Control of a Hybrid Wind-PV and Energy Storage System

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Abstract—Distributed energy generation systems deployment is rapidly increasing globally, offering many major advantages and benefits. The integration of distributed generation at distribution system and close to the load reduce the network losses, improve the reliability when the grid is not available, and economically sounds if the distributed generation cheaper than the grid. The use of Renewable Energy sources like the photovoltaic (PV) panels and the wind turbines leads to reduction in fuel consumption which in turn leads to less toxic emissions to the environment. However, the energy production from wind turbines and PV panels is not reliable by itself as wind speed is irregular and not all wind speed can be harvested. Similarly, the solar irradiation is unpredictable in nature and PV system output is variable during the day and not available at night. That means when depending only on energy from wind turbine alone or PV system alone, the power may not be available when needed or at least not matching the demand. Here comes the need to aggregate the wind turbine with PV system and integrate the energy storage system (ESS) to overcome the intermittent behavior of Wind-PV and balance power generation. The hybrid wind-PV-ESS would improve the system reliability, reduce the intermittency of supply, and enhance the system security. The ESS can store extra produced energy and use it to compensate the reduction in power generation and balance out the fluctuations of the wind-PV power in short and long time periods. Additionally, the energy storage devices have a faster response to handle load variations. This paper, will focus on developing a control system for the hybrid Distributed Generation resources (DGs) utilizing the wind turbine with PV panels and integrated energy storage systems (ESS). Integrating the wind turbine and the PV energy generation with energy storage would balance the variations of the wind power and the load ones. The suggested model automatically controls the power flow of hybrid system according to the availability of power and changes in load as well. The contribution of battery storage is to substitute sudden/average fluctuations in power changes that results in the DC link, improve energy efficiency, and

limit current stress on battery. The hybrid system has been modeled and simulated in MATLAB Simpower toolbox and the results show a satisfactory response.

I. INTRODUCTION

SINCEsun irradiation is usually unpredictableand wind speed is intermittent, the power production from the PV and the wind turbine imposes more uncertainty into operating power. The maindisadvantage to use wind and PV as a source of energy is that wind-PV power may not be available when needed[1]. Having said that, integrating energy storage systems ESS can waive this disadvantage by smoothing the fluctuations of wind energy generation and balance the whole system power production.

The residential appliances requested energy introducesunpredictable behavior, which could be greater or lower than the produced power from the renewable sources. EmployingESS along with the PV and the wind turbine energy generation system wouldbalance the random variations of the load and the wind power ones [1].

It is essential to control wind turbines and PV panels in such a way that they wouldproduce maximum power so as to reach higher efficiency rates in hybrid systems.The power electronic circuits can deliver full system efficiency byregulating duty cycle and continuously examining the output of wind turbines and PV panels [6]. Powerexchangebetween hybrid systems and the grid is achievedthrough an effective coordination between different hybrid system elements and a proper control unit. These control units manage the power flow between sources by regulating the DC bus voltage[5]. The design and control of control unit and power electronic circuits is the main challenge of Wind and PV integrated hybrid energy systems. AC to DC rectifiers, DC/DC converters and DC to AC inverters are utilized in Wind / PV hybrid systems. PID controllers are being utilizedin order to control the output voltage of a DC/DC converters which have a wide range of variable input voltage.Typically, the output voltage can be regulated by adjusting the duty cycle of transistors in DC/DC converters [3].

Controlling distributed generation energy sources to function autonomously as a microgrid, wouldimprove the performanceof the microgrid. This integrated system could be accomplished by an energycontrol and management system, working to monitor and control thepower flow within the microgrid [2].

An appropriateenergy management systemissuggested for the Wind-PV hybrid renewable and grid connected system with integrated battery and supercapacitor ESS.Additionally, it is illustrated that the energy management system (EMS) can achieverapid and robustDC link voltage control compared with the

AC line current regulation technique. Storage system integration and coordinated management with renewable energy sources can open the way to larger level of renewable penetration into electric distribution networks [6].

The operation and of such hybrid system is considered complicated and encloses various challenges since it is considered to be a System of Systems (SoS). The hierarchical control method is one of the common configurations for the operation. It consists of primary, secondary and a tertiary controller, where the primary controller is located at the DG source (i.e. the local converter) and responds to variations of voltage and frequency to adjust the generated real and reactive power. On the other hand, secondary controller oversees and coordinatesthe operation of multiple primary controllers and, hence, check for any deviations caused by local controllers and sets the reference operating point. The secondary controller considers all connected DGs and local loads in the system to achieve a consistent operation. Finally, the tertiary controller is located at the Point of Common Coupling (PCC) and responsible for efficient and economic operation as well as the exchange of power with the main grid. Tertiary control is referred as EMS [18].

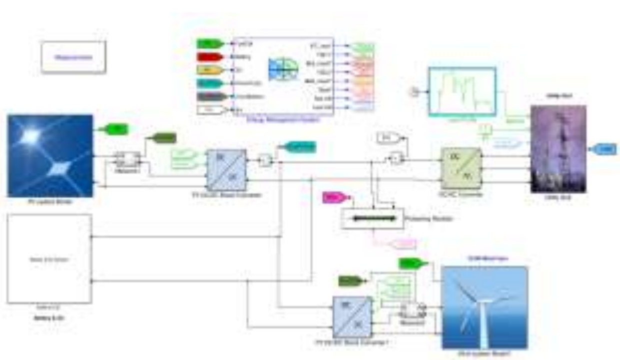

Fig. 1. Overview of the system Layout as modeled in SIMULINK

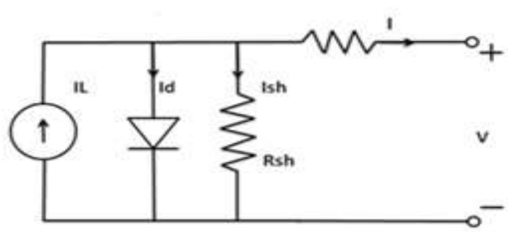

Fig. 2. Single PV Cell Model

This project will focus on developing the energy management system for the hybrid Distributed Generation resources (DGs) utilizing the wind turbine with PV panels and integrated energy storage systems (ESS). Integrating the wind turbine and the PV energy generation with energy storage wouldbalance the variations of the wind power and the load ones. The suggestedmodelautomaticallycontrols the power flow of renewable integrated systems according to the availability of their power and changes in load as well. The contribution of battery–supercapacitor storage is to substitute sudden/average fluctuations in power surges that results in fast dc link voltage regulation, improve energy management efficiency, and limit current stress on battery.

Matlab and Simulink modeling tools will be used to simulate the model and generate the results.

II. Modelling of Hybrid System

A. System Layout

The system layout is illustrated in Fig. 1where the wind turbine and the PV are connected throughDC/DC converters to the DC buswith the power production optimized using the maximum power point tracking (MPPT). The energy storage system ESS consisting of lithium battery and a supercapacitorare integratedin the system and connected in parallel with DC bus in order to balance out the intermittent power from the wind turbine, PV and the load. The battery is connected via DC/DC boost buck converter in order to control the charging and discharging as well as to limit current stress on battery while the supercapacitor is connected directly to have quicker response to voltage surges and fluctuations.

The suggested scheme of power system consisting of actual power components interconnected by a three-phase 260-V power grid of North America along with communication and control nodes interconnected to monitor and control the power flow.

B. PV Model

The used model of the PV cells is displayed in Fig. 2 as a current source simulating light generated current in the cell represented by IL, I_D represents the voltage dependent current lost to recombination and I_{sh}represents the current lost due to shunt resistance, I_D is modeled using the Shockey equation for an ideal diode.

The model implemented in this system is 2 by 7 array of 6 kW total power at full sun irradiance.The Maximum Power Point Tracking (MPPT) controller is based on the 'Perturb and Observe' technique. This MPPT system dynamicallyadjusts the VDC reference signal of the inverter VDC regulator so as to figurethe DC voltage which wouldobtain maximum power from the PV array as displayed in the I-V characteristics of the modeled PV panel in Fig. 3.

$$I_{sh} = \frac{(V + IRs)}{R_{sh}} \quad (1)$$

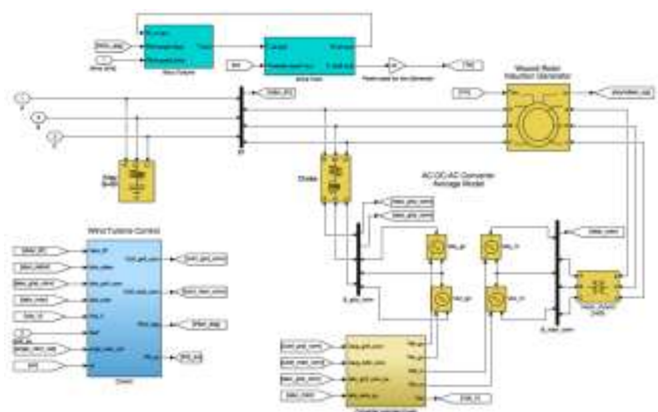

Fig. 4. Wind Turbine Model in Simulink

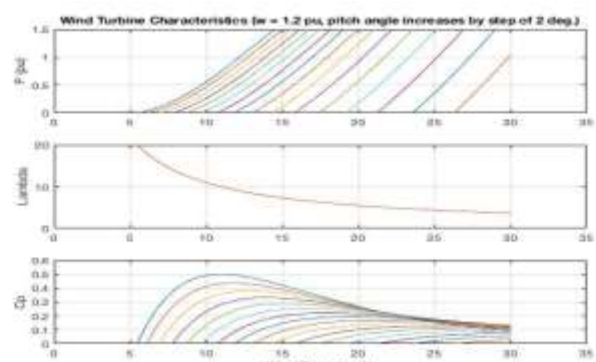

Fig. 5. Characteristics of Wind Turbinewhere lambda is the ratio of wind speed to turbine speed

$$I = I_L - I_0\left[\exp\left(\frac{V + IRs}{\eta V_T}\right) - 1\right] - \frac{(V + IRs)}{R_{sh}} \quad (2)$$

IL = light current (A).

I0 = Diode reverse saturation current (A).

Rs = Series resistance in (Ω)

n = Diode ideality factor.

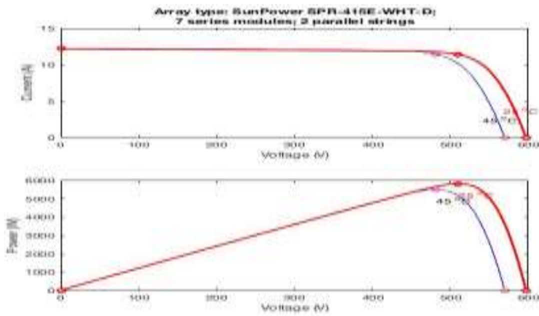

Fig. 3. I-V Characteristics of PV panel

C. Wind Turbine and DFIG model

Wind turbines implemented in this model include a doubly-fed induction generator (DFIG) comprise of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter modeled by voltage sources. The stator winding is connected straight to the 60 Hz grid while the rotor is injected at variable frequency through the AC/DCinverter. The DFIG technology facilitates theextraction of maximum power from the wind for low wind speeds bycontrolling the turbine speed, thoughreducing mechanical stresses on the turbine during wind surges.

In this model, the wind speed is varied between5 and 15 m/s. The control system implements a torque regulator in order to obtain maximum power of 15 kW. The reactive power generated by the wind turbine is maintained at 0 Mvar by incorporating a smoothing capacitor.

The model is shown in Fig. 4 and. Fig. 5 show the characteristics of wind Turbine.

D. Battery Modelling

The Li-ion battery is known for its high power capabilities. A combination of series and parallel connections of Li-ion battery is utilized in our system to form the required high power battery. The battery characteristics is modeled through the following charging and discharging equations:

$$f_1(it, i^*, i) = E_0 - k \cdot \frac{Q}{it + 0.1Q} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot \exp(-B \cdot it) \quad (3)$$

$$f_2(it, i^*, i) = E_0 - k \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot \exp(-B \cdot it) \quad (4)$$

where E0 is the initial voltage, K is the polarization resistance in ohms, i* is the low-frequency dynamic current in Amps, i is the battery current in Amps., it is the battery extraction capacity (Ah), Q is maximum battery capacity (Ah), A is the exponential voltage, B is exponential capacity in (Ah)−1.

The proposed battery properties in this model is 100 kWh, 48

Depending on the consistency of forecast errors would determine the capacity of the storage system. Additionally, the determined threshold of generated and exported power to the grid would have a major factor on determining the size of battery capacity. At the currentphase, there are no studies that have been done to analyze this aspect of the project.The main target at this stage to analyze the performance of the model rather than evaluating a technical andeconomical optimization.

E. SC Modelling

The wind/load fluctuationsproducetwo types of power oscillations that the energy storage devices need to balance, which consist of the HFC and the LFC. That means, using only the battery to smooth these fluctuationsreduces its lifetime, while using the SCs without the battery to compensate these fluctuationsrises the size and cost of SCs. The best technique to meet these fluctuations is combine both battery and SCs in the system.The SCs havea life time that is about ten years longer than of the battery. Moreover, they can handle HFC better due to their electrical property of quick dynamic performances in terms of the charging/discharging cycle.Additionally, the SCs have a power density from 10 to 100 times higher than that of the battery. However, their energycapacity much less; this is the reason for combining the battery with the SCs to balance the variating power[1].

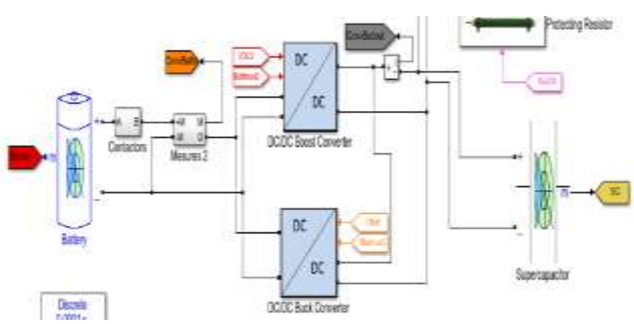

Fig. 6. Battery and SC model with DC/DC buck boost converters

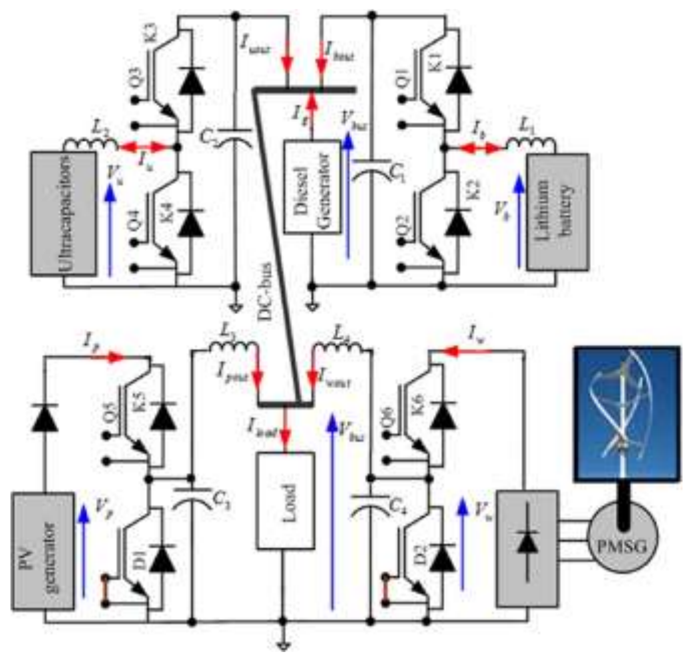

Fig. 7. Connection of Buck-Boost converters for SC and Li-Battery

The Super Capacitor (SC) is grouped with the battery system and directly connected to the DC bus in order to rapidly compensate the high fluctuations voltage induced by slow response of DC/DC and AC/DC converters.

A 291.6 V, 15.6 F, supercapacitor system (six 48.6v cells in series) is used for our system.

Fig. 6 shows the modulation of Battery and SC along with DC/DC buck-boost converters used for charging and discharging.

F. Buck-Boost Converters Modeling

In order todevelop anoverall model of the buck-and-boost converters displayed in Fig. 7, it is important to examine the buck and the boost converter operations [1]. During Boost Mode, K_2 and K_4diodes are turned ON, and K_1 and K_3 are reversed biased (i.e. switched OFF). In this state, the SCs and the battery deliverpowertotheDC-bus.Inbuckoperation,K_1 and K_3 are turned ON, and K_2 and $K_4$are reversed biased (i.e. switched OFF). Then, the SC and the battery absorbpower from the DC-bus.

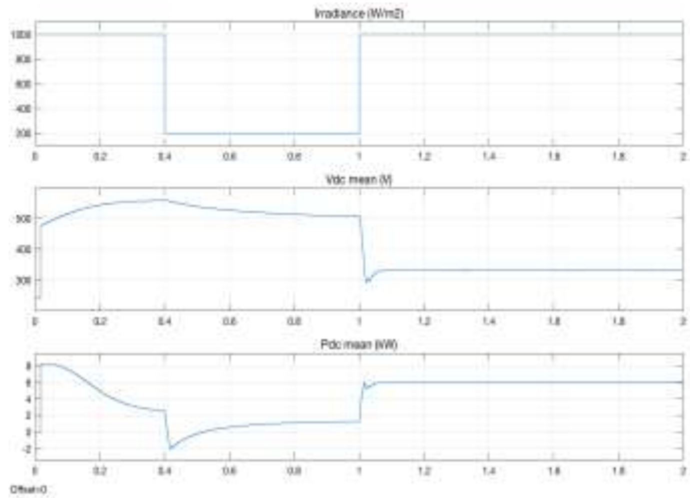

Fig. 8. Variable Sun Irradiance Simulation

III. Energy Management System and Control Unit

The central control unit in Renewable Energy Management System is responsible for deciding the operation mode and controlling the flow of energy as well as maintaining optimum performance of each energy source[3].The main inputs to the control unit in order to effectively execute the energy management algorithms are wind turbine and PV panels power production values, the battery power level, grid and connected loads [3]. Central control unitdutyis to govern the energy flow between system components. However, because energyproductionchanges over time depending on the weather conditions, energymanagement scheme can get very complicated.

Central control unit which is developedfor this project, manages the operation of the hybrid system as autonomous and gridconnected at the same time. The control unit has output terminals in order tocontrol the grid DC/AC inverter switch, the load inverterswitch and the battery DC/DCconverter switch.

Depending on renewable energyexistence and load power requirement, the suggestedEMSmanages the workingcondition of the whole system. It has the following roles: 1) To always operate the battery and SCs within their higher and lower boundary limits; 2) To deliverssmooth mode exchange; and 3) And to minimize current stress on battery units and thusprolong its life span.

To achieve the above, I have modified an existing state-machine controller to suit and handle my EMS and integrated its linked Matlab code.

According with the measurements obtained from input nodes, the control units runs the algorithms required to decide which output connected switchesto open and close.EMS algorithms aredeveloped based on the whole powerproduced by the hybrid system and so as to manage the transfer of generated power to grid or batteries as required.

IV. Simulation and Results

A. Simulation of Wind Turbine Connected to Grid

The simulation of wind turbine standalone system connected to the grid with input of variable wind speed is displayed in Fig. 8 in order to see response of wind turbine and its controller. The graph clearly shows how turbine speed follows wind speed and the extraction of maximum possible real power as well. The reactive power generated by the wind turbine is maintained at 0 Mvar by incorporating a smoothing capacitor.

B. Simulation of PV Connected to Grid

The simulation of variable irradiance and its effect on PV output power is shown in Fig. 9. The modeled MPPT works seamlessly extracting maximum power from PV panels.

C. Simulation of power flow between Energy sources, load and Grid.

A simulation of constant wind speed and constant sun radiation was done to simulate the power flow in the hybrid system with and the utility grid. At the beginning total power from PV and wind turbine (13 kW) is exported to the grid. Initially, load-1(10 kW) is connected and at 3s, load-2 (4 kW) is connected. Two methods are used to control the distribution of generated power. First method, illustrated by Fig. 9, the charging and discharging of the storage system is controlled in order to control the output power of the inverter. Second method, displayed in Fig. 10, the Inverter output power is controlled by controlling Inverter current in VSI mode and using SVPWM with current feedback. The second method requires decoupling control of d and q current components.

Both methods functioned well. However, controlling Battery charging/discharging operation would affect the DC voltage level as it essentially controlled the battery while in the other hand, controlling the output current has better response but requires special design of the LC filter.

In Fig. 9, the Inverter output power is increased between 3-4 sec and the battery system acted accordingly to achieve it and keep it constant despite fluctuations in PV and Wind output power.

Fig.10, the Inverter output power was kept constant at 10 kW. The system was able to maintain this level of output power despite change of connected load and local generation. The extra connected 4 kW load was supplied by the grid.

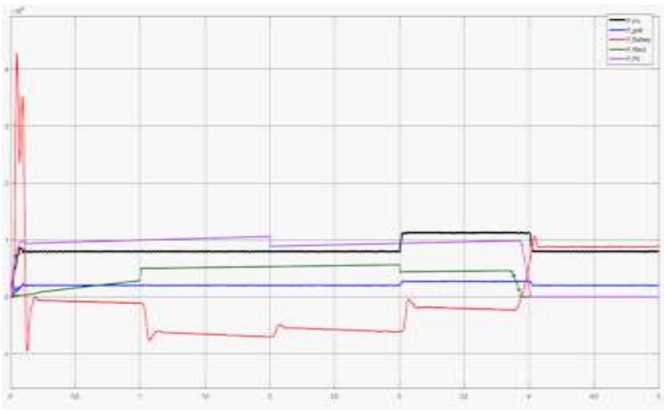

Fig. 9. Poweroutputof PV, Wind Battery and Inverterby controlling Battery charging and discharging.

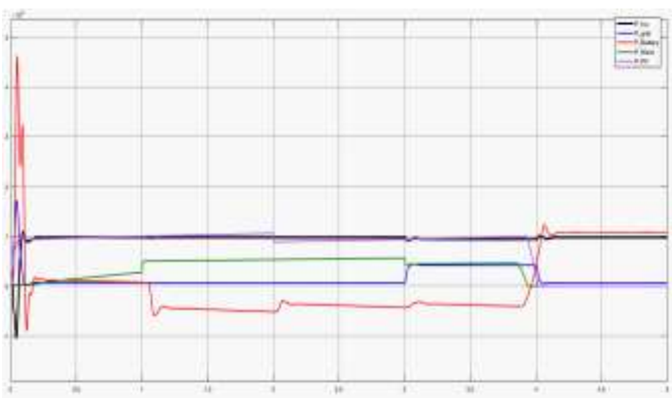

Fig. 10. Power flow between Energy sources, Inverter and Grid Using Current Control

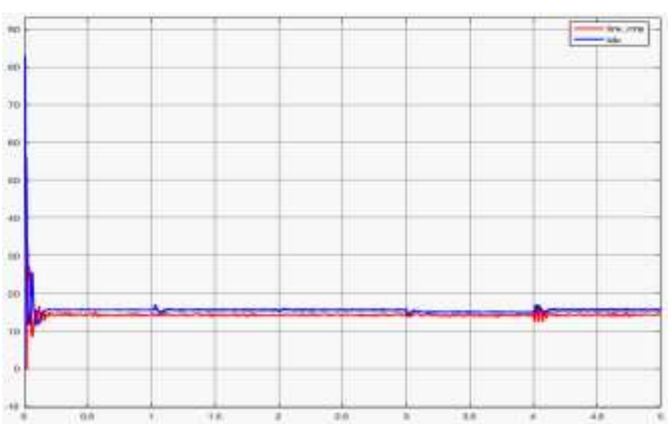

Fig. 11. Inverter Current output Vs. DC Current

V. Conclusion

Hybrid Energy system thatis made of wind turbines and PV panels is developed in such a way that would perform either on-grid operation or autonomous off-grid operation.The PV panel and wind turbine DFIG generator are set as the main energyproducer in the system.

Due to the demand forconsistent and reliable energy, energy storage system of battery and SC is integrated to compensate for wind power fluctuations and load variations.Power electronic circuits of AC/DC rectifiers, DC/DC converters and DC/AC inverters are implemented in the distribution system to interface with different energy generators, battery system and system loads. Such devices impose an extended technical challenges.

During autonomous operation, byregulating the Distributed Generators, wouldimprove the efficiency of the system. This smart coordinated system could be accomplished by an energy management system and central control unit, functioning to govern the energy flow inside the system.

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