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Monitoring, Control and Energy Management of Smart Grid System via WSN Technology Through SCADA Applications

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Abstract For robust monitoring, control and proper energy management of renewable energy sources (RES), wireless sensing networks (WSNs) are proved to be a vital solution. Since the power system is stepping towards the smart grid system and the use of WSNs provides numerous advantages in terms of economical, reliable and safer transmission of controlling and monitoring signals, with their low cost and easy deployment. This research proposes a new architecture for efficient monitoring, control and proper energy management of smart grid system. The architecture is evolved by taking into account the SCADA system in-conjunction with WSNs as sensor nodes. The data transmission is done though wireless link based on IEEE 802.15.4 security protocol. The WSNs are arranged in multi-hop mesh network for efficient data transmission between sensor and coordinating nodes. A new economical model based on Wireless Switch-yard System is used for integrating RES. Three different scenarios are considered, i.e., with RES, without RES and with both, RES and main grid supply for proper energy management and control strategy. A total of 10.5 kW is connected as smart home load to smart grid system. The State of Charge of battery storage system varies for maintaining the constant DC link voltage at 100 V. The efficacy of proposed model is verified through laboratory setup on Power Hardware-In-Loop system.

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1 Introduction

The traditional grid station poses many issues while controlling and monitoring it. The power system becomes unstable, inefficient and unreliable due to continuous system's outages and power theft [1]. The key responsibility of an electrical grid station is to manage the balance of energy flows between the producers and consumers [1]. When such an imbalance between the production and utilization of an electrical energy occurs, ultimately the power system becomes unstable and its control is disturbed significantly.

Since, by the beginning of twenty first century, the entire world has serious concerns about the global warming due to CO_2 emissions. This ultimately requires, utilizing the renewable energy sources (RES), to meet the required energy demands. Since, the integration of RES affects the operation and control (OC) of power system because the power flow becomes bidirectional but it also supports the energy management solutions [2]. This calls for an intelligent system which has bidirectional data flows, to foster the problem of OC of power system thereby managing proper energy management [3].

The smart grid system is an efficient, robust and reliable system with bidirectional communication and power flows [3]. The smart system involves the information and communication technologies (ICT) for monitoring and control [3]. It is a closed loop system which includes the feedback for its automation [3]. During any contingency, the smart grid system automatically senses the abnormalities either fault or power imbalance and takes the necessary actions accordingly. While keeping in view the OC issues with traditional grid station, the smart grid system itself updates its statuses and restores to initial condition after contingency analysis, which is called its self healing power [4]. Since, the traditional sensing elements for voltage and current are potential transformer (P.T) and current transformer (C.T) respectively. But these sensors create issues in measurements during zero crossing of signals and also due to their magnetic core saturation [5]. However, the WSNs have no such issues; they record discrete data at regular intervals and generate flags and signs accordingly, during the steady state and dynamic operations as well [5].

With the advancement of technology, the wireless sensor networks (WSNs) are finding their place in controlling and monitoring applications. The WSNs are robust, small in size, economical and energy efficient. The WSNs are invariably being used in smart grid system for controlling and monitoring the defined areas [6]. The WSNs are being deployed in the field area at the different loading points on the electrical lines to record the electrical quantities such as; current, voltage and power [6]. All the measured quantities are in the discrete form. The real time data is then transmitted to the SCADA centre through wireless link based on IEEE 802.15.4 security protocol [7]. The received data is being analyzed accordingly for proper monitoring and control. Since the grid codes are always being defined by national power system operators. These codes should not be violated by any means, if the controlled and stable power system operation is required. But if they are violated, then a signal from SCADA centre will be generated to bring them back under the limits.

Kantarci et al. [8] evaluated the cost effective strategy for residential load management in smart system by using wireless sensing networks (WSNs). The evaluation was made on basis of cost of energy, reliance on consumers' maximum demand, energy saving and reduction in CO_2 emissions, by applying in-home-energy management (iHOM) technique and was compared to optimization based residential energy management (OREM) technique. The performance of iHOM technique was analyzed for capacity development of local resources, for prioritizing the loads and online pricing of energy supplied [8]. Batista et al. [9] analyzed the monitoring performance of Photovoltaic (PV) and wind energy system in smart grids by using ZigBee technology. Different tests were made for energy management solutions through ZigBee and the use of smart metering system for efficient bi-direction energy control and monitoring was examined with the experimental results [9]. Tushar et al. [10] presented the energy management solution for using distributed sources into smart grids using algorithm based on Stackelberg equilibrium (SE). The conclusion was made that energy production could be done at cheaper rate when SE reaches closer to the energy demand of residential units (RUs) and energy trend of shared facility controller (SFC) for energy storage device [10]. Zhou et al. [11] proposed the energy management model for maintaining energy balance between the supply and demand in smart grid system with the use of bi-directional communication system. A mathematical structure was presented for optimal operation of system while maintaining the defined standards limits. The Photovoltaic (PV) was taken into distribution system as an auxiliary power source. An optimization algorithm was used to reduce the cost of energy supplied and thus minimizing the load demands by keeping in view the conditions of customers and suppliers respectively [11]. Zhao et al. [12] investigated the energy management at load and supply sides using optimization algorithm based on convexity of power balance between the supply and demand. The objective function was evolved to minimize the transmission losses by converting equality constraints into inequality ones. Direct communication system was developed between distributed resources and loads using consensus-based distributed energy management (CEMA) technique based on social welfare maximization i.e., lowering tariff and maintaining the power balance [12]. However, our research work proposes a new model based on Wireless Switchyard System (WSS) for efficient energy management and control of smart grid system. Since the integration and disconnection of RES has been wired so far now. But with proposed model, the RES can be taken in and out of system wirelessly, based on the environmental conditions and status of load demand.

This research primarily focuses on the development of architecture for monitoring, control and energy management of smart grid system. The collection of data at the field area is done through WSNs and their coordination and control is achieved through central SCADA system. The proposed architecture involves a new technique for efficient and economical integration of RES into the smart grid system through WSS, thus creating a sink. The propositions are verified through experimental setup on Hardware-In-Loop (HIL) Power system at laboratory. The laboratory based micro grid system was designed for visualizing the energy management and controlling of system in real time. The proposed system uses LabVIEW algorithm for entertaining the energy management and controlling solutions. The system takes into account the available energy from the RES, load energy demand, energy from battery banks and the power supply from national grid station, to make the smart grid system as an independent network. Ultimately, the voltage profile of load is monitored so that power transfers at high efficiency from the renewable energy sources and national grid station to the load.

2 Research Methodology

The proposed architecture for monitoring and controlling the smart grid system is shown in Fig. 1. The wireless sensor networks (WSNs) are deployed at the place of load centre, which is required to be monitored and controlled. The values for current and voltage are recorded through WSNs as sensor nodes and then they are being processed towards the coordinating nodes through wireless link. The coordinating nodes are responsible for synchronizing the sensors nodes and retrieving data through them [13]. All the coordinating nodes are interlinked with each other for timely data transmission and command activation, in multi-hop mesh network [7]. The information from all the coordinating nodes is then sent to the central data hub (CDH) through wireless link again. At CDH, the information is analyzed and is loaded on the priority slots. The data with highest priority, having large number of flags is processed first towards the SCADA centre and then the succeeding ones. At SCADA system, the data is investigated on the basis of predefined norms, called grid codes. If any of the norms is violated then it generates command signal for its control at the load centre. A Wireless Switchyard System (WSS) based on Micro-processor based relay is shown to be connected as a buffer between RES and traditional power system. The control of this switching scheme is again done wirelessly through SCADA signals. When the system is running at peak demands and the capacity of RES is not enough to maintain the balance between generation and demand, then a command signal is being sent to WSS to take traditional power system into network. The wireless integration and disconnection of RES, done through WSS is the unique contribution of developed architecture for efficient energy monitoring and control of smart grid system. The propositions are verified through Power-Hardware-In-Loop (PHIL) laboratory setup.

The wireless transmission of data is done through IEEE 802.15.4 security protocol which is called ZigBee communication. The IEEE 802.15.4 accounts for the low rate wireless communication [14]. Multi-hop network of ZigBee based WSNs is proved to be most effective and secure solution for fastest packet delivery as shown in Fig. 2.

Multi-hop mesh network is single point-to-multi-point configuration [15]. It is central hub based wireless system architecture. The central hub is called access point (AP), which controls the entire system and acts as a gateway to other networks for proper

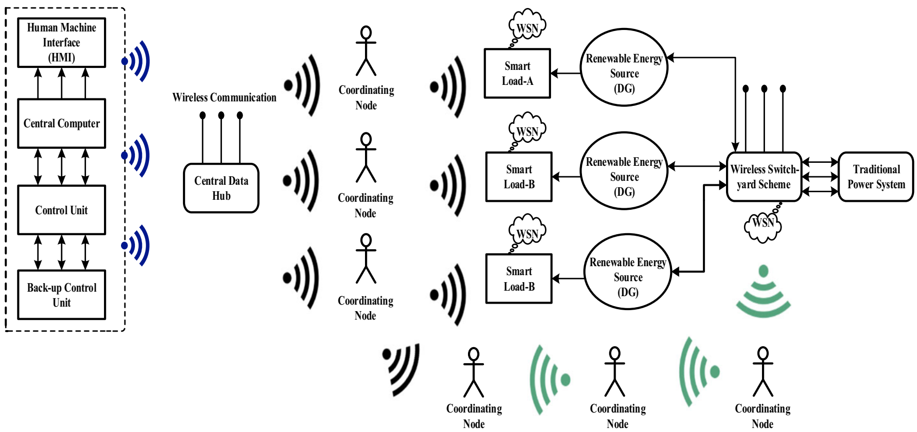


Fig. 1 Architecture for monitoring and control of smart grid system

synchronization and coordination [15]. The use of IEEE 802.15.4 avoids the issue of interference with other APs. The multi-hop mesh configuration itself is less prone towards the inference, surrounding atmospheric disorder, and ensures excessive quality of service (QoS) [16].

The IEEE 802.15.4 protocol is also cheaper than IEEE 802.11 radio, which can be found in networks with larger bandwidth, making it a right option for low cost and high data rate applications like, wireless sensors networks (WSNs), switching devices etc. [17]. The sensor nodes, coordinating nodes, microprocessor based switching scheme and central data hub are powered through stand-by auxiliary supply units [18]. The sensor nodes are based on CC2530 IC [18].

2.1 Power Hardware-In-Loop (PHIL) System

Power Hardware in the Loop (PHIL) system is a technique to implement real time smart grid system on laboratory basis, as shown in Fig. 3 [19]. The smart grid system more commonly is based on renewable energy sources (RES) with battery bank system for storage and numerous components of power electronics for its monitoring and control [19]. Since, the number of RES and the smart loads would be in limited quantity and there would be least number of practical observations around the system. Hence, the Simulink modeling has becomes the most promising solution and powerful tool for analyzing the smart grid system in conjunction with laboratory based simulators [20]. The use of power electronics devices into smart grid system poses two important issues such as complexity of system due to bigger and larger number of switching circuits and need of high frequency PWM signals [21]. Therefore, the use of FPGA cards in simulators reduces the step size to 500 ns for multi-phase voltage source inverter. Although, the laboratory based smart grid system model designed for wind and solar systems and along with two converters, can run with a switching speed of 1000 Hz in real time environment [22].

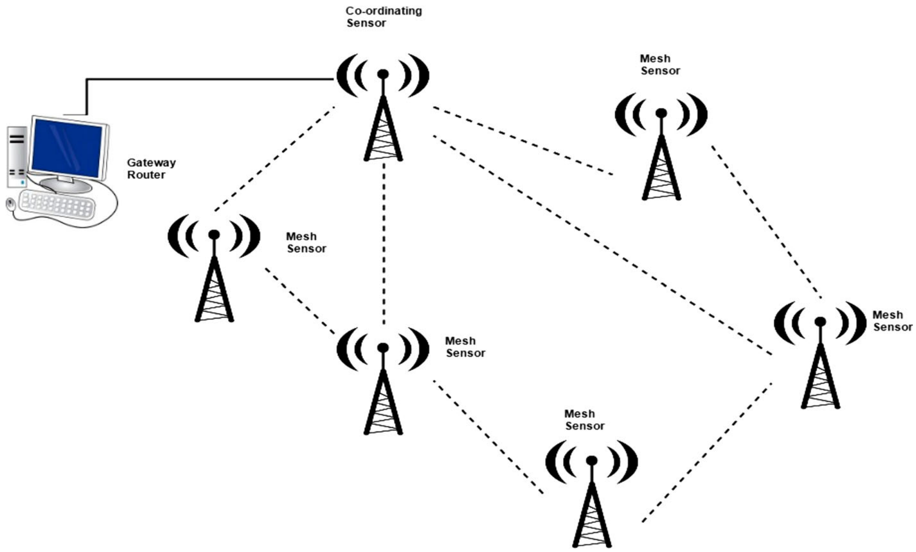


Fig. 2 Multi-hop mesh network

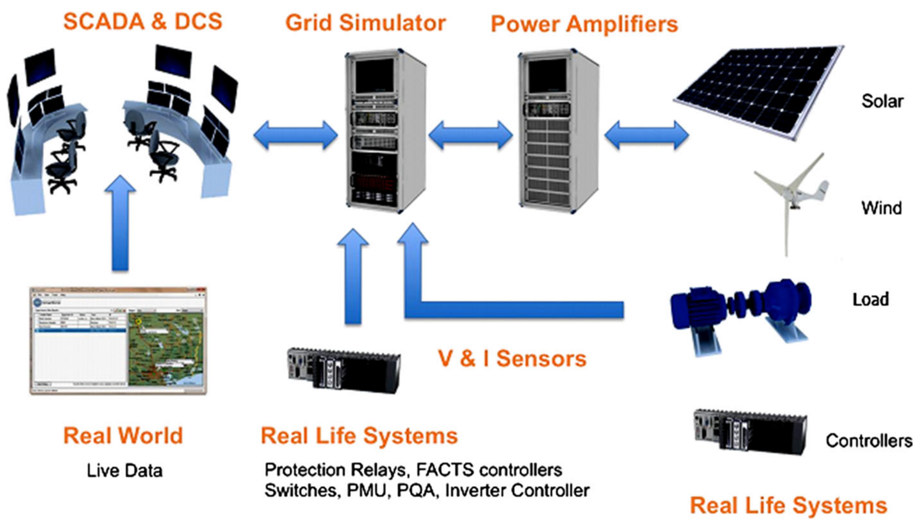


Fig. 3 Proposed laboratory setup for smart grid PHIL system

2.1.1 *Real Time Monitoring and Control Hardware*

The rapid control prototyping (RCP) used in smart grid system is consisted of renewable energy sources i.e., wind and solar system with necessary battery storage and its control [23]. RCP and its controller use the LabVIEW code, burnt in FPGA cards for system deployment [23]. The RCP involves small-scale three-phase inverters containing IGBTs half- wave bridges rated for 48 V, 5 A, designed to adopt and testify the advanced FPGA based algorithms [24].

2.1.2 *Real Time Monitoring and Control Software*

The real-time PHIL system is developed with compact Reconfigurable Input–Output (RIO) system consisted of SMPS (switched mode power supply) simulator that calculates the simulated response of a three-phase system at the megahertz speeds using open-source LabVIEW based FPGA state-space modeling [25]. The real time SMPS simulator produces simulated current and voltage feedback signals that are connected to the analog inputs of grid system for proper monitoring and control through embedded control unit [25].

The laboratory based PHIL system is based on different workstations running on Windows operating system and are based on PXI technology as shown in Fig. 4. The system is consisted of four simulators with PXI based power hardware in loop system for HIL simulations having 32 current or voltage sources, 32 current or voltage measurements, 72 switching elements and 150 L/C components with unlimited resistors. Further it has [26, 27]

- Better efficiency—all slots have bandwidth up to 8 GB/s with system bandwidth of 24 GB/s
- Synchronization with compact PCI express modules, compact PCI, PXI express and PXI
- Intel Xeon E5-2618L v3 processor with 2.3 GHz eight-core turbo boost mode

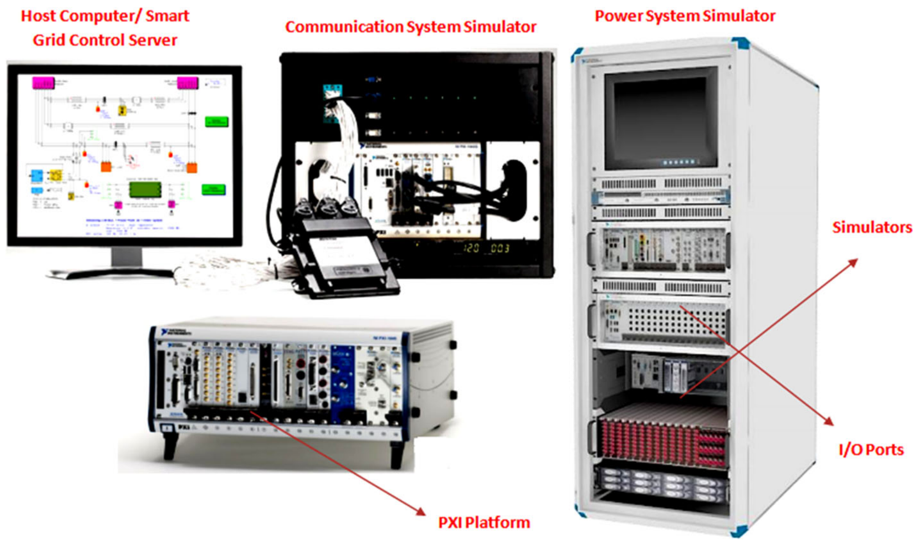


Fig. 4 Combined simulation platform of power system and communication system

- Three-channel 1866 MHz standard RAM DDR4 with 8 GB DIMM, 24 GB maximum
- DSP-focused Xilinx Kintex-7 FPGA programmable with the LabVIEW FPGA Module
- 32 simultaneously sampled 1 MS/s analog output channels
- 54 single-ended digital I/O channels
- 16 simultaneously sampled 50 MS/s channels
- FPGA based floating point solver to simulate an electric circuit on FPGA

All the devices are compatible with SimPower systems MATLAB, PLECS, PSIM and Multisim. Moreover, with the facility of parallel computational, the laboratory based PHIL system is able to simulate more complex subsystem extending up to 48 in number. Further, the use of FPGA has increased the switching frequency and reduced the complexity of switching with reduced number of switching devices. This research divides the proposed micro-grid system into several sub systems intentionally, in order to visualize the performance of each daughter system individually. The RES such as wind and solar systems are simulated as parallel units of simulators with a supportive battery bank unit. All of these are distributed into the cores of simulators, which are then executed and synchronized with high precision. The real time PHIL system along with RCP controller provides an ease of simulating communication link and distributed control in the proposed micro-grid system in an economical manner. With such architecture, it would be more effective to visualize the different factors affecting the communication link in micro-grid system, like, IEEE 802.15.4 security protocol, dormancy and data transmission rate requirements, security risk, and data processing [28].

3 Results and Discussion

The laboratory based smart grid system is consisted of solar and wind energy sources with storage battery system as shown in Fig. 5. The storage battery is controlled by a battery controller. Battery storage system absorbs surplus power when there is an excess energy in the smart grid system and provides additional power if there is a power shortage in the smart network. Two smart homes are connected to station as loads. Since, the appliances at smart homes are dynamic to communicate with each-other and also with supplier to determine their status, conditions and need for energy demand. The use of smart homes as load provides remote monitoring, system security and stability, energy efficiency and comfort and expediency at all stages [29]. These houses consume maximum of 10.5 kW. The smart grid system is connected to the traditional power network via a pole mounted transformer (PMT), which lowers the voltage from 6.6 kV to 220 V. The solar power generation and storage battery are DC power sources that are converted to single-phase AC along with synchronized wind power generation. The control strategy assumes that the smart system does not depend entirely upon the power supplied by the national grid station but the power supplied by the solar and wind power generations and battery storage are sufficient to meet the load demands at all times.

Different scenarios with variable power generations from all the available sources were made; with and without wind, solar and grid powers along with the declared load demand. The wind speed control was simulated through wind turbine simulator control function while the irradiation for PV system was controlled by switching the various lamps ON and OFF locally [31].

The designed setup runs for 1 min of time due to restricted amount of memory storage available in host computer/SCADA server. This research only presents the small scale demonstration of smart grid system and its functionality and enhanced real time system will be practiced sooner in future. Initially, the proposed setup was evaluated under normal balanced conditions with solar and wind energies being supplied to the installed load, as shown in Fig. 6. The power generation from wind and solar systems is distributed and the load connected to the system is kept constant. The speed of turbine is varying with the system's step run time, as shown in Fig. 7, thereby varying the position of wind-speed slider, and the solar system is designed to operate under the varying radiance by connecting and disconnecting the lamps at various time intervals as shown in Fig. 8. The prime focus

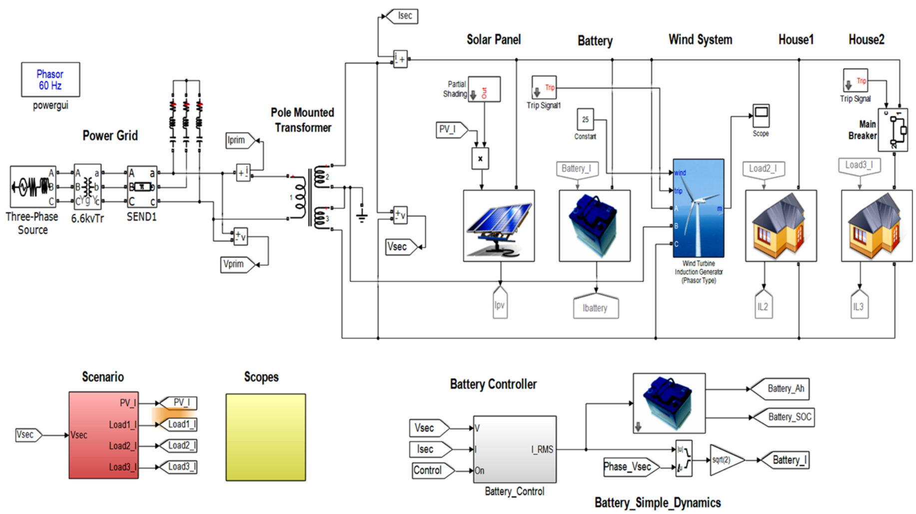


Fig. 5 MATLAB model of smart power system [30]

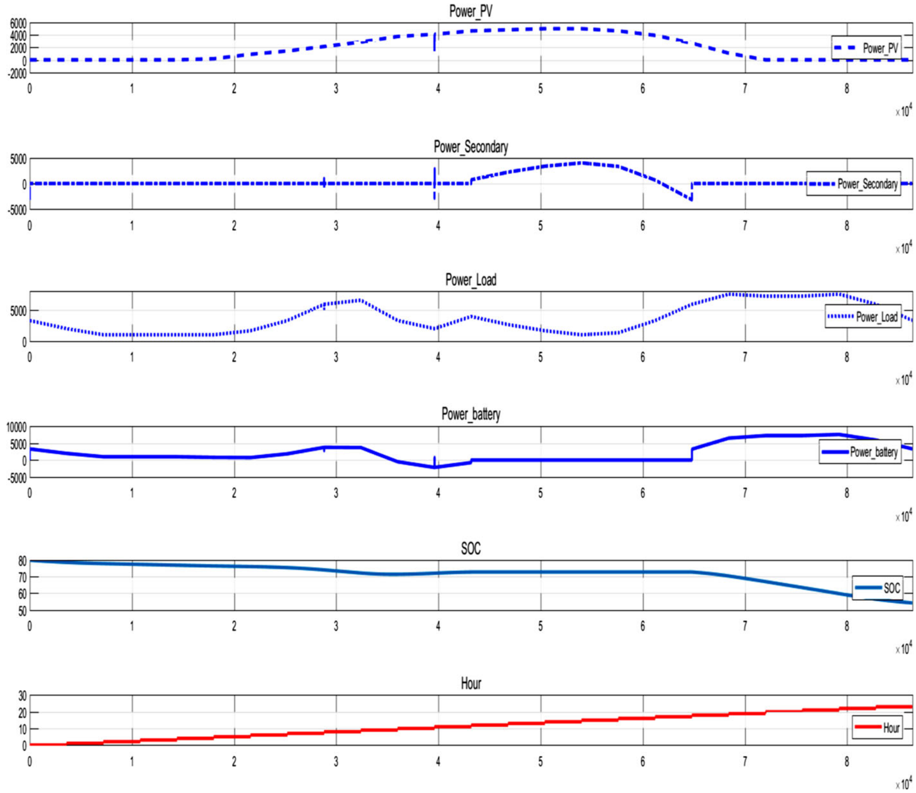


Fig. 6 Power at different locations in the smart grid system at normal condition

is to ensure that the constant power is delivered to the load by maintaining the voltage profile of it, apart from the energy supplied from both RES.

The Voltage and current profiles of national grid station connected with smart system for supplying load are shown in Fig. 9. Figure 9 indicates that the supply is maintained at 4.66 kV rms and 28.5 A, regardless of variations in environmental conditions. When there is no or least wind and the sun is not available, the load is catered through the national grid system, as shown in Fig. 10. Figure 10 also indicates that maximum load demands reaches at 9th hour (3.24×10^4 s) of the simulation time and thus more power is retrieved from PV system and main grid supply. By maintaining the constant DC link voltage at 100 V via charging and discharging of the battery inside the system, the power equilibrium is achieved as shown in Fig. 11. The power balance in the system can be observed from Fig. 10, the power in the system is in equilibrium condition until t = 15 s. The battery bank is charging because the power generated by the installed solar and wind system surpasses the available load power demands. When the power output from deployed renewable energy sources drops down, the battery starts to discharge, in order to ensure proper energy management at the load side. The battery discharges at speedy rate between t = 30 and 40 s, as power from PV modules decreases. But this discharge rate of battery slows down after t = 40 s, when the wind system generates more power and that is being added to the system. The power at load side is maintained constant during entire process of power transfer, as can be visualized from Fig. 10. For maintaining the load profile at constant

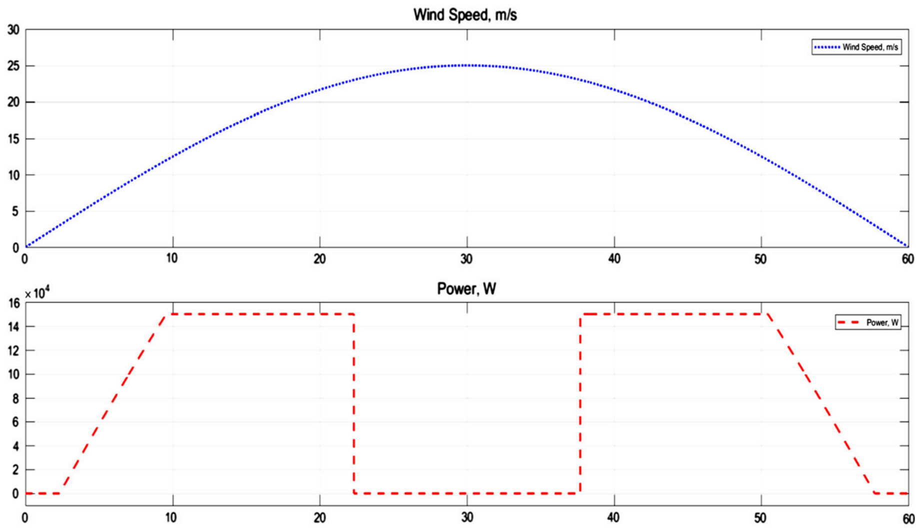


Fig. 7 Speed and power of wind turbine generating system

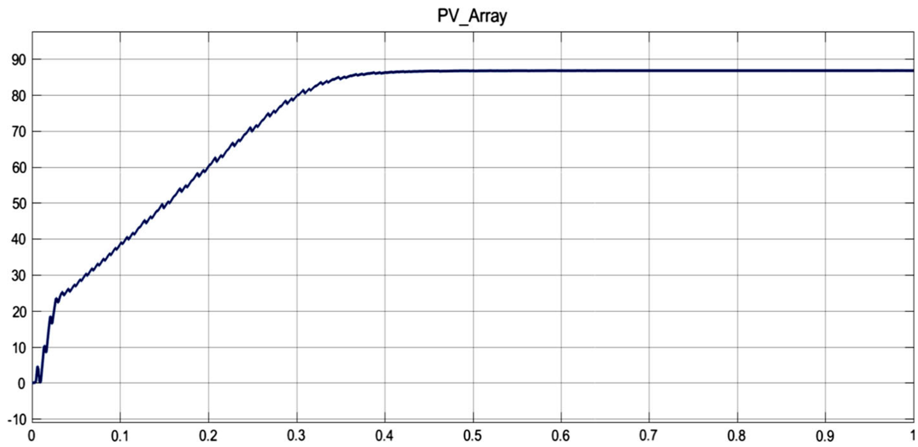


Fig. 8 Photovoltaic (PV) array voltage profile

level, the SOC of battery bank is following the trends of its charging and discharging patterns.

The system is also evaluated without RES. The energy management of circuit with the power supplied by national grid system is shown in Fig. 12. Till t = 45 s of the total simulation time, the load demand decreases and the battery is charging from the extra power supplied by the national grid station. After t = 45 s, the battery starts to discharge as suddenly the power demand on system increases. The SOC of battery is following the different trends, depending upon the condition of load supplied by the smart grid system. However in all the scenarios, the DC-link voltage is forced to remain constant during the entire working process of smart system under the variable load conditions, so as to

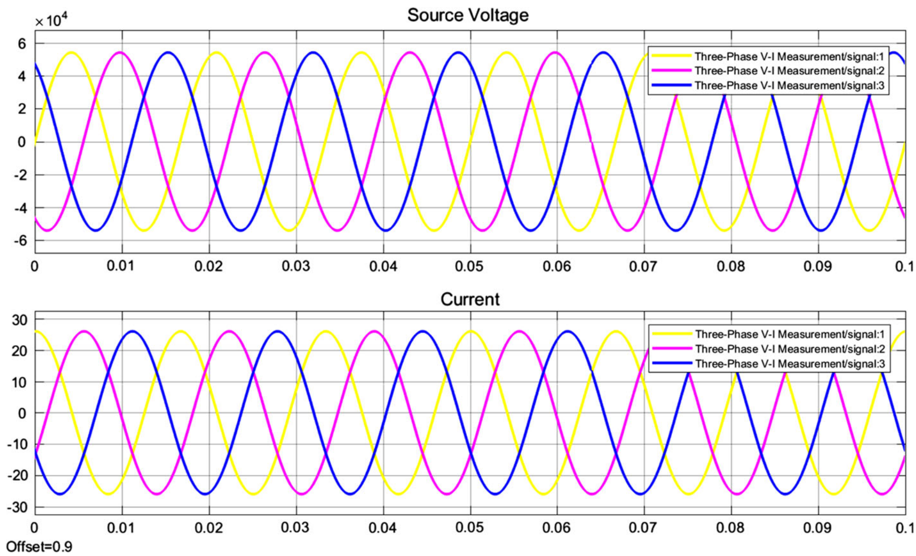


Fig. 9 Voltage and current from national grid station

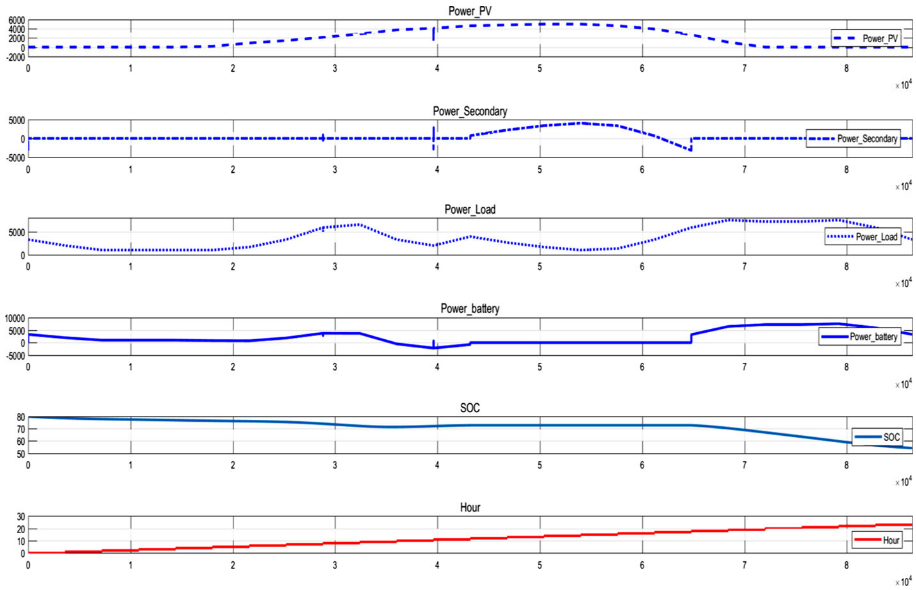


Fig. 10 Power at different locations in the smart grid system with RES and national grid

maintain the voltage profile of load under the defined grid codes thereby ensuring constant average power delivered to load.

The Wireless Switch-yard System (WSS) based on ZigBee shield is shown in Fig. 13. The RCP controller after getting commands from main server at SCADA generates signals through aurdino, that are being transferred to sensor nodes deployed at load side, with the

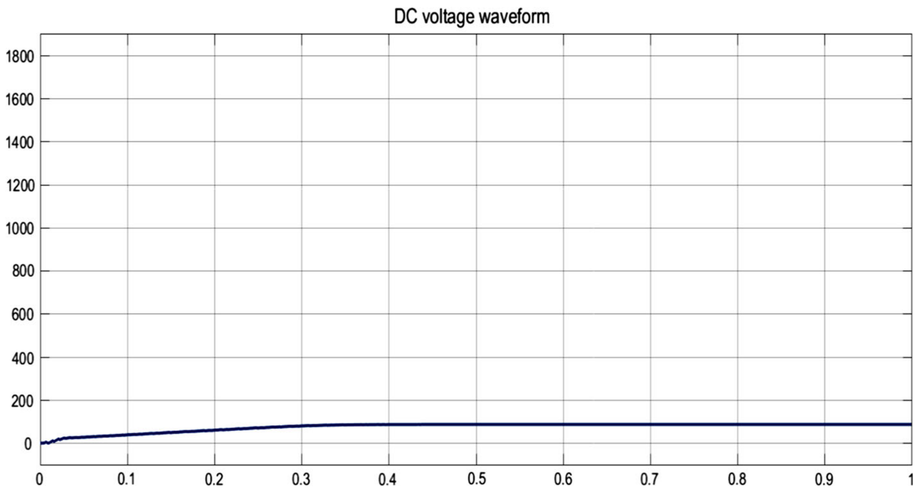


Fig. 11 DC link voltage

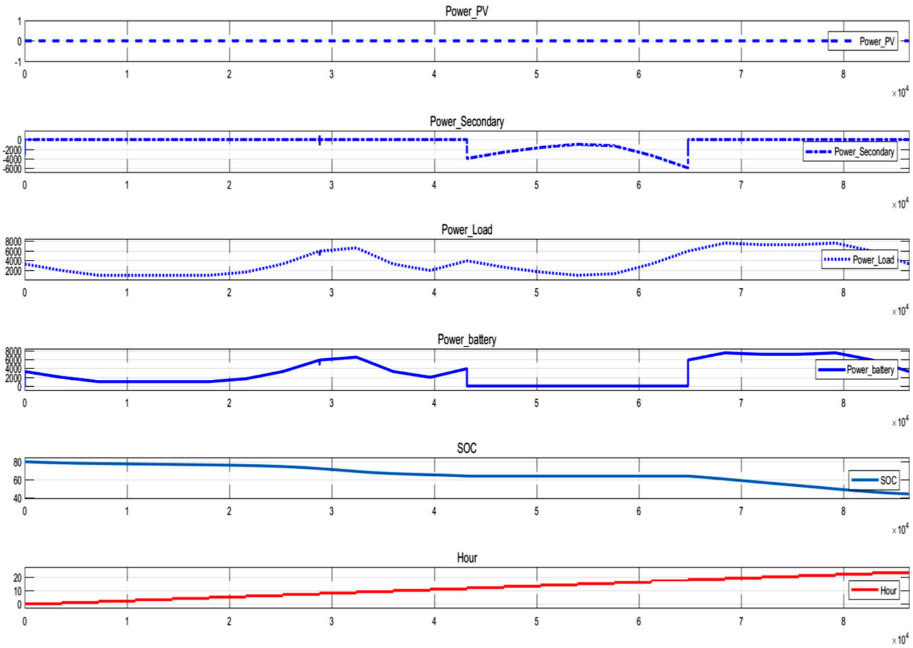


Fig. 12 Power at different locations in the smart grid system without RES

help of ZigBee module. The monitored LED device gets on and off according to the generated switching signals.

The addresses for coordinating and routing nodes, defined through ZigBee shield are shown in Fig. 14. The communication between the RCP controller and the ZigBee modules is achieved in a multi-hop mesh network as shown in Fig. 15. This ultimately strengthens the switching commands being transferred to the working devices and avoids

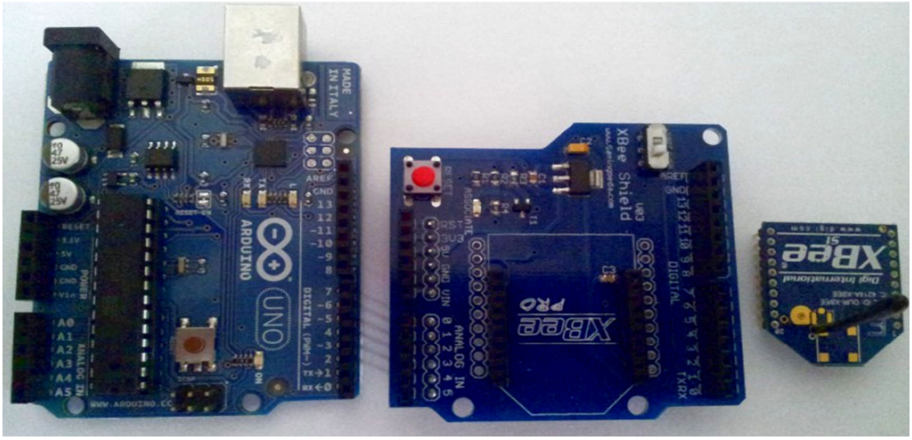
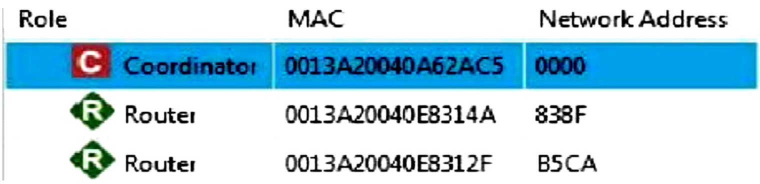


Fig. 13 Arduino Uno, XBEE shield and XBEE module connections

any stray effects. The signals generated from Aurdino are entirely being transferred to the device, in the proper way and with the priority scheme as shown in Fig. 16. Again, the data retrieved from field devices, which is being processed for necessary actions through ZeeBee is also being received in sequence and timely manner as shown in Fig. 17.

4 Conclusion and Recommendations

This research focused the monitoring and controlling of smart grid system through SCADA applications. The Wireless Sensor Networks (WSNs) were deployed at the field lines to record the power variables, i-e voltage, current and power flows. The WSNs formed the multi-hop mesh network for efficient and reliable co-ordination. The power variables were then transferred to main control centre through wireless link. In order to assure the security of wireless signals, IEEE 802.15.4 protocol was used. If the predefined limits at SCADA's main control center were violated by the measured power variables then a command signal was generated to take necessary control actions i-e, Load Frequency Control (LFC), automatic voltage regulation (AVR) etc. The beauty of this research lies in the use of Wireless Switch-yard System (WSS) and efficient energy management. The renewable energy sources (RES) were taken into system according to the load requirements via WSS. The load management was done and its consequences on power variables were observed through results. The response of smart grid system with load management was observed. A laboratory based Power Hardware-In-Loop (PHIL) setup was designed and the results were verified practically. Three Scenarios were considered with and without solar, wind and grid



Role	MAC	Network Address
C Coordinator	0013A20040A62AC5	0000
R Router	0013A20040E8314A	838F
R Router	0013A20040E8312F	B5CA

Fig. 14 Address of the nodes

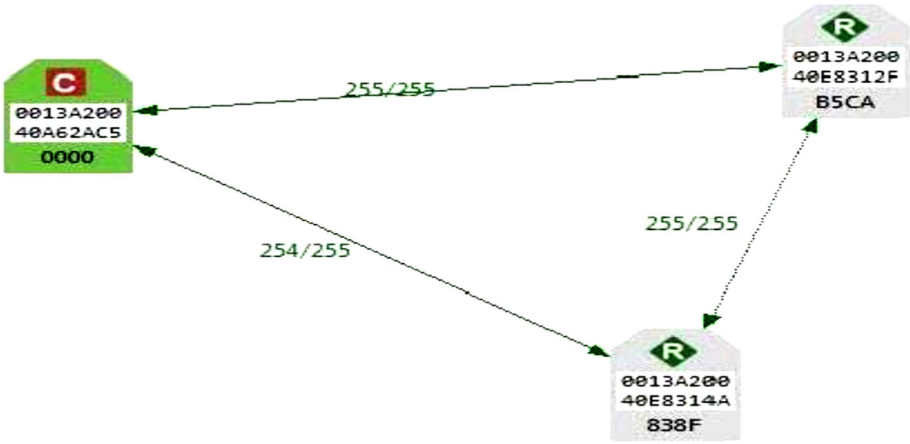


Fig. 15 Designed structure of the mesh network

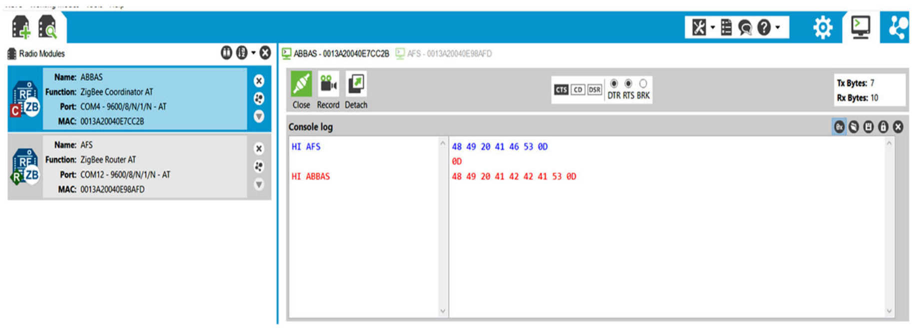


Fig. 16 Console mode communication coordinator to router

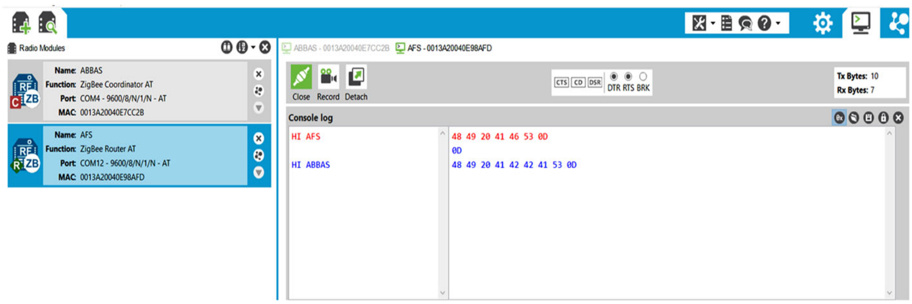


Fig. 17 Console mode communication router to coordinator

supply with proper load management. In scenario-1, the maximum load on system was 9.1 kW and supplied by RES (solar and wind) alone. The SOC of battery storage system varies for maintaining constant DC link voltage at 100 V. During scenario-2, the total load of 10.5 kW was supplied by wind, solar and main supply systems altogether within defined voltage and current limits. The State of Charge (SOC) energy storage system is almost constant and does not change. While in scenario-3, the entire power was supplied by main grid station and the maximum load of 7 kW was supplied. The energy management and control of smart grid system was achieved at different power balance scenarios under the different environmental and loading conditions.

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Publisher's Note

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