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OFF-GRID SYSTEMS' ECONOMICAL SUITABILITY FOR RENEWABLE ENERGY

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ABSTRACT

A comprehensive approach to addressing the energy needs of remote areas and islands by transitioning from traditional diesel generators to a more sustainable and costefficient power supply system centered around renewable energy sources The proposal acknowledges the limitations and challenges associated with traditional diesel generators, including high-fuel costs, transportation difficulties, and operational inefficiencies at partial loads. It also mentions the environmental and logistical drawbacks of relying on fossil fuels.

The project proposes an efficient strategy for high renewable energy penetration in isolated power systems, optimizing resource utilization, and ensuring reliable power supply. This strategy emphasizes the long-term benefits of transitioning to renewable energy sources, such as reduced carbon emissions, increased energy independence, and reduced vulnerability to fuel price fluctuations. It also emphasizes mitigating environmental concerns and enhancing sustainability. Intermittency in electricity generation sources can pose challenges to grid stability and reliability, requiring the integration of advanced technologies like smart grids and demand response systems.

The project plan includes the integration of multiple components, such as solar operation units, wind energy systems, batteries for energy storage, and low-load diesel generation for improving system stability. The loading technique applied to renewable energy systems can attain stability and viability similar to conventional power plants. Wind turbines can provide frequency response using speed and pitch controllers, enabling the system to operate more effectively while overcoming obstacles to renewable energy penetration. These components work together to optimize system

performance and stability. The project intends to use MATLAB/Simulink for simulation and analysis to evaluate the performance of the proposed strategy. Simulation allows for testing different scenarios and fine-tuning the system design before implementation.

1. INTRODUCTION

Energy is a fundamental requirement of modern life. High purchase and transportation costs of diesel fuel pose economic challenges for isolated communities, prompting the exploration of alternative, efficient, and reliable power supply options. Transitioning from traditional diesel generators to a sustainable, cost-efficient power supply system based on renewable energy sources is being implemented to meet the energy needs of remote areas and islands.

While renewable energy sources offer cost reduction opportunities, their high penetration is hindered by the need for expensive enabling technologies like energy storage. The stochastic and intermittent nature of renewable sources, such as wind and solar, adds complexity to control systems, diminishing power system reliability.

This project recommends a fuel-efficient control strategy, involving low-load diesel application. The goal is to reduce fuel consumption, enhance renewable energy penetration, and improve overall efficiency without overly complicating the control architecture.

Isolated power systems (IPSs) are conventionally dependent on diesel generation, which, despite low installation costs, reliability, and operational simplicity, incur significant operational costs. The emission of greenhouse gases is another discouraging factor of diesel technology.

The most abundant RESs in such areas, wind, and solar, are stochastic and intermittent. Thus, instantaneous power supplied by RESs rarely matches the power demand.

To improve system stability, wind and solar generation units should be operated similarly to conventional power plants i.e., using droop controllers, and de-loading techniques for wind turbines. All these approaches increase the spillage of renewable energy, complicate the control architecture, and penalize economic efficiency.

Energy storage system (ESS) services are one solution to a high share of energy sources in HIPS. Despite being proven to be cost-efficient, this technique requires interconnected communication networks and sophisticated control strategies, which increases the complexity of control systems and demands highly qualified personnel.

To create a Hybrid Isolated Power System (HIPS) with solar and wind as renewable energy sources and Low Load Diesel (LLD) generators as conventional energy. To reduce fuel consumption, enhance renewable energy penetration, and improve overall efficiency without overly complicating the control architecture.

2. LITERATURE SURVEY

An overall survey has been done on the topic and emerged with the following good literature survey useful for our problem formulation. Remote communities often lack affordable electricity due to geographical separation and size. Renewable energy sources like wind and solar are being promoted, and energy storage systems can help reduce costs and pollution[1-7].

Power quality can be enhanced using batteries, supercapacitors, and superconducting magnetic energy storage (SMES). Flywheels can increase system inertia in high renewable penetration power grids, while batteries can emulate inertia response. Despite decreasing storage technology costs, significant installation investments remain[8-12].

Demand side management is a cost-efficient method used in IPSs to maximize renewable energy generation and provide flexibility. However, it requires complex control strategies and highly qualified personnel. Another approach is to operate wind and solar generation units similarly to conventional power plants using droop controllers. De-loading techniques for wind turbines and PV units can provide frequency response using speed and pitch controllers, and maximum power point tracking for PV units[13-16].

Wind turbines can mimic inertial response, but this can increase renewable energy spillage and complicate control architecture. Despite global inexperience, Australian IPS projects have shown successful technology and control approaches, such as King Island IPS (Australia) and Flinster Island IPS (Australia). King Island achieved high renewable energy penetration (> 60% p.a.) with multiple ESSs, while Flinders Island achieved significant reductions in battery capacity and installation costs. Rottnest Island achieved greater than 50% renewable energy penetration without the ESS. Control strategies with different objectives result in different IPS compositions, element sizing, and operation procedures. State of the charge balancing of distributed battery ESS has been proposed to maximize energy utilization and reduce battery lifetime. However, some approaches may increase renewable energy spillage[17-22].

Wind and solar energy can improve economic and environmental performance but can cause reliability and stability issues. Utilizing an Energy Storage System (ESS) is a state-of-the-art approach for high renewable generation in High-Intensity Power Plants (HIPSs). Combining different types of energy storage, such as access-oriented and capacity-oriented storage, requires significant capital investments and complex control schemes. Ancillary services can improve system reliability and economic efficiency, depending on the HIPS technologies used. The three-level control hierarchy is used to implement control actions in the power system, including primary, secondary, and tertiary control[23-27].

3. PROPOSED SYSTEM

3.1 BLOCK DIAGRAM OF HYBRID ISOLATED POWER SYSTEM

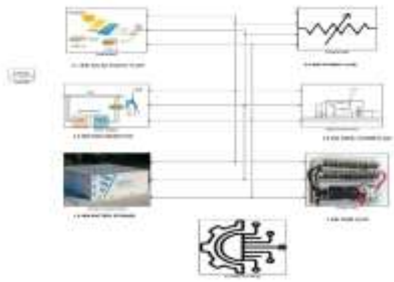

Fig 3.1 block diagram of Hybrid Isolated Power System

The block diagram shows the systems used in the project with the ratings of the individual systems. The hybrid isolated power system is the designed by utilizing all available solar and wind power, the hybrid isolated power system seeks to lessen reliance on diesel fuel and, as a result, lower energy consumption prices.as the solar plant capacity of 0.1MW,wind farm of 4.8MW ,Diesel plant of 3.8MW,Energy storage system 1.6MW based on case studies capacity of storage system would vary and the dump load of bearable capacity of 1MW.Enabling technologies like MPPT, VSC controllers ,converter etc were used to ensure the reliability in the system as given an output of 25KV to the grid .Within the IPS, the yearly average penetration rate of renewable energy surpasses 60%. When the wind farm and resistive load are combined, the security margin is increased and quick frequency management is offered. However, the dump load's power consumption is wasted as waste heat, which lowers cost efficiency. MATLAB was used to model the suggested HIPS arrangement, which was the verified by measurements taken over a day. To validate the model, taking into account both low and high RE penetrations.

3.2 ALGORITHM FOR HYBRID ISOLATED POWER SYSTEM

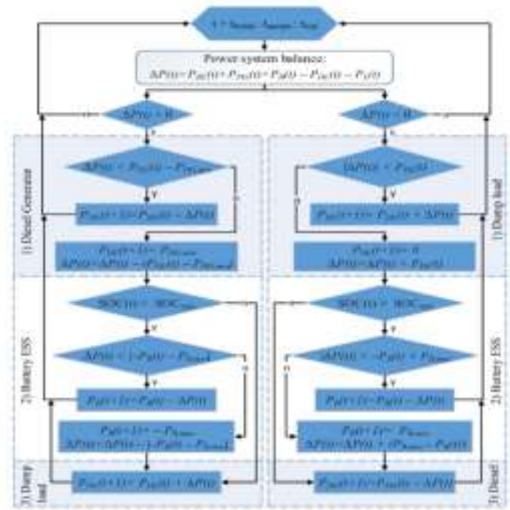

Fig 4.2 Algorithm for Hybrid isolated Power System

The economic dispatch objective function is expressed as follows:

$$\min\,[Fg\,(PG) + Fb\,(PB) + FDL(PDL)],$$

subject to:

$$PRE + PG + PB - PDL - PL = 0$$

$$PGmin \le PG \le PGmax$$

$$PB, min \le PB \le PB, max$$

$$0 \le PDL \le PDL, max$$

where PRE is the power provided by RES, PL is the system load; PG, min and PG, max are lower and upper limits of the diesel generator output, PB, min and PB, max are lower and upper limits of the BESS output (if SOC ≤ SOCmin then PB, min = 0 and if SOC ≥ SOCmax then PB, max= 0), PDL, max is an upper limit of a dynamic dump load. Priority dispatch allocates generationaccording to the priority associated with each energy source determined by the system objective. For example, to achieve maximum renewable energy generation within IPS the priority may be assigned as shown in Figure 6 according to the system imbalance between generation and load:

- P =P RE + PG + PB - PDL - P L

i) If $\Delta P > 0$: available generation exceeds the IPS load. The following dispatch priority is used: diesel generator, battery ESS, and dump load.

1. The diesel generator decreases its output until it reaches its low load limit (PG ≥ Pb, min).

2. If (PG = Pb, min): Battery is charged until it reaches its operational or SOC limits.

3. If (PG = Pb, min) and (the battery is fully charged or it has reached its limits): Dump load is used to spill the excess of RE to maintain system security.

Note that RES curtailment is implemented within the primary control scheme and executed if system frequency goes beyond the specified threshold f(t) > fmax.

ii) If $\Delta P < 0$: available generation is not sufficient to supply the IPS load. The following dispatch priority is used: dump load, battery ESS, diesel generator.

1. Dump load decreases its consumption until it reaches zero (PDL = 0)

2. If (PDL = 0): The battery is discharged until it reaches its operational or SOC limits.

3. If (PDL = 0) and (the battery is fully discharged or it has reached its limits): The diesel generator increases its output to supply the load.

SAMPLING TIME:

The time considered in the cases is designed with a sampling time of 5e^5.

When considered in the case studies, this provides one sample for every 0.594 seconds.

T initial = 0

T sample= 5e^5

T end =5.4

4. RESULTS

4.1 SCENARIOS FOR HIPS

SENARIO 1: High RE penetration under low demand.

SENARIO 2: Low RE penetration under high demand

SENARIO1: High RE penetration under low demand.

The diesel generator operates at a low load limit. The excess generation supplied by the wind turbines is absorbed by the dump load, which in this operational mode performs the frequency regulation to ensure the required security margin. We created a hybrid isolated power system. We need to make sure that its

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values are in the acceptable security margin, which is 5% for voltage and 1% for frequency.

To test our system, we considered two extreme cases

- High renewable energy penetration with low demand
- Low renewable energy penetration with high demand

In the first case, we considered the renewable energy to be very high. Whereas the demand is very low. The diesel generator operates at a low load limit. The excess generation supplied by the wind turbines is absorbed by the dump load, which in this operational mode performs the frequency regulation to ensure the required security margin.

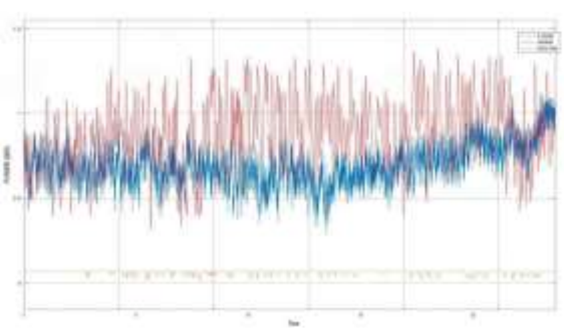

Fig 4.1 Power-Time Graph 1 for Scenario 1

Power-Time Graph: In the graph, the red line depicts the wind energy, the blue line represents the load and the orange line shows the solar energy. From the graph, we can see that the renewable energy which is produced is greater than the required demand. So, we operate the diesel generator at its minimum capacity, which is 0.5 MW as shown in the graph. We have excess energy produced in our system than the required power. That excess power is fed to the dump load.

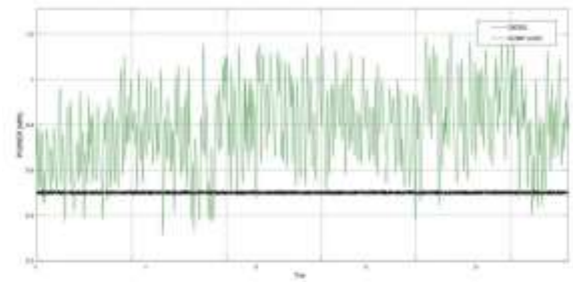

Fig 4.2 Power-Time Graph 2 for Scenario 1

In the graph, the black line is the diesel generator and the green line represents the dump load. From the graph, we can observe that the excess power which is generated in the system is directed to the dump load which ensures that the power dissipation is safe.

Voltage & Frequency Graph:

Fig 4.3 Voltage Graph for Scenario 1

Fig 4.4 Frequency Graph for Scenario 1

The above graphs show the voltage and frequency of the system The voltage in the graph is peak voltage, and when converted into RMS voltage it gives a steady 25kV.

From the voltage graph, we can observe that the voltage is in the security margin of 5. In the frequency graph, we can see that there is a steady frequency of 60Hz, and the system

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frequency is within the security margin limits of 1%.

SCENARIO 2: Low RE penetration under high demand.

The operation of diesel generators under low and no RE penetration. In this case, diesel generation is matched to varying demand, providing frequency support and security margin.

Power-Time Graph:

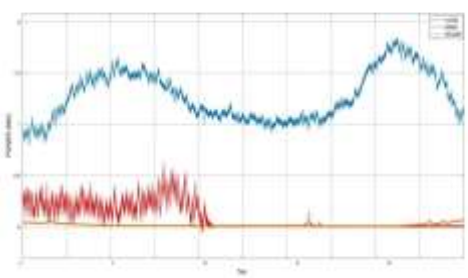

Fig 4.5 Power Time Graph 1 for Scenario 2

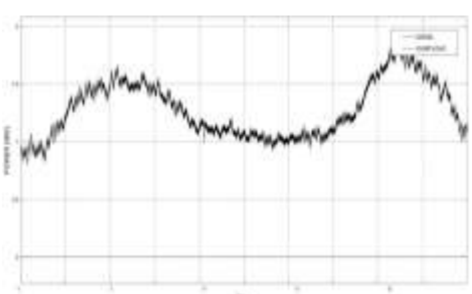

Fig 4.6 Power Time Graph 2 for Scenario 2

In the graph the blue line represents the load, the red line represents the load and the orange line represents the solar power. In the graph, we can observe that the renewable energy produced is less than the required loaddemand.

In this case, we need to use the diesel generator to meet our demands. From the above graph, we can see that there is no power supplied to the dump load as we do not have excess power generated.

The excess power is generated from the diesel generator.

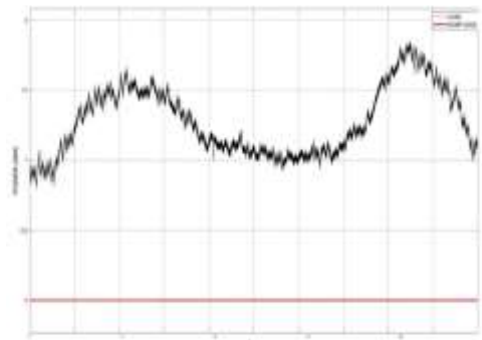

Fig 4.7 Power Time Graph 3 for Scenario 2

In this graph the black line represents the load and the red line represents the dump load. From this, we can say that the excess power required is supplied by the diesel generator.

Voltage Graph:

Fig 4.8 Voltage Graph for Scenario 2

Frequency Graph:

Fig 4.9 Frequency Graph for Scenario 2

The above graphs show the voltage and frequency of the system The voltage in the graph is peak voltage, and when converted into RMS voltage it gives a steady 25kV. From the voltage graph, we can observe that the voltage is in the security margin of 5%.

In the frequency graph, we can see that there is a steady frequency of 60Hz, And the system frequency is within the security margin limits of 1%. From both scenarios, we can observe that even in extreme conditions the system values are within the security margin.

4.2 CASE STUDIES

The main purpose of conducting these case studies is to observe the variations of the energy spillage in various conditions. The main motive of the project is to minimize the conventional diesel generation and high penetration of renewable energy sources taking the economic viability into account. By observing all the cases we will be able to study the intensity of the penetration due to the Renewable Energy which we used. And Cost analysis also the most important aspect to study on. So, this case studies are very much useful in analysing the Economical Viability.

Here we have three case studies that we observed

- **Case 1:** Case study one investigates minimal diesel fuel consumption, maximizing RE utilization with low-capacity battery ESS.
- **Case 2:** Case study two considers high-capacity ESS as a means to facilitate zero-diesel operation (ZDO) at peak renewable energy penetration.
- **Case 3:** Case study three adopts a low-load diesel application, aimed at minimizing the operational cost

Case 1: IPS control strategy involving low-capacity BES

If we look into case 1, In this case study we maximize the renewable energy penetration and simultaneously minimize the diesel generation as minimizing the fuel consumption is the main motive. If we observe the graph that we obtained, it is very clear that the renewable energy penetration is more and the demand is less., So the diesel generation is kept at a minimum load condition. So, the excess generated energy is utilized by the low-capacity battery which we place as a storage system. After the battery is fully charged the rest of the energy is absorbed by the dump load that we connected. This energy which is being absorbed by the dump load is nothing but spilled energy. Again, the battery discharges at the point where the renewable energy decreases.

Power-Time Graph:

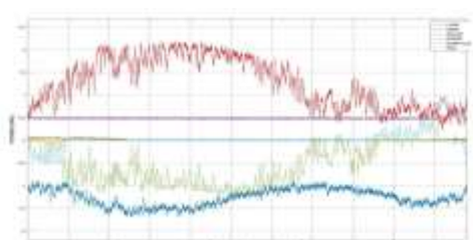

Fig 4.10 Power-Time Graph for Case 1

GRAPH EXPLAINATION:

If we observe the graph that we obtained, it is very clear that the renewable energy penetration is more and the demand is less., So the diesel generation is kept at minimum load condition.

So, the excess generated energy is utilized by the low-capacity battery which we place as a storage system. After battery being fully charged the rest of the energy is absorbed by the dump load that we connected. This energy which is being absorbed by the dump load is nothing but the spilled energy. Again, the battery discharges at the point where the renewable energy decreasing.

COST ANALYSIS:

The Cost analysis mainly includes the cost due to diesel and battery storage. As we used low capacity battery storage and the diesel engine is operated at low load i.e., at minimum load, the cost due to diesel and ESS is combinedly observed in this first case. Here as per the observations the cost is calculated as moderate but not really low. On the other hand, the spillage of the energy is increased.

ENERGY SPILLAGE:

Energy spillage is nothing but the wasted or diverted energy. As we had included a dump load for excess energy diversion. The amount of energy absorbed by the dump load is nothing but the spilled energy. If we observe the graph the area covered by the dump load is more so the spillage of energy is more. As the spillage is more the Efficiency of the system is less.

CASE 1 PIE CHART:

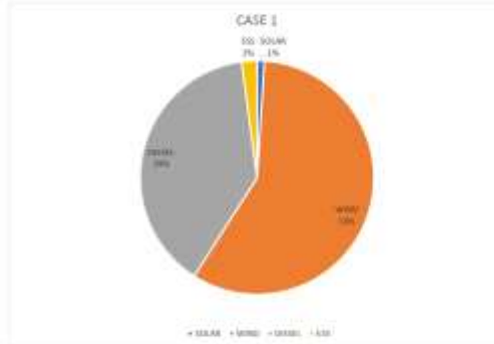

Fig 4.11 Pie Chart Representation of Case 1

Case 2: IPS control strategy involving high-capacity BES

If we investigate case 2, in this case, we consider high-capacity ESS to facilitate zero diesel operation (ZDO) at peak renewable energy penetration.

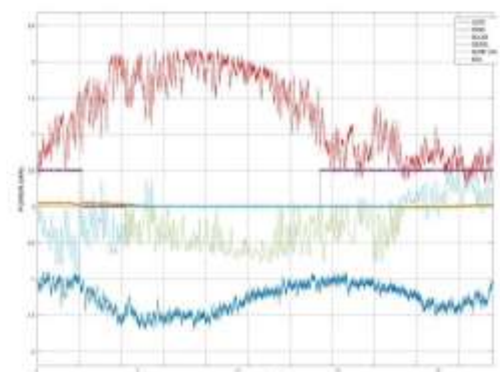

Fig 4.12 Power-Time Graph for Case 2

If we observe the graph that we obtained, at low demand and high renewable penetration the battery gets charged, diesel generation being minimum i.e., operating under low load conditions. After the battery is charged greater than 65% then the diesel generation inactivates i.e., becomes zero diesel operation. After the battery is fully charged dump load is activated as in case 1. Again, at a point where the renewable energy is decreased then the diesel generation activates to its minimum

CASE 2 PIE CHART:

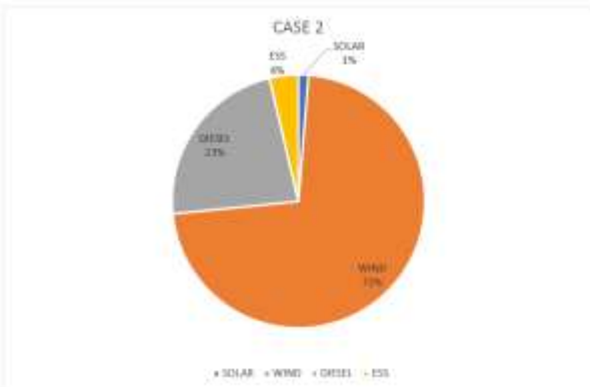

Fig 4.13 Pie Chart Representation of Case 2

COST ANALYSIS:

As the Spillage is more in Case1, we replaced low-capacity battery with high-capacity battery in order to reduce the Energy spillage. In the process of reducing the spillage the cost of the entire system increases as we used high-capacity battery. When compared to Case 1 the cost due to the diesel engine and the battery storage is increased.

ENERGY SPILLAGE:

If we observe the graph of Case 2 it is very clear that the area covered by the dump load decreased when compared to Case 1. As the penetration due to the battery storage is improved the battery consumes more power to charge despite spillage. So, it is very clear that the energy spillage got reduced and Efficiency is also improved.

If we can observe two cases the area occupied by the dump load is more in case 1 when compared to case 2. This mean to Spillage of energy is more in case 1 with low-capacity battery. With high-capacity battery we observed spillage being reduced. But with high-capacity battery economical disputes occur. So, in order to reduce this problem, we conduct case study 3 which has low load diesel application.

Case 3: IPS control strategy involving LLD.

To achieving the high penetration of renewable energy by adopts LLD technique. Here LLD operates in low load, allowing the great penetration of renewable energy which makes to improve the system security margin and less fuel consumption is occurred with reasonable cost.

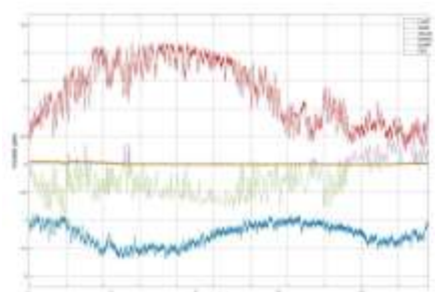

Fig 4.14 Power-Time Graph for Case 3

CASE 3 PIE CHART:

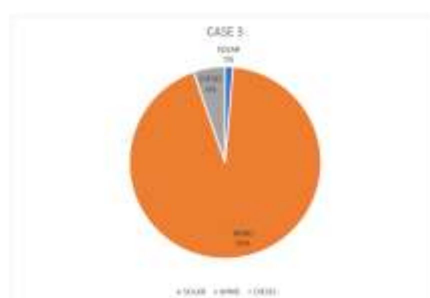

Fig 4.15 Pie Chart Representation of Case 3

4.3 OBSERVATION TABLE:

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Cases	Percentage Of Renewable Energy Penetration				Total Renewable Energy Penetration	Cost ($/MWh)	Spilled Energy
	Wind	Solar	Diesel	ESS	Wind + Solar		
1	58%	1%	39%	2%	59%	211$/MWh	11.235MWh
2	72%	1%	23%	4%	73%	263.86$/MWh	4.989MWh
3	93%	1%	6%	0%	94%	134.95$/MWh	6.533MWh

Comparison of operational cost in 3 cases:

Case 1:

Considered minimal diesel fuel consumption (maximising RE penetration) with lowcapacity battery ESS. With increase the wind power the diesel generator lowers its output. Whenever the engine reached its low load limit which causing the battery to switch into the charging mode. Once the battery is fully charged, the dump load starts dissipating electrical power. The penetration of renewable energy sources is 59% whereas generation of diesel is 39% and the storage of the battery is 2%. Here the diesel engine always operates at low load limit for some reasons the engine cannot be disconnected, which causes the battery to switch into charging mode.so the overall penetration of renewable energy ,diesel generation and less capacity battery is 211$/MWh which is at reasonable cost but spillage of energy is more that is 11.235MWh due to the usage of low-capacity battery.

Case2:

For achieving the high renewable energy penetration(a high-capacity battery is required) as a means to facilitate zero diesel operation . With increase wind power the larger battery is able to store a great portion of spilled energy which increases the system security margin .As a result the system can operate in a zero-diesel operation which means wheneverthe generation of the renewable energy is more at that time diesel engine will be in off condition due to the usage of large capacity battery. In this condition the penetration of renewable energy is 73% whereas the generation of diesel is 23% and the energy stored in the battery is 4%. The overall operational cost of the system is 263.86$/MWh which is more due to the usage of high capacity battery but the spillage of energy is less ie.4.989MWh due to usage of high-capacity battery which can be storage maximum amount of energy generated from the renewable energy sources.

Case3:

To achieving the penetration of high renewable energy with low cost and less spillage of renewable energy by adopting a low load diesel application to minimise the operational cost. LLD application affords diesel generation improved range, flexibility by permitting system acceptance of additional renewable energy via reduction in diesel engine load limit. Conventionally once the engine hits 30% of load limit any additional renewable energy is split from the system whereas under Low load application this additional generation is accepted via further diesel load reduction. Low load diesel allows an engine full capacity to utilised by removing the engine's low load limit. The overall penetration of renewable energy is 94% and generation of diesel engine is 6% with low spilled energy of 6.533MWh. The overall operational cost is less i.e. 134.95$/MWh due to the usage of low load diesel application.

5. CONCLUSION

5.1 CONCLUSION

Economic control strategies for high renewable energy penetration in isolated power system were discussed. The proposed strategies were applied to the island power system, comprised of diesel generators, wind turbines, solar arrays, a controlled resistive load and a battery energy storage system or low load diesel generator. It was shown that high renewable penetration (> 70%) can be approached by using BESS, a promising technology with a great future. However, it was demonstrated that, as of today, use of BESS for energy shifting is noncommercial, with barriers including high operation cost. The overall operational cost of the system is 263.85$/MWh but the spilled energy is reduced to 4.989MWh due to the usage of high-capacity battery.

Given an inability to eliminate diesel generation from a HIPS, LLD was shown to be a suitable BESS substitute, capable of providing a comparable level of RE penetration, for a reduced cost. To achieving the penetration of high renewable energy with low cost and less spillage of renewable energy by adopting a low load diesel application to minimise the operational cost. LLD application affords diesel generation improved range, flexibility by permitting system acceptance of additional renewable energy via reduction in diesel engine load limit. Conventionally once the engine hits 30% of load limit any additional renewable energy is split from the system whereas under Low load application this additional generation is accepted via further diesel load reduction. Low load diesel allows an engine full capacity to utilised by removing the engine's low load limit. The overall penetration of renewable energy is 94% and generation of diesel engine is 6% with low spilled energy of 6.533MWh. The overall operational cost is less i.e., 134.95 $/MWh due to the usage of low load diesel application. LLD is recommended as a transitional technology for all HIPSs as storage technology matures along the experience curve. The approach enables power system operators to transition to increased RE utilization with minimal disruption.

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