 4.54 A
Sample time : 1.00E-06

The characteristics of the solar module used can be shown as:

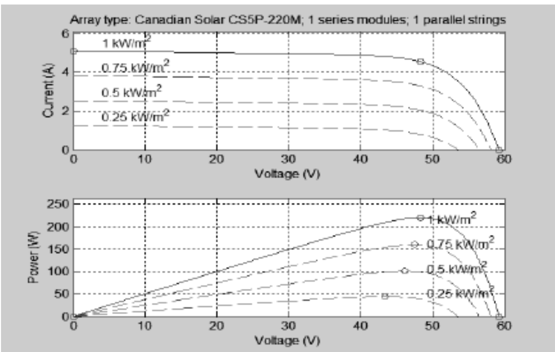

Figure 5. I-V, P-V Characteristics Of Array at 250C.

The solar irradiation as a function of time taken for the simulation is plotted and displayed in fig 6. as

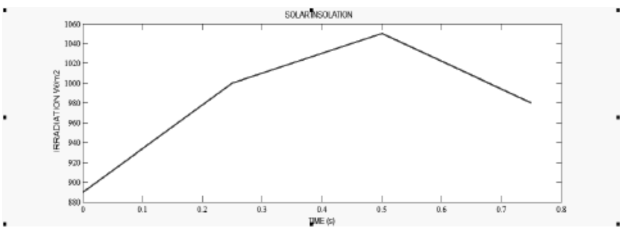

Figure 6. Insolation Plot

Similarly, the battery used as here a lead-acid battery with the following parameters:
Nominal voltage : 50 V
Rated Capacity : 6.5 A
Initial State of charge : 100 %
Maximum capacity : 8 Ah
Fully charged Voltage : 52V
Nominal Discharge Current: 5.5 A
Internal Resistance : 0.0018462
Capacity @ Nominal Voltage: 6.25 Ah

The DC output of the solar module is shown in figure-7 as:

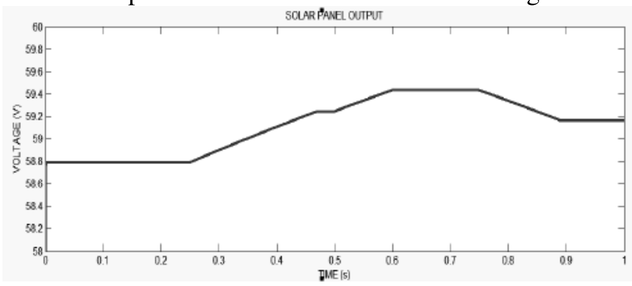

Figure 7. DC Output Of The Solar Module

The Single phase output of the multilevel inverter is shown in figure-8 as:

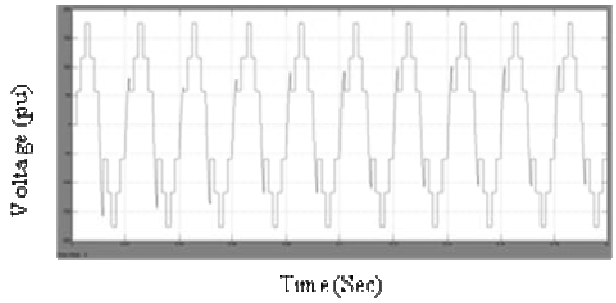

Figure 8. Single Phase Output Of The Multilevel Inverter

The Phase voltage of the three phase PV system is shown in figure 9 as:

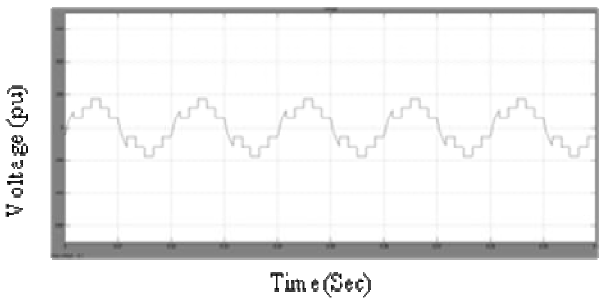

Figure 9. Phase Voltage Of The Three Phase PV System

The Three phase RMS voltage at generator bus (bus 1) and load bus (bus 5) respectively are shown in figure-10 as:

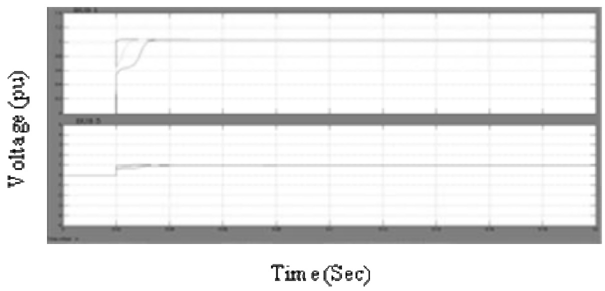

Figure 10. Three Phase Rms Voltage At Generator Bus (Bus 1) And Load Bus (Bus 5)

A. *Result:*

The bus voltages at all the buses are listed in the table 2:

TABLE 2. BUS VOLTAGES IN PER UNITS

Bus No.	Voltage (pu)	Bus No.	Voltage (pu)
1	1.015143527	8	1.012934649
2	1.040391553	9	0.98398143
3	1.029143689	10	0.984292008
4	1.018104473	11	1.004629565
5	1.022478674	12	1.021498803
6	1.035501198	13	0.97822907
7	1.00063217	14	0.979625316

IX. CONCLUSIONS

The paper has presented the integration of Renewable energy source with the microgrid system, considering the standard IEEE fourteen bus system data as reference. The result has been analyzed and summarized and it has been shown that the voltage values obtained is within the ±5% tolerance of the standard voltage value (1 pu).

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