Impact of PV Systems and Battery Storage in Hybrid Power Systems with Grid Connection

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***Abstract*—Hybrid system is a form of distributed generation technology that is located very close to the consumers and operates optimally with the utility grid to provide a sustainable power solution at the load points. The hybrid system is signed by independent power providers to harnesses energy from numerous renewable energy technologies and provides storage capabilities with the application of battery system. The power solution power solution provides by the hybrid system is cost-effective and efficient as well as improves the entire system capacity, security and reliability. Solar or wind power alone can fluctuate, but the perfect solution is to combine two or more forms of energy sources to provide a reliable source of energy. The stochastic nature of renewable energy sources has instrumented to a choice of multiple configurations with diverse generation technologies and battery system for sustainable power solution. Hybrid system is required to ensure reliability of power system and for peak shaving applications, improving the voltage level or connecting isolated areas that are far from the utility grid. This paper will show the modeling of a PV system from solar panels, DC-DC converter, inverter and until the system is grid connected to feeder X to improve the voltage levels of this feeder as it has low voltages, the circuit will be modeled on PSIM and Power factory software.**

Keywords-DC/DC converters; distributed generation configuration; grid connection; hybrid system; PV system; inverter

I. INTRODUCTION

Electric power systems are designed by the utilities to saisfy the electrical power demand at the load points with the application of centrally coordinated power plants that are connected to the transmission and distribution lines based on the voltage levels [1]. With the deregulation, competition is particularly fostered in the generation side, thus allowing more and more generation units to be connected to the grid [2]. Distribution generation (DG) plays a significant role in the deregulated market and upgrading of traditional power system infrastructure owing to the application of smart grid features [3]. This DG is a set of electrical power sources such as renewable and non-renewable resources connected to the distribution system or the customer side of the meter [4]. DG's are usually relatively small, they are in the kW to MW range [2], and they are generally connected to the grid at some selected node of the distribution network mainly the remote parts of the network or as stand-alone systems. There are several renewable energy sources in operation over recent years. These include wind turbines, photovoltaic cells, biomass, batteries and small hydro.

The energy available in wind is kinetic energy of large masses of air that moves over the earth's surface [5]. The kinetic energy will then be harnessed by the blades of the wind turbine, and transformed into electrical energy. Photovoltaic system consists of solar cells, where they can convert direct sunlight to electricity [6]. Biomass energy resources include industrial organic waste, tree branches, crop stalks, animal manure, energy crops, municipal solid waste, etc. Biomass direct combustion means using biomass as fuel and directly burned in the boiler to produce steam and drive turbine [7]. Hydropower is the generation of electricity from run-of the-river with the application of a dam that stores water in a reservoir. The hydropower is designed in such a way that water released from the reservoir flows through a turbine blade and spins it; this in turn activates a generator to produce electricity.

The aim of this paper is to investigate the impact of PV systems with Battery storage on the grid. The objective is to highlight the use of PV systems in improving the voltage levels of constrained feeders as well as peak shaving during peak hours using battery storage. The system is modeled and sized accordingly for optimal operation.

II. LITERATURE REVIEW

Energy security has been attributed to introduction of cost effective technologies and diversification of primary energy supplies. The diversification of primary energy supplies increases energy security and the reliability of the electricity system. The application of distributed generation in the traditional power system can reduce the risks and costs that related to blackouts owing to failure of the power system's components. In South Africa, the largest percentage of population lives in rural where it is difficult to connect to the utility grid owing the cost implication, economic non-feasible and some areas are not accessible as a result of terrain constraints. In addition to this, the cost of fossil fuel transportation is very expensive and it is not affordable by the rural dwellers [8]. Consequently, the choice of a hybrid system provides a sustainable power at a low cost when compared with the cost that related to the extension of the utility grid to rural areas [9]. Moreover, this system is cost effective owing to its relative low maintenance and operation cost.

i. Photovoltaic system configuration

The hybrid system is configured in two ways, centralized or distributed. For centralized configuration as shown in Fig. 1, the objective is to ensure a continuous operation of the power system, instead of supplying certain critical loads. This configuration has advantages such as, lower cost, little and easy maintenance. The biggest disadvantage of this is that the whole power system would fail if the central converter fails.

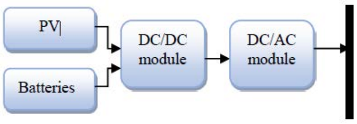

Figure 1. Centralized configuration

With distributed configuration as shown in Fig. 2, the system has separate conditioning units for every renewable input, thus the system operates in parallel to increase the availability of uninterrupted power supply [10]. The advantage is that this configuration permits easy upgrading of the system when higher capacity is needed. The notable disadvantage is that the system is more costly when compared to centralized configuration.

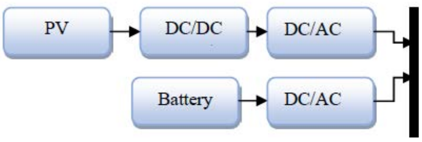

Figure 2. Distributed configuration

ii. Types of Photovoltaic Systems

When it comes to types, the photovoltaic (PV) systems can be grid connected or they can be used on stand-alone applications. Grid connected systems requires compliance with the regional (grid code) and make sure that it injects high quality current and most importantly it should synchronize with the grid. The stand-alone can generally be used in remote areas where the cost of extending the grid is high, or used for supporting specific critical loads.

iii. Energy storage devices

Depending on the nature of application of the PV system, energy storage can be required. For applications where the PV system is required for peak shaving, energy storage is important because of the unpredictability of PV source. Various energy storage devices can be utilized, like pump storage, Battery Energy Storage Systems, super capacitors, and fuel cells.

A. *PV system*

Photovoltaic systems play a promising role in the generation of clean energy. Nevertheless, the push for the adoption of renewable energy sources, such as PV, results in an increased penetration of an unstable energy source. The intermittent nature of the source is of concern with regards to the stability and reliability of the electric network because the fluctuations are reflected in the network [11], [12].

B. *Modelling of PV system*

The modeling of the hybrid system is designed to utilize solar and battery storage for an annual year, thus a daily time scale is used to obtain the model the system. Fig.2 shows a schematic of the hybrid model that is intended to be optimized to supply a dynamic load. The power obtained from the grid is used to supply the load and renewable sources to achieve the load balancing. In the model, it is assumed that the load will use all the electrical energy obtained from the solar and battery storage, thus the sizing of the systems must be done to ensure that the maximum size is achieved whilst ensuring the capacity doesn't exceed the load power.

i. Photovoltaic cell

PV cells are connected in series or parallel or both to produce higher currents, voltages and power at the terminal of the circuits. PV modules consist of one or more cells sealed in an environmentally protective laminate, and are the major building blocks of PV systems.

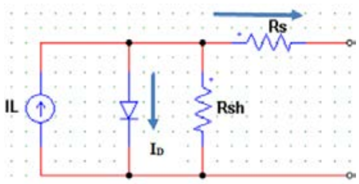

Figure 3. PV cell model

Figure 3 shows a PV cell where shorting the leads of the equivalent circuit of a PV cell causes no current to flow through the diode as voltage across the diode equals zero. However, all the current flows through the shorted leads. Thus, short-circuit current equals the magnitude of the ideal current source itself (IL = ISC). According to Kirchoff's current law, the current for the equivalent circuit can be written as:

$$I = I_{SC} - I_D \quad (1)$$

where I_D can be substituted by the Shockley diode equation that describes a p-n junction diode as follows:

$$I = I_{SC} - I_o\left(e^{qv_d/kT} - 1\right) \quad (2)$$

Rewriting equation (2), the short-circuit current for the PV cell can be expressed as:

$$I_{SC} = I + I_o\left(e^{qV_d/kT} - 1\right) \quad (3)$$

where q and k are the electron charge and Boltzmann's constant respectively. V_d represents the voltage between the diode terminals measured in volts and T represents the junction temperature measured in Kelvin.

Since a single cell produces around 0.5 Volts, it is not so useful for application therefore the cells are cascaded in series to boost the voltage level and connected in parallel to increase the current output [13]. A basic building block is the PV module, which consists of a number of series connections of solar cell. A PV array consists of n-number of PV modules as shown in Fig. 4. Typically, 36 cells are designated for 12 Volts, but for grid-connected modules, many solar cells are connected to meet the required voltage. A module connection is in series therefore according to Kirchhoff's law current in series connection current stays the same but voltage is added therefore total voltage is given as presented in equation (4).

$$V = \sum_{i=1}^{n} V_i \quad (4)$$

The figure below depicts the solar PV from cell to array

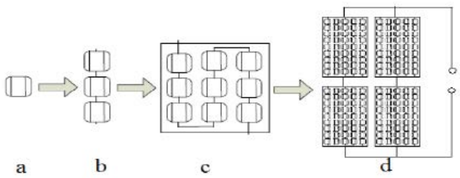

Figure 4. (a) Photovoltaic cell, (b) cell series string, (c) cell module (d) PV array

ii. Sizing PV arrays

In determining, the optimal size of the PV systems one should define data such as solar radiation, ambient temperature, output power, nature of system application. Total power of a PV array is calculated using the average working time, average power of the load as well as the conversion coefficient. The formula for power calculation is shown in equation (5) below [14].

$$P = \frac{\mu T P_L}{H} \quad (5)$$

where H is the $sunshine\ hours\ of\ radiation$ (h), T is the $daily\ avarage\ work\ of\ load$ (h), PL is the $avarage\ load\ power$ (W) and μ is the conversion coefficient.

The conversion coefficient includes all the undesirable factors and it can be calculated using equation (6) below.

$$\mu = \mu 1 \mu 2 \mu 3 \mu 4 \quad (6)$$

where $\mu 1$ is the charging and discharging efficiency, $\mu 2$ is the temperature compensation, $\mu 3$ is the loss coefficient of a PV array and $\mu 4$ is other factors.

iii. Irradiation and temperature

Solar panels are often in hot locations, dissipating as heat most of the solar energy they receive. The cell temperature is given by equation (7) below, where NOCT is the normal operating cell temperature (usually given on manufacturer's datasheet) and S is the insolation of one Sun (1 kW/m^2).

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20^{o}C}{0.8}\right) \times s \quad (7)$$

Fig. 5 indicates that changing the cell temperature will not affect the system current as the change is not significant. But one notifies that with an increase in temperature the open circuit voltage also changes.

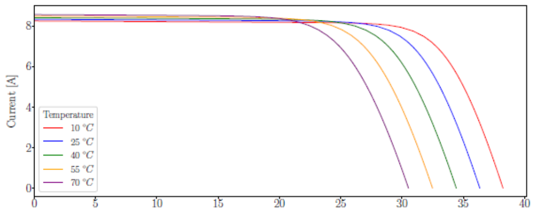

Figure 5. Effects of changing irradiance

Irradiation or light intensity will affect the output current as the increase in irradiance will change the output current. More light effectively shifts the curve up in I, but V_{OC} does not change much. By varying the insolation, we obtain not a single I-V curve, but a collection of them. Fig. 6 shows that with the absence of light the PV system will not be producing any current.

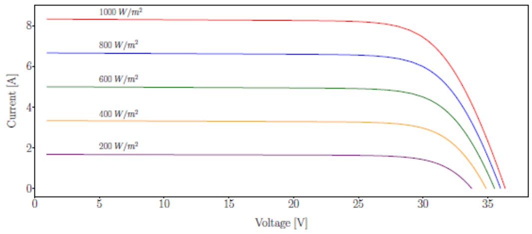

Figure 6. Effects of changing irradiance

iv. DC-DC converter

The utilization of DC distributed power systems have increased significantly due to deployment of multiple renewable energy sources and application of DC based equipment. A DC-DC converter is required to convert power directly from the renewable sources to the desired voltage for the DC bus/load. Boost converter is a high efficiency step-up converter. It uses a transistor switch, typically a MOSFET to pulse width modulate the voltage into an inductor. The following shows the ideal relationship between input and output voltage of the boost converter, where δ is the duty cycle.

$$V_{out} = \frac{V_{in}}{1-\delta} \quad (8)$$

v. DC-AC converters

The inverters convert the DC voltage into AC voltage. For grid connected inverters they utilize the grid frequency. This is necessary to avoid energizing the grid during outages and for protection purposes. Thus as one of the requirements for grid connection the inverter should use the system frequency such that the inverter module will be off when the grid frequency is also off.

vi. Battery Modeling

Like humans, batteries are made up of various different parts with age and wear out as shown in Fig. 7. Repeated electrochemical reaction tires the electrolyte within the battery and prevents the battery from performing as before.

There are some factors that influence a battery's degradation; a deep depth of discharge, high c-rates, high and low temperatures and extreme states of charge levels. A method is required with which one can model the degradation of the electrolyte in order to be more accurately estimating the state of the battery's health. In literature, we find various derived models based on different approaches.

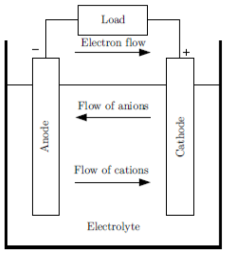

Figure 7. Basic battery model [15]

In this paper, batteries are considered to solve certain problems such as feeding the grid at night when there is no sunlight, larger PV installations on a weak network and peak load shaving of overloaded distribution feeders. The problem with selecting batteries, especially with there being a range of similar battery chemistries, is whether or not the battery is sufficient for its purpose and if it is performing well enough under its operating conditions. Modeling a battery can provide a means of estimating the battery's performance. Modeling entails the representation of a battery in a mathematical form; however this can be a difficult process when high accuracy is required.

vii. Battery Storage Sizing

The size of the battery energy storage system (BESS) is determined mainly by two parameters: peak power and maximum energy. The values of these parameters depend primarily on the desired peak power of the feeder. This can be specified either as a percentage reduction (σ_{red}) or as a desired power level ($P_{desired}$). Applying the desired power level to the feeder, the required battery power output (P_{bat}) can be determined using expressions (9) and (10). P_{peak} represents the peak power that the feeder experiences.

$$P_{battery} = \sigma_{red} \times P_{peak} \tag{9}$$

$$P_{battery} = P_{peak} - P_{desired} \tag{10}$$

Losses with regard to power and energy will occur when the batteries charge or discharge through the power conversion units. Taking these losses into account, the required BESS power (P_{BESS}) can be represented in equation (11) and the losses are represented by an overall efficiency (η).

$$P_{BESS} = \frac{P_{battery}}{\eta} \tag{11}$$

viii. Grid connected PV systems

The utilization of grid-connected PV systems in the integrated power solution has become so popular owing to some technical benefits. The grid-connected PV systems are tied to the utility grid through inverters. This indicates that batteries are not required since the utility grid can accept all of the power generated by PV system [16]. The grid connected PV system can be categorized into two major sections such as the interfacing unit and solar power conversion unit as shown in Fig. 8. The interfacing system is integrated into the utility grid through low or medium voltage transformer. The LV/MV transformer can be utilized to appropriately adjust the voltage level and acts as an isolation transformer when required [17]. The impact of PV modules to the grid is to be considered according to the South African Grid Code.

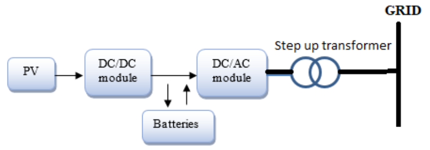

Figure 8. Grid connected PV system with battery storage

ix. South African Grid Code

For renewable source to be connected to the South African grid, a documented procedure is to be followed titled "Grid Code for Renewable Power Plants (RPPs) Connected to the distribution system in South Africa". This document stipulates the minimum design and technical requirements to support grid operations and stability. The PV system to be allowed connect to the Power station distribution network must be able to meet the minimum requirements as listed by the SAGC.

III. RESULTS OF SIMULATION

To analyze the behaviour of PV system as shown in Fig. 9, a circuit model is implemented on PSIM software. For grid connection, the model was also connected to an 11kV feeder implemented on Digsilent (Power factory) software to analyze the impact of PV on the feeder.

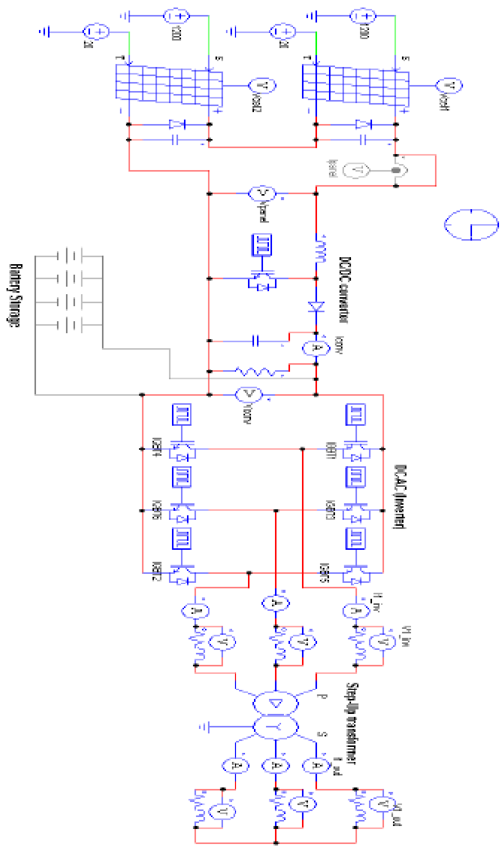

Figure 9. Grid connected PV system with battery storage modeled on PSIM software

The above grid connected circuit was modeled using PSIM software to investigate effects of varying temperature and irradiance on DC-DC converter efficiency and PV system efficiency. The model was also tested on a feeder with low voltages to test for improvement in voltage levels. For this the model was implemented in Digsilent (Power factory) software.

i. Solar Panels

Tables 1 and 2 show the results of varying temperature on the output of the converter and effects of varying irradiance on the PV system efficiency.

TABLE I. EFFECT OF TEMPERATURE ON OUTPUT VOLTAGE

Temperature	Vpanel	Vout (Converter)
20	80.03	419.81
22	79.39	416.62
24	78.75	413.44
26	78.12	410.24
28	77.84	407.04
30	76.84	403.83

TABLE II. EFFECT OF IRRADIANCE ON OUTPUT POWER

Irradiance	Pin (panel)	Pout (Converter)
400	94.91	60.51
600	150.23	123.67
800	198.63	165.95
1000	247.58	206.48
1200	296.88	258.30

ii. DC-DC converter module

The step-up DC-DC converter module was modeled in such a way that for varying dc input from the solar panels, the output voltage should remain constant at 400Vdc. The voltage is kept constant because it will also be used to charge the battery. Fig. 10 shows the operation of step-up DC-DC converter from 80Vdc to 400Vdc. The red is the output voltage from solar panels and the blue graph is the output of the converter.

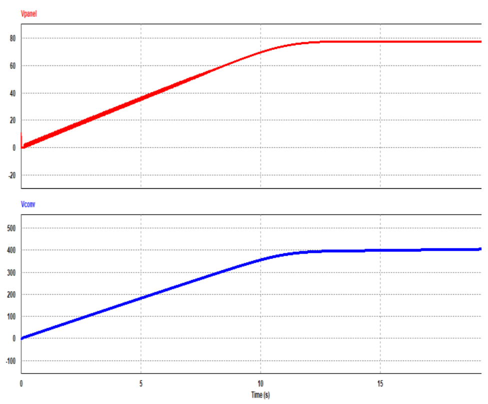

Figure 10. Panel output voltage (red) and converter output voltage (blue)

iii. Inverter module

Because the output of the DC-DC converter will not fluctuate with the fluctuating weather conditions (temperature and irradiance), the output of the inverter will not fluctuate. Fig. 11 shows a waveform with amplitude of 400Vac from the simulated inverter model.

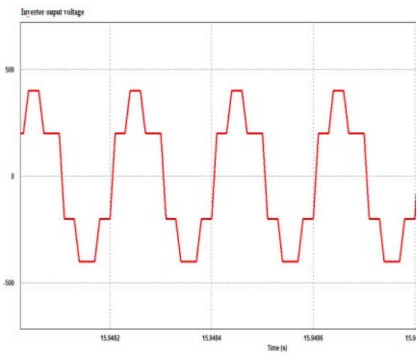

Figure 11. AC voltage from the inverter

iv. Step up Transformer (400/11kV)

The ac voltage waveform after the step up transformer is presented in Fig. 12.

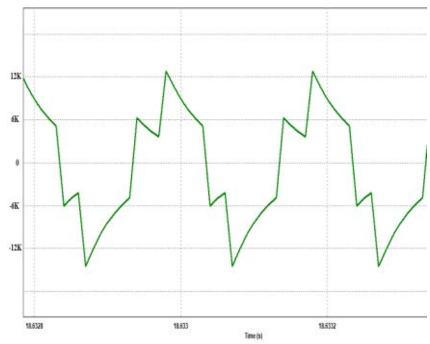

Figure 12. AC voltage from the transformer

v. Peak shaving application (Power factory modeling)

Because the circuit modeled in Fig. 8 using PSIM software could not be tested for peak shaving applications. Another identical model was implemented in Power factory software for peak shaving applications.

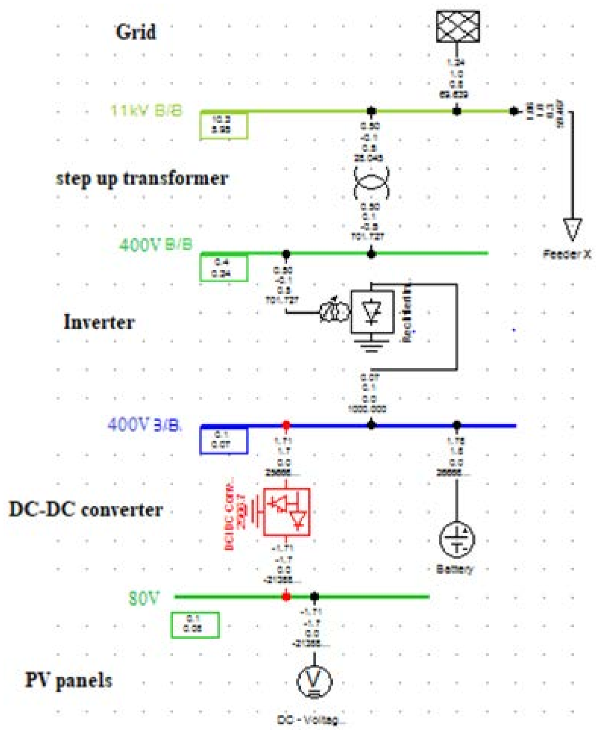

Figure 13. Power factory modeling

To investigate the effects of connecting PV system with battery storage. The model presented in Fig. 13 was connected to a Feeder X which experiences low voltages. Fig. 14 shows the voltage profile of the feeder before the hybrid system is connected.

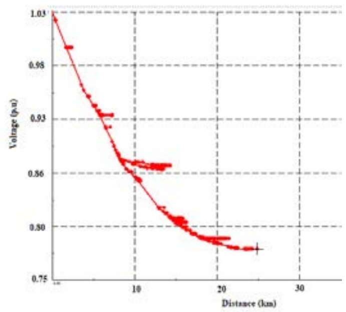

Figure 14. Voltage profile of feeder X before hybrid system is connected

To improve the voltage profile of the feeder X, the hybrid system was connected at a point in the feeder where the voltages were at 0.945 per unit voltage. Fig. 15 shows the voltage profile.

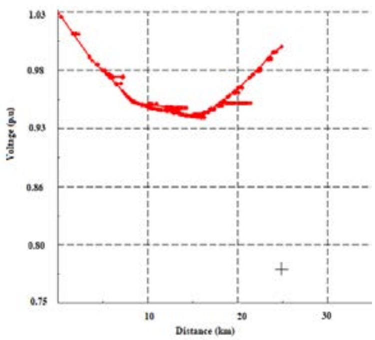

Fig. 14. Feeder X voltage profile after hybrid system is connected.

IV. CONCLUSION

The PV and battery system are modeled developed in the study to assess the performance of renewable energy technologies in a hybrid system. The model was simulated to produce voltage and current waveforms which conform to the expected outcome. The outcomes of the study show that the design is suitable for a grid-connected hybrid power system. This can be attributed from the application of PV and battery systems in the grid-connected hybrid that improved the voltages of feeder X that was having low voltages. The proposed hybrid system is reliable due to application of multiple power sources that can guarantee uninterrupted power supply. This result in significant improvement in performance of a traditional power system due to use of renewable energy sources and an energy storage device and also promotes an energy balance in the power system.

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