Supervisory control for Energy Management of Islanded Hybrid AC/DC Microgrid

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Abstract
This paper presents the modeling for islanded hybrid AC/DC microgrid and the verification of the proposed supervisory controller for energy management for this microgrid. The supervisory controller allows the microgrid system to operate in different power flows through the proposed control algorithm, it has several roles in the management of the energy flow between the different components of the microgrid for reliable operation.
The proposed microgrid has both essential objectives such as the maximum use of renewable energies resources and the reduction of multiple conversion processes in an individual AC or DC microgrids. The microgrid system considered for this study has a solar photovoltaic (PV), a wind turbine (WT), a battery (BT), and a AC/DC loads. A small islanded hybrid AC/DC microgrid has been modeled and simulated using the MATLAB-Simulink. The simulation results show that the system can maintain stable operation under the proposed supervisory controller when the microgrid is switched from one operating mode of energy flow to another.
Key words:
Islanded Hybrid AC/DC Microgrid; Supervisory Controller; Energy Management System; Photovoltaic array; Wind Turbine; Battery.

1. Introduction

The microgrids are defined as a cluster of loads, distributed energy resources, and storage devices, which are receiving worldwide attention owing to the increasing rate of consumption of nuclear and fossil fuels, and the community demand for reducing pollutant emission in electricity generation fields. Currently, with the rapid development of renewable generation, the renewable energy sources such as photovoltaic (PV) array and wind turbine (WT) systems have been the main sources in microgrids [1]-[5]. Hybrid power systems such as Photovoltaic array (PV) and Wind Turbine (WT) are among the most promising microgrids for the production of electric power for remote areas with access difficulties to the power grid. There are several states of systems where the islanded mode of microgrid operation is intentionally deployed for a wide range of applications such as safety, economic reasons or during maintenance sessions, shipboard power systems and military applications [6]-[8]. The characteristics of a microgrid system depend on the type and size of the generation units, and the availability of the primary energy resources on the site, especially renewable power sources.
The microgrid can be operated freely in the grid connected or islanded mode of operation, the energy balancing during islanded mode of operation in microgrid system is entirely difficult than in the grid-connected mode of operation. So, the islanded mode operation is generally unplanned and it is mainly considered to enable microgrid to continue to serve and increase the system availability and reliability. subsequently, there are several methods proposed of centralized/decentralized power flow control in islanded microgrids for solved this problem [9]-[11].
In islanded hybrid AC/DC microgrid, the generated power is strongly dependent on weather conditions. This dependency will affect energy balance and may lead to supply disruptions. To deal with these issues, an energy storage system (ESS) is generally added to the microgrid. It is one of the best solution to ensure the reliability and power quality of the hybrid energy systems[12]-[15]. Hence, energy storage systems (ESSs) are required for the care of energy-shortage, grid-fault, and load fluctuations. So, To ensure the balance of stored energy between renewable energy sources and energy storage systems, coordinated control is needed in order to enhance microgrid system stability and reliability [16],[17].
Most applications based on islanded hybrid microgrid are for standalone operations, where the main control target is to balance local loads [18]. This type of system offers then interesting perspectives and advantages for isolated sites [19]-[21].
During the last years, the increasing share of renewable energy sources; integration of more Energy storage systems; inclusion of new technologies like electric vehicles and smart devices; need for energy in remote and more extreme environments, etc., have posed serious challenges especially for energy management of islanded microgrids. Hence, the interest for the improvement of energy management system as the core of islanded microgrids has been considerably increased to facilitate the incorporation of more renewable energy sources into the electricity

Manuscript received March 5, 2022
Manuscript revised March 20, 2022
https://doi.org/10.22937/IJCSNS.2022.22.3.1

system in a safe, reliable, stable, optimal, robust and coordinated way [22]-[24].
Since energy management, control, and operation of a hybrid grid are more complicated than those of an individual AC or DC grid, different operating modes of a hybrid AC/DC grid have been investigated.
To ensure efficient operation of microgrids, it is necessary to develop a supervisory controller to manage the energy flow in a microgrid in order to achieve a balance between power supply and demand [25]-[27].
Therefore, some works are reported in the literature on the problem of energy management in hybrid AC/DC microgrids.
In [18], a coordination control method is proposed to manage the energy flow in a hybrid AC/DC microgrid. In [36], the AC and DC microgrids are treated as two separate entities with individual droop representations, where the information from these two droop characteristics is merged to decide the amount of energy to exchange among the microgrids. In [28] and [29], considers the power flow control and management issues amongst multiple sources dispersed throughout both AC and DC microgrids to determine the amount of power which should be exchanged between the microgrids. In [21] and [30], a droop-based controller is presented to manage energy sharing between the AC and DC microgrids.
The main contributions of this paper, can be summarized as follows:

- In most studies of microgrids, there is a single source of renewable energy. The current work presents the simulation of a microgrid model that includes two renewable energy sources; Photovoltaic (PV) and a wind turbine (WT).
- Developing a supervisory controller for power management system for an islanded hybrid AC/DC microgrid, in order to achieve a robust, efficient and optimal energy flow in the hybrid AC/DC microgrid.
- Meet the demand for AC / DC loads with maximum use of renewable resources using an islanded microgrid.
- In terms of energy management, the Energy management control is first tested through the different modeled components of microgrid which allow to emulate the different states of energy flow of the proposed microgrid.
- Assessment of the proposed system performance in meeting the design requirements and considering the constrains of the battery maximum power.

This paper is organized as follows. Section 2 presents the structure and modeling of proposed microgrid system, section 3 describes the energy management control and the proposed supervisory algorithm, Section 4 illustrates the effectiveness of the proposed technique with simulation results and Finally, Section 5 summarizes the main outcome of this paper.

2. Microgrid Structure and Modeling

The following Fig. 1 shows the considered structure and the conceptual hybrid microgrid system configuration where various renewable energy sources and loads are connected to the DC bus and AC bus. The AC and DC links are connected together through a bidirectional AC/DC converters. A hybrid AC/DC microgrid is modeled using the MATLAB-Simulink to simulate system operations and flows controls. Such as a PV arrays are connected to DC bus through a DC/DC boost converter to supply the DC load and AC load by the AC/DC bidirectional converter . A wind turbine with permanent magnet synchronous generator (PMSG) is connected to DC bus by a AC/DC/DC boost converter to supply the DC load and AC load through the AC/DC bidirectional converter . A battery as energy storage is connected to DC bus through a bidirectional DC/DC converter. DC load and ac load are connected to DC and AC buses respectively.
In this islanded microgrid structure, the battery plays a very important role for both power balance among power energy sources and load demands and voltage stability. Control objectives for various converters are dispatched by energy management system. The main converter is controlled to provide a stable and high quality AC bus voltage. Both PV and WT can operate on maximum power point tracking (MPPT) to provide a stable and high quality of power.

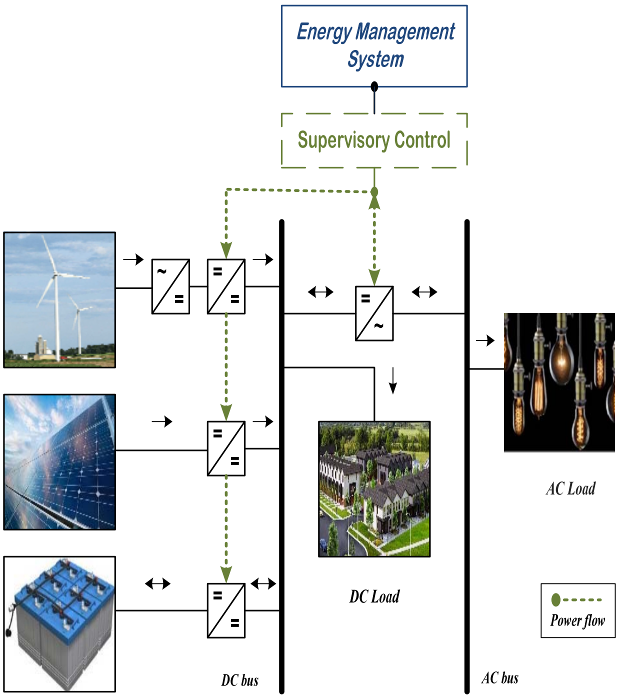

Fig. 1 Structure of hybrid AC/DC microgrid.

2.1 PV Model

Each photovoltaic cell can be modeled by electrical equivalent circuit. Mathematical modeling method is used in this article, the advantage of this method is that we can generate this model only with information and data provided by manufacturer [31]-[33]. Fig.2 shows the typical model for photovoltaic cell. Photovoltaic current, reverse saturation current and saturation current of the solar modules are calculated in order by equations (4), (5), (6):

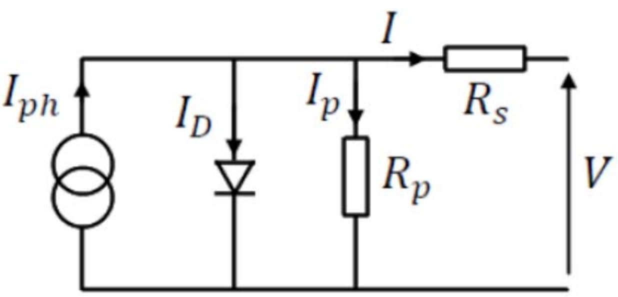

Fig. 2 Photovoltaic cell model

$$I = I_{ph} - I_D - I_p \quad (1)$$

$$I_D = I_0 \left[exp\left(\frac{V+Rs*I}{Vt*\alpha}\right) - 1\right] \quad (2)$$

$$I_p = \frac{V+Rs*I}{Rp} \quad (3)$$

$$I = I_{ph} - I_0 \left[exp\left(\frac{V+Rs*I}{Vt*\alpha}\right) - 1\right] - \frac{V+Rs*I}{Rp} \quad (4)$$

$$I_{ph} = (I_{ph,n} + KI*\Delta T)\frac{G}{Gn} \quad (5)$$

$$I_0 = \frac{Isc,n+KI*\Delta T}{exp\left(\frac{Voc,n+KV*\Delta T}{Vt*\alpha}\right)-1} \quad (6)$$

$$Vt = k \times T/q \quad (7)$$

q: electron charges (1.602 10–19 c)*

K: boltzmann Constant

I: PV output current (A)

I_{ph}*: photocurrent*

Rs: cell Serial Resistance

I_0*: diode reverse saturation current (A)*

Rp: cell parallel resistance

Vt: thermal voltage of the PV

G: solar radiation (W/m2)

Gn: nominal irradiation

2.2 Battery Model

In hybrid systems, the Batteries can be used for two important functions: Storage of generated excess energy and Provision of additional power requested by the load. It's possible to charge or discharge the battery due to its charging state. Control on the battery terminal voltage is workable by adjusting the power output of the photovoltaic power generation system. When the power generated by the renewable energy sources is more than power requested by load, State of Charge (SOC) increases and when power provided by the renewable energy sources power is lower than power requested by load, SOC will be reduced. To protect the battery from damage and to extend the life of battery, the battery has to be prevented from overcharging and over-discharging. SOC_BTmin and SOC_BTmax characterize the minimum and maximum SOC limits for storage operation [33].

For energy conversion, a simple modeling approach has been adopted for the battery. The battery equivalent circuit is illustrated in Fig. 3, where the battery voltage is given by:

$$V_{bat} = E_0 - R_{bat}i - V_{Cbat} \quad (8)$$

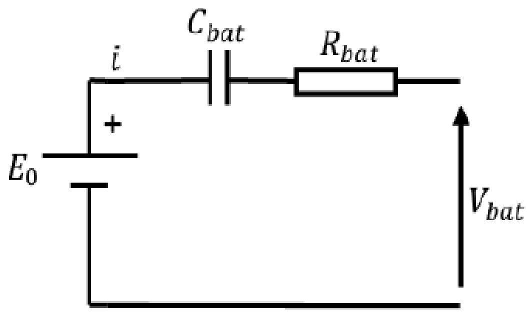

Fig. 3 Battery model

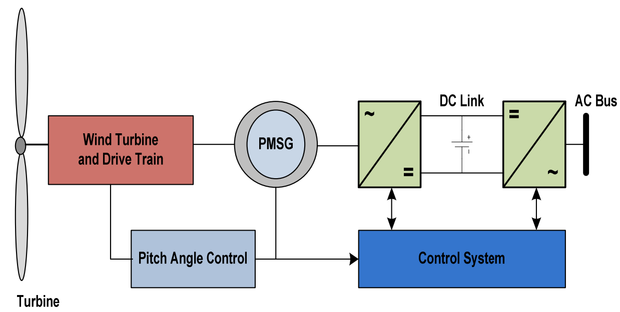

Fig. 4 PMSG based wind energy conversion system

The modeling takes into account the charge and discharge technique of the battery and described in the following equation 9:

$$SOC(t) = SOC_{initial} + \int_0^t \frac{I}{Cbat}\, dt \quad (9)$$

where:

$SOC(t)$: battery state of charge of time t [%]

$SOC_{initial}$: battery initial state of charge of time [%]

I: charge/discharge current [A]

C_{bat}: battery capacity

t: time

2.3 Wind Turbine Model

In this paper, the AC microgrid is based on Wind turbine. Wind energy conversion system (WECS) consists of a wind turbine, pitch angle control, drive train, generator, and power converter. There are many kinds of generators used in WECS such as induction generator (IG), doubly fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG) [33]-[35]. The (PMSG) based variable speed wind turbines are considered feasible technology in wind energy generation system since PMSGs is self-excited, and thus allows operation at high power factor and high efficiency. As seen in Fig.3, the PMSG is connected to the AC bus through an AC–DC–AC back-to-back converter set.
In most instances, generating electricity from wind turbines is a two-stage process. In the first stage, the turbine rotor converts kinetic energy from the wind into mechanical rotational power. In the second stage, a generator converts mechanical power into electrical power. The WECS consists of two main parts are the Mechanical parts and electrical parts.

A. The Mechanical Component Model

The alternative name of the mechanical component model most widely used is a wind turbine rotor-generator drive train model [34]. The mechanical output power of the wind turbine is given by:

$$P_{mech\ Wind} = \frac{1}{2} \rho \pi R^2 C_P (\lambda, \beta) v^3 \quad (10)$$

where:

P mech Wind: the mechanical output power extracted from the wind (W)

C_P : the performance coefficient or the power coefficient

λ: the tip speed ratio between turbine speed and wind speed,

β: the pitch angle of the rotor blades (deg)

ρ: the air density (Kg/m3)

R: the area covered by rotor blades (m2)

v: the wind speed (m/s)

$$\lambda = \frac{w_m\ R}{v} \quad (11)$$

w_m = the rotor speed of wind (rad/s)

T_m : the mechanical torque of wind turbine

The mechanical torque is given by:

$$T_m = \frac{P_{Wind}}{w_m} \quad (12)$$

The performance coefficient C_P is a function of the tip speed ratio λ and the pitch angle of the rotor blades β. The power coefficient is given by.

$$C_P(\lambda,\beta) = \frac{1}{2}\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\left(\frac{21}{\lambda_i}\right)} \quad (13)$$

B. The Electrical Component Model

In this part the PMSG converts the mechanical power from the wind and drive train to AC electrical power, which is then converted to DC power converter connected with DC-link at its DC port. Inverter will convert DC voltage from the DC-link capacitor to AC voltage at fundamental frequency. The stator voltage equations of the PMSG in direct and quadrature axes, V_d and V_q, are given as follows:

$$\frac{d}{dt} I_d = \frac{1}{L_d}V_d - \frac{R}{L_d}I_d + \frac{L_q}{L_d}\, p\, w_r\, I_q \quad (14)$$

$$\frac{d}{dt} I_q = \frac{1}{L_q}V_q - \frac{R}{L_q}I_q + \frac{L_q}{L_d} p\, w_r\, I_d - \frac{\lambda\, p\, w_r}{L_q} \quad (15)$$

where L_d=L_q, and R respectively represent the inductance and, resistance of the PMSG winding, W_r is the angular velocity of the rotor, λ is the amplitude of flux induced, p is the number of pole pairs and I_d,I_q ,V_d,V_q are the direct and quadrature components of the machine currents and voltage respectively. So the electromagnetic torque Te is:

$$T_e = 1.5p[\lambda\, I_q + (L_d - L_q)\, I_d I_q \quad (16)$$

3. Supervisory Algorithm and Energy Management Control

The Modeling of the islanded hybrid AC/DC microgrid system operation under the powerful graphical interface Simulink Matlab described in Section II and it's regulated through the centralized energy management system. As well as a new control algorithm for the hybrid AC/DC microgrid system is proposed to monitoring the microgrid, in order to determine efficient strategies for power flow between renewable energy resources [25]. According to the control algorithm at supervisory, as shown in Fig. 5, the operating mode in the hybrid AC/DC microgrid system is decided by 4 important inputs variables:

- P_{PV}: power supplied by solar photovoltaic system.
- P_{BT}: power available for Battery.
- P_{WT}: power supplied by Wind turbine system.
- $P_{LD:}$ power required by loads which consists of (load AC1, load AC2 and load DC). And their power respectively P_{LAC1}, P_{LAC2} and P_{LDC}, such as P_{LD}= P_{LAC1}+P_{LAC2}+ P_{LDC}.

The invariants are designed and recognized for all situations of the islanded microgrid operation and they're classified into 4 energy flows., as illustrated in Fig.5.

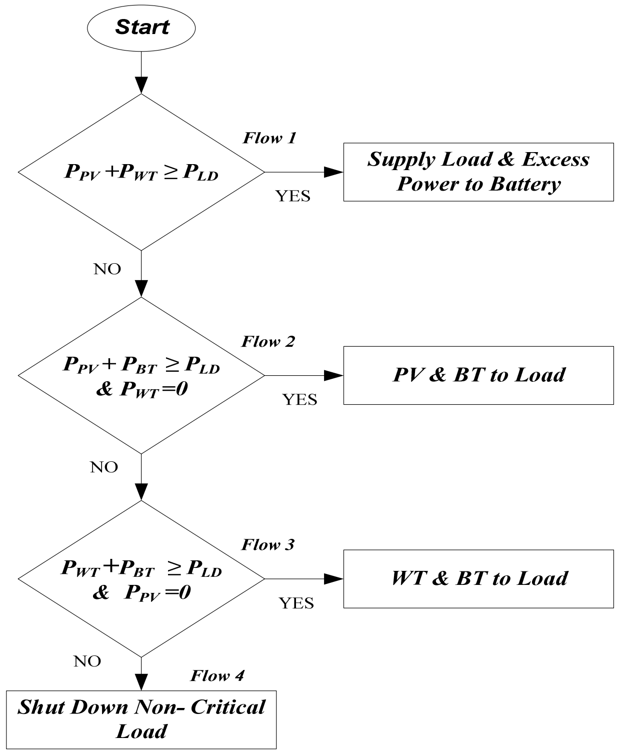

Fig. 5 Flowchart of Supervisory Controller Algorithm.

Flow 1:

P_{PV} +$P_{WT} \geq P_{LD}$: when the load demand is satisfied by the PV and WT. If the renewable energy generated by the PV and WT are equal to the load demand (P_{PV} +P_{WT} = P_{LD}), the PV and WT only supply the load.

If there is excess power generated by the PV and WT apart from consumed by Load, it is also possible to charge the battery. The power generated by the PV and WT can be used to supply the load as well as to charge the battery until their SOC_BTmax is reached.

Flow 2:

P_{PV} + $P_{BT} \geq P_{LD}$ & P_{WT} =0: during unforeseen conditions, such as sunny weather, the power generated from the WT system is inadequate or negligible and the powers generated by the PV and the battery are sufficient to meet the load demand, the battery is discharged until their SOC is greater than SOC_BTmin.

Flow 3:

$P_{WT} + P_{BT} \geq P_{LD}$ & $P_{PV} = 0$: during unexpected conditions, inclusive of cloudy weather, or normal phenomena, inclusive of nighttime, the energy generated by the PV is negligible. The powers generated by the WT and the battery are sufficient to meet the load demand, the battery is discharged until their SOC is greater than SOC_BTmin.

Flow 4:

$P_{PV} + P_{BT} + P_{WT} < P_{LD}$: the final flow of power is supply only critical load based on the priority. This scenario is rarest while all of the energy generated from PV, WT and BT isn't enough to satisfy load. Hence non-critical loads like heating devices, chillers are shut down temporarily to meet the energy demand.

4. Simulation Results and Discussion

In order to validate the proposed design and verify the energy management system, the hybrid AC/DC microgrid system is modeled in MATLAB-Simulink. To perform the tests, the nominal power of the system is considered as P_{WT} = 2.7 kW, P_{PV} = 5 kW, P_{BT}= 5 kW and P_{LD}= 7.7 kW which consists of (P_{LAC1} = 2.6 kW; P_{LAC2} = 2.6 kW and P_{LDC} = 2.5 kW) as shown in Fig.11-13. This study is carried out to observe the operating modes in the islanded microgrid. Simulations are executed to check the controller algorithm of energy management for diverse case studies. The following Fig.6-9 shows different energy flows observed in the hybrid AC/DC microgrid.

Each period of time in the graphs of each power figure of each microgrid component represents a check for invariants for the power flow, which must be satisfied to produce an efficient power management system. The operating mode includes the coordinated charging and discharging conditions of the battery, as shown in the Fig.10, in addition to the energy flow from PV, BT and WT.

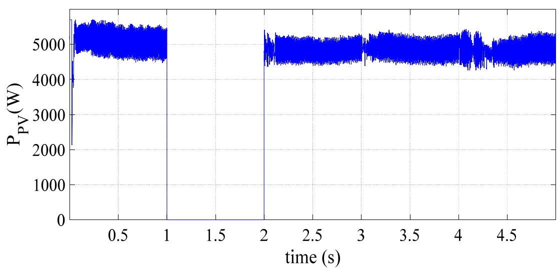

Fig. 6 Power of solar photovoltaic.

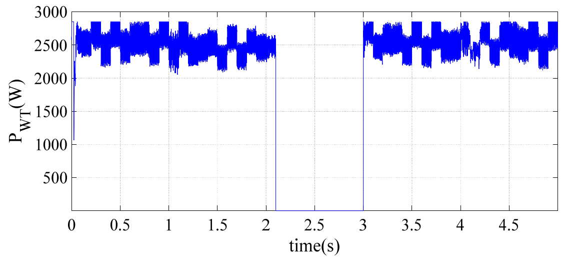

Fig. 7 Active power of WT.

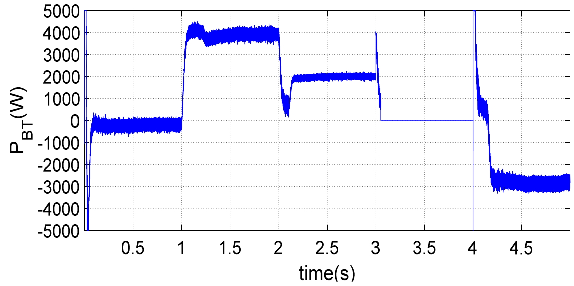

Fig. 8 Power of Battery.

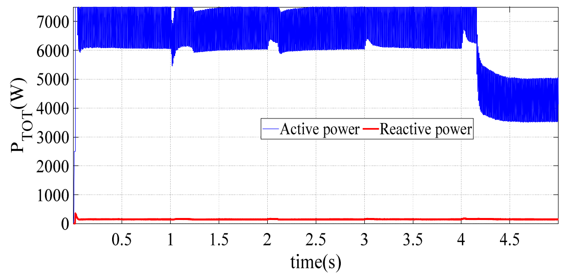

Fig. 9 Active power of AC/DC Loads.

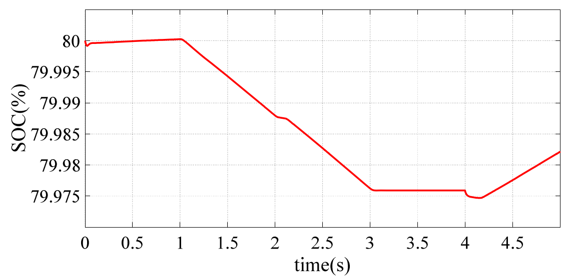

Fig. 10 State of charge (SOC) of the Battery.

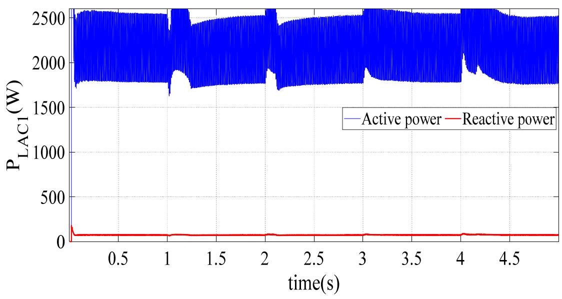

Fig. 11 Active power of load AC1.

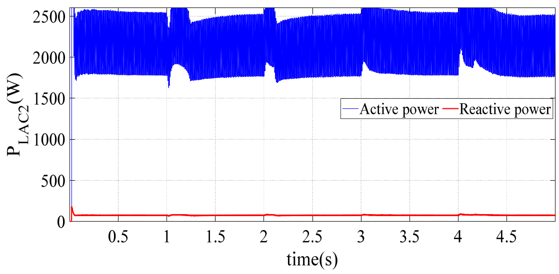

Fig. 12 Active power of load AC2.

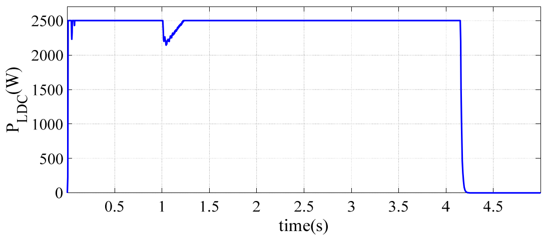

Fig. 13 Active power of load DC.

Power flow from PV +WT to LD + BT: When t = {0-1s}, P_{PV} = 5 kw, P_{WT} = 2.7 kw and P_{LD} = 7.7 kw as shown in Fig. 6-13. The Powers generated from PV and WT are enough to supply load.

At t = {4.2-5s}, when $P_{PV} + P_{WT} > P_{LD}$, the excess power is used to charge the battery as shown in Fig. 10.

Power flow from WT + BT to LD and P_{PV} = 0 : Power flow from P_{WT} and P_{BT} is shown in Fig. 7,8 .

At t = {1-2s} where P_{PV} = 0, P_{WT} = 2.7 kw and P_{LD} = 7.7 kw. The load is oscillating from 7 kw to 7.7 kW to meet the demand. P_{WT}, and P_{BT} are coordinated to achieve power balance between the load and power source. The battery is discharged in parallel to meet the loads demands as shown in Fig.10.

Power flow from PV + BT to LD and P_{WT} = 0 kw : The power flow of PV and BT is shown in Fig. 6,8 .

At = {2.1-3s}, where the P_{WT} = 0 kw, P_{PV} = 5kw and the P_{LD} = 7.7 kw. Same case as P_{PV}= 0 kw, the load is oscillating from 7 kw to 7.7 kw to meet the demand. PV power and battery power are coordinated to achieve a power balance between the load and the power source. The battery is discharged in parallel to meet the load demands, as shown in Fig. 10.

5. Conclusion

In this paper, the supervisory energy management system for an islanded hybrid AC/DC microgrid is validated by designing invariants for all possible power flows between the components in the microgrid system. This is achieved by modeling the dynamics of each component of microgrid, such as PV, WT, BT, LD using MATLAB-Simulink.

The models of components of microgrid are controlled by the proposed supervisory control algorithm. The designed components enable the stable and efficient operation of the hybrid AC/DC microgrid system by training the load effectively. This study allowed us to conclude that the "island hybrid AC / DC microgrid modeling" can be a reliable technique to manage a microgrid design verification based purely on renewable energy resources and validation of supervisory control of energy management system strategy for a Microgrid.

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