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Research Paper

DESIGN AND IMPLEMENTATION OF AN ENERGY MANAGEMENT SYSTEM FOR A SMALL-SCALE HYBRID WIND–SOLAR–BATTERY MICROGRID

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ABSTRACT An efficient energy management system for a small-scale hybrid wind-solar-battery based microgrid is proposed in this paper. The wind and solar energy conversion systems and battery storage system have been developed along with power electronic converters, control algorithms and controllers to test the operation of hybrid microgrid. The power balance is maintained by an energy management system for the variations of renewable energy power generation and also for the load demand variations. This microgrid operates in standalone mode and provides a testing platform for different control algorithms, energy management systems and test conditions. A real-time control is performed by rapid control prototyping to test and validate the control algorithms of microgrid system experimentally. The proposed small-scale renewable energy based microgrid can be used as a test bench for research and testing of algorithms in smart grid applications.

Keywords: *Energy management system, hybrid system, microgrid, solar energy, standalone system, wind energy*

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I.Introduction

The increasing global demand for electricity and the urgent need to reduce carbon emissions have accelerated the deployment of renewable energy-based distributed power systems. Small-scale hybrid microgrids combining solar photovoltaic (PV), wind turbines, and battery energy storage systems (BESS) have emerged as viable solutions due to their sustainability, modularity, and ability to operate autonomously. These systems are ideal for rural electrification, off-grid locations, and regions with weak transmission infrastructure.

However, renewable energy sources such as solar and wind are intermittent and highly unpredictable. This variability affects system reliability, voltage stability, and power quality. To address these challenges, a robust Energy Management System (EMS) is required. The EMS supervises power flow, optimizes resource usage, and ensures reliable supply to connected loads. For small-scale microgrids, the EMS must be simple, cost-effective, computationally efficient, and capable of handling real-time operational complexities.

The primary objective of this work is to design and develop a wind–solar–battery hybrid microgrid, integrated with an EMS capable of maintaining power balance under varying generation and load conditions. The proposed setup is also suitable for real-time rapid control prototyping, allowing researchers to evaluate converter controls and EMS algorithms under realistic operating conditions.The microgrid should comply with the interconnection standards as mentioned, during the grid connected mode of operation. In this paper, a comprehensive review of literature is carried out on the control methods in the AC, DC, and AC-DC microgrids along with evolving trends in the microgrid research. Previous survey articles have reported hierarchical control systems in microgrids without categorizing them concerning different microgrid-architectures. The motivation behind this review paper is to coordinate and categorize the research carried out in AC, DC, and hybrid AC-DC microgrids hierarchically with a focus on the primary and secondary level of control. Such categorization of control strategies in different microgrid-architectures, i.e., AC, DC, and AC-DC appears to have not been reported in an independent article. Also, some evolving trends in microgrid control from the literature review are discussed which can lead to more contributions in these areas. The proposed system is shown in Fig. 1. It can be divided into three parts; i) solar and wind based renewable energy sources supported by a battery storage system along with their converters connected to the DC bus, ii) the load side inverter and single-phase load, iii) real time controller implementing the energy management system. The wind energy conversion system consists of a permanent magnet synchronous generator (PMSG) based wind turbine. The solar photo- voltaic (PV) panel is operated with maximum power point tracking (MPPT) when the power generated by both PV and wind are less than the load demand. When the power generated is more than the demand, the excess power is supplied to the battery and when it is no longer safe for the battery to be charged, the MPPT is turned off. The battery storage system is used to maintain the energy balance in the system. An energy management system is used to control the power flow under different conditions in order to supply to the load through a single-phase inverter.

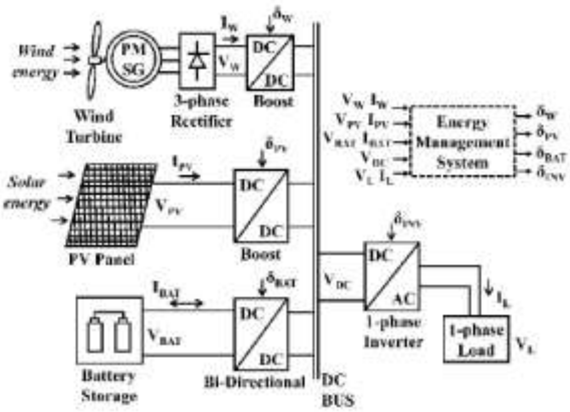


Figure 1. Components of small-scale wind-solar-battery microgrid with
EMS.

II. Performance of Solar Energy Conversion System

The Solar Energy Conversion System (SECS) consists of:

- Solar PV panel
- DC–DC boost converter
- Maximum Power Point Tracking (MPPT) controller

A schematic of the SECS is shown in Figure 1. The MPPT controller operates in two modes depending on the battery's State of Charge (SOC):

1. **MPPT Mode:** When the battery SOC is below SOCmax_\text{max}max, the MPPT extracts maximum power from the PV panel.
2. **OFF-MPPT Mode:** When SOCmax_\text{max}max is reached, the MPPT is disabled to reduce solar generation and prevent battery overcharging.

The P–V characteristics under different irradiance levels (400–1200 W/m²) at 25°C are illustrated in Figure 3. At an irradiance of 1000 W/m², the maximum power of the PV panel reaches approximately 66 W at 17.6 V.

The PV panel power is given by:

The MPPT algorithm flowchart (Figure 4) regulates the duty cycle of the DC–DC boost converter to ensure maximum power extraction [7].

III.Energy Management System (EMS)

The EMS acts as the supervisory controller that coordinates all converter operations in the microgrid. Every converter control mode is assigned based on EMS logic and system requirements.

EMS Responsibilities

- Maintain DC bus voltage stability
- Select MPPT or OFF-MPPT mode for SECS
- Decide charging/discharging mode for battery
- Manage boost converter operation of WECS
- Maintain supply-demand balance

EMS operation is dictated by two conditions:

1. **Power generation level**
2. **Battery SOC**

Mode 1: Excess Power Available (Generation > Load)

- Battery charges until SOC reaches SOCmax_\text{max}max
- When SOCmax_\text{max}max is reached → MPPT is switched OFF
- Excess renewable energy is curtailed

Mode 2: Balanced Condition

- Renewable generation approximately equals load
- Battery remains idle (zero power exchange)

Mode 3: Power Deficit (Generation < Load)

- Battery discharges to supply deficit power
- Discharging continues until SOC reaches SOCmin_\text{min}min

Mode 4: Critical Shortage

- If SOC ≤ SOCmin_\text{min}min, load shedding is performed
- Priority is given to critical loads

The EMS is the primary controller which coordinates and controls all control action in the microgrid system. All the controllers of the converters in the previous sections operate based on the EMS control mode. The boost converter of the solar energy conversion system operates in two modes depending on the power generation; MPPT mode/ off-MPPT mode.

The Battery bidirectional converter operates in charging or discharging mode and maintains the DC bus voltage constant, the DC-DC boost converter of the wind energy conversion system operates in boost mode. The power in the microgrid must be balanced under different generation of power from renewable energy sources and load demand conditions. The power balance equation is given as follows. Regarding to architecture of microgrid control or any control problem there are two different approaches can be identified: centralized and decentralized. A fully centralized control relies on a big amount of information transmittance between involving units and then the decision is made at a single point. Hence, it will present big problem in implementation since interconnected power systems usually cover extended geographic and involves enormous number of units. The fully centralized control is currently considered as infeasible solution. On another hand, in a fully decentralized control each unit is controlled by its local controller without knowing the situation of others. The fully decentralized control is also irrelevant in this context due to strong coupling between the operations of various units in the system. A compromise between those two extreme control schemes can be achieved by means of a hierarchical control scheme consisting of three control levels: primary, secondary, and tertiary

IV.Controllers in the Microgrid

The microgrid incorporates multiple power electronic converters, each playing a specific role:

DC–DC Converters (Choppers)

A DC–DC converter changes the input DC voltage level to a desired output voltage. Key characteristics:

- Converts fixed DC input into a controllable DC output
- Uses SCRs, MOSFETs, IGBTs, or BJTs
- Can operate in continuous or discontinuous conduction mode
- Used in PV boost converter, wind boost converter, and battery bidirectional converter

DC–AC Converters (Inverters)

Inverters convert DC power to AC, using high-frequency switching techniques.

Modulation techniques include:

- PWM (Pulse Width Modulation)
- SPWM
- Space Vector Modulation (SVM)
- Selective Harmonic Elimination (SHE)

Types of Inverters

- **Voltage Source Inverters (VSI)**
- **Current Source Inverters (CSI)**
- **Multilevel Inverters** (produce near-sinusoidal output)

VSIs are widely used in microgrids due to their ability to generate stable AC voltage waveforms.

A variable speed wind turbine is used in this system. The characteristics of the wind turbine is shown in Figure. 5; the Cp for various wind speeds at different pitch angles. A permanent magnet synchronous generator is selected for its low maintenance and low operational cost. The generator output is dependent on the wind speed. The three-phase output of the generator is rectified using a diode rectifier and then the voltage level is increased with the help of a DC-DC boost converter as shown in Figure. 6.

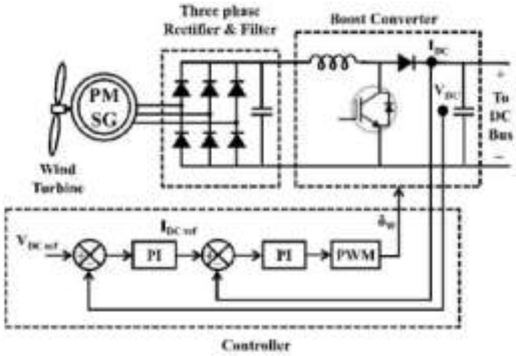


Figure 2. Wind energy conversion system with controller

DC to AC power conversion is the result of power switching devices, which are commonly fully controllable semiconductor power switches. The output waveforms are therefore made up of discrete values, producing fast transitions rather than smooth ones. For some applications, even a rough approximation of the sinusoidal waveform of AC power is adequate. Where a near sinusoidal waveform is required, the switching devices are operated much faster than the desired output frequency, and the time they spend in either state is controlled so the averaged output is nearly sinusoidal. Common modulation techniques include the carrier-based technique, or Pulse-widthmodulation, space-vector technique, and the selective-harmonic technique.

Voltage source inverters have practical uses in both single-phase and three-phase applications. Single-phase VSIs utilize half-bridge and full-bridge configurations, and are widely used for power supplies, single-phase UPSs, and elaborate high-power topologies when used in multicell configurations. Three-phase VSIs are used in applications that require sinusoidal voltage waveforms, such as ASDs, UPSs, and some types of FACTS devices such as the STATCOM. They are also used in applications where arbitrary voltages are required as in the case of active power filters and voltage compensators.

- Current source inverters are used to produce an AC output current from a DC current supply. This type of inverter is practical for three-phase applications in which high-quality voltage waveforms are required.
- A relatively new class of inverters, called multilevel inverters, has gained widespread interest. Normal operation of CSIs and VSIs can be classified as two-level inverters, due to the fact that power switches connect to either the positive or to the negative DC bus. If more than two voltage levels were available to the inverter output terminals, the AC output could better approximate a sine wave. It is for this reason that multilevel inverters, although more complex and costly, offer higher performance.
- Each inverter type differs in the DC links used, and in whether or not they require freewheeling diodes. Either can be made to operate in square-wave or pulse-width modulation (PWM) mode, depending on its intended usage. Square-wave mode offers simplicity, while PWM can be implemented several differen
- ways and produces higher quality waveforms.

Voltage Source Inverters (VSI) feed the output inverter section from an approximately constant-voltage source.

The desired quality of the current output waveform determines which modulation technique needs to be selected for a given application. The output of a VSI is composed of discrete values. In order to obtain a smooth current waveform, the loads need to be inductive at the select harmonic frequencies. Without some sort of inductive filtering between the source and load, a capacitive load will cause the load to receive a choppy current waveform, with large and frequent current spikes.

PI CONTROL MODE

Proportional-Integral controller mode results from the combination of the proportional and the integral mode. Certain advantages of both control actions can be obtained from this mode. This mode is also called as the proportional plus reset action controller. Equations for the proportional mode and integral mode. The proportional gain, by design, also changes the net integration mode gain, but the integration gain, can be independently adjusted. It is understood that the proportional offset occurred, when a load change required a new nominal controller output, and this could not be provided except by a

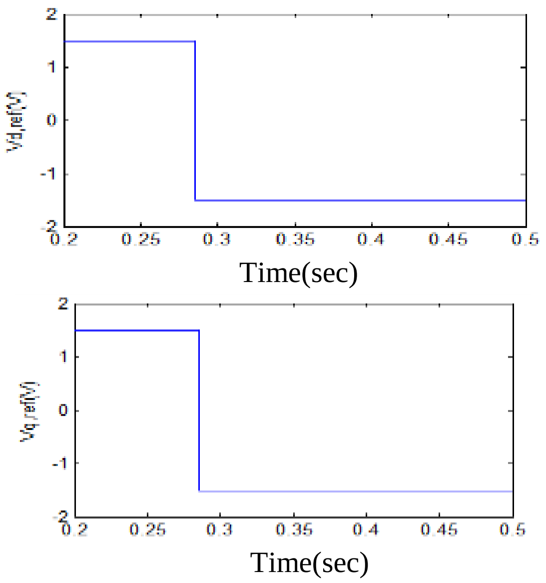
fixed error from the set point. In the present mode, the integral function provides the required new controller output, thereby allowing the error to be zero after a load change. The integral feature effectively provides a 'reset' of the zeroerror output, after the load change occurs. At time t1 a load change occurs, that produces the error. The accommodation of the new load condition requires a new controller output. The controller output is provided through a sum of proportional plus integral action that finally leaves the error at zero. The proportional part is obviously just an image of the error.

CHARACTERISTICS OF THE PI MODE

When the error is zero, the controller output is fixed at the value that the integral term had, when the error reduced to zero. This output is given by pt(0) simply because we choose to define the time at which observation starts, as t = 0. If the error is not zero, the proportional term contributes a correction and the integral term begins to increase or decrease the accumulated

5. Simulation Results

MATLAB simulations were utilized to assess the performance of an Energy Management System - EMS designed used a compact mixture microgrid incorporating wind, solar, and battery storage. Findings show that the EMS effectively manages power distribution, maintaining a stable energy supply despite variations in renewable sources. The system intelligently controls battery charging and discharging based on energy availability and load requirements, ensuring optimal utilization. MATLAB simulation results confirm the EMS's capability to minimize power imbalances, enhance system reliability, and decrease reliance on external power sources. Overall, the EMS improves microgrid stability, facilitates better integration of renewable energy, and ensures smooth operation in both standalone and grid-connected configurations. To make sure a stable power supply to the load under varying generation conditions. This is achieved by adjusting solar irradiance levels, which are controlled by turning the lamps on and off to create different lighting intensities as shown.



(a)

Figure 4. Load power for constant load with variable RES

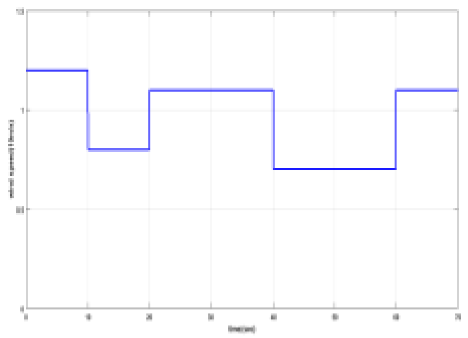


Figure 5. Wind speed

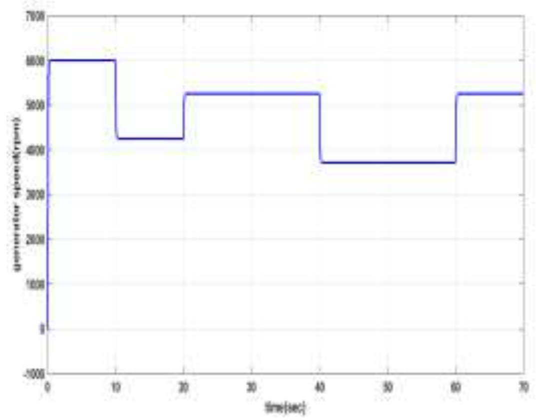


Figure 6 Wind Generator speed

Figure.5 shows the generator operating at a constant 5290 rpm, correlating with the steady wind speed shown in Figure 6.

6. Conclusion

A small-scale hybrid solar-wind-battery microgrid, featuring an integrated energy management system, was designed and built. Experimental tests assessed the system's performance under fluctuating renewable energy and load conditions. The control algorithms and management system were first developed through simulations, which demonstrated the system's adaptability to fluctuations in both energy generation and consumption. The controller effectively facilitates energy distribution, ensuring efficient operation. This test setup serves as a foundation for future research, enabling further experimentation with different scenarios and control strategies in hybrid renewable energy microgrid systems.

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