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Internet of things based smart energy management in a vanadium redox flow battery storage integrated bio-solar microgrid

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ABSTRACT

In this paper, an optimized energy management scheme for Solar PV, Biogas, Vanadium Redox Flow Battery (VRFB) storage integrated grid-interactive hybrid microgrid system has been implemented using a low-cost Internet of Things (IoT) based smart communication platform. The energy monitoring and control architecture of the proposed system consists of four main parts; 1) Low-cost energy meter for real-time data acquisition for multiple renewable energy sources (Solar PV, Biomass), VRFB storage, grid and loads. 2) Monitoring, control & fault detection using Raspberry-Pi (Single Board Computer) platform and MODBUS over TCP/IP platform. 3) Cloud-based remote monitoring unit (RMU) using Message Queuing Telemetry Transport (MQTT) server and ThingSpeak Middleware. 4) Capacity measurement of biogas production along with automatic start/stop control of biogas engine-generator. 5) VRFB storage scheduling for peak demand shaving. A PSCAD simulation study has been done to realize the hybrid microgrid interconnection. The developed smart communication system performance is validated by a practical 10kW Solar PV, 15kVA biogas plant, 6 kWh VRFB storage integrated hybrid microgrid which satisfies peak demand management and ensures zero loss of power supply probability for dynamic load profile. Four real-life case studies have been done for the practical realization of the proposed energy management algorithm performance. Another significant contribution of this paper is the utilization of the solar PV power even during grid outage scenario at day time. It is made possible by intelligent interfacing of biogas power generator which acts as a reference AC bus for the grid-tied solar inverter and thus the available solar PV power can be used to serve the critical loads during grid outage condition. The proposed smart hybrid microgrid solution claims to be a generalized one, low cost compared to existing alternatives and applicable to satisfy scalable community energy security as well.

1. Introduction

In the present era of the rapid growth of renewable energy-based applications, community electricity demand management is a challenging issue while ensuring 24 × 7 energy security. The need for local management of demand and supply of management of energy has assumed greater importance in the currently prevailing Covid-19 syndrome. To satisfy this energy security demand and to ensure a cleaner environment, renewable energy source integrated microgrid [1–7] system claims to be a potential community-scale solution. Considering the intermittency of renewable energy (RE) sources, multiple energy sources such as solar PV, biomass along with battery energy storage system (BESS) forming a hybrid microgrid [8] can be a potential solution. Besides the interconnection among the RE sources, real-time scheduling is also important at both generation and load end. Therefore, an optimal combination of multiple RE sources and BESS operating through a distinct network for specified load patterns forming a smart microgrid [9] can satisfy the demand response management (DRM). So far, numerous research articles have been published on microgrid and smart microgrid operation, control and stability issues [10–17]. Reyasudin M et al. [18] introduced multi-agent-based distributed control architecture for microgrid energy management and optimization. Mehrasa M et al. [19] demonstrated the control technique for enhancing the stable operation of distributed generation units within a microgrid. In order to achieve optimal energy management [20–27], one of the core performance requirements of smart microgrid is two-way communication.
between the energy consumer end and the energy source operator end. Data acquisition systems for performance analysis and fault detection, online monitoring and control are usually found in large power systems because complex monitoring systems and relatively high costs make those solutions less practical for micro and mini-grid power generation clients [28–34]. In fact, a pilot hybrid microgrid plant has been installed consisting of integrated 10kWp solar PV, 15kVA biogas engine-generator and 1 kW 6 kWh VRFB storage at the Indian Institute of Engineering Science and Technology (IIEST), Shibpur campus, India, which has been reported by Sarkar et al. [8]. In their work, the microgrid energy management and control were done by LabVIEW based smart controller. However, apart from the investment cost of the controller and communication module, one of the limitations of using LabVIEW for such small community-scale microgrids is the lack of open source connectivity in wireless communication.

Hence, to overcome these limitations while establishing smart communication and controlling the microgrid power system operation [35,36], in this paper a Linux software platform based low-cost supervisory control and data acquisition (SCADA) system for hybrid microgrid energy monitoring and control (Locally or Remotely), a cloud-based Internet of Things (IoT) enabled system has been proposed and demonstrated. The major facility of using the IoT based communication in a microgrid is its open-source compatibility with the other communication modules. The remote monitoring and control of microgrid become easier to implement by using this platform. Here, an optimized energy management scheme for the multiple RE sources such as solar PV, biogas and VRFB BESS integrated grid-interactive hybrid microgrid system has been implemented using the IoT based low-cost smart communication platform for the first time. As BESS, VRFB storage has been used in this work because of its several advantages like scalability and longest cycle life compared to the other conventional battery storages (Li-ion, Lead Acid, etc.). The proposed microgrid energy monitoring and control architecture consist of four major subsystems: 1) Low-cost energy meter for real-time data acquisition for multiple RE sources, grid and load, 2) Monitoring and control using Raspberry-Pi (Single Board Computer) platform and MODBUS over TCP/IP platform, 3) Cloud-based [37–40] remote monitoring unit (RMU) using Message Queuing Telemetry Transport (MQTT) server and ThingSpeak [41,42] Middleware, 4) Capacity measurement of biogas production along with biogas engine Start/Stop control. It is to be noted that the HyperText Transfer Protocol (HTTP) has been one of the most popular servers for remote monitoring and its various applications. But in this work, MQTT has been adopted as a smart microgrid monitoring protocol because of its significant advantages. MQTT works on lower bandwidth internet, whereas HTTP works on higher bandwidth internet. MQTT is a lightweight; publish/subscribe messaging protocol specially designed for the IoT based applications, establish wireless communication between multiple devices, developed by IBM in 1999. MQTT protocol is used in the application layer of TCP/IP. It can publish the data based on a topic from a device; any device can receive those messages by subscribing to the topic. The message that is exchanged between the devices is mainly commands or data. For example, device 1 publishes based on a topic and device 2 subscribes the same, then device 2 receives the message published by device 1. The Broker is the major subsystem of the MQTT server that is primarily responsible for receiving all the messages. The Broker also allows a new device filtering the messages and publishing for all the subscribed clients [43–46]. There are several existing brokers like Mosquito that is primarily responsible for MQTT messages is being used in this work. The message sending and receiving speed depends on the server internet speed. With 8 bytes (Fixed/Variable) header, the topic enables arbitrary payload up to 256 MB of memory. With minimum packet size of just 2 bytes with a single byte control field and a single byte packet length field, allows MQTT to claim as a popular IoT Protocol in lower bandwidth connectivity, whereas the popular HTTP needs more internet bandwidth to work properly. For multi-client messaging HTTP needs more time to execute because of individual messaging to every time whereas MQTT needs single messaging to the entire connected client or node. Thus the above-mentioned advantages are the major reasons for using MQTT protocol for establishing smart communication among multiple RE sources, VRFB storage, loads, and the distribution grid. In this paper, the ThingSpeak platform has been used to monitor and control the real-time microgrid data coming from the Raspberry-Pi processor. ThingSpeak is an IoT Middleware that can connect cloud storage or local MQTT broker, used to analyze mass data in a realizable graphical form. ThingSpeak is an open-source IoT application launched by IoTbridge in 2010. ThingSpeak uses the Application Programming Interface (API) to store and retrieve data or command from devices using the MQTT protocol over the internet or via a Local Area Network.

For performance validation of the developed energy management algorithm and the proposed IoT based smart communication scheme, four practical case studies for the whole day load profiles have been chosen. To meet the dynamic load demand, the integrated bio-solar-VRFB storage based hybrid microgrid system [8] that has already been installed at the Indian Institute of Engineering Science and Technology (IIEST), Shibpur campus, India has been used as an energy source in both the grid-connected and off-grid mode. The off-grid or grid outage scenario sometimes occurs during day time also. Considering this practical condition, another major contribution of this paper is the utilization of the available solar PV to meet the critical load demand even during day time grid outage scenario. It has been made possible by optimized scheduling of biogas power generator which acts as a reference AC bus for keeping the grid-tied solar inverter during operational during day time grid outage condition. During night time or cloudy days, the grid outage is period is managed by biogas and VRFB storage depending upon their available capacity. The presented IoT based smart microgrid controller is a low-cost solution. The cost analysis of the proposed smart microgrid controller will be discussed in Section 4 of this paper. The rest of the paper is organized as follows; Section 2 describes the schematic, modeling, and simulation study of the proposed hybrid microgrid consisting of multiple renewable energy sources, VRFB storage. Section 3 discusses the system operation details of the proposed IoT based smart microgrid. In Section 4, the results and analysis are provided. Finally, Section 5 includes the conclusion of this paper.

2. Microgrid modeling

The schematic of the proposed hybrid microgrid has been shown in Fig. 1a. Renewable energy sources (solar PV, biogas) and VRFB storage are interconnected via an AC bus which is further connected with the distribution grid and the loads. The Biogas power generator is synchronized with the grid via a suitable synchronizer panel and it can run in isolated mode also to serve the local loads under grid outage condition. A suitable AC/DC bi-directional converter with charge controller has been interfaced to optimally charge and discharge the VRFB storage to ensure peak load shaving. The individual subsystem of the proposed microgrid and the electrical interconnection has been modeled using the PSCAD simulation platform as shown in Fig. 1b. The solar PV array, Biogas engine-generator capacity, and VRFB storage capacity has been estimated based on the results obtained by Sarkar et al. [8] where the capacity of each renewable energy source and storage of a hybrid microgrid was estimated using HOMER software platform. The PSCAD model of the hybrid microgrid shown in this paper is built using the technical specifications and relevant equations of different subsystems (solar PV, biogas plant, VRFB storage) from Sarkar et al. [8]. But the significant contribution of this paper lies in the real-time or online management of the smart hybrid microgrid whereas Sarkar et al. [8] demonstrated offline management of the hybrid microgrid performance.

2.1. Modeling of solar PV system

DC power output from a solar PV source [8] is expressed by,
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2.2. Modeling of biogas power plant

Electrical power generated from the biogas plant [34,35] can be expressed by,

$$ P_{bg} = \eta_{gen} \cdot D_{wt} \cdot Y_{bg} $$

Where, $\eta_{gen}$= Generator/alternator efficiency; $D_{wt}$= Collected biodegradable kitchen & table waste/day (kg); $Y_{bg}$= Generated biogas/kg of kitchen waste; Now, the volume of the digester can be calculated by,

$$ V_{slr} = \frac{(V_{bg} \cdot T_{gas})}{0.5} $$

Where, $V_{slr}$= Volume of the slurry/day which can be further expressed by,

$$ V_{slr} = 2 \cdot D_{v} $$

As the slurry is produced by mixing water in a ratio of 1:1, $T_{rs}= $ Slurry retention time within the digester

In the biogas digester, slurry occupies up to 50% of the digester volume and the rest 50% is covered by the generated gas. Biogas to electricity generation plants has two major parts; the internal combustion (IC) engine and a three-phase AC generator which is mechanically coupled with the engine. In addition to these, a governor is attached to the IC engine which controls the generator shaft speed by adjusting the gas supply at the engine input valve using a feedback control topology. A field exciter and a voltage regulator are attached with an alternator for controlling the DC field excitation and the alternator terminal voltage respectively.

The amount of fuel being taken by the biogas generator to drive a certain load is expressed by,

$$ F_{gas}(t) = (m_{0} + P_{gas}(t)) \cdot m_{0} \cdot P_{rated} $$

Where, $P_{rated}$= Rated power of the biogas generator (kVA); $F_{gas}(t)$= Hourly fuel consumption (m$^{3}$/hour); $P_{gas}(t)$= Generator power at time‘; $m_{0}$ & $n_{0}$ = Calibration coefficient of fuel

Eq. (10) describes that the fuel consumption of a biogas engine-generator set which depends on generated power as well as the rated power and thus it is limited to,

$$ P_{gas\_min}(t) \leq P_{gas}(t) \leq P_{gas\_max}(t) $$

Where, $P_{gas\_min}(t)$= Minimum operating power (kVA); $P_{gas\_max}(t)$=  

Fig. 1. (a) Schematic of the Solar PV-Biogas-VRFB storage based hybrid microgrid system. (b) PSCAD model for interconnection of the proposed hybrid microgrid system.
Maximum operating power (kVA)

The biogas power generator characteristics have been simulated in PSCAD using the practical specification of the 15 kVA biogas engine-generator system [8] in the microgrid. The engine dynamics and the coupled three-phase alternator model are used to determine the electrical power output for interfacing the biogas generator with the microgrid. The parameter specifications considered for modeling the 15kVA biogas engine – generator set [47,48] are; two-cylinder engine with AC three-phase 4 pole alternator having 1500 r.p.m as the rated speed of the generator.

2.3. Modeling of VRFB storage

Some of the major advantages of VRFB storage over the other conventional batteries are; its highest cycle life (around 13,000) and scalability of power and energy capacity. Such merits of VRFB have made it one of the most potential battery storage for stationary renewable energy applications and microgrid to ensure energy security and reliability.

The following equations [49] have been used to simulate the VRFB charge/discharge characteristics [50] which would be further used to design the suitable charge controller for the VRFB system.

\[ V_{bat} = V_{stack}(SOC, Q, n_cell) ± I_{stack} \times R_{specific}(I_{stack}, Q, T) \]  

(12)

Where, \( V_{bat} \) = VRFB terminal voltage (V); \( V_{stack} \) = VRFB stack open-circuit voltage (V); \( I_{stack} \) = VRFB stack terminal current (A); \( R_{specific} \) = Specific resistance of the VRFB stack (mΩ); \( Q \) = Electrolyte flow rate (ml/sec.); \( T \) = Operating temperature of VRFB

Further, the state of charge (SOC) of VRFB is calculated by,

\[ SOC = \frac{C(t)}{C_{Ref}} \]  

(13)

Where, \( C(t) \) = Battery capacity at time instant ‘t’ (Ah); \( C_{Ref} \) = Reference capacity (Ah); Now, \( C(t) \) is calculated by,

\[ C(t) = q(t_0) + q_d(t) + q_c(t) \]  

(14)

Where, \( q(t_0) \) = Initial quantity of charge (Q); \( q_d(t) \) = Charge in during charging process; \( q_c(t) \) = Charge out during the discharging process

The parameter specifications for modeling the VRFB storage have been considered based on a practical 1 kW 6 kWh VRFB system [8,32] for its integration with the microgrid. For its integration with the microgrid. The VRFB system has a stack consisting of 20 series cells with a voltage range of 20–32 V and a maximum allowable stack current of 60 A. Two electrolyte tanks with a volume of 180Litre each are integrated with the VRFB stack through two micro-pumps having a capacity of 65 W each. The VRFB charge controller [32] for the microgrid operation has been designed based on the above-mentioned specifications.

Fig. 1a shows the schematic of the solar PV–biomass–VRFB BESS based hybrid microgrid system. For validation of the proposed work, practical building energy consumption per day has been chosen. To satisfy the load demand profile the optimized scheduling of different RE sources and BESS will be executed with the help of the proposed IoT based smart energy management algorithm. The electrical interface and the microgrid subsystems are modeled using the PSCAD simulation platform as shown in Fig. 1b.

3. Experimental setup and proposed system operation

In this paper, a hybrid microgrid system consisting of 10kWp solar PV, 35 cubic-meter bio-digester with 15 kVA generator, and 1 kW/6 kWh VRFB storage have been set up at the microgrid center within the IIEST, Shibpur campus for experimental study as shown Fig. 2. The renewable energy sources along with load and the distribution grid have been connected with the Main Control Panel (MCP) with a proper protection system. As shown in Fig. 2, the 10 kWp solar PV power plant is connected to the AC grid via a three-phase 10 kW grid-tied inverter. The biogas generated inside the biogas digester is fed to the engine-generator set and the further synchronized with the grid. The VRFB storage used as BESS is interfaced with the AC distribution grid bus via a bi-directional converter. The real-time monitoring and control of the microgrid systems have been done through the Raspberry-Pi communication platform with MODBUS over TCP/IP & RS485 platform link. The main server is installed in the microgrid center for monitoring and control purposes. Thus the installed hybrid microgrid has been upgraded into a smart microgrid by establishing IoT based intelligent control and communication among the RE sources, VRFB storage, connected loads and the distribution grid through energy meters as shown in Fig. 3a. The process flow of the IoT based two-way communication has been shown in Fig. 3b. In Fig. 3a, the energy meters are installed to display real-time information from the RE sources (Solar PV and biogas power), grid, and loads. These energy meters are further connected to the Ethernet

![Fig. 2. Experimental set-up of the hybrid microgrid at IIEST, Shibpur campus. (a). 10kWp roof-top Solar PV power plant. (b). 15 kVA Biogas plant (Digester is shown). (c). Power conditioning unit (Grid-tied solar Inverter and control panels) for the microgrid. d. 6 kWh VRFB storage system with its controller and interfacing units.](image-url)
switchboard via MODBUS TCP/IP communication protocol. Besides this, the biogas generator automatic start-stop operation is also executed by a micro-controller unit operational on Raspberry-Pi. This information is then communicated to the Raspberry-Pi processor for working on the real-time data received and controlling the operation of the proposed smart microgrid. The two-way communication is executed by MQTT protocol as shown in Fig. 3a. MQTT is a simple messaging communication protocol designed for constrained devices with low-bandwidth. Therefore MQTT claims to be a perfect solution for the Internet of Things (IoT) based applications. MQTT allows sending commands to control outputs, reads, and publishes data from sensor nodes. Therefore, it becomes easy to establish communication among multiple devices. It can send a command to control the output and read the data from the sensor and publish it.

As shown in Fig. 3b, the mosquito broker enables an asynchronous bidirectional communication with the neighboring devices (Raspberry Pi Single Board Computer, Laptop, and mobile) through MQTT. To access the data from the broker, a SUBSCRIBE message is sent from a subscriber to the broker, specifying the requested topic. Querying a data for an existing topic, a PUBLISH message is sent from the publisher node to the broker which allows a publisher to write data on an existing topic or to create a particular topic if that does not exist in the broker yet. Also, a default node is allowed to create any topic within the broker [45]. The topic may be any electrical parameter (Line voltage, Line current, Energy, etc.) measured by the energy meters. The topic can be used as implicit key-value storage so that the device which is subscribed to a particular topic can automatically update the key value. This is a desired feature for any remote monitoring, data storage, and control scheme. The broker also keeps track of all the session’s information as the devices go on and off called "persistent sessions", which is ideal for intermittent connectivity. That means if devices are going off-line the message is queued and when the devices go on-line it will be automatically updated which is a significant advantage of MQTT over the HTTP server.

Fig. 4 shows the flowchart of the proposed IoT based energy monitoring and management of the smart hybrid microgrid. The smart communication system is implemented on the practical microgrid by the proposed energy management algorithm. The priority scheduling of RE (solar PV, biogas power) generators, VRFB storage and the distribution grid (if available) have been executed to satisfy 24 × 7 access to electricity to the community loads. Depending on the availability of the solar PV power in the day time, the highest priority is given to it at any time of the day for demand management. Biogas plant being an energy source and a reservoir as well is scheduled after or along with the solar PV source depending upon its availability and load demand. As shown in the flowchart in Fig. 4, the usable biogas capacity is kept at a safe limit of a minimum of 60% of its reserve capacity to serve the load demand under no grid or grid outage condition. The 60% has been intentionally set in this paper in order to match the load demand profile under no grid...
or grid outage condition. Under this scenario, the biogas generator output helps in creating a reference AC bus that acts as a dummy grid in order to keep the grid-tied solar inverter functional during day time. If the solar PV power generation remains adequate and the biogas available capacity remains 60% greater than its reserve capacity, then for a load demand of greater than 60% of the biogas power generator capacity the combination of solar PV and biogas generator satisfies the load demand. The VRFB storage shall be charged from the AC bus depending upon its SOC level. The grid power is used to meet the load demand only when there is insufficient solar PV, biogas and low VRFB storage SOC in order to reduce the electricity tariff expenditure at the consumer end. All these instructions and scheduling sequences are sent to the main processor by MQTT which publishes the message and maintains smooth communication in the microgrid system.

Fig. 4. Flowchart of the proposed IoT based Smart Microgrid operation.

Fig. 5. Demand-side management on Sunny Day.
4. Results and discussion

The performance of the proposed IoT based smart communication scheme and the energy management algorithm has been validated by the practical Solar PV-Biogas-VRFB storage integrated hybrid microgrid system. A 24 h duration practical load demand profile (6:00 A.M to the next day’s 6:00 A.M) has been chosen. The peak load demand is 6.5 kW therefore to match with the daily demand profile the solar PV (10kWp), biogas engine-generator (15kVA), and VRFB storage (6 kWh) have been integrated to form the smart hybrid microgrid. Figs. 5–7 shows three practical case studies for demand-side management under a sunny day, cloudy day, and rainy day respectively. Fig. 8 shows a special case where the uninterrupted load demand management has been performed by the proposed energy management scheme even during a grid outage scenario. Here in this case study, from 3:00 PM to 7:30 PM the grid outage occurs. Then the biogas power generator acts as the temporary grid by creating a reference AC bus for the microgrid system to keep the load demand satisfied by the available solar PV power and the Biogas power. The VRFB storage is charged by the bi-directional converter from the AC bus if the VRFB SOC remains below a certain level of 60% as mentioned in the energy management algorithm flowchart in Fig. 4. In this paper, the total daily energy demand is of the building is calculated as 55.5 kWh. As shown in Figs. 5–8, the negative power signifies the charging of VRFB storage whereas the positive power signifies the discharging. For biogas power generator the power never becomes negative as it acts as a reservoir and serves the load till the biogas is sufficient inside the digester. The negative power in the case of the grid signifies the power import from the grid and positive power signifies export to the grid under excess solar PV power generation. The overall smart microgrid operation monitoring and control have been executed by the low-cost IoT enabled MODBUS based communication platform which plays with the real-time data of PV power generation, biogas power generation, VRFB charging/discharging, grid export/import and the connected load demand.

Regarding the cost of implementation of the IoT based smart controller for the hybrid microgrid energy management in this paper, it is claimed that the use of Raspberry-Pi platform has reduced the cost compared to the LabVIEW based controller used in the microgrid energy management demonstrated by Sarkar et al. [8] as discussed in the introduction section of this paper.

Table 1 shows a comparative cost analysis of the IoT enabled Raspberry-Pi based smart microgrid controller implemented in this work and the LabVIEW based smart controller system.

From the given cost analysis in Table 1 a and b, it is thus claimed that the proposed IoT enabled Raspberry-Pi based smart microgrid controller is a low-cost solution for energy management.

5. Conclusion

In this paper, an IoT based smart communication system is developed and validated by a practical 10 kWp Solar PV, 15 kVA biogas plant, 6 kWh VRFB storage integrated hybrid microgrid. An optimized energy management algorithm has been proposed for satisfying peak demand management and ensuring zero loss of power supply probability under dynamic load profile. Four real-life case studies have been considered for the practical realization of the proposed energy management algorithm performance. The real-time monitoring and controlling of the microgrid system operation are implemented through the Raspberry-Pi based smart communication scheme. A PSCAD simulation study has been done to realize the hybrid microgrid electrical interface circuits and system. The experimental results demonstrate field validation of the developed IoT based smart communication scheme and the energy management algorithm. The results show that the dynamic load demand of the chosen community is satisfied continuously by optimized scheduling of RE sources, VRFB storage and grid (if available). It has also been observed from the results that during grid outage scenario at day time, the load demand is still met by optimized scheduling of biogas power generator which acts a local AC reference bus, thus satisfying the required load demand and utilizing the available solar power by maintaining the solar PV integrated grid-tied inverter operation with the help of biogas generator supported dummy AC grid bus. This feature ensures energy security in addition to the demand management. At the end of this paper, a cost comparison between the LabVIEW based and Raspberry-Pi based smart microgrid controller has also been shown to establish the economic viability of the proposed Raspberry-Pi based smart communication system in the microgrid energy management. Thus, the proposed IoT enabled smart communication scheme and the energy management solution presented in this paper are scalable and claim to be very useful for providing real-time monitoring and control of smart microgrid which satisfies the uninterrupted power supply to the community under both on-grid and grid outage scenarios.

![Fig. 6. Demand-side management on Cloudy Day.](image-url)
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author statements

All the authors have seen and approved the final version of the revised manuscript being submitted. The authors warrant that the article is the authors’ original work, hasn’t received prior publication and isn’t under consideration for publication elsewhere.

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