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Preventive Maintenance of Solar PV Systems using wireless Real-Time Data Acquisition

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***Abstract*—Solar photovoltaic (SPV) power generation has become an indispensable component of modern renewable energy systems. Ensuring the reliable operation of SPV installations, particularly those deployed in remote or inaccessible locations, requires continuous monitoring of critical electrical and environmental parameters to facilitate timely preventive maintenance. To address this requirement, a cost-effective real-time energy monitoring system has been designed and developed specifically for SPV applications. The proposed system employs multiple sensors strategically installed at different stages of the photovoltaic system to acquire operational data, which are transmitted wirelessly through an RF XBEE communication network integrated with a low-cost PIC microcontroller.**

A custom graphical user interface (GUI) developed using Visual Basic enables users to observe live operating parameters on a server computer while simultaneously archiving instantaneous measurements for future analysis. The continuous data acquisition and storage capability supports rapid identification of abnormalities, including power fluctuations, performance degradation, and fault conditions, thereby minimizing manual intervention and improving system reliability. The wireless communication architecture offers a simple, scalable, and economical solution for remote monitoring applications.

Compared with conventional monitoring approaches, the developed system addresses several practical limitations, including high implementation cost, restricted memory capacity, limited PC connectivity, inadequate software programming flexibility, and fewer analog sensor interfaces available in standard controllers. A comparative performance evaluation between the proposed monitoring platform and existing systems demonstrates its effectiveness and practicality. Furthermore, the XBEE modules were configured using XCTU software, and the wireless communication network was verified through simulation before being integrated with the experimental SPV setup, ensuring reliable system operation.

***Keywords*— Real Time Energy Monitoring, Solar Photovoltaic, ZigBee wireless network, Microgrid, PAN.**

I. Introduction

Solar Photo Voltaic (SPV) System is gaining a huge interest as a renewable, low carbon emission source of electrical energy for domestic as well as large consumers. It generally comprises of Solar Photovoltaic Array, DC-DC converter for level shifting from lower voltage to higher one and a DC-AC inverter for domestic and industrial load in dual stage system [1]. Its application area may include the remote location where the existing utility GRID is yet to reach. Hence monitoring of different parameters like voltage, current and power [2], insolation [3], temperature [4] etc. from the SPV system at its different stages is a big challenge for proper operation and maintenance of the system [5][6][12]. This may recall the infrastructure of Automatic Meter Reading (AMR) [7]. AMR industries are working with different architectures and networks technologies in wired and wireless communication. [7][8]. The ZigBee network is one of the wireless topologies and has wide application in industrial automation, home automation, smart grid, smart grid monitoring etc. [9]. This network works in wireless IEEE 802.15.4 standard and it can send real time data wirelessly to a remote location where no internet /Wi-Fi is available. This system consumes very low energy compared to all counterpart available in wireless technology and easy to install which make it suitable for scalable network and simpler automation. These characteristics makes the ZigBee networks cheap [5], secure and efficient system [10][11]. So, a dedicated ZigBee Energy Monitoring system can be developed for the monitoring and acquisition of different important parameters [15][17][18]. This may be a possible solution for a short-range communication technology [20].

A wireless network for Solar PV home grid/microgrid can overcome the wiring network issues [7][9]. The sending and receiving data can be saved in local storage or send to a cloud/server IOT system which connect the data throughout the world [13][16]. This brings the new concept of intelligent/smart micro grid system for solar PV system [16]. A smart inverter with centralized MPPT [14] is also possible with such arrangement. The modern architectures of PV monitoring, control [15][18] and abnormality diagnosis [17] make Smart grid (SG) and Smart Home (SH) solution [9] [12].

The proposed system is designed and developed as a dedicated multi-Sensor star connected centralized Zigbee Communication network to compute and storage data for a SPV system. This work is all about the Advance Meter Reading System (AMR) with a Solar PV Personal Area Network (PAN). This communication network has been chosen for the low cost, low power consumption which reflects the better efficiency and reliability in operational performance. The results obtained in transmission of data with this developed system is quite satisfactory. These real time data may help in detection of fault in different stages of SPV System and hence maintenance can be initiated accordingly.

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II. PROPOSED REAL TIME ENERGY MONITORING SYSTEM ARCHITECHTURE

The Proposed Monitoring system is relatively new concept in this field. The architecture of this proposed monitoring system can be categorized into three layers as shown in Fig.1.

The Data acquisition Layer comprises of sensors connected with the ADC port of PIC for obtaining SPV system parameter such environmental and electrical data. This layer is controlled by PIC microcontroller. It is responsible for sending information to a connected XBEE module through Rx and Tx pin. The network layer performs the data transmission and receive through air after receiving frame from PIC connected UART ports. Lastly at the receiving end XBEE obtain the data packet and transfer to the central PC. The collected information is stored into computer hard disk for future data-management. This layer is supervision layer which offers a user interface to monitor and store the information for the end users. This can send encouraging area of smart metering infrastructure and open a valuable dimension for research in modern smart grids.

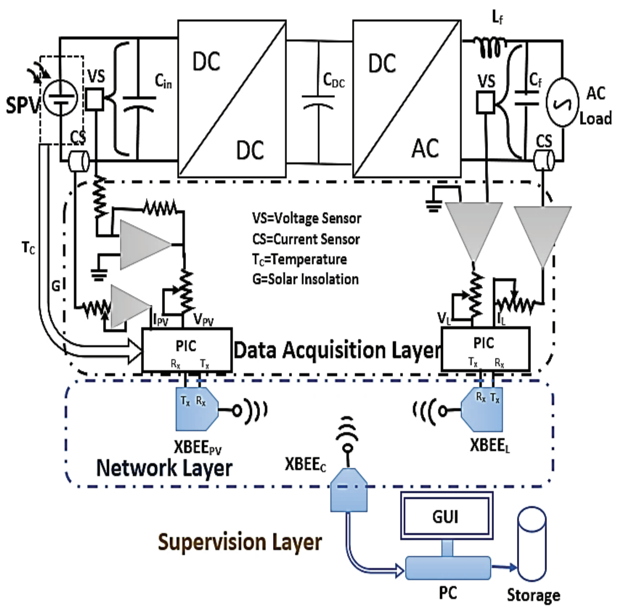

Figure1: Layer diagram of the proposed system architecture for a Solar PV system

A. Data acquisition layer:

This layer acquire data from a SPV system which consists of PV array and power electronics converter. The converter can change the SPV generated DC power to user specific value (DC for ESS and AC for household load). Here two type of data acquisition system has been implemented. First fetch data from the PV array (voltage and current) and Meteorological data (Temperature and Insolation) for the same. These acquired data are converted within the range of 0-5 V level and send to the ADC port of a PIC microcontroller. In next stage the microcontroller processes the data to make it suitable for the XBEE module. The transmission of data between the XBEE module and microcontroller is done by the RS232 protocol (UART). Similarly, at the converter end, data acquisition system process AC load data (RMS Voltage and current) to 0-5 V range before sending to the PIC microcontroller. This scaling down of data prevent the damage of PIC as it can operate only in the range of 0-5 V. It can operate with low power self-supplied source (Battery/SPV) which may improve the power consumption efficiency, results into an economical model.

B. Network Layer:

Radio Frequency based ZigBee communication is the basic building block of this network layer. It can form Wireless Personal Area Network (WPAN) or WLANs. It may give users flexibility in connections for a remote location area where no physical cable can be connected. In this case, ZigBee protocol is working in star topology (Fig.3) among the available star, tree, and mesh network topologies. All the Zigbee in the network has a 64-bit unique address and can join the network only with a unique personal area network (PAN) ID which makes it very secure from external interfere. It is expandable and can cover wide area (300–1500 m) by repeaters Zigbee nodes (Hopping). The transmission rate is 250 Kbps with 2.4 GHz band at its operating range. ZigBee network architecture form with stack of various layers as shown in Fig.2[19]. Coordinator initialize the communication by choosing the channel with a unique PAN ID. The combination of router and coordinator unit may form a distributed multi-cluster communication network for the proposed renewable energy system over a vast area.

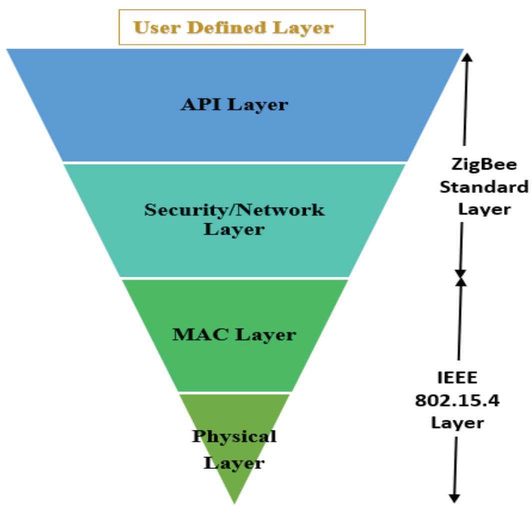

Figure.2: ZigBee working layer architecture.

The information exchange in the system need some time for data transmitting as well as receiving among the XBEE other than user defined delay which can be incorporated in the microcontroller programming. It is sometime called operational delay. Let the time takes by node $XBEE_{PV}$/$XBEE_L$ to gain access of the communication network, μ_{PV} and time for sending the message μ_C.
So, the overall transmission delay (τ_D) can be written as:

$$\tau_D = \mu_{PV} + \mu_C \qquad (1)$$

where, μ_{PV}=delay at solar panel output end, μ_C= delay at power electronics converter

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TABLE II: Laboratory prototype specifications for operation

Hardware section	*Components*	*Specification*
Data acquisition (Sensing)	Voltage Sensor (Potentiometer)	Resistance base potential divider circuit
	Current Sensor (LA 25P)	• Supply voltage:12 V± 5 % • Current consumption :10 mA (@ ± 15 V) • Conversion ratio- 1: 1000 • Measuring Range :0-25A • Operating temperature: - 25 to + 85 °C
	Temperature Sensor (LM 35)	• Calibration Range: −55°C to 150°C • Operation Voltage: 4 V to 30 V • Current Drain: 60 µA
	Analog sensor data Process Unit (PIC 16F877A)	• Working voltage range:2.0V to 5.5V • Current Consumption:15mA • Operating clock speed: 20 MHz. • Flash Program Memory: 8K x 14 words. • Memory (RAM):368 x 8 bytes of Data. • EEPROM Data Memory: 256 x 8 bytes. • Analog-to-Digital Module 8 input channel of 10-bit • Universal Asynchronous Receiver Transmitter (UART):9-bit address detection.
ZigBee Wireless network	XBEE Module (S2C)	• Supply Voltage:2.1-3.6V • Transmit current: 45mA (max) • Transmit power output(max): 6.3mW • RF data rate: 250 kbps. • Receiver sensitivity: -100dBm • Maximum RF input level at antenna port:6 dBm. • Working Temperature: -40^{0}C to 85^{0}C
Storage and Supervision	VB based GUI in centralized PC	Windows OS with VB installed
	Storage	1TB Hard Disc Drive

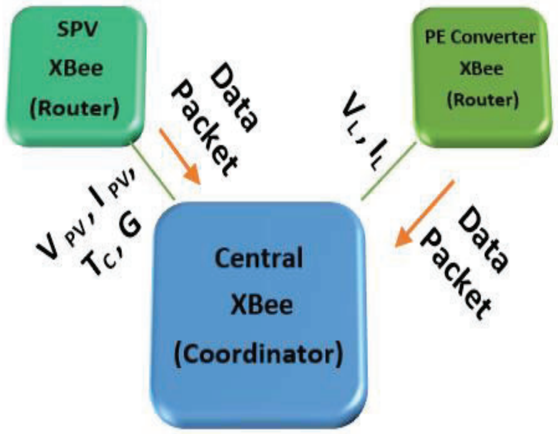

Figure.3: Proposed ZigBee Network topology.

C. Real Time Data Management User Interface:

An indigenous graphics UI for live parameter streaming has been developed in Visual Basic. It may help in performance evaluation and abnormality detection. The $XBEE_{PV}$ and $XBEE_L$ send data to a Centralized master $XBEE_C$ connected to a Personal Computer (PC). It is connected via USB which perform two task power supply and data exchange, results into less energy loss. Master XBEE collect data in terms of data packet consisting of a XBEE information and sensed data. The PC identify the actual data from the incoming data packet frame and display it in the developed GUI. It has the facility of storing the incoming data for the future use. This can enable energy monitoring with more efficient way and can provide system data for future use.

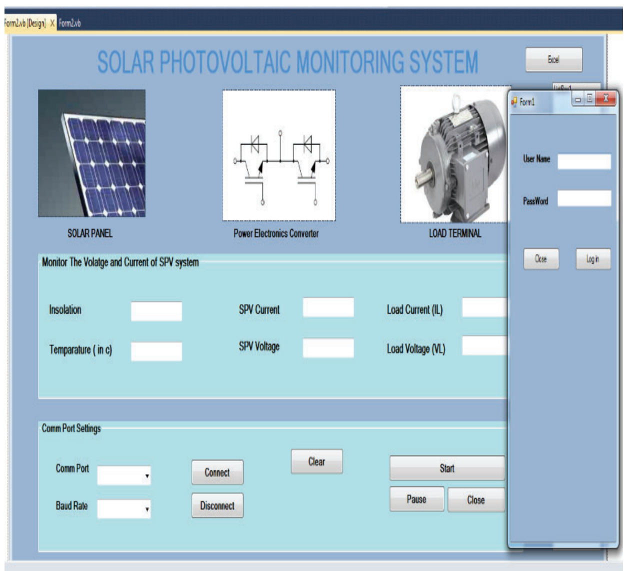

Figure.4: Developed GUI in Visual Basic for real time monitoring

III. EXPERIMENTAL OBSERVATION

The proposed system architecture has been tested for feasibility with a small-scale experimental laboratory setup. The details of the components can be seen in the Table: I. At the sensor end, all parameters are scaled down to a range of 0-5V and collected by the PIC controller ADC. Three dedicated XBEE is forming the wireless personal area network layer with a unique PAN ID. The communication process built a wireless network which transmits the solar PV array parameter (Insolation, Temperature, Voltage, Current) and Load data to the central XBEE connected to a PC. All information exchange has been converted to digital data frame by the PIC controller as shown in Table III and Table IV in appendix. Here all XBEE are working in API mode and consume very low power during operation. The details of the frame data are given in Table-III and Table-IV in appendix. The results presented here is for a single instant data transfer and it will keep repeating in the same manner.

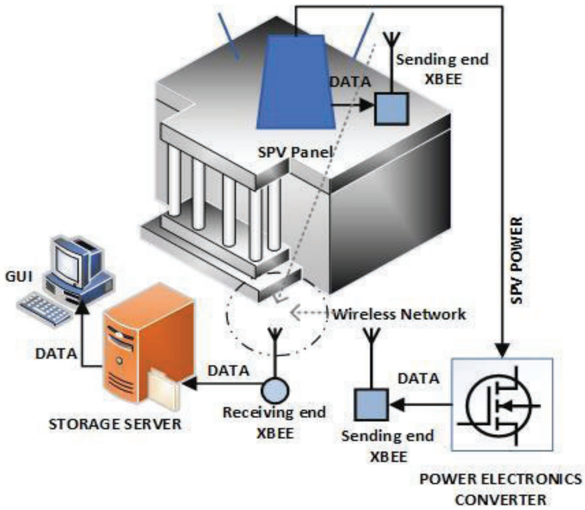

Figure.5: proposed system information flow schematics

An operation delay time as told in Eq.1 is the basic need of the network. A single byte exchange must accompany with a start bit (low) and a stop bit (high). So, for transferring a byte total bit count must be 10 (start bit + 8bit data +stop bit). So, time required to exchange single byte between XBEE and microcontroller Rx/Tx pin is 10 Bit × (1÷ 9600) s/Bit or 1.04 ms.

Now we can find the total time required to transfer a data frame for $XBEE_{PV}$ =1.04 ms/Byte ×22 Byte = 22.88 ms.

Similarly, for $XBEE_{L}$=1.04 ms/Byte ×20 Byte = 20.8 ms.

This time delay is the interval for exchange of information between microcontroller and XBEE module.

Similarly, the data transmission through air add time delay. The physical layer 802.15.4 allows a band rate of 250 kbps or 4 µs/Bit. The total time required to transfer a data frame through air for $XBEE_{PV}$ = 4 µs / Bit×10 Bit ×22 Byte = 880 µs. Similarly, for $XBEE_{L}$ = 4 µs / Bit ×10 Bit × 20 Byte =800 µs.

So, the Total Time Delay for all XBEE for sending a data frame = Operational Time Delay + User defined time delay = 30 second (approximate)

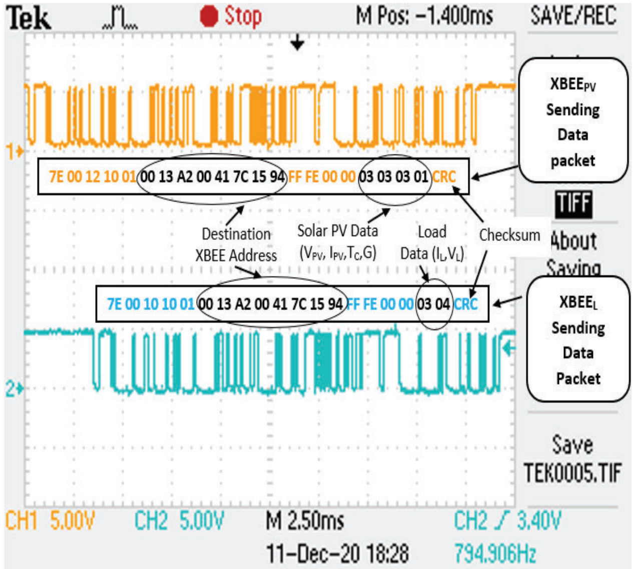

Figure.6: Wireless transmitted data frame from the two sending end XBEE

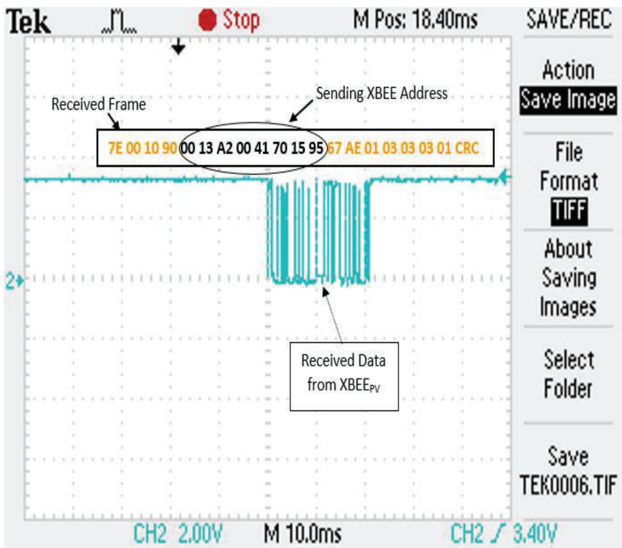

Figure.7: Received data frame at the computer connected XBEE

The sense data at the sending end of the network layer processes with the PIC controller to transmit through air by $XBEE_{PV}$ and $XBEE_{L}$ and is received by a centralized $XBEE_{C}$ (Fig.6, Fig.7) which is connected with the server room PC. The central PC processes the incoming data from the $XBEE_{C}$ and can display in the developed VB based GUI at the computer monitor.

The actual parameter data at the sending end such as solar array voltage (V_{PV})=93.5V, current (I_{PV})=3A, array temperature (T_{C})=35^{0}C, solar insolation(G)=1.0kW/m^{2} have been scaled down to 0-5V range. It can be seen as the data payload in the transmitted data frame. So, a multiplying factor for the same at the GUI end will display the actual value of system parameter. Similarly, RMS value of load voltage (V_{L}) and current (I_{L}) can be sent as data packet by $XBEE_{L}$ and recalculated to display in real value at the VB end.

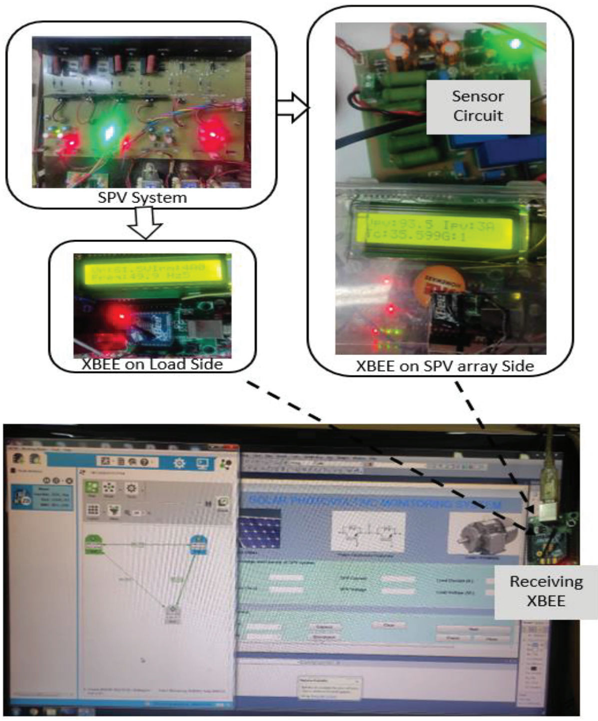

Figure.8: Developed hardware and GUI System for experimental observation

TABLE II: Comparation of Real time monitoring operation architecture

	[2]	[3]	Proposed
Controller	89C51	8051	PIC16F877A
ADC	External ADC	External ADC	Inbuilt 8 ADC
Clock input	Slow	Medium	Fast
No.of sending ZigBee Node	One	One	More than One
Parameter Measure	less	Very less	More
Power Consumption	More	Medium	Less

IV. CONCLUSION

The proposed system can provide real time data of most essential parameters of a SPV system at its different stages which may help in prevention of major fault. So, AMR for this Solar PV system provides atmospheric data such as solar insolation, array surrounding temperature and SPV as generated voltage and current. Also output load current and voltage. Other parameters like load power, PV power, frequency of the generated AC voltage, power factor of the load also can be monitored. These information's facilitate the inspection of the SPV generation efficiency, consumption trend and detection of PV panel failures. Furthermore, in future it may be analyzed for monitoring and control of different SPV system activities such as MPPT conditions, grid management, failure recognition system, weather prediction and load forecasting etc.

REFERENCES

[1] D. K. Mandal, S. Chowdhuri, S. K. Biswas and S. S. Saha, "A Soft-Switching DC-DC Boost Converter for Extracting Maximum Power from SPV Array," *2020 IEEE 5th International Conference on Computing Communication and Automation (ICCCA)*, Greater Noida, India, 2020, pp. 363-368, doi: 10.1109/ICCCA49541.2020.9250818.

[2] Khan, M, Iqbal, J, Ali, M, Muhmmad, A, Zahir, A, Ali, N." Designing and implementation of energy-efficient wireless photovoltaic monitoring system". *Trans Emerging Tel Tech*. 2019;e3685. https://doi.org/10.1002/ett.3685

[3] Liu Y., Li W., Baoyintu, Jia B. (2019) "Design of ZigBee-Based Energy Harvesting Wireless Sensor Network and Modeling of Solar Energy". In: Li J., Liu Z., Peng H. (eds) Security and Privacy in New Computing Environments. SPNCE 2019. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, vol 284. Springer, Cham. https://doi.org/10.1007/978-3-030-21373-2_47.

[4] H. E. Gad and H. E. Gad, "Development of a new temperature data acquisition system for solar energy applications," *Renew. Energy*, vol. 74, pp. 337–343, 2015, doi: 10.1016/j.renene.2014.08.006.

[5] Siva Ramakrishna Madeti, S.N. Singh,"Monitoring system for photovoltaic plants: A review",Renewable and Sustainable Energy Reviews,Volume 67,2017,Pages 1180-1207,ISSN 1364-0321.

[6] S. C. S. Jucá, P. C. M. Carvalho, and F. T. Brito, "A low cost concept for data acquisition systems applied to decentralized renewable energy plants," *Sensors*, vol. 11, no. 1, pp. 743–756, 2011, doi: 10.3390/s110100743.

[7] R. Rashed Mohassel, A. Fung, F. Mohammadi, and K. Raahemifar, "A survey on Advanced Metering Infrastructure," *Int. J. Electr. Power Energy Syst.*, vol. 63, pp. 473–484, 2014, doi: 10.1016/j.ijepes.2014.06.025.

[8] Y. Kabalci, "A survey on smart metering and smart grid communication," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 302–318, 2016, doi: 10.1016/j.rser.2015.12.114.

[9] M. A. Setiawan, F. Shahnia, S. Rajakaruna, and A. Ghosh, "ZigBee-Based Communication System for Data Transfer Within Future Microgrids," *IEEE Trans. Smart Grid*, vol. 6, no. 5, pp. 2343–2355, 2015, doi: 10.1109/TSG.2015.2402678.

[10] Fourty, .N. Bosseche, A.V; Val. T., "An advanced Study of Energy Consumption in an IEEE 802.15.4 Based Network: Everything but the truth on 802.15.4 node lifetime", Computer Communications, *Elsevier*, **vol.35**, no.14, pp. 1759–1767, **(2012)**.

[11] Casilari, E., Cano-García .J.M; and Gonzalo .C.G., "Modeling of Current Consumption in 802.15.4/ZigBee Sensor Motes", *Sensors*, **vol. 10**, no. 6,pp. 5443-5468, **(2010)**.

[12] M. M. Rahman, J. Selvaraj, N. A. Rahim, and M. Hasanuzzaman, "Global modern monitoring systems for PV based power generation: A review," *Renew. Sustain. Energy Rev.*, vol. 82, no. October, pp. 4142–4158, 2018, doi: 10.1016/j.rser.2017.10.111.

[13] R. I. S. Pereira, S. C. S. Jucá, and P. C. M. Carvalho, "IoT embedded systems network and sensors signal conditioning applied to decentralized photovoltaic plants," *Meas. J. Int. Meas. Confed.*, vol. 142, pp. 195–212, 2019, doi: 10.1016/j.measurement.2019.04.085.

[14] S. Moon, S. G. Yoon, and J. H. Park, "A New Low-Cost Centralized MPPT Controller System for Multiply Distributed Photovoltaic Power Conditioning Modules," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2649–2658, 2015, doi: 10.1109/TSG.2015.2439037.

[15] Katsioulis V., Karapidakis E., Hadjinicolaou M., Tsikalakis A. (2011) "Wireless Monitoring and Remote Control of PV Systems Based on the ZigBee Protocol". In: Camarinha-Matos L.M. (eds) Technological Innovation for Sustainability. DoCEIS 2011. IFIP Advances in Information and Communication Technology, vol 349. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-19170-1_32

[16] Hashmi, SA, Ali, CF, Zafar, S."Internet of things and cloud computing-based energy management system for demand side management in smart grid". *Int J Energy Res*. 2020; 1– 16. https://doi.org/10.1002/er.6141.

[17] P Guerriero, F D. Napoli, G Vallone, V d'Alessandro, and S Daliento "Monitoring and Diagnostics of PV Plants by a Wireless Self-Powered Sensor for Individual Panels" IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 6, NO. 1, JANUARY, 2016.

[18] Lazzaretti, A.E.; Costa, C.H.; Rodrigues, M.P.; Yamada, G.D.; Lexinoski, G.; Moritz, G.L.; Oroski, E.; Goes, R.E.; Linhares, R.R.; Stadzisz, P.C.; Omori, J.S.; Santos, R.B. "A Monitoring System for Online Fault Detection and Classification in Photovoltaic Plants". *Sensors* **2020**, *20*, 4688.

[19] A. Narmada and P. S. Rao, "Average end-to-end delay of customised ZigBee stack," *2017 National Conference on Parallel Computing Technologies (PARCOMPTECH)*, Bangalore, 2017, pp. 1-7, doi: 10.1109/PARCOMPTECH.2017.8068333.

R. Das and J. N. Bera, "Development of NAN for Energy Monitoring System using ZigBee," *2019 IEEE Region 10 Symposium (TENSYMP)*, Kolkata, India, 2019, pp. 611-616, doi: 10.1109/TENSYMP46218.2019.8971051.

APPENDIX:

Information of the wirelesslessly exchanged packets

Table-III

Transmit Request (of)	**(HEX) $XBEE_{PV}$**	**(HEX) $XBEE_{L}$**
Start Delimiter (1 Byte)	7E	7E
Frame Length (2 Byte)	00 12	00 10
Type of Frame (1Byte)	10	10
Frame ID (1 Byte)	01	01
Destination address (8 Byte)	**00 13 A2 00 41 7C 15 94**	**00 13 A2 00 41 7C 15 94**
Reserve (2 Byte)	FF FE	FF FE
Broadcast area (1 Byte)	00	00
Transmit options (1 Byte)	00	00
SPV system Data	03 03 03 01	03 04
CRC (1 byte)		

Table-IV

Received Packet (From)	**(HEX) $XBEE_{PV}$**	**(HEX) $XBEE_{L}$**
Start Delimiter (1 Byte)	7E	7E
Frame Length (2 Byte)	00 10	00 0E
Type of Frame (1Byte)	90	90
Source address (8 Byte)	**00 13 A2 00 41 70 15 95**	**00 13 A2 00 41 89 F7 F7**
Sender address (2 Byte)	67 AE	E8 A3
Receive Options (1 Byte)	01	01
SPV system Data	03 03 03 01	03 04
CRC (1 byte)		