Dynamic Energy Balancing and Control Algorithm for 100 kWp PV-Diesel Generator Hybrid Power Plant System

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ABSTRACT

The PV-diesel generator hybrid system with using AC coupling configuration is an application of remote area power system that can be generally defined as an effective electricity production and distribution systems suitable for stand alone power system. The system consists of a combination of PV generators, diesel generators and also includes battery storage. The hybrid system controller with dynamic energy balancing and control algorithm is a supervised controller which is designed for 100 kWp PV-Diesel Generator Hybrid Power Plant System (PVHP) at Kapas Island, Malaysia in this paper can optimize the usage of renewable energy and always balance energy at every instant point of time to avoid energy reversing from excess PV energy. Another advantage of the dynamic energy balancing algorithm is to serve the short term peaking load by using reserved energy from battery bank which results in avoiding the other generator to start-up in order to reduce the diesel fuel consumption that can increase the performance of hybrid system. In addition, this algorithm determines the efficiency of battery charging. Moreover, this algorithm also can control generator not to be operated below a generator's preferable minimum load and frequently started-up and shut-down which can increase the generator life expectancy and generally diminish the maintenance requirement frequency. The dynamic energy balance algorithm is implemented and evaluated for PVHP at Kapas Island, Malaysia which is using GSM modem to allow remotely connecting to access hybrid system controller at Kapas Island, Malaysia for real time monitoring system and retrieving data logging information in order to evaluate the performance of the system.

Key Words: *PV-Diesel Generator Hybrid Power Plant System, Dynamic Energy Balancing Algorithm*

1. INTRODUCTION

The PVHP at Kapas Island, Malaysia uses AC-coupling configuration. All system components operate independently and equitable on AC bus. The designing of PVHP is complex task because of the uncertain PV generated energy supplies, load demands and the non-linear characteristics of some components. Furthermore, the energy of PV combined with diesel generator might excess and reverse back which cause generator to shutdown and then the system will blackout. Thus, in order to guarantee the reliable power supply and increase the performance of PVHP, an intelligent supervisory control is necessary [1, 2, 3].

The hybrid system controller with dynamic energy balancing algorithm is a supervised controller which is designed for PVHP to automatically control the system operation by communicating with grid connected inverter (PV-INV), Bi-directional inverter (BD-INV), load power meter, diesel generator controller and battery monitoring system through RS-485.

2. DYNAMIC ENERGY BALANCING ALGORITLUN

The hybrid system controller with dynamic energy balancing algorithm is used for controlling operation of PVHP and balancing energy between production and consumption to optimize the usage of PV generated energy. The concept how to control PVHP operation with this algorithm is explained as following:

- In case of the PV generated power is more than the load demand, the energy from PV-INV flows to load according to AC coupling principle. This gives the highest efficiency to supply energy from PV to load. The excess energy after supplying to load utilizes to charge the batteries connected to the BD-INV to prevent the generator from starting and operate at lower load than the rated one [1, 4].
- In case of the PV generated power is lower than the load demand and the status of battery charging has reached its lowest allowable point (normally 30%) [5, 6], the diesel generator will be started one by one according to load demand and then BD-INV charges the battery.
- BD-INV either supports the diesel generator (DG) when there is no PV generated power, and if load demand is higher than 80% of DG power selected to run at that time or serve the short term peak load, avoiding the system to start next DG if the peak load is small and occurred in short period in order to reduce the diesel fuel consumption.

3. PVHP CONFIGURATION

The dynamic energy balance algorithm is implemented and evaluated for PVHP at Kapas Island, Malaysia using AC coupling configuration as shown in Fig 1, which consists of the Crystalline silicon (c-Si) PV 100 kWp with 42 strings in parallel of PV array which 14 strings are connected with each PV-INV of 30 kW model GTP501 x 3 units. Another part is constructed with 9 strings in parallel of PV array which 3 strings are connected with each PV-INV 3.5 kW model G-304 x 3 units. There is 60 kW BD-INV model MTP616F with deep cycle lead acid 240 Vdc, 480 kWh batteries. For DG used in this plant are DG 100 kW x 2 units, 150 kW x 1 unit. An independent power backup system for emergency system recovery which can be used to monitor the system continuously consists of a 3.5 kW BD-INV model S-218C with 48 Vdc, 6 kWh batteries, which charged by 3.15 kWp PV through PV-INV 3.5 kW model G-304. This PV array power 3.15 kWp consists of 3 strings of PV array. When battery is charged up to full capacity, then this grid back up system can feed power to the grid depending on available energy as shown in Fig 2.

The communication of PVHP at Kapas Island, Malaysia uses RS-485 interface to connect PV-INV, BD-INV, diesel generator controller and load power meter with hybrid system controller together with energy balancing, control and operation of the system. These system parameters are measured and recorded power of PV generators, DGs, loads and charging and discharging of the battery bank in every 10 milli-seconds.

This system uses GSM modem, which allows remote connection to access hybrid system controller at Kapas Island, Malaysia in order to real time monitoring of system and retrieve logged data information, which is then used for evaluating the output performance of the PVHP.

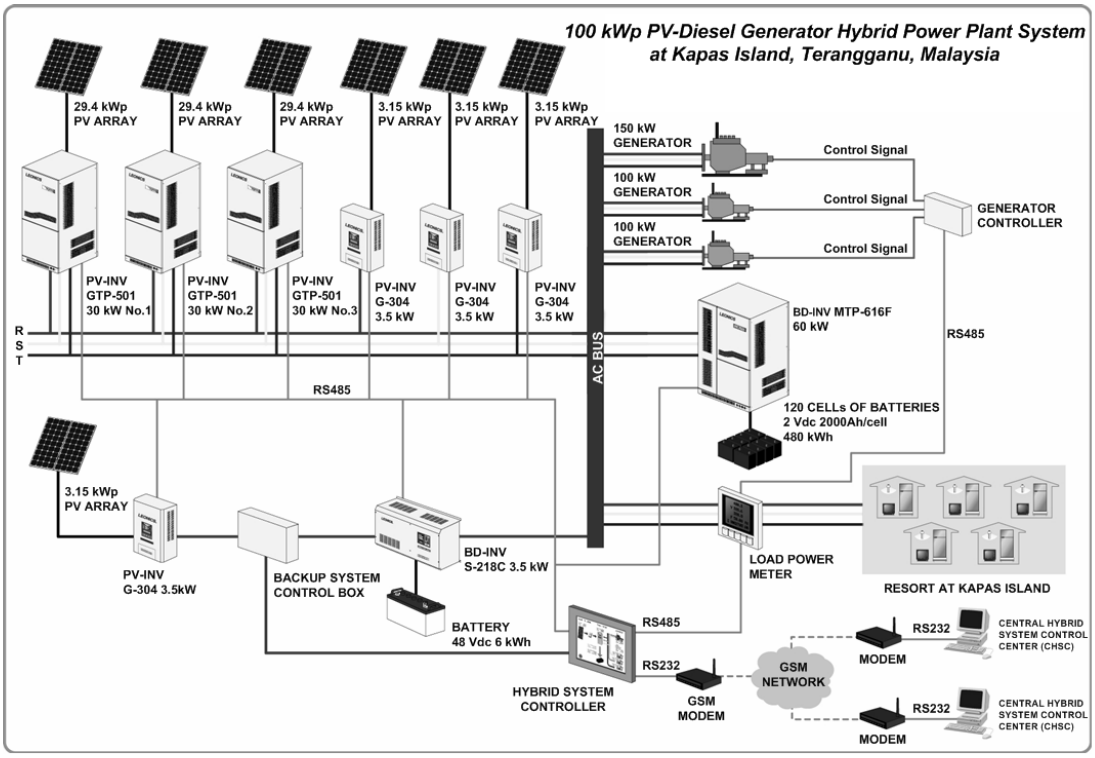

Fig. 1 System diagram of PVHP at Kapas Island, Malaysia.

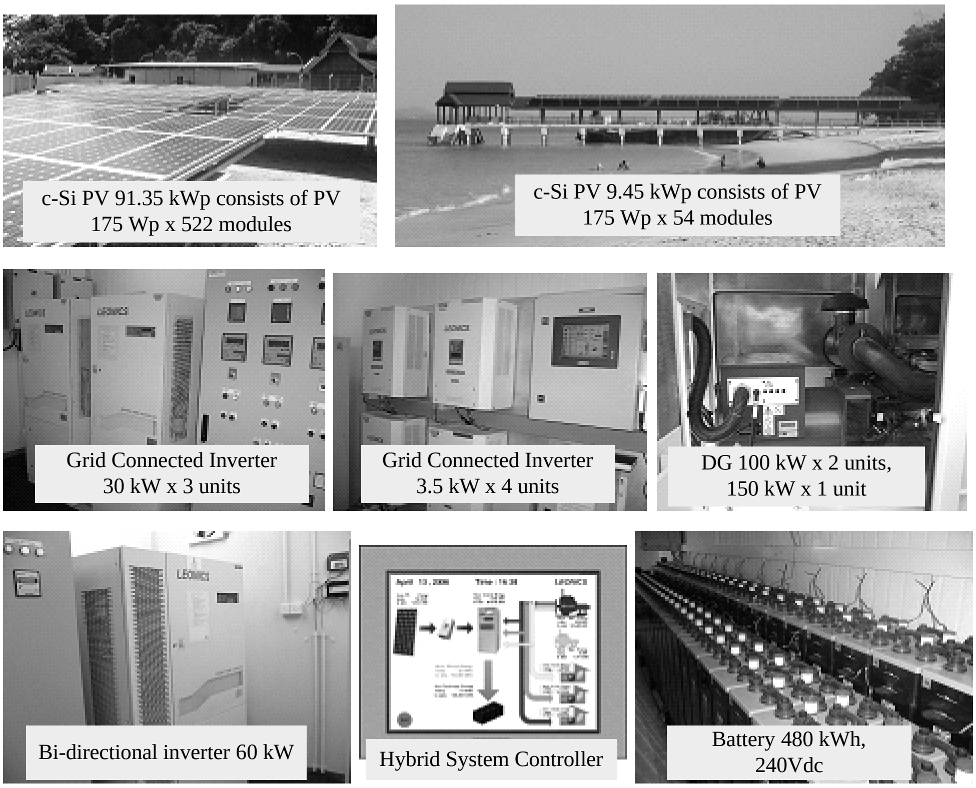

Fig. 2 PVHP component at Kapas Island, Malaysia.

3.1 System Operation

The hybrid system controller is designed to control automatically the operation of the system in each mode (inverter mode, feeding mode or charging mode) by sending command functions to BD-INV after that the system operation is controlled by BD-INV. Moreover, this supervised controller used also handles the excess PV generated power by sending command to PV-INV through RS-485 communication interface to limit power production from PV generator. The system operation can be explained as following:

- At first start of the system, all DGs are started to be the prime power supply of the Kapas grid.
- Hybrid system controller starts monitoring load demand, battery SOC and then sends command to start the BD-INV or DG. In this case, which DG power rating of (100 kW or 150 kW or 100 kW+150 kW or 100 kW +100 kW) is selected to run and is controlled by diesel generator controller according to the load demand and availability of energy sources.
- When BD-INV detects that battery SOC is lower than "Battery SOC" level or load capacity is more than BD-INV power rating (60 kW) and load demand is more than 120% of PV generated power, it will send command to "start DG"
- After DG is already started and run up to normal operation speed, then BD-INV synchronizes its output frequency and voltage with the DG.
- Then all loads are transferred to use power from DG and BD-INV works in charging mode by getting power from DG.
- When the battery SOC rises up to "Full Charge" level, BD-INV stops the charging mode, then DG power is reduced to supply only the total load.
  a. If total load demand is lower than BD-INV power rating (60 kW), then BD-INV sends command to stop DG and take over all load by running in inverter mode.
  b. If total load power consumption is higher than DG capacity to run only one DG, BD-INV feeds power under feeding mode to support loads together with DG.

3.2 Dynamic Energy Balancing Algorithm

The working condition of dynamic energy balancing algorithm for PVHP can be distinguished by BD-INV functions into inverter mode, feeding mode and charging mode.

- **BD-INV runs in inverter mode**

When battery SOC is more than battery SOC 80% [5, 6] and load demand in any phase is lower than 98% rated power of BD-INV in any phase for 10 minutes, then BD-INV changes operation to run in inverter mode in which BD-INV is working as grid forming to supply load, and then hybrid system controller sends command to each PV-INV GTP-501(No1, No2, and No3) in order to set PV power limit (*Plim*). This results in automatic balance of PV generated energy. The *Plim* can be determined as follows:

1. If no PV generated power, battery is discharged power to supply all load power.
The equation of power from battery to supply load power is given by

$$P_{BattDisCharge} = \left(P_{L,PhR} + P_{L,PhS} + P_{L,PhT}\right)$$

Where:

$P_{BattDisCharge}$	=	Power from battery to supply load power, kW
$P_{L,PhR}$	=	Load power phase R, kW
$P_{L,PhS}$	=	Load power phase S, kW
$P_{L,PhT}$	=	Load power phase T, kW

2. If accumulated PV generated power is less than accumulated load demand, PV generated power feeds to load and battery supports load demand.

The equation for power generated by PV array of each PV-INV GTP-501(No1, No2, and No3) is given by

$$P_{pv1} = I_{A1} \; x \, V_{A1}$$

Where:

P_{pv1} = Power generated by PV array which is connected to PV-INV 30 kW GTP-501(No1), kW

I_{A1} = Current generated by the PV array, Amp

V_{A1} = Applied voltage of the PV array, Volt

PV generated power by each PV-INV 30 kW GTP-501(No1, No2, and No3) is given by

$$P_{pv1,ac} = P_{pv1} \; x \; \eta_{PV-INV}$$

Where:

$P_{pv1,ac}$ = PV generated power by PV-INV 30 kW GTP-501(No1), kW

η_{PV-INV} = PV-INV 30 kW efficiency, %

Accumulated PV generated power by all 3 phase PV-INV 30 kW GTP-501(No1, No2, and No3) 3 units are given by

$$P_{pv,ac} = P_{pv1,ac} + P_{pv2,ac} + P_{pv3,ac}$$

Where:

$P_{pv,ac}$ = Accumulated PV generated power by PV-INV 30 kW GTP-501(No1, No2, and No3) 3 units, kW

$P_{pv2,ac}$ = PV generated power by PV-INV 30 kW GTP-501(No2), kW

$P_{pv3,ac}$ = PV generated power by PV-INV 30 kW GTP-501(No3), kW

Plim of each PV-INV 30 kW GTP-501(No1, No2, and No3) to supply load power is given by

$$Plim_{InverterMode} = \frac{P_{pv,ac}}{3}$$

Where:

$Plim_{InverterMode}$ = PV power limit of each grid connected inverter 30 kW GTP-501 (No1, No2, and No3) in inverter mode, kW

Power from battery into the loads for supporting is given by

$$P_{BattDisCh\arg e} = \left(P_{L,PhR} + P_{L,PhS} + P_{L,PhT}\right) - P_{pv,ac}$$

3. If accumulated PV generated power is more than accumulated load demand then excess PV power is used to charge the battery.

The equation for *Plim* of each PV-INV GTP-501(No1, No2, and No3) to supply load power and charge battery is given by

$$Plim_{inverterMode} = \left[\frac{(P_{L,PhR} + P_{L,PhS} + P_{L,PhT}) + (P_{BattPVCharge,Max})}{3} \right] xSF_{Inv}$$

Where:

$P_{BattPVCharge,Max}$ = Maximum PV charging power into battery in inverter mode, kW

SF_{Inv} = Safety factor in inverter mode, %

Excess PV generated power to charge battery is given by

$$P_{ChargeBatt} = (P_{pv,ac}) - (P_{L,PhR} + P_{L,PhS} + P_{L,PhT})$$

Where:

$P_{ChargeBatt}$ = Excess PV generated power to charge battery, kW

4. If accumulated PV generated power is more than accumulated load demand and the battery voltage rises up to fully charge level, BD-INV stops charging the battery.

The equation for *Plim* of each PV-INV 30 kW GTP-501(No1, No2, and No3) to supply load demand is given by

$$Plim_{inverterMode} = \left[\frac{(P_{L,PhR} + P_{L,PhS} + P_{L,PhT})}{3} \right] xSF_{Inv}$$

- **BD-INV runs in feeding mode**

When battery SOC is more than battery SOC 80% [5, 6], load power of all phases is higher than 80% of DG power selected to run at that time and no PV power for 10 minutes, then BD-INV changes operation to run in feeding mode in which DG is working as grid forming. At this time, load is supplied by DG and BD-INV which controlled to feed power by hybrid system controller. This results in automatic balance of energy. The feeding power can be determined as follows:

The equation of feeding power into loads to support and balance load power of BD-INV is given by

$$P_{FeedMode} = \left| (P_{Gen,Max}) - (P_{L,PhR} - P_{L,PhS} - P_{L,PhT}) \right|$$

Where:

$P_{FeedMode}$ = feeding power into loads to support and balance load power, kW

$P_{Gen,Max}$ = DG preferred maximum load to run DG power at high fuel efficiency, kW

- **BD-INV runs in charging mode**

When battery SOC is lower than battery SOC 30% [5, 6] for 5 minutes or load power in any phase is more than 98% of BD-INV capacity per phase for 5 minutes, then BD-INV changes operation to run in charging mode in which DG is working as grid forming to supply load, and then hybrid system controller sends command to each PV-INV 30 kW GTP-501(No1, No2, and No3) in order to set *Plim*. This results in automatic balance of PV energy. The *Plim* can be determined as follows:

1. If no PV generated power and battery power is less than battery SOC 80%, DG supplies power to all loads and charges battery.

The equation for DG supplies power to all loads and charges battery as well to utilize maximum DG output power to run up to high fuel efficiency is given by

$$P_{GenCharge} = P_{GenMax} - \left|\left(P_{L,PhR} + P_{L,PhS} + P_{L,PhT}\right)\right|$$

Where:

$P_{GenCharge}$ = Battery is charged by DG, kW

2. If no PV generated power and battery power rises up to fully battery SOC 80%, DG only supplies power to all loads.

The equation for DG supplying power into loads is given by

$$P_{Gen} = P_{L,PhR} + P_{L,PhS} + P_{L,PhT}$$

Where:

P_{Gen} = DG supplying power into loads, kW

3. If accumulated PV generated power is less than accumulated load demand, PV generated power feeds to load and DG supplies power to support deficit load demand and charge battery as well.

The equation for power generated by PV array of each PV-INV 30kW GTP 501 (No1, No2 and No3) is given by

$$P_{pv1} = I_{A1} \; x \, V_{A1}$$

PV generated power by each PV-INV 30 kW GTP-501(No1, No2, and No3) is given by

$$P_{pv1,ac} = P_{pv1} \; x \, \eta_{PV-INV}$$

Accumulated PV generated power by all 3 phase PV-INV 30 kW GTP-501(No1, No2, and No3) 3 units are given by

$$P_{pv,ac} = P_{pv1,ac} + P_{pv2,ac} + P_{pv3,ac}$$

Plim of each PV-INV 30 kW GTP-501(No1, No2, and No3) to supply load power is given by

$$Plim_{ChargeMode} = \frac{P_{pv,ac}}{3}$$

Where:

$Plim_{ChargeMode}$ = PV power limit of each grid connected inverter 30 kW GTP-501 (No1, No2, and No3) in charging mode, kW

DG supplying power to charge battery is given by

$$P_{GenCharge} = P_{Gen,Max} - \left|\left(P_{L,PhR} + P_{L,PhS} + P_{L,PhT}\right) - \left(P_{pv,ac}\right)\right|$$

4. If accumulated PV generated power is more than accumulated load demand, excess PV power charges the battery then the excess PV generated power is reduced.

The equation for *Plim* of each grid connected inverter 30 kW GTP-501(No1, No2, and No3) to supply load demand and charge the battery is given by

$$Plim_{ChargeMode} = \left[\frac{\left(P_{L,PhR} + P_{L,PhS} + P_{L,PhT}\right) + \left| \dfrac{P_{ChargeBatt}}{\eta_{BI-INV}} \right| - P_{Gen,Min}}{3} \right] xSF_{Charge}$$

Where:

$P_{Gen,Min}$ = DG preferred minimum load, Kw

η_{BI-INV} = BD-INV 30 kW efficiency, %

DG and excess PV generated power supplying power to charge battery is given by

$$P_{ChargeBatt} = P_{Gen,Min} + \left| \left(P_{pv,ac}\right) - \left(P_{L,PhR} + P_{L,PhS} + P_{L,PhT}\right) \right|$$

Where:

$P_{ChargeBatt}$ = Battery power is charged by DG and excess PV power, kW

5. If accumulated PV generated power is more than total load demand and the battery SOC rises up to fully charge level, then BD-INV stops charging the battery.

The equation for *Plim* of each PV-INV 30 kW GTP-501(No1, No2 and No3) to supply load demand is given by

$$Plim_{ChargeMode} = \left[\frac{\left(P_{L,PhR} + P_{L,PhS} + P_{L,PhT}\right) - P_{Gen,Min}}{3} \right] xSF_{Charge}$$

Where:

SF_{Charge} = Safety factor in charging mode, %

4. RESULT

The designed dynamic energy balancing algorithm has been evaluated with 100 kWp PV-Diesel Generator Hybrid Power Plant system (PVHP) at a resort in Kapas Island, Malaysia which has variable load profile depending on tourist season. Power consumption at resort is higher during holidays and tourist season. For weekdays, power consumption is low. Therefore, result measurements are divided according to load demand in order to show efficiencies and performances at each load demand level.

According to collected data for 12 months, consumed power was equal to room occupancy 75%-100% in high season (March-September), while consumed power was equal to room occupancy 25%-50% in low season (October-February) as shown in Fig 3.

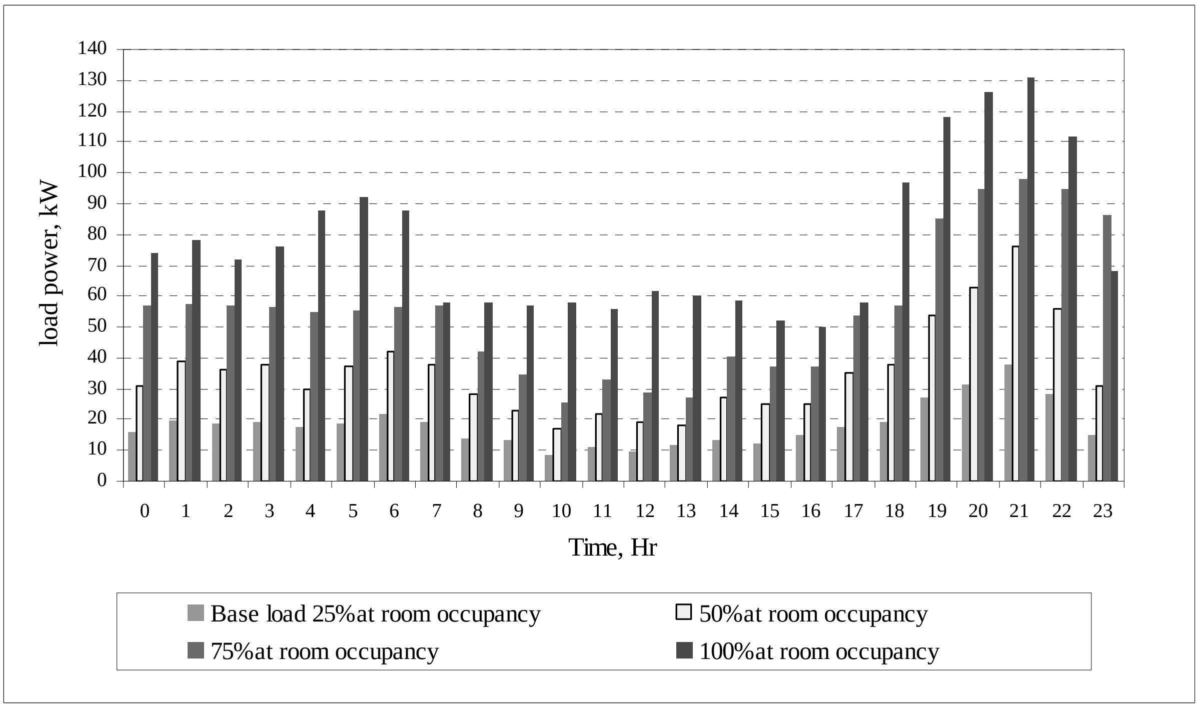

Fig. 3 Daily load profile of Kapas Island Malaysia.

Fig. 3 shows load demand in 24 hours under the various of room occupancy. Each bar chat compares power consumption with room occupancy percentage. During high season, room occupancy is high (75%-100%), while room occupancy is low (25%-50%) in low season.

The different conditions for each load level to make algorithm to work in different modes. The experimental result at 100% room occupancy is shown in Fig 4.

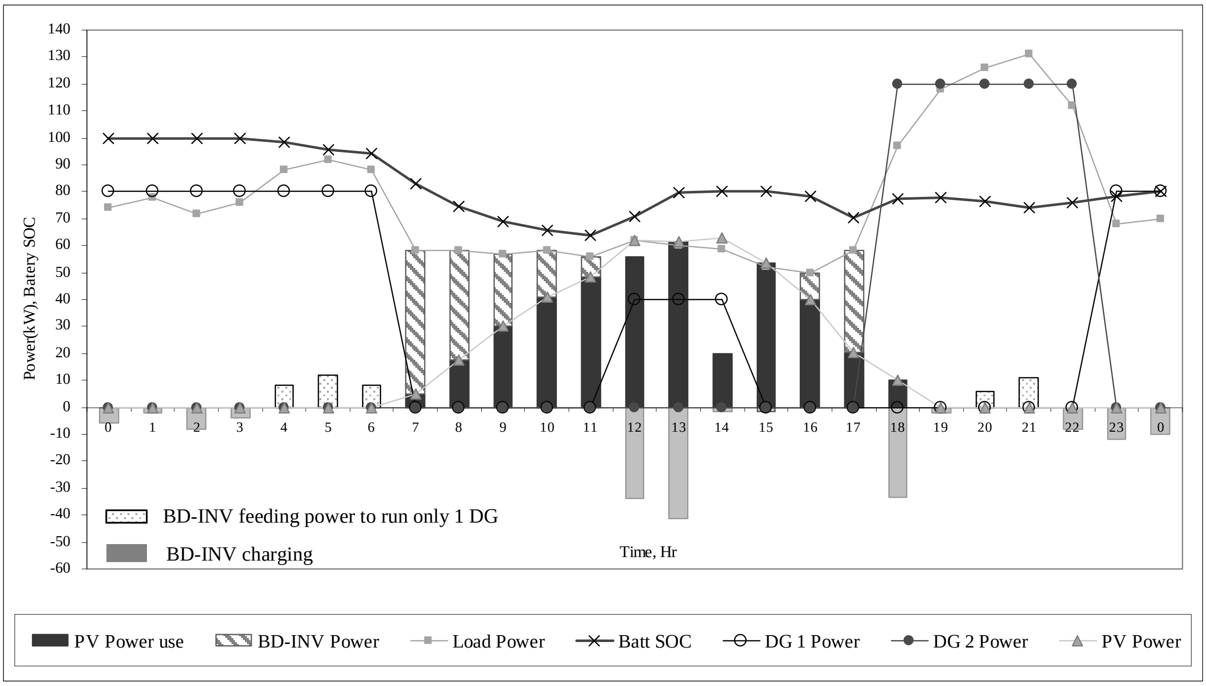

Fig. 4 System operation results in case of 100% room occupancy.

Fig 4 shows the operation of PVHP which has load demand at 100% room occupancy can be explained as follows:

- During day time, PV generated power is not enough for load demand of 100% room occupancy at Kapas Island thus all PV generated power and battery power are used by load and DG has to be started since load demand is higher than BD-INV capacity (60 kW). At the same time, battery power is charged by DG and excess PV generated power until the battery rise up to fully charge level then BD-INV stops charging the battery and DG runs to supply load demand which is equivalent to generator's preferred minimum load and the PV generated power is limited equivalent to support remaining load demand for balancing energy between production and consumption to prevent the PV excess energy reversing back to DG which can cause DG to shutdown and then the PVHP is blackout.
- At the end of the day, battery SOC is much enough for the BD-INV to feed power to keep running only one 150 kW DG.
- In the morning, load demand decreases but still higher than 80% of 100 kW DG, thus one unit of 150 kW or 2 units of 100 kW DG need to be started. However, BD-INV can help supporting load demand to maintain by running only one 100 kW DG.
- The dynamic energy balancing algorithm controls BD-INV to feed power for maintaining load of DG to prevent running 2 DGs between 20:00 to 22:00 and between 04:00 to 07:00. As a result, the PVHP has total diesel cost equal to USD 397.78 per day (base on using diesel cost =1USD/Liter) which can save fuel cost about 5.0%.
- The daily energy produced by PV is 452.45 kWh, the daily PV generated energy used for supplying load and charging battery are 403.52 kWh and daily DG energy for supplying load and charging battery are 1,340 kWh. Daily PV generated energy for supplying load is 98.36% and daily excess PV generated energy for charging battery is 0.66%, then the daily energy produced by PV not in use is 0.98%. Consequently, the dynamic energy balancing algorithm can optimize the usage of PV generated energy.

5. CONCLUSION

The dynamic energy balancing algorithm is successfully implemented for PVHP with using AC coupling configuration at Kapas Island, Malaysia which can continuously provide electricity for 24 hours. The PVHP operation can optimize the usage of PV generated energy and always balance energy at every instant point of time to avoid power reversing from excess PV generated energy. In addition, the PVHP at Kapas Island, Malaysia saves fuel cost because BD-INV feeds power to support loads to keep run only one DG in case there is the short term peaking load or load demand higher than 80% of 100 kW DG which have to start the next DG.

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