An Energy Management Approach for Isolated Power System using Low Load Diesel

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Abstract:

Renewable Energy Sources (RES) are well known sources for providing energy in distant regions. This is the reason that Hybrid Isolated Power System (HIPS) is utilized which integrates solar energy and wind energy. Renewable Energy (RE) relies on the environmental conditions. The technologies such as batteries or Diesel Generator (DG) need to be employed to meet the load demand. Battery Energy Storage System (BESS) can diminish the limitation but this can add expense and intricacy to the system. DG is an excellent choice to meet load demand but it has certain limitations. Due to diesel load set point, excess RE generation is consumed via regulating devices such as dump load or BESS. As a result, systems designed for high RE penetration are now more complex, expensive, and wasteful. This study analyses Low Load Diesel (LLD). It is a method for minimizing surplus generation hence decreasing system intricacy. It also reduces fuel utilization without causing the control architecture to become overly complicated hence reducing the need for BESS. It provides an alternate method for redefining diesel generation's low load capacity. This work provides an economic analysis of LLD including comparisons to traditional BESS applications. This analysis shows low operational cost of the system including LLD than BESS. Hence demonstrating that BESS can be replaced with LLD. The use of LLD also lowers fuel usage. A power system model of HIPS is simulated using MATLAB/Simulink.

Keywords: *renewable energy sources, hybrid isolated power system, diesel generator, battery energy storage system, low load diesel*

1. Introduction

Isolated Power System (IPS) cannot totally depend on widely accepted typical grid system as it is uneconomical across long distances [1]. In order to facilitate these areas with electricity, diesel generators are playing a vital role [2]. Diesel generation has always provided readily available, dependable, and well-supported generating solutions [3]. Unfortunately, it has certain drawbacks, one included is considerable operational costs. Furthermore, diesel fuel may travel long distances which results in financial challenges. Another disadvantage of diesel technology is the release of greenhouse gases [4][5].

Relevant authorities have established objectives supporting the use of *Renewable Energy Sources* (RES) for generation of electricity in distant areas in an effort to minimize energy prices and pollution as they are environmentally safe and cost-effective alternatives to diesel [6]. The two most common RES are wind and photovoltaic (PV),

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however both are stochastic in nature [7][8]. As a result, there is an imbalance between power supply and demand which causes reliability and stability concerns [9][10]. When there is high Renewable Energy (RE) penetration, the diesel generator runs inefficiently while low load conditions, consuming more fuel causing greater damage to the engine. There is a variety of technologies and techniques available to assure system security; however, these techniques currently increase the system's cost and complexity. The objective of any IPS is to employ the smallest number of the techniques capable of balancing generation and power demand, permitting enough diesel capacity to maintain the supply and effectively utilizing existing renewable production to reduce operating expense [11]. Multiple technologies, including as dump load, battery and flywheel, are provided to improve the renewable penetration.

The Energy Storage System (ESS) is one method to enhance flexibility and control in an IPS [12]. Unfortunately, because of the premature battery degradation, using a vast battery-based ESS is now too costly [13]. Flywheel storage technique is often less expensive than Battery Energy Storage Systems (BESS), but it has mechanical restrictions that energy can be exchanged only for a short period of time (seconds) [14]. As a result, flywheel use is restricted, and it is most frequently linked with fast-start diesel engines. Balancing of State Of Charge (SOC) of BESS as a means for maximum use of combined power and energy capacity has been recommended [15][16]. These techniques lower the battery's maximum depth of discharge, therefore extending its lifetime. Dump load technique is used to spill surplus energy. Energy spillage that occurs as a result is irrecoverable, decreasing efficiency of the system and lowering RE use.

Demand Side Management (DSM) is also a viable and practical method for assisting system functioning while also reducing energy consumption [17][18]. It is also utilized in IPS to improve RE output and provides the system more flexibility [19]. But

it is a complex system and requires highly skilled staff.

A further way to increase power quality is to use droop controllers to control wind and solar production in the same way that conventional power stations do [20]. The dynamic droop scheme proposed in [19] retains the benefits of traditional droop control methods while also providing flexibility and effectiveness during fluctuating RES. Maximum Power Point Tracking (MPPT) is a technique used in PV systems to optimize the output power of solar arrays regardless of temperature, irradiance, or electrical characteristics of load [21]. Although these techniques have a beneficial impact on grid qualities but it causes increased RE spilling and reduces the economic productivity.

Many different IPS projects are available to demonstrate an effective control strategy for high acceptance of RE. Different techniques are investigated in three case studies on Australia's King Island, Flinders Island, and Rottnest Island. First technique outlines integration of wind and storage. Flinders Island describes about integrating PV, wind and storage. The third technique outlines a mechanism for integrating PV, wind and without the need of storage. All options allow for significant RE penetration, with each island receiving the bulk of its energy from RE sources. The first technique demonstrates King Island being one of the high RE penetration IPS. The second technique considers the advantages of RE diversity. The third technique focuses at how Low Load Diesel (LLD) and DSM technologies may be used to rationalize energy storage. The third approach observed a 32% cut in capital costs, establishing the economic reasons for the approach by suspending integration of the energy storage [19].

Diesel technology should not be entirely eliminated in isolated communities. Diesel fuel efficiency may be enhanced without compromising power quality or stability by aiming to reduce the amount of energy produced by the fuel. Using LLD methods,

this technique may be maximized. LLD methods minimizes the reliance on fossil fuels in the system, resulting in greater adoption of RE and reduced power costs.

From the above literature it is observed that ESS is one solution to enhance system efficiency, however it is costly. Diesel Generator (DG) is an excellent choice but still there is a need to manage fuel consumption. The main objectives of this paper are to minimize operational cost and use of fossil fuel of the system and to accept high RE.

The following is the structure of this paper; Section 2 describes the modelling of the system. Model verification with different control techniques is discussed in Section 3. Results and discussions are presented in Section 4. Section 5 is concluding the paper.

2. Modelling of the System

Solar energy system comprises PV array, DC-DC boost converter, an MPPT controller and DC-AC converter as displayed in Fig. 1. In solar system the MPPT technique maintains the PV voltage close to MPP voltage. The MPPT technique either operates in on mode or off mode, it depends on the SoC of BESS. V_{PV} is the voltage from photovoltaic array while V_{DC} is the voltage from DC-DC converter.
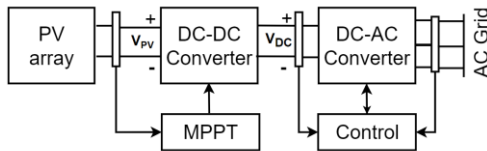

Fig. 1. Solar Energy System

Wind energy system contains wind turbine, Doubly Fed Induction Generator (DFIG), AC to DC converter, a power converter and a DC to AC converter as displayed in the Fig. 2. In Fig. 2, w_m is the rotor speed whereas θ is the pitch angle of the turbine blade.

The wind turbine's received power can be defined by the following formula [22].

$$P = \frac{1}{2} \rho A V_w^3 \, C_{pow}(\lambda, \theta) \tag{1}$$

Where P is the mechanical power of the turbine, ρ is the density of the air which is approximately $1.225 kg/m^3$, A is the swept area of turbine blade, V_w^3 is the wind speed and C_{pow} is the coefficient of turbine power. C_{pow} depends on λ – tip speed ratio and θ – turbine blade pitch angle. The pitch control serves to alter the power captured by adjusting the angle of attack of the blades by rotating them in their longitudinal axis.

DFIG makes use of a variable-speed wind turbine. The minimal maintenance and operational costs of a DFIG makes it a good choice. Wind speed affects the generator output. A power converter is used to raise the voltage level.
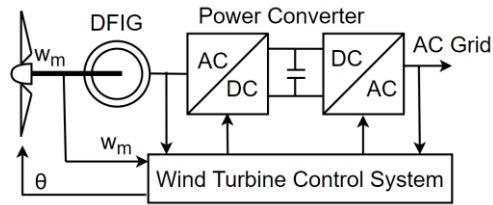

Fig. 2. Wind Energy System

The BESS comprises lead-acid battery and a bidirectional DC-DC buck boost converter which is in charge of maintaining the DC bus voltage using a controller as displayed in Fig. 3. The battery has two modes of operation: charging and discharging. It depends upon power produced by RES. The bidirectional converter couples RES and BESS. By means of a bidirectional converter, power may flow in both ways, from load to BESS and vice versa. When the available RES are enough to generate the desired power for load, power flows from RES to BESS and BESS charges. The bidirectional converter will be operating in buck mode. When the supplies of RES are insufficient to fulfill the load demand, power flows from BESS to load and BESS discharges. At this moment, the bidirectional converter is operating in boost mode. The battery runs in these two modes as well, dependent on the energy limitations specified by the SOC limits [23].

$$SoC_{max} \geq SoC \geq SoC_{min} \qquad (2)$$

The allowable limit of SoC of battery is described in (2).

SoC_{max} shows the battery's maximum permitted SoC. It denotes the maximum charge level or threshold over which the battery is not recommended to be charged anymore. Excessive charging can result in overcharging, that can lower battery lifespan, or even cause safety issues. SoC_{min} indicates the battery's lowest allowable SoC. It is the lower limit or threshold under which the battery is prohibited from being discharged significantly. SoC indicates the battery's current SoC. It represents the real amount of energy stored in the battery at any particular time.
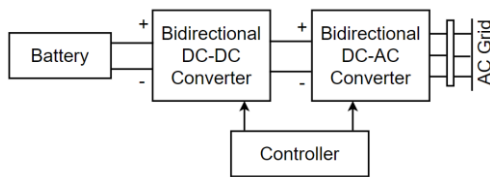
Fig. 3. Battery Energy Storage System

During periods of excess RE absorption, a diesel engine operates at low load in Hybrid Isolated Power System (HIPS). At certain situations, the operator has two options: keep a constant diesel output while spilling extra RE, or reduce diesel output while absorbing more RE [24]. LLD technology is the capability to run diesel generator below conventional load limits in order to accept greater RE input. By eliminating the engine's low load constraint of ~30-40% of rated capacity, LLD permits the engine's full capability to be used. The lesser the diesel output, the more load may be shifted to RE sources. LLD does not require any new hardware, as it uses current diesel components and does not require any changes to the mechanical or electronic design. As a result, the LLD has a model that is identical to a conventional diesel engine [22]. It only differs in terms of engine characteristics that have to be adjusted, particularly by reducing temperature and pressure of cylinder. It is the effect of a complex combination of lower combustion efficiency, decreased ring orientation between the cylinder and the piston, lower turbo spool velocity as well as significantly lower air charge boost pressures. All of this leads to low engine efficiency when the load is lower. LLD technology can be simulated by modifying engine specific delay (τ_1). Utilizing the Watson method to forecast τ_1, the value must be 0.3-0.5ms greater for LLD as compared to conventional generators [24].
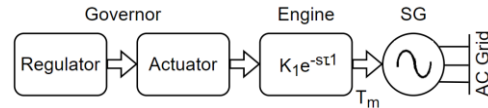
Fig. 4. Conventional Diesel Engine

The dump load is a regulated resistive load. It is used to convert electricity into heat depending on the governor actuator signal as shown in Fig. 4. T_m is the mechanical torque whereas diesel engine is denoted by K_1 which is the steady state gain and is multiplied by $e^{-s\tau 1}$. Dump load facilitates the integration of RE and increases security of the system.

There are three different dispatchable factors which are taken into consideration for the HIPS scenario: LLD, BESS, and the dump load. In this case, operational costs are calculated according to the following formulas [22].

$$C_{LLD} = a_{LLD} + b_{LLD}\,P_{LLD} + c_{LLD}\,P_{LLD}^2 \qquad (3)$$

$$C_{BESS} = a_{BESS} + b_{BESS}(P_{BESS} + 3P_{BESS.max}(1-SOC)) + c_{BESS}(P_{BESS} + 3P_{BESS.max}(1-SOC))^2 \qquad (4)$$

$$C_{dl} = r_{ele}\,P_{dl} \qquad (5)$$

where C_{LLD}, C_{BESS} and C_{dl} are the cost functions for LLD, BESS and dump load respectively.

P_{LLD}, P_{BESS} and P_{dl} represents the power levels for LLD, BESS and dump load respectively. The maximum power level for BESS is represented by $P_{BESS.max}$.

SOC indicates the state of charge of storage system.

The utility's rate for electricity is referred to as r_{ele}.

a_{LLD}, b_{LLD} and c_{LLD} are cost coefficients for LLD while a_{BESS}, b_{BESS} and c_{BESS} are cost coefficients for BESS. Their values are given in TABLE I.

TABLE I. Cost Coefficients

Sources	a	b	c
LLD	30	$4e^{-8}$	$6e^{-11}$
BESS	20	$5e^{-5}$	$8e^{-11}$

3. Model Verification

The suggested HIPS consists of average load of 2 MW and contains LLD, solar arrays, wind turbines, BESS and dump load. MATLAB is used to model the suggested HIPS structure, and several situations were observed.

3.1. Control Technique including BESS

The first case illustrates the control strategy by modelling HIPS containing solar energy, wind energy, BESS and dump load. The framework design and energy stream for the proposed solar, wind framework with BESS is displayed in Fig. 5. The metrics for HIPS including BESS are given in TABLE II.
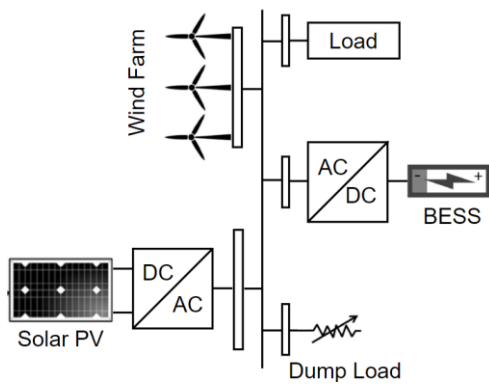

Fig. 5. Hybrid Isolated Power System including BESS

TABLE II.   Metrics of Hybrid Isolated Power System including BESS

Peak Load (MW)	2
Average Load (MW)	1.5
Solar PV Capacity (MW)	2.3
Wind Capacity (MW)	1.3
BESS Capacity (MW)	1.5
Dump Load Capacity (MW)	1.5

The framework can be simply controlled as there is just a single dispatchable power source which is the BESS. When the net load which is the difference between the actual load and the RE output is negative, implying that power provided by the RE is adequate to serve the load, the abundance energy is then used to charge the BESS and any further excesses are dumped. Whenever the net load is positive, the BESS discharges energy to fulfill the load. The operating plan of this sort of framework is displayed in Fig. 6.
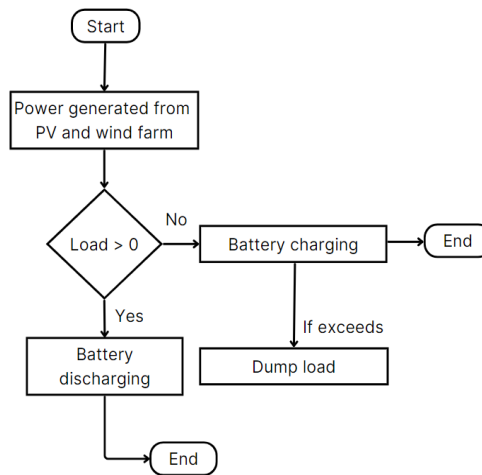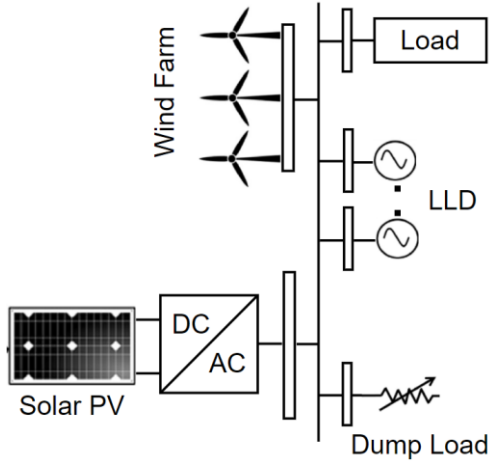

Fig. 6. Hybrid Isolated Power System including BESS dispatch algorithm

3.2. Control Technique including LLD

The second case illustrates the control strategy by modelling HIPS containing solar energy, wind energy, LLD and dump load as shown in Fig. 7. The metrics for HIPS including LLD are given in TABLE III.
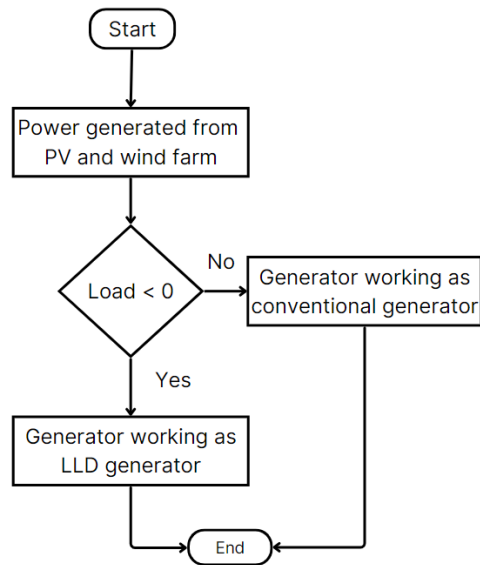
Fig. 7. Hybrid Isolated Power System including LLD

TABLE III.   Metrics of Hybrid Isolated Power System including LLD

Peak Load (MW)	2
Average Load (MW)	1.5
Solar PV Capacity (MW)	2.3
Wind Capacity (MW)	1.3
Diesel Capacity (MW)	2
Dump Load Capacity (MW)	1.5

Generally, diesel engine companies defined a minimum typical working load for their engines, often 30% of rated capacity [25]. As a result, load thresholds limit the maximum RE contribution within an IPS. Unlike these conventional diesel generators, LLD are able to operate under 30% threshold load for longer amount of time. LLD will dump energy peaks and respond fast at all times, by low loading the engines a very high amount of RE penetration can be achieved. The dump load controls the power balance during periods of surplus energy and assist LLD during fast load variations. A magnetic clutch is fitted between the diesel engine and alternator. The pre-heater system maintains an optimal temperature of the engine during low load operation. The cooling fan is operated separately from the engine. The pre-pressure system ensures pressure in the combustion air receiver during low load operation.

When RE is not available LLD provides power like any conventional diesel generator. RE is now increasing, the LLD decreasing load and controls voltage, frequency and power balance. When the LLD drives under the 30% load threshold, the pre-pressure and the pre-heater system becomes active. This is the beginning of low load operation. RE continues to increase and load on LLD continues to decrease controlling voltage, frequency and power balance. When there is excess of RE penetration, it starts to deviate frequency. To control frequency, surplus RE is dumped. When the dumped amount of RE becomes stable, the engine cutches out and stops. The spinning alternator does not stop and connected to the bus bar it always provides reactive power. When RE is decreasing, the diesel engine starts, it starts fast as it is already warmed, pre-pressurized and is disconnected from the alternator. It then clutches in to add load. This adaptation takes only a few seconds. LLD operates in high fuel savings in a smooth operation and without the use of BESS. The operating plan of HIPS including LLD is displayed in Fig. 8.

Fig. 8. Hybrid Isolated Power System including LLD dispatch algorithm

4. Results and Discussions

To validate the efficacy of proposed LLD, two cases are simulated in MATLAB. One is HIPS including BESS, the other is HIPS including LLD and their metrics are given in TABLE II and TABLE III respectively. In (Fig. 9), non- dispatchable variables which are solar power, wind power and power demand are displayed. These variables are same in both the control techniques.

4.1. HIPS including BESS

The battery runs in discharging mode from 18:00 to 05:00, supplying power and meeting electricity demand along wind energy. The technique makes use of the battery's stored energy as well as the steady availability of wind power during the night. As a result, the battery drains its stored energy while the wind turbines continue to generate electricity, delivering a constant and consistent power supply during this time.

The scenario shifts from 05:00 until 18:00. Solar energy and wind energy are principally in charge of meeting electricity demand during these daytime hours. The PV panels capture and convert sunlight into energy, while the wind turbines continue producing power. These RES work together to supply the energy demands.

During this period, the battery changes to charging mode. The excess power generated by the PV panels and wind turbines above the present need is stored in the battery for use later on. Surplus energy may be stored and used during periods of higher demand or lower RE generation by charging the battery during the daytime when the generation of electricity is normally higher.

The process of discharging the battery and using wind energy at night, and charging the battery while using solar and wind energy during the day, results in an effective power supply system. It optimizes energy storage, maximizes the utilization of RES, and assures an uninterrupted supply of electricity throughout the day, efficiently balancing energy output and demand.

4.2. HIPS including LLD

The simulation results of control technique including LLD are shown in (Fig. 11). LLD is aiming to minimize the operational cost. It offers considerable economic advantages to HIPS by offering extra 30% of engine capacity in favor of lowering operational expenses. More RE penetration is the indirect result of this strategy.

There is a considerable penetration of RE in the system between 06:00 and 17:00. As a result, the LLD generator runs at low load. When the RE penetration exceeds the power demand, the excess power is routed to a dump load. This controlled disposal of surplus power assists to ensure system stability, preventing possible instabilities caused by an excess of energy. The system enables stable and balanced operation during periods of high RE penetration by properly managing extra power via the dump load.

From 17:00 to 05:00, both wind energy and the LLD generator work together to deliver electricity to fulfil demand. During this period, wind energy provides a large share of power generation, while the LLD generator complements the supply as needed. This cooperative operation assures a constant and stable energy supply throughout the night by using available wind resources and optimizing the utilization of the LLD generator.

Overall, using LLD in the HIPS system reduces costs, stimulates increased RE penetration, and keeps the system stable. The system maximizes the benefits of RES while assuring a dependable and cost-effective operation by effectively managing power generation and utilization.

By using (3)(4) the operational costs of BESS and LLD are analyzed for over 24 hours and the results are given in TABLE IV.

TABLE IV.   Comparison of control
techniques over one day

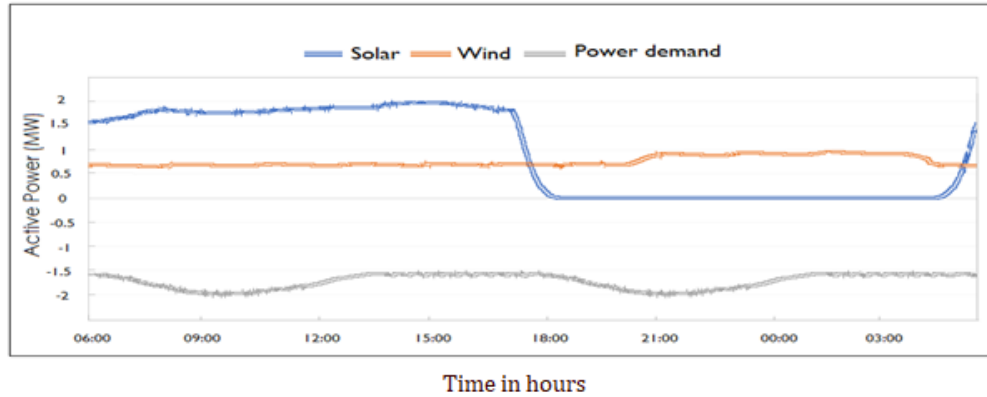| System	Operational cost in $/MWh
including BESS	485.88
including LLD	330

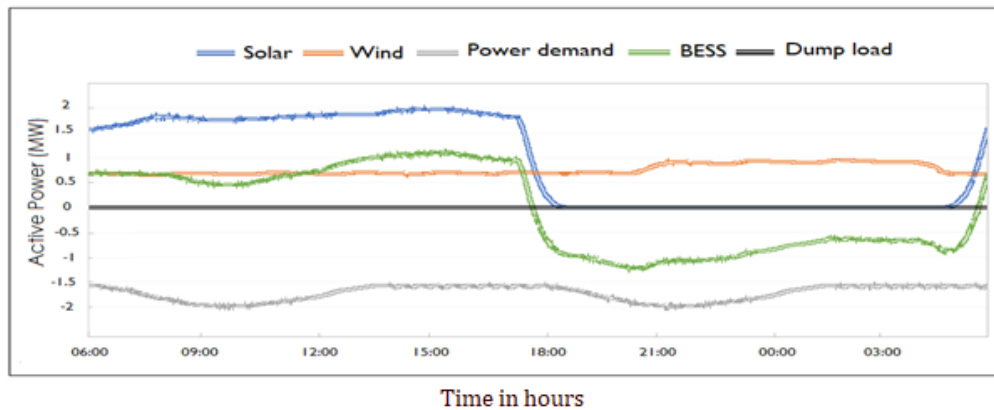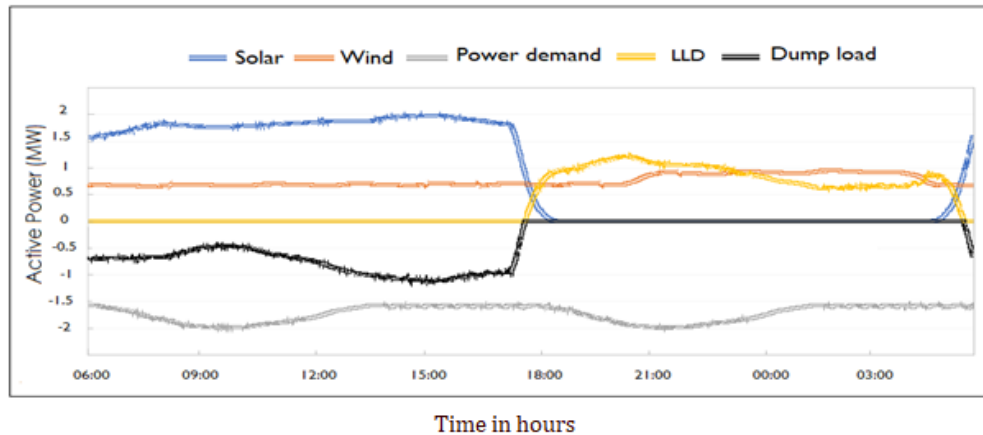**Fig. 9.** Non-dispatchable variables

Fig. 10. Hybrid Isolated Power System including BESS

Fig. 11. Hybrid Isolated Power System including LLD

5. Conclusion

An energy management approach for IPS is discussed in this paper. Two cases are modelled using MATLAB. First case comprises solar arrays, wind turbines, dump load and BESS. In this case, it is demonstrated that high RE can be captured by utilizing BESS but unfortunately it has high operational cost which has been measured to be 485.88 $/MWh. The second case includes solar arrays, wind turbines, dump load and LLD. It is demonstrated that BESS can be replaced with LLD because of its low operational cost recorded 330$/MWh. The development of IPS is costly by following conventional system designs as it causes high operational costs. The use of LLD lowers fuel usage while eliminating the necessity for BESS inside the system. LLD is distinct between many existing technologies because it may serve both low and high RE penetration IPS without adding to the expense, complexities, or threat to system stability.

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