Smart Micro Grid Power With Wireless Communication Architecture

Case of a hybrid power system PV/Wind/ Battery

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Abstract—**Since the term Smart Grid has become an extensively used word in the operation of electric power systems and since intermittent renewable energy sources had been and will be massively integrated in electrical grids, it became mandatory to think about smarter communication methods to make the power grid more flexible and robust. In order to address this issue, this paper presents a simplified energy flow average models for hybrid PV/Wind/Battery Micro Grid. Two cases of operation are described in this paper; On-Grid and Off-Grid systems with wireless communication networks architecture simulated using Matlab Simulink. Such models help modeling and sizing Micro Grid systems. The simulation results prove the indispensability of the wireless network communication component on the energy control and management in the Smart Grid power in the isolated sites where wired connection is difficult.**

Keywords—Smart grid; hybrid system; PV Wind Battery; Wireless Smart Grid Communication; Micro Grid; Energy Control and Management.

I. INTRODUCTION

The Smart Grid communications infrastructure is expected to incorporate a hybrid mesh of different communication technologies to provide efficient and consistent access to grid components in diverse environments [1]. Thanks to the new information technologies and communication networks, communication in real time between all actors in the electric power grid that incorporate diversified renewable energy resources became an innovation [2]. In order to perform the modern electric power grid, several searches contribute to an adequacy between production, distribution and consumption using wireless communication protocols [3, 4]. Communication technologies in smart grid can be classified into two main categories: wired and wireless technology. Several studies have embarked on using wired technology such as Power Line Communications (PLC) [5], Digital Subscriber Lines (DSL) and Optical Communications with a special type called Optical Power Ground Wire (OPGW) [6]. The use of PLC was confronted several problems especially in the signal propagation characteristics in the case of a high signal attenuation and interference with other signals such as the nearly electric appliances or external electromagnetic sources [7, 8]. On the other side, wireless technology offers low installation costs with minimal cabling and give a rapidly connectivity in areas where there is not a preexisting communication infrastructure. Nowadays, several researches converge to improve the energy efficiency of mobile-connected devices [9]. For that reason, to build their communications infrastructure, electricity companies are growing on wireless technologies [8].

To make smart grid a reality, the standardization of communication architecture for smart grid is one of the key questions in its design [10, 11, 12, 13]. In this context, the aim of our work is to develop an architecture of communication in hybrid PV/Wind/Battery micro grid system. To make it autonomous, wireless communication architecture and an algorithm of control and energy management are needed and will be described in this paper. To test our wireless communication architecture an average model of a hybrid micro grid system will be detailed.

In this paper, we will study a simplified example of a micro grid represented by its energy flow average models consists of a photovoltaic (PV) and Wind power systems, Storage Battery (SB), AC load and DC dump load. Two operations modes of this system will be mentioned, On Grid and Off Grid. Fig.1 shows the proposed hybrid system respectively Off-Grid and On-Grid configuration [14, 15, 16]. We will also present an algorithm of control and energy management for this micro grid system. Some of the major wireless communication technologies which include IEEE specified ZigBee, WIMAX and LAN WiFi technologies will be studied and used to ensure the data flow within this micro grid and other components of the whole smart grid such as the Neighborhood Area Network (NAN) and Wide Area Network (WAN). Due to its superior technology, the ZigBee is the best protocol for the Home Area Network (HAN) [1, 4].

This paper starts by showing the mathematical energy flow model of the components such as PV-Wind-Battery [14], thereafter communication architecture based on wireless protocols with an energy control and management algorithm. Finally, the simulation results and conclusions obtained from the control and management performance and real time behavior of the proposed system using real metrological data and load demand are shown, thus verifying the good behavior of our proposed system.

Meteorological data obtained are measured for each hour. To improve the precision of control and management in our system, the sampling time measurement should be less than one hour.

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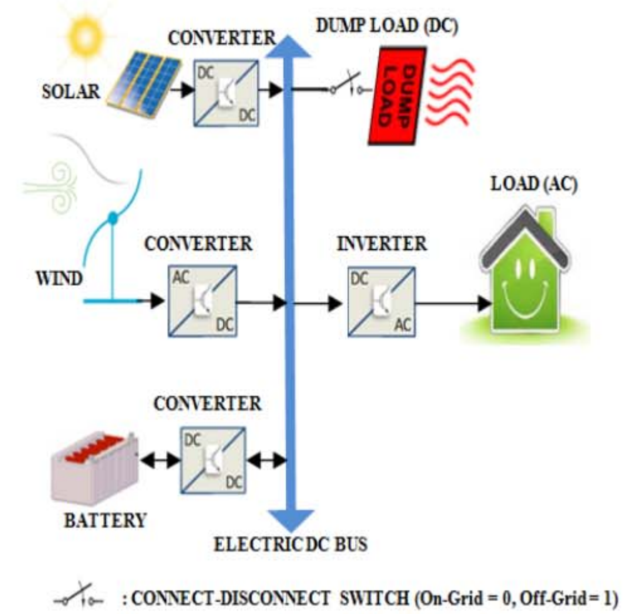

Fig. 1. The studied hybrid system configuration (On-Grid, Off-Grid).

II. Energy Flow Modeling

A. Wind turbine

The mechanic power P_m captured by the wind generator is a function the blade shape, the pitch angle, and the radius and the rotor speed of rotation [14].

$$P_m = \frac{1}{2} \pi \rho C_p(\lambda, \beta) R^2 V^3 \tag{1}$$

Where:
ρ: air density (typically 1.25 kg/m3)
β: pitch angle (in degrees)
$Cp(\lambda, \beta)$: wind-turbine power coefficient
R: blade radius (in meters)
V: wind speed (in m/s)
λ: tip-speed ratio and equal [14]

$$\lambda = \frac{\Omega R}{V} \tag{2}$$

Ω is the Wind Generator rotor speed of rotation (rad/s).

Considering the generator efficiency η_G, the total power produced is below

$$P = P_m \, \eta_G \tag{3}$$

The output energy of our wind generator can be described as function of wind speed as is shown in Fig.2 and can be described as follows [14]

$$P = \begin{cases} 0, & V_{cut\,out} < V < V_{cut\,in} \\ P_{rated}, & V = V_{rated} \\ f(V), & V_{cut\,in} < V < V_{rated} \end{cases} \tag{4}$$

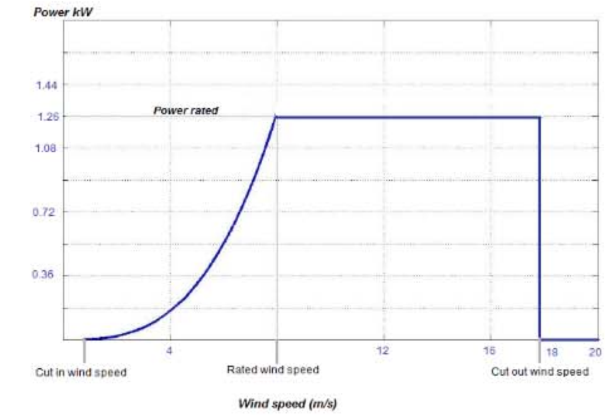

Fig. 2. Wind turbine power characteristic curve.

The energy of the wind generator (E_{wind}) depends on the time step of wind speed data. If the step is one hour then E_{wind} is equal to $P_{wind}(t)$.

B. Photovoltaic system

Several mathematical models have been developed to convert the energy from the source to the load. Our system consisting of a photovoltaic module/array, charge or maximum power point tracking (MPPT) controller, battery and an inverter to convert power from DC bus to load Fig.1.

A photovoltaic array converts the sun radiation and converts it to DC current. To supply the AC load, an inverter is needed to convert DC current through the DC bus to AC current. The output power produced by the photovoltaic module is given by the equation below (5) and as a function of the cellule temperature T_c and the solar radiation G [14].

$$P_{pv}(t) = \left[P_{peak} \left(\frac{G(t)}{G_{standard}} \right) - \alpha_T \left[T_c(t) - T_{standard} \right] \right] * \eta_{inv} * \eta_{wire} \tag{5}$$

Where:
P_{peak}: peak power of PV module
$G_{standard}$: solar radiation in the standard test conditions
$T_{standard}$: ambient temperature in the standard test conditions
η_{inv}: efficiency of inverter
η_{wire}: efficiency of wires

α_T: temperature coefficient of the PV module power (can be obtained the manufacturer datasheet)

The energy of the photovoltaic module (E_{pv}) depends on the time step of solar radiation data. If the step is 1 hour then E_{pv} is equal to $P_{pv}(t)$. The daily solar energy can be calculated by [14]

$$E_{pv}(t) = P_{pv}(t) * S \tag{6}$$

Where S is the day length and equal,

$$S = \frac{2}{15} \cos^{-1}(-\tan L * \tan \delta) \tag{7}$$

Where,

L: the latitude

δ: the angle of declination and equal [14]

$$\delta = 23.45 * \sin\left[\frac{360*(284+N)}{365}\right] \tag{8}$$

With N is the day number.

C. Battery system

The energy flow across the battery depends of difference (E_{dif}) between photovoltaic-wind sources and the energy demanded by the load. E_{dif} can be expressed by [14],

$$E_{dif}\,(\mathrm{t}) = \left(E_{pv}\,(\mathrm{t}) + E_{wind}\,(\mathrm{t})\right) - E_{load}\,(\mathrm{t}) \tag{9}$$

The (9) is positive if $(E_{pv}(t)+E_{wind}(t))$ great then $(E_{load}(t))$ then will be an energy excess (E_E) and is negative if $(E_{load}(t))$ great then $(E_{pv}(t)+E_{wind}(t))$ then there is a deficit in energy (E_D). In the case of excess, energy is stored in the battery or in the grid to use it later if there is a deficit. The energy flow battery can be calculated by [14],

$$E_{Battery}(t) = \begin{cases} E_{Battery}(t\text{-}1) * h_{inv} * h_{wire} * h_{discharging} + E_{dif}(t) & ,if\ E_{dif}(t) < 0 \\ E_{Battery}(t\text{-}1) * h_{charging} - E_{dif}(t) & ,if\ E_{dif}(t) > 0 \\ E_{Battery}(t\text{-}1) & ,if\ E_{dif}(t) = 0 \end{cases} \tag{10}$$

Where:

η_{inv}: efficiency of inverter
η_{wire}: efficiency of wires
$\eta_{charging}$: efficiency of battery charging
$\eta_{discharging}$: efficiency of battery discharging

III. Smart Grid Communication Networks

The smart grid communication networks need to spread over large geographical areas including generation, transmission, and distribution to the consumer premises. The Home Area Network (HAN) provides access to in-home appliances while the Neighborhood Area Network (NAN) links smart meters to local access points, and the Wide Area Network (WAN) supplies communication links between the grid and core utility systems [4,18]. Fig. 3 shows a basic illustration of the electrical power grid and the Smart Grid multi-tier communication networks.

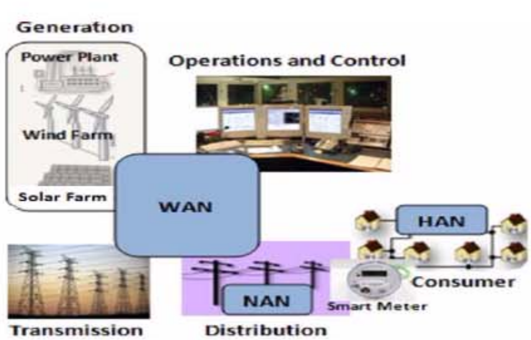

Fig. 3. Smart grid multi-tier network.

A. WIMAX

WIMAX is a fourth generation wireless technology based on the IEEE 802.16 series of standards that offers long-range (around 5 km), high capacity wireless connections and is currently one of the front runners for Smart Grid WANs. WIMAX provides flexible broadband links and features low latency (10-50 ms) in both fixed (IEEE 802.16d) and mobile (IEEE 802.16e) versions. It also features inherent support of different levels of Quality of Service (QoS), allowing the smart grid operator to prioritize time-sensitive traffic.

TABLE I. Following is the chart of various IEEE 802.16 Standards related to WIMAX.

Standard	802.16	802.16a	802.16e
Spectrum	10-66 GHz	2-11 GHz	<6GHz
Configuration	Line of Sight	Non-Line of Sight	Non-Line of Sight
Bit Rate	32 to 34 Mbps	< 100 Mbps	Up to 15 Mbps
Modulation	QPSK, 16QAM, 64QAM	256 Sub-Carrier OFDM using QPSK, 16QAM, 64QAM, 256QAM	Same 802.16a
Mobility	Fixed	Fixed	Mobil
Channel Bandwidth	20,25;28 MHz	Selectable 1.25 to 20 MHz	5MHz (Planned)
Typical cell Radius	1-3 miles	3-5 miles	1-3 miles
Completed	Dec.2001	Jan.2003	2005

B. WiFi

The Neighborhood Area Network (NAN) in the smart grid communications architecture supports multiple communications technologies; in addition to WiFi Power Line Communications (PLC), cellular, radio-frequency, serial and Ethernet can be used [2]. In our solution we proposed the wireless solution of WiFi (IEEE 802.11x) for it facilitates interoperability with other types of network.

TABLE II. Following is the Standards of various IEEE 802.11 related to WiFi.

Standard	Frequency	Rate	Range
WiFi A (802.11a)	5 GHz	54 Mbit/s	10 m
WiFi B (802.11b)	2.4 GHz	11 Mbit/s	100 m
WiFi G (802.11g)	2.4 GHz	54 Mbit/s	100 m

C. ZigBee

The Home Area Network (HAN) is used to collect sensor information from a variety of devices inside the home, and optionally send control information to these devices to better control energy consumption [19].

ZigBee (IEEE 802.11) is a superior technology for the HAN of the Smart Grid. It is anticipated to be able to eliminate electrical cabling in home. ZigBee, as a wireless mesh networking scheme low in cost, power, data rate, and

complexity, is ideal for smart home and grid applications. In the Table III, we will compare the ZigBee protocol with others technologies like Bluetooth and WiFi [21, 22].

TABLE III. THE KEY CHARACTERISTICS OF ZIGBEE, WIFI AND BLUETOOTH

	ZigBee	Wi-Fi	Bluetooth
Range	10-100 meters	50-100 meters	10 – 100 meters
Networking Topology	Ad-hoc, peer to peer, star, or mesh	Point to hub	Ad-hoc, very small networks
Operating Frequency	868 MHz (Europe) 900-928 MHz (NA), 2.4 GHz (WorldWide)	2.4 and 5 GHz	2.4 GHz
Complexity (Device and application impact)	Low	High	High
Power Consumption (Battery life)	Very low (Low Power is a design goal)	High	Medium
Maxi Number of Devices	2 - 65,000	8	32

To better control energy consumption in the Smart Home, the Home Area Network (HAN) is used to collect sensor information from a variety of devices inside the home, and optionally sends control information to it [19]. The structure of Wireless Sensor Networks (WSN) in the smart home requires three different devices: Coordinator, Router and End Device.

All home environments can then be monitored and the required data can be delivered to the coordinator. After the treatment of the data, the appropriate control commands are sent through coordinator to home appliances or the renewable energy sources surrounded the home [19, 22, 23].

IV. OUR MICRO GRID ARCHITECTURE

The Fig.4 presents our Micro Grid architecture and configuration.

Two wires are mentioned on the Fig. 4: electric wire and communication wire. The communication wire presents three areas networks WAN, NAN and HAN with three different protocols WIMAX, WiFi and ZigBee, respectively.

The data flow can be circulated inside the HAN with ZigBee Protocols from all components to Home Management and Control (HMC) [24] or vice versa. On the other hand, the data flow between Grid Management and Control (GMC) and HAN must go through two networks in the tow ways: from NAN (through WiFi protocol) to WAN (Through WIMAX protocol) [2,4]. The HMC can be realized with FPGA or Microcontroller with monitoring.

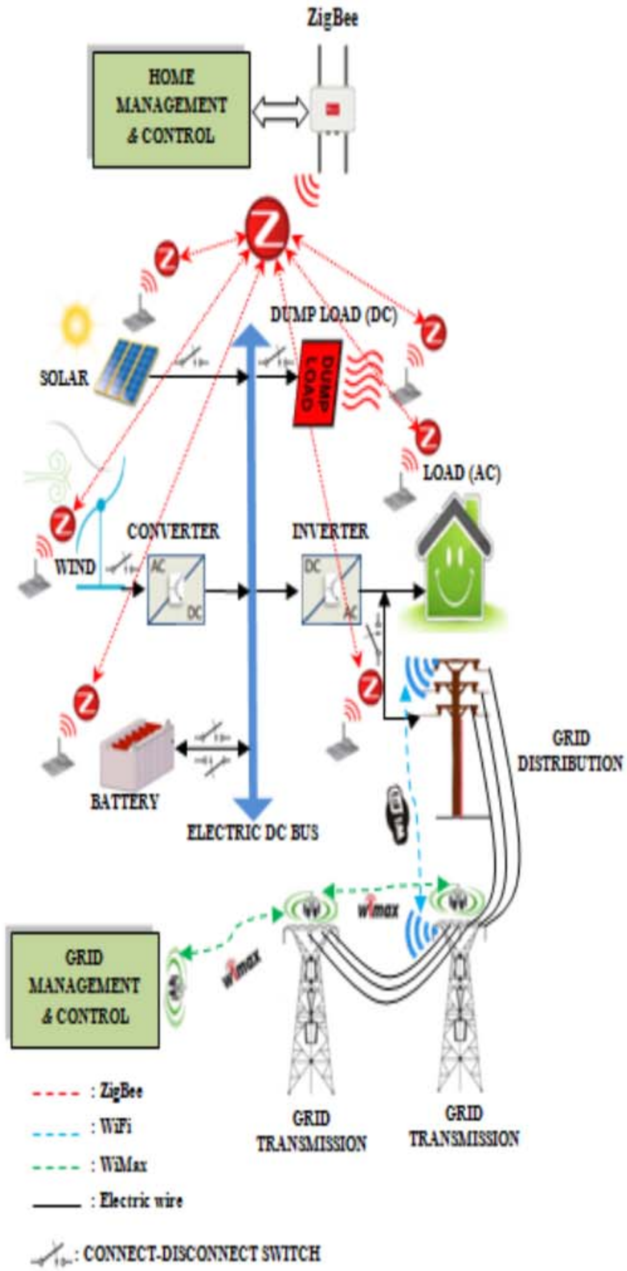

Fig. 4. Micro grid architecture

The following Fig. 5 shows the energy flow configuration in the proposed architecture from the sources to the load, where η_{inv} ,η_{conv} , η_{wire} , $\eta_{charging}$ and $\eta_{discharging}$ are the efficiencies of inverter, converter, wire, charging and discharging battery, respectively.

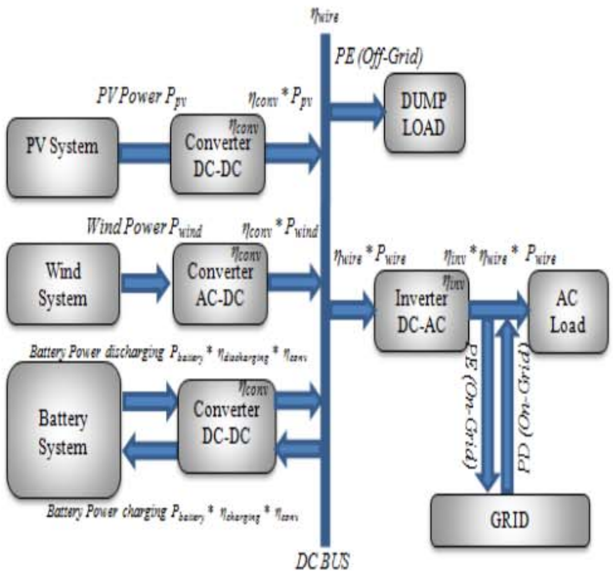

Fig. 5. Energy flow

V. Control And Management

Our architecture operates in two modes: On Grid and Off Grid. The decision to integrate the excess energy (EE) in the grid ($G_{Decision}$) and grid state (G_{State}) are controlled by the GMC, on the other side, our system can be disconnected or connected automatically (switch G) by the HCM in the event that there are a deficit (ED) or excess (EE) energy. The DMP switch is used to connect or disconnect the dump load in the case of excess energy (EE). The overall control can be summarized by the following table.

TABLE IV. System Control

G_{State}	$G_{Decision}$	Mode	G	DMP
0	0	Off-Grid	0	1 if EE
0	1	Off-Grid	0	1 if EE
1	0	On-Grid	1 if ED	1 if EE
1	1	On-Grid	1 if ED or EE	0

A. Control and Management

The management of flow energy is different in On-Grid and Off-Grid mode, and depends to the control configuration [14, 16, 17]. Fig. 6 shows the logic diagram of two modes and those configurations.

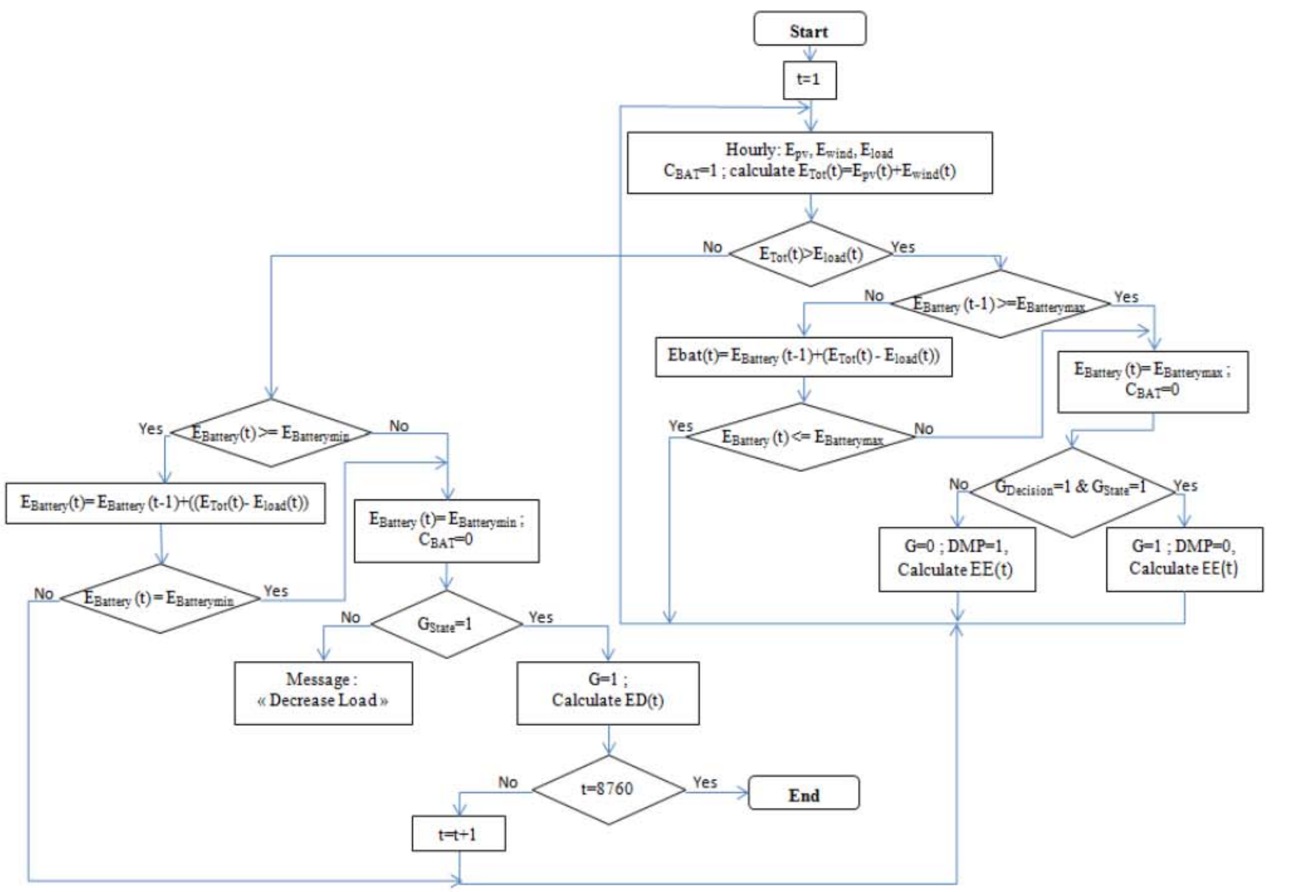

Fig. 6. Control and Management algorithm

The HMC process starts by reading the load power demand, the power data from the photovoltaic system and the wind generator system in order to calculate the total energy produced (E_{Tot}) and connect the battery to all the system (C_{BAT}=1). The data power is expected and calculated every hour that is why the power data is equal energy data.

In the first time we compare the total energy (E_{Tot}) and the load energy demand (E_{load}). In the deficit case ($E_{Tot}<E_{load}$), the system inspect the battery state of energy ($E_{Battery}$), if it is full discharging ($E_{Batterymin} \geq E_{Battery}$) the system must connecting to grid to compensate the deficit (ED) if the system is configured at On-Grid (G_{State} = 1) and setting the grid switch to "on" (G=1). In the Off-Grid mode (G_{State}=0), a message will be showed "Decrease Load".

In the On-Grid mode (G_{State}=1) and if the energy is exceeded ($E_{Tot}>E_{load}$) and the battery is full charging ($E_{Battery} \geq E_{Batterymax}$), the system verified the grid decision, if it is "on" ($G_{Dcision}$=1) all excess energy (EE) must be integrated in the grid and the switch grid will be "on" (G=1). Else, (Off-Grid mode (G_{State}=0)) or ($G_{Dicision}$=0), the excess must be dumped in the dump load (DMP=1).

The next hour (t=t+1)), the same control and management will be repeated.

VI. SIMULATION RESULTS AND DISCUSSION

To validate the proposed average models, our system was simulated with Matlab Simulink in near-real-time. The wireless communication architecture was also implanted in the power system Fig. 7.

A. Technical characteristics

TABLE V. summarized technical characteristics of each system components.

TABLE V. TECHNICAL CHARACTERISTICS

Module	Technical characteristics
PV	P_{peak}= 2.500 kW, $G_{standard}$= 1000 W/m2, α_T= 0.05 [14] , $T_{standard}$= 25°C
Wind system	Rated Power = 1.26 kW, Rated speed= 8m/s Cut in speed= 0.5m/s, Cut out speed= 18m/s
Battery	Nominal voltage = 12V, Nominal energy =1.4 kWh SOCmax= 90%, SOCmin= 30%, $\eta_{charging}$=0.80 $\eta_{discharging}$=0.80
Inverter	η_{inv}= 0.95
Converter	η_{conv}= 0.85
Wire	η_{wire}=0.98

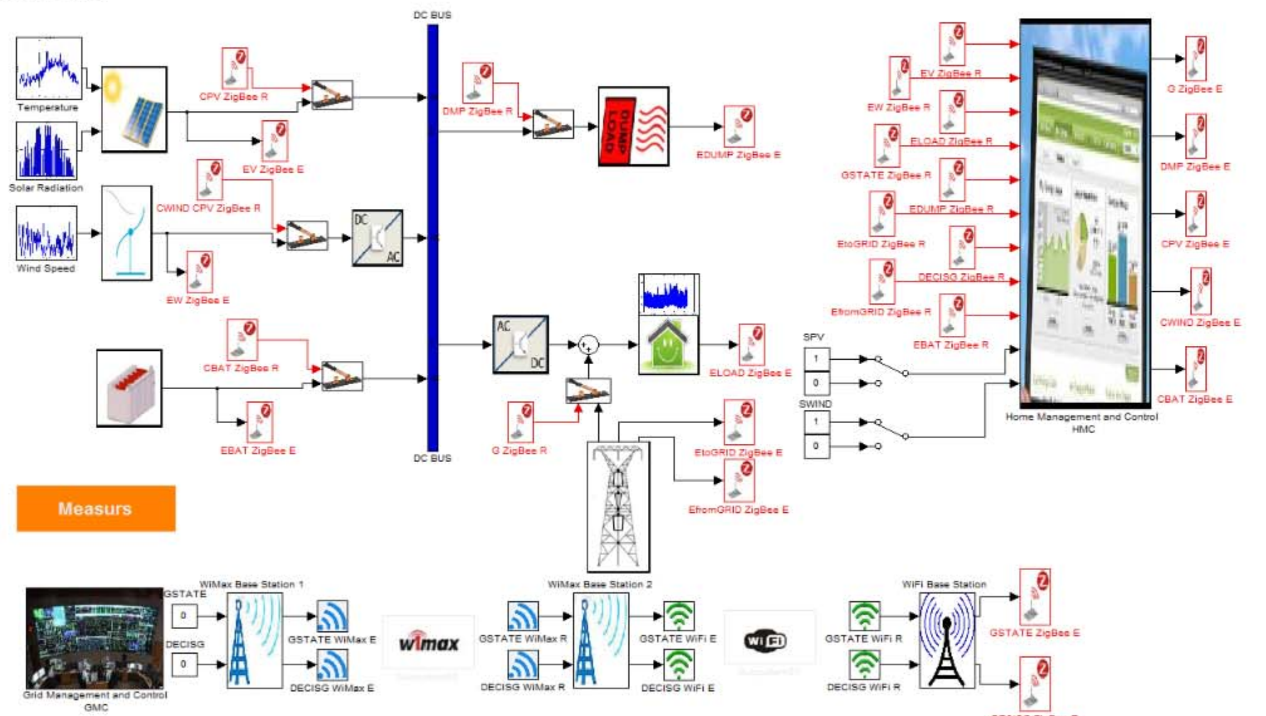

Fig. 7. Micro Grid power and communication architecture with Simulink

- Fig. 8 shows an example of hourly load demand during one year,

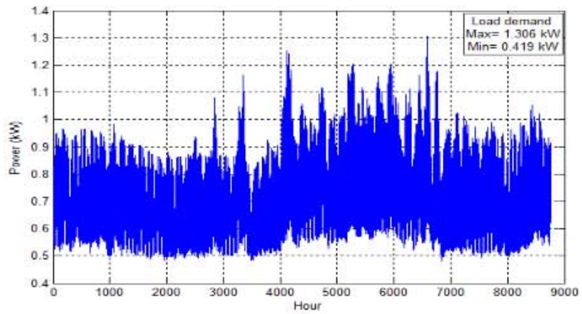

Fig. 8. Hourly load demand

- The hourly meteorological data wind speed, solar energy and ambient temperature are illustrated in Fig. 9. These data are for the city of Tunis (year 2003).

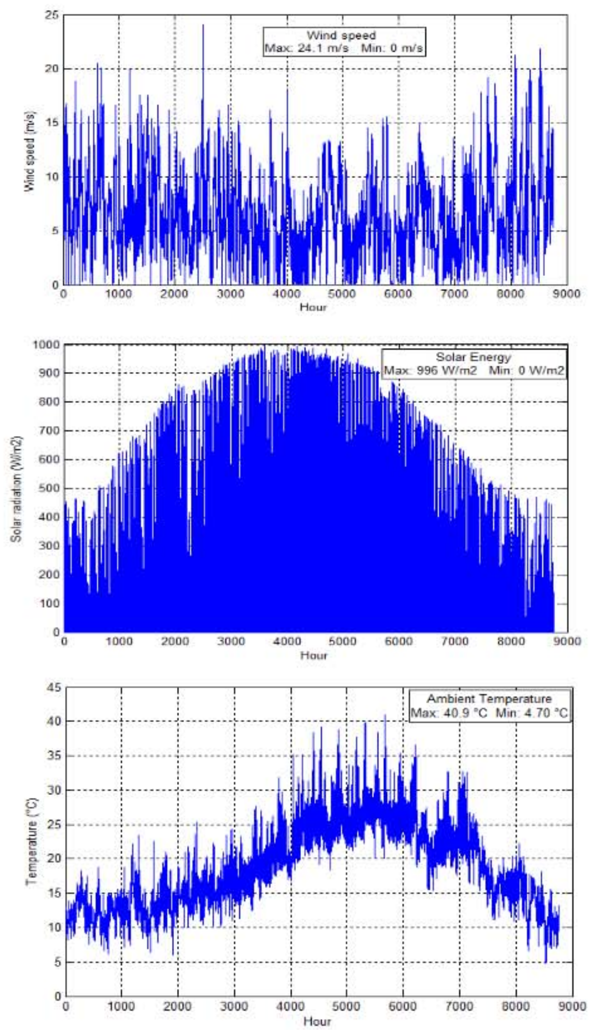

Fig. 9. Hourly meteorological data.

B. Simulation

All wireless protocols are simulated with Matlab Simulink through an Additive White Gaussian Noise (AWGN) channel with Signal-to-Noise Ratio (SNR) equal to 15 dB.

- Fig. 10 and Fig. 11 below shows the tow scenarios of ZigBee communication inside the micro grid and the two-ways data flow between the micro grid and the Home Management and Control system.

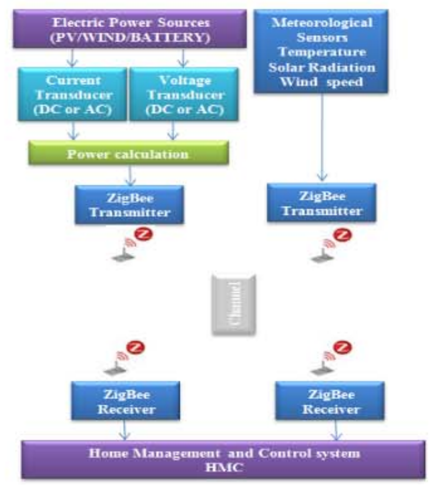

Fig. 10. ZigBee communication process: Micro Grid to HMC

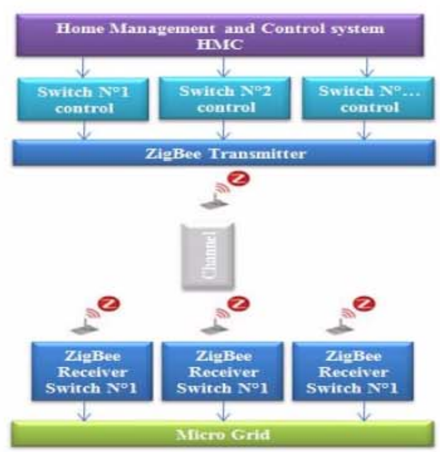

Fig. 11. ZigBee communication process: HMC to Micro Grid

The ZigBee specifications for 2.4 GHz simulated with Matlab Simulink are mentioned in the TABLE VI below.

TABLE VI. ZIGBEE SPECIFICATION

Parameter	Specification
Operating frequency	2.4 GHz
Channel spacing	5MHz
Data rate	250Kbps
Spread spectrum	Direct Sequence Spread Spectrum DSSS
Modulation	OQPSK

The simulation results for the two scenarios described above are in the Fig. 12. These results show the reliability of data flow between the ZigBee transmitter and receiver. The data is 16 bits code.

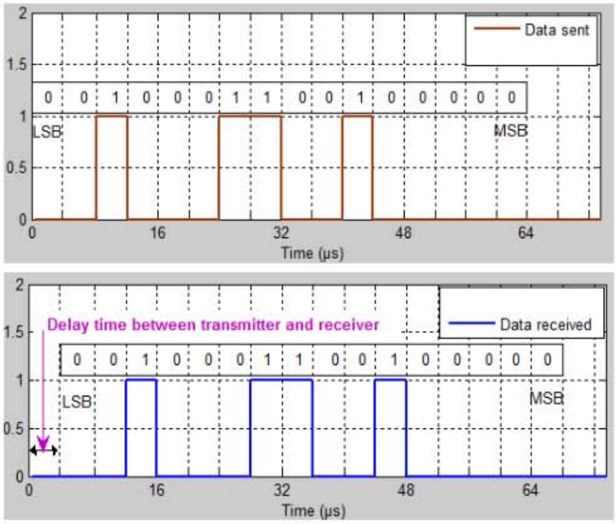

Fig. 12. Data transmitted and received with ZigBee protocol.

- The Fig. 13 presents a block diagram of the wireless communicationhe architecture and the process between three areas HAN, NAN and WAN. The simulation consists to send data from point A to point B (ZigBee transceiver to WIMAX transceiver) Fig. 13 and interpret the reliability of the data under well determinate conditions on channel, coding and modulation Fig. 14.

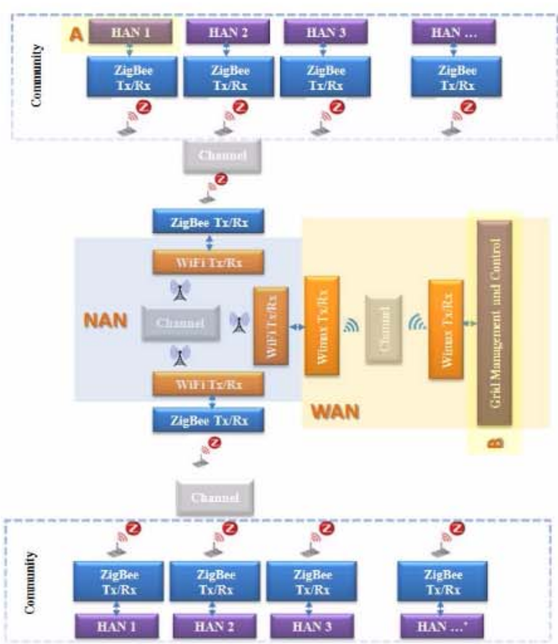

Fig. 13. Block diagram of the wireless communicationhe architecture

WIMAX and WiFi specifications for 2.4 GHz operating frequency simulated with Matlab Simulink are mentioned in the TABLE VII below.

TABLE VII. ZIGBEE SPECIFICATION

Parameter	**Specification**	
	WiFi	WIMAX
Data Rate	48 Mbps	5Mbps
Modulation	64-QAM	256 SUB-CARRIER OFDM USING QPSK
Coding Rate	2/3	1/2

The simulation results shows in Fig. 14 prove that the data sent is the same than the data received with little time delay.

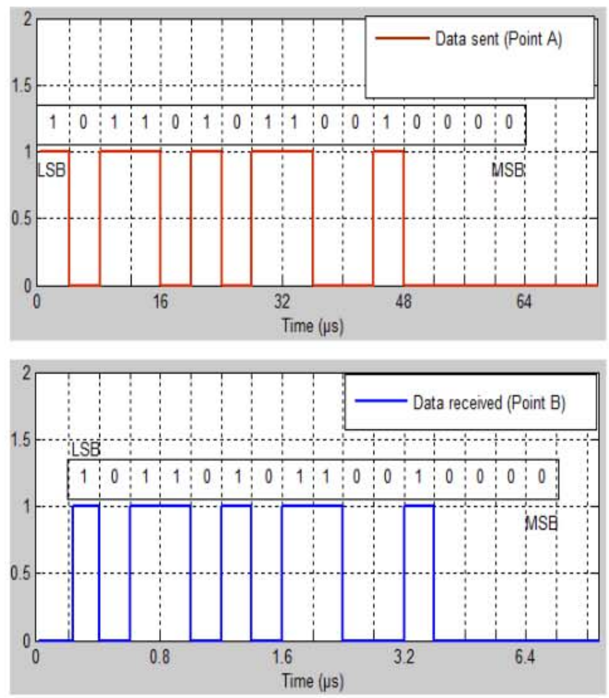

Fig. 14. Data sent and received from point A to point B.

Our wireless communication architecture will be tested in the hybrid micro grid power system Fig. 4. Thereafter, the simulation results will be discussed.

Three scenarios will be simulated (for one month),

- The first is that the system is configured on mode Off-Grid (G_{State}= 0) Fig. 15.
- The second scenario is the system in the On-Grid configuration but the decision set on “off” ($G_{Decision}$= 0) Fig. 16.
- The last is On-Grid mode and $G_{Decision}$= 1 Fig. 17.

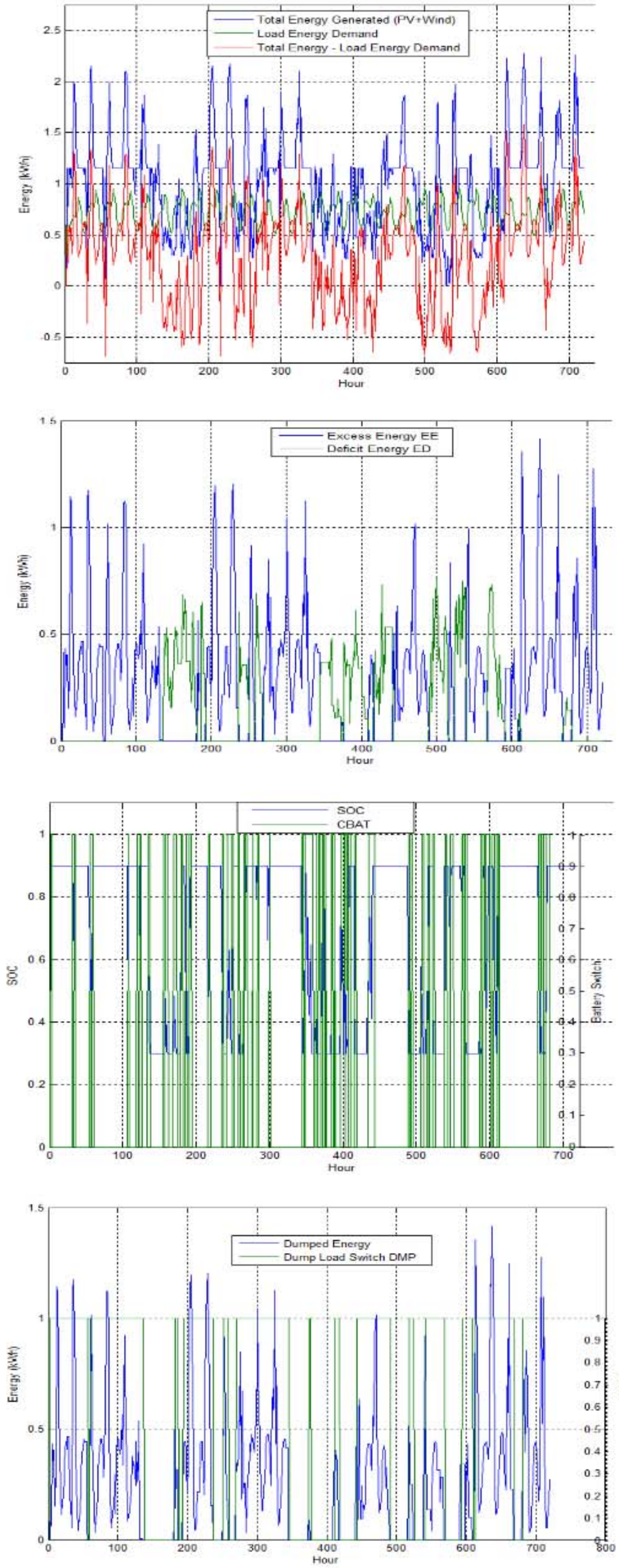

Fig. 15. Off-Grid mode

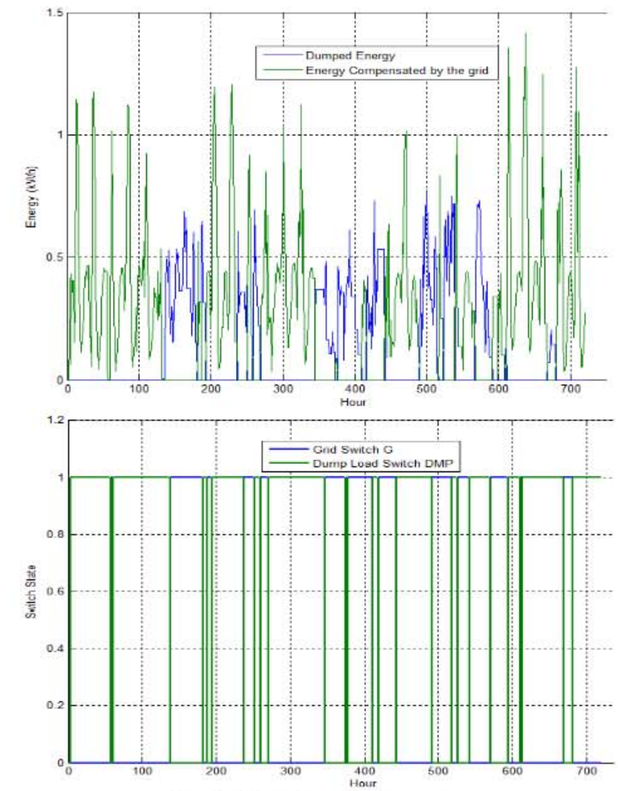

Fig. 16. On-Grid mode, $G_{Decision}$=0

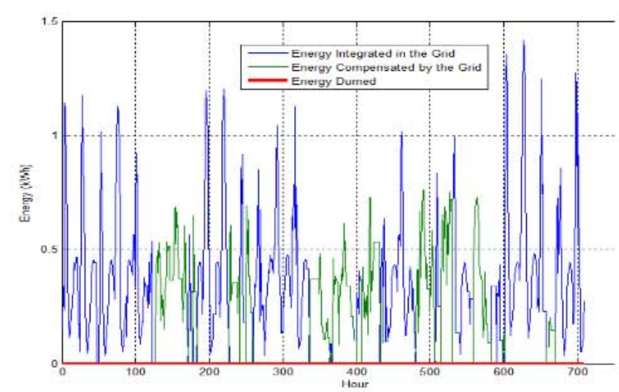

Fig. 17. On-Grid mode, $G_{Decision}$=1

C. Discussion

The communication protocols such as WIMAX, WiFi and ZigBee are simulated in the Additive White Gaussian Noise (AWGN) channel with 15 dB Signal-to-Noise Ratio (SNR). In order to improve the performance of these protocols in noisy environments, some studies will be effectuated.

The simulation results showed that our wireless communication architecture is successfully validated with power flow of the proposed models. On the one hand, our system can give information to the consumer in real time, the state of grid or a prediction in future time. In the other hand, independently to the state of the network, our wireless

communication architecture ensures goodness and reliability data flow between all components of the micro grid. It can be implemented and tested on dynamic power systems.

The dumped energy is useful in estimating the needed dumped load or the number of battery to store all the excess energy.

In addition advantages previously mentioned, the proposed system can simulate any month or any day of the year, and also can see the behavior of the system for each hour.

The disadvantage of the proposed systems is that it is not able to compensate the deficit energy when the Off-Grid mode is configured. To resolve this problem, we can add a diesel generator and setting on in the deficit time.

VII. Conclusion

To make the actual electricity grid more flexible and versatile, a robust data flow interexchange infrastructure must be created. It is in this context that our work has been based. In this paper Energy flow for three models was proposed. These models are PV model, Wind model and battery model. Wireless communication architecture was discussed first and then an energy control and management algorithm was provided and obtained in order to control the whole system in real time with a real time meteorological data such as sun radiation, ambient temperature and wind speed. The simulation results showed the validity of the proposed energy flow and data flow architectures. Such models and architecture help in modeling and sizing smart home or smart grid.

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