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Voltage Control in a Distribution Network Using Energy Storage Systems for PV Penetration

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ABSTRACT

Integrating Photovoltaic (PV) systems with battery energy storage in the distribution network will be essential to allow for continued update of domestic PV system installations. With increasing concerns regarding environmental and climate change issues, incorporating sources of renewable energy into power networks across the world will be key for a sustainable future. A new application of electrical energy storage (EES) systems and demand side response (DSR) operating collaboratively to enable voltage control within distribution networks. Modelling and simulation work is presented, which demonstrates the operation of the control system. To study the variability and the interaction between feeders including VRB, PV system and active units an overvoltage controller has also been developed, implemented and tested successfully.

KEYWORDS: *Vanadium Redox Battery (VRB), State of Charge (SOC), Distributed Energy Resources (DER).*

I. INTRODUCTION

The European Union is aiming at a specific CO2 reduction in the electricity sector in the near future (20 % reduction by 2020). This will involve a significant increase in PV installation all over Europe resulting in a few Giga watts of additional capacity [1]-[4].

Increased distributed generation is becoming more important in the current power system. In the future it will rely more on DER components with energy storage and on smart grids. The flexible smart-grid must be able to import/export energy from/to the grid, to control the active and reactive power flows, and to manage the storage of energy [2], [5]-[8].

The battery package is an interesting option for storing excess energy from the grid (e.g. resulting from solar and wind intermittency) for later use. It may also act as a peak shaving unit and thereby contribute to a stronger grid. Vanadium redox flow batteries have many advantages over other storage technologies, including storage efficiency, low maintenance costs and a long life cycle [9]-[13]. In order to study various aspects of battery storage systems accurate battery dynamic models are required [9], [11]-[20]. Control strategies for battery energy storage systems have become a critical design issue. The challenge is to smooth the intermittent power output of RES, and to keep the rated voltage of the distribution substation within the standard limits [3], [15]-[18].

This paper focuses on simulation models, validated by measurements using experimental facility of an active and distributed power systems laboratory, of a small-scale storage system connected to a PV System and a wind turbine with controllable loads at a distribution network. A local voltage controller of the bus-bar to which the VRB was connected is also described. This was also developed and implemented in MATLAB/Simulink and Power Factory, and validated through simulations.

II. SOFTWARE DESCRIPTION

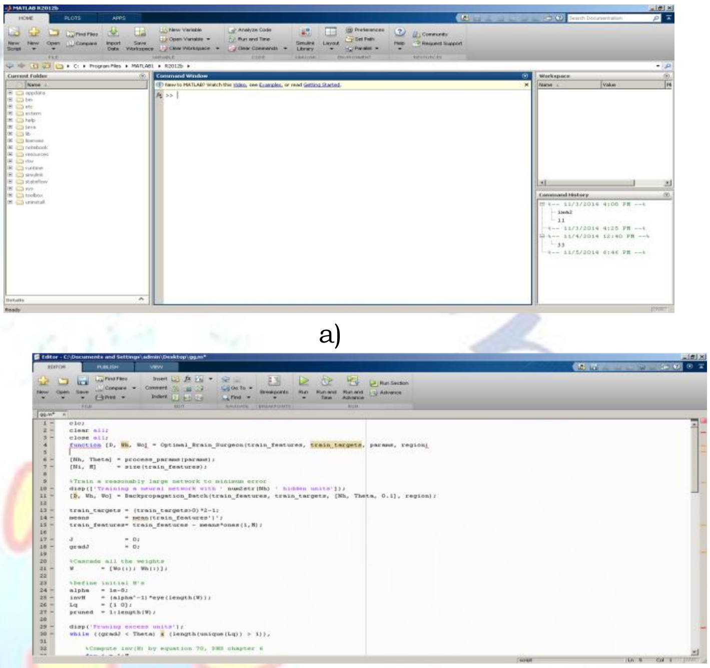
MATLAB (Matrix Laboratory) is a special-purpose computer program optimized to perform engineering and scientific calculations. It is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include,

- Math and computation
- Algorithm development
- Modeling, simulation and prototyping
- Data analysis, exploration and visualization
- Scientific and engineering graphics
- Application development, including Graphical User Interface building

MATLAB is a multi-paradigm numerical computing environment and fourth-generation programming language. Developed by Math Works, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, and fort ran. MATLAB is a high-level language and interactive environment for numerical computation, visualization, and programming. Using MATLAB, you can analyze data, develop algorithms, and create models and applications.

MATLAB is a high-performance language for technical computing. It integrates Computation, visualization, and programming environment. Furthermore, MATLAB is a Modern programming language environment: it has sophisticated data structures, contains Built-in editing and debugging tools, and supports object-oriented programming. These factors Make MATLAB an excellent tool for teaching and research. MATLAB has many advantages compared to conventional computer languages for solving technical problems. MATLAB is an interactive system whose Basic data element is an array that does not require dimensioning. The software package has been commercially available since 1984 and is now considered as a standard tool at most Universities and industries worldwide. It has powerful built-in routines that enable a very wide variety of computations. It also has easy to use graphics commands that make the visualization of results immediately available. Specific applications are collected in packages referred to as toolbox.

MATLAB has four signed and four unsigned integer classes. Signed types enable you to work with negative integers as well as positive, but cannot represent as wide a range of numbers as the unsigned types because one bit is used to designate a positive or negative sign for the number. Unsigned types give you a wider range of numbers, but these numbers can only be zero or positive.



a)

b)

Fig. 1. a) MATLAB command window, b) Program running window

III. SIMULATION MODEL OF THE HYBRID –SYSTEM

The Simulink model of the system was implemented using the MATLAB. It combines two renewable systems of PV and Wind. The VRB battery is used in this system. Wind MPPT controls the input of the system. The SOC (State Of Charge) is used to control the both input and output of the system. Finally it gives the controlled output voltage of the system.

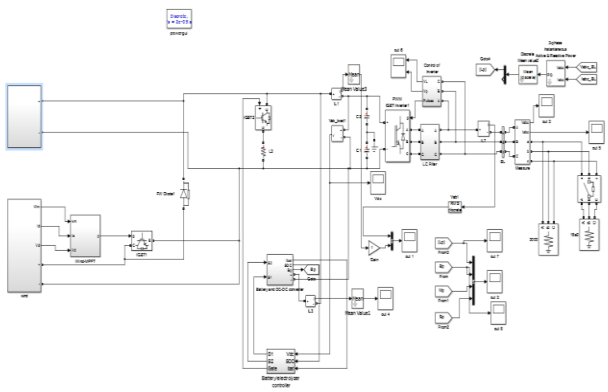


Fig.2. Simulink model of the hybrid system.

IV. PV SYSTEM MODELLING

4.1 Photovoltaic cell

A photovoltaic cell or photoelectric cell is a semiconductor device that converts light to electrical energy by photovoltaic effect. If the energy of photon of light is greater than the band gap then the electron is emitted and the flow of electrons creates current. However a photovoltaic cell is different from a photodiode. In a photodiode light falls on n-channel of the semiconductor junction and gets converted into current or voltage signal but a photovoltaic cell is always forward biased.

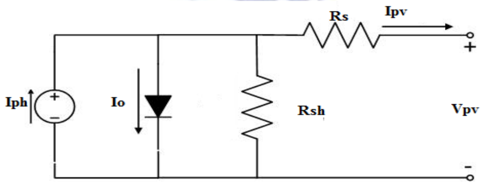


Fig.3. Solar cell equivalent electrical circuit.

4.2 PV module

Usually a number of PV modules are arranged in series and parallel to meet the energy requirements. PV modules of different sizes are commercially available (generally sized from 60W to 170W). For example, a typical small scale desalination plant requires a few thousand watts of power. A PV array consists of several photovoltaic cells in series and parallel connections. Series connections are responsible for increasing the voltage of the module whereas the parallel connection is responsible for increasing the current in the array the most important component that affects the accuracy of the simulation is the PV cell model. Modeling of PV cell involves the estimation of the I-V and P-V characteristics curves to emulate the real cell under various environmental conditions. An ideal solar cell is modeled by a current source in parallel with a diode.

4.3 Simulation model of the PV system

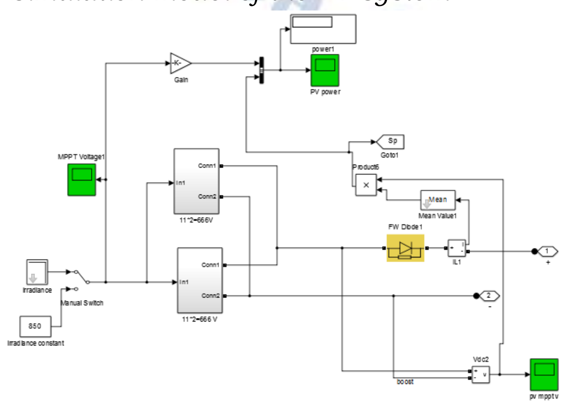


Fig.4. Simulink model of PV.

A PV system modelling consists of irradiance as well as irradiance constant. The meaning of irradiance is radiant flux received by a surface per unit area. This is sometimes also confusingly called "intensity". Irradiance constant or the solar constant, a measure of flux density, is the conventional name for the mean solar electromagnetic radiation (the solar irradiance) per unit area that would be incident on a plane perpendicular to the rays, at a distance of one astronomical unit (AU) from the Sun (roughly the mean distance from the Sun to the Earth). Irradiance constant value is 850. The Manual Switch block is a toggle switch that selects one of its two inputs to pass through to the output. To toggle between inputs, double-click the block. The block propagates the selected input to the output, while the block discards the unselected input. The Manual Switch block retains its current state when you save the model.

V. WIND SYSTEM MODELLING

The wind system consists of PMSG, rectifier and generator terminal. The pitch control system is found to have a large output power variation and a large settling time. The pitch function gives full control over the mechanical power and if the most common method is used for the variable speed wind turbines. At wind speeds below the rated power of the generator, the pitch angle is at its maximum though it can be lower to help the turbine accelerate faster. Above the rated wind speed, the pitch angle is controlled to keep the generator power at rated power by reducing the angle of blades. The pitch control system is one of the most widely used control techniques to regulate the output power of a wind turbine generator. The method relies on the variation in the power captured by the turbine as the 63 pitch angle of the blades is changed. Hydraulic actuators are used to vary the pitch angle. The wind turbine generator describes the design of the pitch controller and discusses the performance of the system in the presence of disturbances.

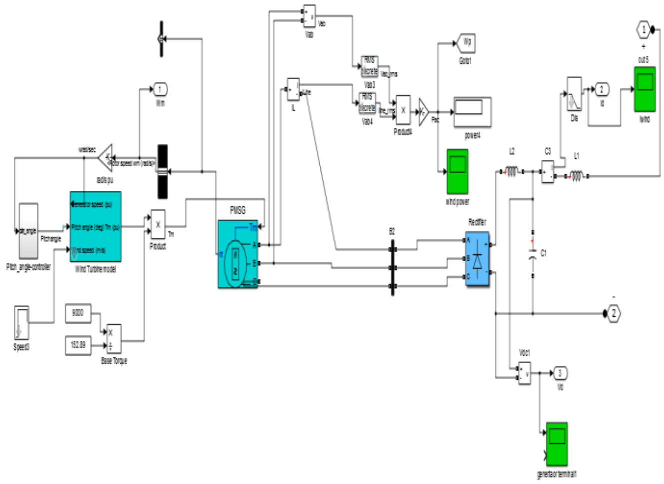


Fig.5. Simulink model of wind.

5.1 Permanent Motor Synchronous Generator (PMSG)

Wind turbine technology has developed rapidly over the past decade into one of the most mature renewable power generation technologies. Compared to other wind turbine systems used for commercial power generation, the accelerated evolution of the direct-driven wind turbine (WT) with a permanent magnet synchronous generator (D-PMSG) can be attributed to its simple structure, low cost of maintenance, high conversion efficiency and high reliability. Moreover, its decoupling control performance is much less sensitive to the parameter variations of the generator. Therefore, a high-performance variable-speed generation including high efficiency and high controllability is expected by using a PMSG for a wind generation system.

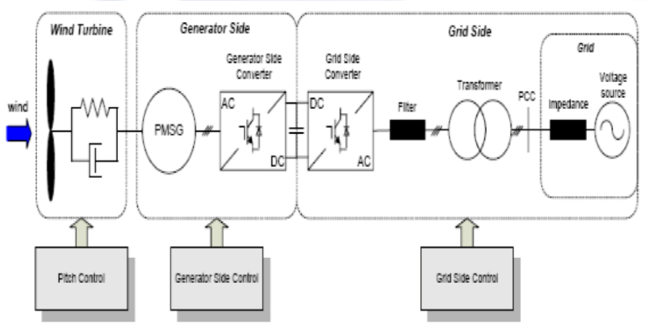


Fig.6. Block diagram of PMSG with WT.

5.2 Wind Turbine model

Wind turbine design is the process of defining the form and specifications of a wind turbine to extract energy from the wind. A wind turbine installation consists of the necessary systems needed to capture the wind's energy, point the turbine into the wind, convert mechanical rotation into electrical power, and other systems to start, stop, and control the turbine.

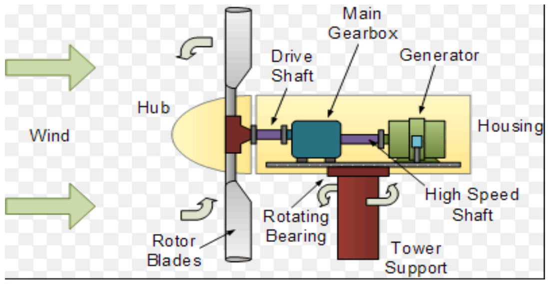


Fig.7. Wind Turbine.

VI. VRB BATTERY IMPLEMENTATION

6.1 Implementation model

The VRB model has been implemented in MATLAB/Simulink and Power Factory and is based on the equivalent electrical circuit and on the power balance between the input and the stored power, which is dependent on the efficiency of different components, such as: cell stacks, electrolytes, pumps, power converter and the power losses, as it is These characteristics of the battery have been computed based on the results of experiments where different electric values at different loads and SOC levels were measured. The power converter was modeled using a look-up table with values relating to the efficiency of the AC-DC converter in both charge and discharge operation modes. When the battery was running under stable conditions during charge/discharge the efficiency of the cell stacks was implemented as a function of the DC power at different SOC levels. The total energy stored in the VRB depends on both the SOC and the amount of active chemical substances.

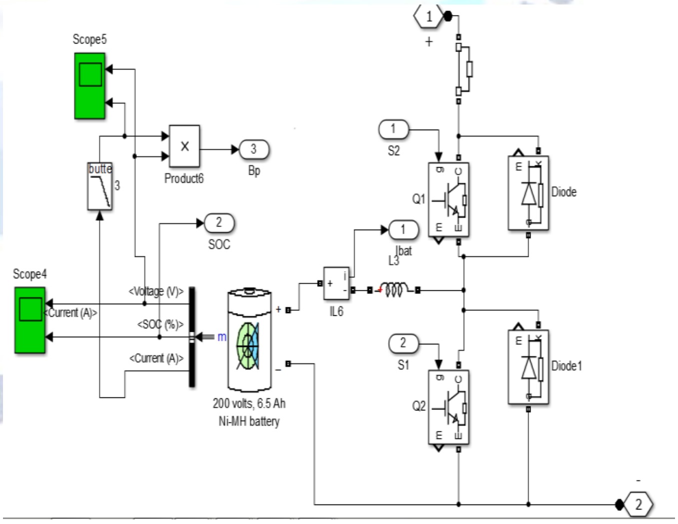


Fig.7. VRB Battery.

6.2 Validation of the model

In order to validate the simulation model, measurements were taken from the DAQ board of the VRB, fed into the model and verifying the output values of the battery and of the model. The sampling time of the simulations and of the measurements data processing has been of 1 second. The following experiment for a time scale of 36 hours was considered: starting from a SOC=93.5% the battery was discharged with a constant power PAC=15 kW, until SOC=18%. Then a charge sequence was considered from SOC=14% until the level of SOC=87% at PAC=10 kW. During the discharging cycle a battery constant pulsed current was applied in order to find out the dynamic characteristics. A comparison between simulations and measurements of SOC level and DC Voltage and Power is presented as can be seen it is a very small difference between graphics (0.1% at full SOC and 1% under 20% Of SOC), which means that the simulation model developed can be an accurate tool for studying and analyzing the characteristics of the energy storage system in a distribution network.

VII. VOLTAGE CONTROLLERS

The simulation models, validated by measurements using experimental facility of an active and distributed power systems laboratory, of a small-scale storage system connected to a PV System and a Flex-House with controllable loads at a distribution network. A local voltage controller of the bus-bar to which the VRB was connected is also described. This was also developed and implemented in MATLAB/Simulink and Power Factory, and validated through simulation.

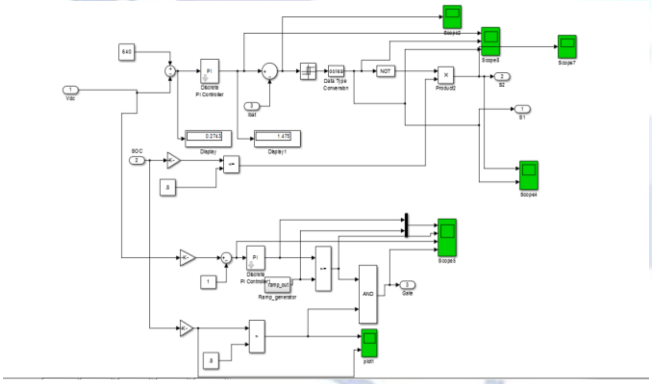


Fig.8. SOC battery controller

Two types of controllers for voltage regulation have been developed and implemented in Simulink based on finite state machine for controlling the bus-bar voltage at the connecting point. One controller is able to control the voltage at the bus-bar charging the battery when an overvoltage is detected. The idea was to control the voltage at the bus bar when exceeds the maximum value, due to the PV production, changing the battery mode of operation (discharging/charging).

The objective of this paper is to present novel control strategies for Micro Grid operation, especially in islanded mode. The control strategies involve mainly the coordination of secondary load-frequency control by a Micro Grid Central Controller that heads a hierarchical control system able to assure stable and secure operation when the islanding of the Micro Grid occurs and in load-following situations in islanded mode. The connection of micro generation to Low Voltage (LV) networks is starting to deserve considerable attention from specialists worldwide, encouraging investigations and pilot experiences.

In this context, a Micro Grid (MG) concept has been developed under the framework of the Micro Grids European Union project. A MG [1] can be defined as a LV distribution system to which small modular generation systems are connected. Generally, a MG corresponds to an association of electrical loads and small generation systems through a LV distribution network. This means that loads and sources are physically close. Considering the currently available technologies, micro generation systems may include several types of devices such as fuel-cells, wind turbines or photovoltaic (PV) systems as well as micro turbines using either gas or bio-fuels. Apart from a LV distribution network, micro generators and electrical loads, a MG must also include some kind of storage devices (such as batteries or flywheels) as well as network control and management systems. The storage devices will play an important role in this kind of network, mainly in what concerns fast load-following situations. At the current research status, it is assumed that the MG can be operated in two main situations:

7.1 Normal interconnected mode

The MG will be electrically connected to the main MV network either being supplied by this network (totally or partially, depending on the generation allocation procedures adopted to operate the micro sources) or injecting power into the main MV grid (when the relation between the micro sources installed capacity and the electrical loads allows this type of operation).

7.2 Emergency mode

In case there is a failure in the main MV network, the MG must have the ability to operate in an isolated mode, that is, to operate in an autonomous way, similar to the power systems of physical islands. A simulation platform under the

MATLAB® Simulink® environment was developed in order to evaluate the dynamic behavior of several micro sources operating together in a LV network under pre-specified conditions including interconnected and autonomous operation of the MG Description of the Simulation Platform To test the effectiveness of the approach considered, a simulation platform under the MATLAB® Simulink® environment was developed. At this stage only three phase balanced operation of the network is being considered. The analysis requires the development of a set of dynamic models able to simulate the response of the MG under pre-specified conditions. For this purpose, several micro sources and storage devices have been modeled. These models, together with control systems, were also implemented in the MATLAB® Simulink® simulation platform.

7.3 Micro-grid control strategies

1. Main concepts

The main control strategy considered involves the passage to islanded operation mode of the MG in case of a fault in the MV network or in other exceptional cases. Contrary to the classic belief that islanded operation must be avoided at all costs, a new strategy is being developed that includes planned operation under these conditions. The islanding procedure is then controlled and made intentionally, corresponding to careful planning about operational conditions concerning not only load levels and levels of the distributed resources but also different types of defaults, etc. The control of the MG is a delicate issue. A complex structure must be developed in order to assure a robust MG operation. The Micro Grid Central Controller is in charge of such MG operation control. MG operation is based on a control scheme that exploits different inverter control modes.

2. MG control and MGCC structure

The MGCC includes a multiplicity of functionalities one of which is secondary load-frequency control. This functionality is similar to the one of a conventional Automatic Generation Control (AGC) system. The MGCC coordinates a hierarchical control scheme, where the control infrastructure

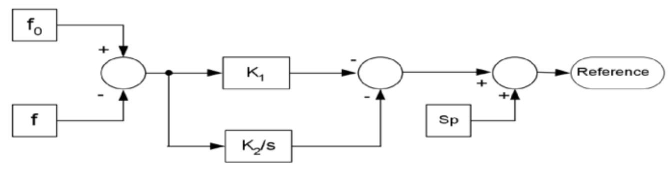
3. Secondary load-frequency control

There are two ways of performing secondary load frequency control of the MG: either locally (using a local PI controller at each micro source, as represented in Figure) or in a centralized and automatic way, mastered by the MGCC. The load frequency control is performed as follows: whenever the MG is operating in interconnected mode with the MV network, the centralized control is disabled; however, when the MG becomes isolated, the MGCC must coordinate the secondary load-frequency control.

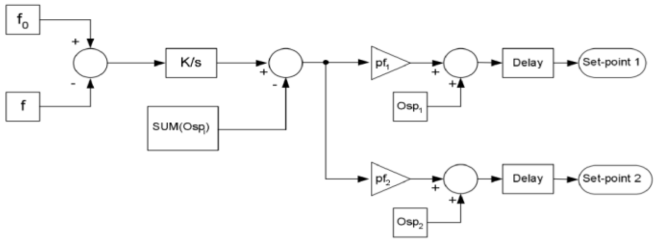
The two main objectives of the secondary control at the MGCC are: To hold the system frequency at or very close to 50 Hz; To maintain each unit's generation at the most economic value. Notice that, unlike AGC standard implementation, timeline control is not applicable since only one control area – the MG – is considered. The secondary load-frequency control is enabled subsequently to the action of local MCs in response to an imbalance between load and generation. This imbalance can be caused either by the islanding of the MG or by variations in load or in micro source generation levels [5] (like the ones that result from wind or PV generation).

In order to perform load-frequency control, the MGCC receives and stores information from the LCs (load levels) and MCs (micro generation active power levels) and frequency measurements. Using the frequency deviation as input and based on participation factors (PF) calculated using cost-functions associated with each micro source and economic set points for the micro generators, the secondary frequency control function implemented at the MGCC specifies active power set-points that are sent back to the MCs in order to adjust the production levels and consequently correct the frequency offset.

The optimal economic set-point (OSP) for each micro source is updated every 60 seconds. These values are entered from a table that contains the results from economic dispatch for a market environment. The centralized secondary load-frequency control structure is presented in Figure



a)



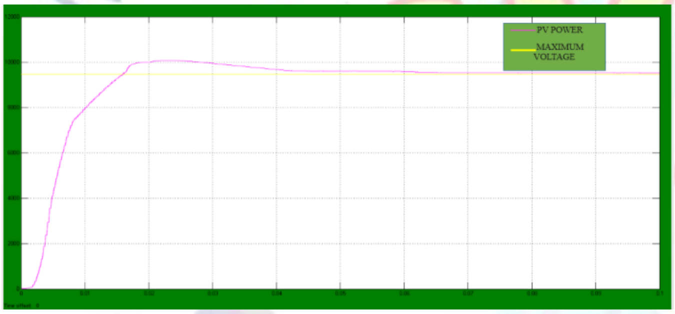
b)

Fig.9. a) Local secondary load-frequency control at each micro source and b) Secondary Load-Frequency Control

The input and the stored power, which is dependent on the efficiency of different components, such as: cell stacks, electrolytes, pumps, power converter and the power losses, as it is These characteristics of the battery have been computed based on the results of experiments where different electric values at different loads and SOC levels were measured. The power converter was modeled using a look-up table with values relating to the efficiency of the AC-DC converter in both charge and discharge operation modes. When the battery was running under stable conditions during charge/discharge the efficiency of the cell stacks was implemented as a function of the DC power at different SOC levels. The total energy stored in the VRB depends on both the SOC and the amount of active chemical substances.

VIII. SIMULATION RESULTS

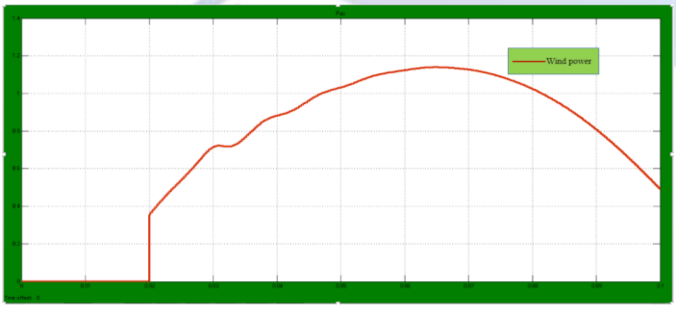
Case 1. PV output



a)

The above waveform shows the PV simulation of the system. The waveform was plotted with the constant value of 850. The irradiance values are Time(s) [0 2], Amplitude [1000 850], Irradiance constant (850), sample time (20e-6).

Case 2. Wind output

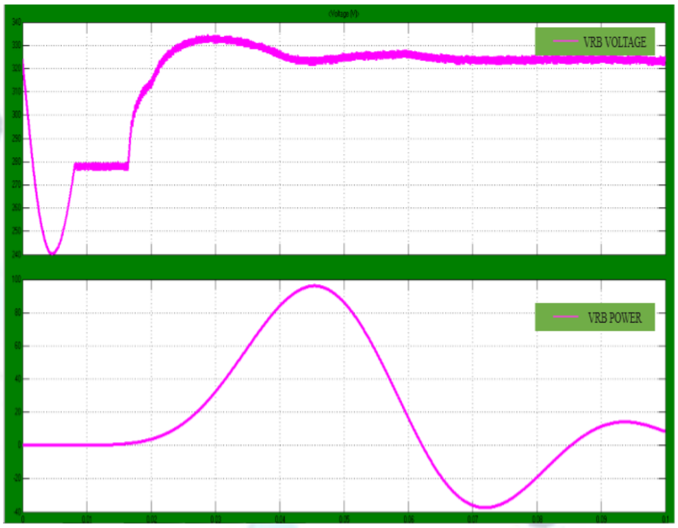


b)

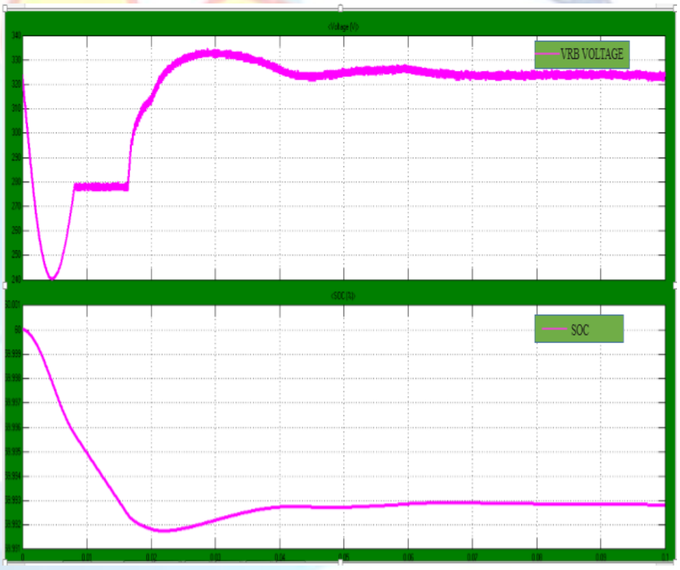
The constant value is 9000, time of the speed 3 [0 .5 3], Amplitude [5 12 9].

Case 3. Battery output

The nominal voltage (v) = 300, Rated capacity (Ah) = 6.5, Initial state of charge (%) = 60, Fully charged voltage (v) = 353.3898, Nominal discharge current (A) =1.3, Internal resistance (ohms) = 0.46154, Battery response time (30) s.



c)



d)

Fig.10. a) PV output power, b) wind power output, c) simulation results of battery maximum voltage and power, d)simulation resulst of SOC and battery voltage

IX. CONCLUSION

In this paper we have described the development of simulation tools for DER components in a distribution network. The main focus was on the modeling of voltage controllers using energy storage systems for PV penetration. The VRB system simulation model has been implemented in MATLAB/Simulink taking into account the efficiency and the power losses of different components. The model has also been validated

using measurements. Two voltage controllers have also been developed and implemented using a state flow chart and a PI controller based on finite-state machine. An overvoltage controller, able to charge the battery when the bus-bar voltage exceeds the limits, and a voltage controller able to set-up the battery to run in schedule mode. In the case of the former, the VRB is connected only when an over voltage occurs and consumes the excess power until the power injected into the grid is not causing the bus voltage to exceed the limit. It means that the battery requires fewer charging/discharging cycles, leading to increased battery life.
Simulation results have shown that the controllers have been designed and implemented successfully.

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