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Improvement of DSM penalties by integrating BESS to a Grid connected Solar PV Generator

Ashish Kumar Upadhyay
Department of Electrical Engineering
S.V. Polytechnic College, Bhopal, India
ash28indore@gmail.com

Namami Krishna Sharma
Department of Electrical Engineering
Prestige Institute of Engineering Management & Research
Indore, India
er.namami@gmail.com

Rajesh Arya
Computer Science and Engg. Department
Sushila Devi Bansal College of Engineering, Indore, India
aryarajesh@yahoo.com

Abstract— The increased penetration of renewable energy (RE) resources in the power system network affects the grid stability due to the non-deterministic nature of RE resources. BESS plays important role in handling the intermittency in power generation offered by RE resources by utilising its charging and discharging capability to ensure grid stability and reliability, further it enables the RE generators to operate within permissible band of deviation settlement mechanism (DSM) penalties. BESS can be placed at different levels of power system to enhance grid flexibility, stability and financial benefits to generators. Installation of BESS in the power system network helps to resolve congestion issue, maintaining frequency regulations, managing DSM penalties and supports round the clock (RTC) operation of RE generators. In this paper a simulated grid connected solar PV generator integrated with BESS is investigated for DSM penalties and grid balance. An optimal BESS placement ensures the economical operation of solar PV generators. The test results shows the saving in commercial losses and rupees per unit penalty for RE generator under Indian power regulatory framework.

Keywords—BESS, Renewable Energy Integration, Grid Stability, DSM penalty, Transmission Congestion.

Abbreviation

RE- Renewable Energy
BESS- Battery Energy Storage System
DSM- Deviation Settlement Mechanism

RTC- Round the Clock

PV- Photo Voltaic

ESO- Energy Storage Obligation

CEA- Central Electricity Authority

ATC- Available Transmission Capacity

TTC- Total Transmission Capacity

PSP- Pumped Storage Plants

VGF- Viability Gap Funding

SERC- State Electricity Regulatory Commission

I. INTRODUCTION

The power generation by RE resources is majorly depends on weather conditions which makes their power generation curve of scholastic nature. To predict these uncertainties various forecasting models are used but they also fail to capture the exact nature of power generation in some time durations which results as over injection or under injection of power from the scheduled power and causes huge DSM penalty and significant affect the grid stability, reliability and power market commitments. BESS plays important role in maintaining grid flexibility, managing DSM penalties and ensures the economical operation of grid connected RE generators by utilizing its charging and discharging capabilities. The central electricity authority of India regulates the BESS policy frameworks and mandates. The newly launched energy obligation (ESO) mandates the installation of BESS alongside the RE projects of minimum 10 % of installed capacity. Since the penetration of BESS is increased with RE expansion the DSM penalties and curtailment losses will decrease and power market revenue will increase [1]. The incorporation of BESS is the enabler of must run status for RE plants. Transmission losses, congestion issues, frequency fluctuation and demand spikes can be improved by BESS [2]. The optimal placement strategies of BESS along all levels of power system are important for maximizing operational flexibility and financial benefits [3]. Various optimal BESS placement strategies at each level of power system are investigated in [4]. An extensive review considering optimal BESS placement strategies, cost analysis and sizing of BESS is presented in [5]. Optimal performances of ancillary services of unbalanced distribution network is deeply investigated in [6]. Prakash et al. in [7] bridges the gap in optimal BESS scheduling algorithm for distribution system. Optimal sizing and placement of BESS considering power system security aspects are discussed in [8-10]. According to the projection published by CEA the growth rate of BESS requirement will follow the steep rise in next two decades. Around 34.7GWh of BESS capacity will be required to support renewable intermittency and grid balance in next two years [11-12]. By 2031-32 this requirement will see further boost of around

236GWh due to the inclusion of large scale RE integration. The projected requirement of BESS will reach nearly 1840GWh by 2047, which will make the BESS as a fundamental pillar of Indian power sector. The standalone BESS and other ancillary services like pumped storage plants (PSP) will also play major role in supporting grid stability and reliability further these two services will complement each other to support grid flexibility and ensures round the clock operation.

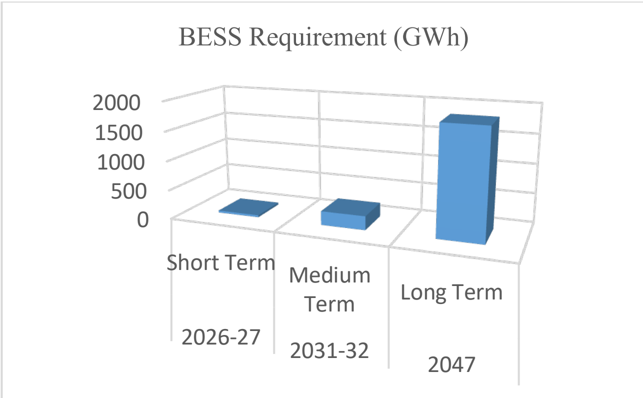

Fig. 1. BESS Requirement GWh (India)

This paper investigates the techno-economic operation of a grid connected solar PV generator integrated with BESS. The structure of the paper is as follows: introduction of the paper is dis cussed in section-1. Section 2 deals with the impact of BESS placement at different levels of power system network. A simulated case study for RE generator with BESS is deeply investigated in section 3 where financial aspects of RE generator are discussed under Indian regulatory framework. Results are discussed in section 4 followed by conclusion section. Supported research articles are listed in reference section. The presented study shows that BESS is the techno-economic enabler of modern power system operation. Incorporation of BESS with RE generator reduces the DSM penalty, increase the accuracy of scheduled power and supports the flexibility in power system operation. These features make the BESS as a crucial asset in evolving Indian power system network.

II. BESS PLACEMENT AT DIFFERENT LEVELS OF POWER STSTEM

The generation, transmission and distribution levels having their own challenges and limitations in maintaining grid stability and flexibility of power system operation. At each level the placement of BESS can address most of the challenges by utilising its power delivery and absorbing capability. At the RE Generation level, BESS is co-located with renewable energy plants (solar/wind). It stores excess energy during low demand and supplies it during peak demand. Its Key Functions include: Smoothing renewable generation variability, Firming power output, Peak shifting, Reducing curtailment. BESS placement at generation level improves renewable energy utilization, enables time-shifting of energy and enhances scheduling accuracy. At the transmission level, BESS is installed at substations or grid nodes to support bulk power transfer and grid stability. Its key functions include: Congestion management, voltage support, frequency regulation, deferral of transmission upgrades. Additionally it enhances grid reliability, reduces capital expenditure on new lines and supports large-scale renewable integration by increasing ATC and TTC of transmission system [13]. At the distribution level, BESS is installed near load centres or distribution substations. Its key functions include: peak load management, demand response, voltage regulation, support for electric vehicle charging. It is advantageous in reducing peak demand charges and improving power quality and helps to enable decentralized energy management [14-16].

TABLE I. COMPARITIVE ANALYSIS

Parameter	**Generation Level**	**Transmission Level**	**Distribution Level**
Primary Objective	Renewable smoothing	Grid stability	Load management
Location	Solar/Wind plants	Substations	Load centres
Benefits	Curtailment reduction	Congestion relief	Peak shaving
Users	Generators	Grid operators	DISCOMs

Typically, the BESS size is about 20–40% of plant capacity with 1–2 hours of storage, and in most real-world Indian projects, AC-coupled systems at the pooling point are preferred due to ease of integration and operational control [17]. Battery Energy Storage System (BESS) costs in India have dropped significantly, with recent bids discovering discharge rates around ₹2.1/kWh (without VGF) for 2-cycle daily usage, down from over ₹10/kWh in 2022-23. Major projects are now seeing tariffs between ₹6.45-₹6.46/kWh for 4-hour storage, driven by Viability Gap Funding (VGF)] schemes [12]. In India, BESS (Battery Energy Storage System) charging and discharging rates are generally discussed in three ways: Technical charging/discharging rate (C-rate), Commercial tariff/rate for storage services and Grid/ancillary service charges. Battery Energy Storage Systems (BESS) in India are primarily deployed for renewable energy integration, peak load management, ancillary services, and energy arbitrage. Most utility-scale projects use lithium-ion technology with 2-hour (0.5C) and 4-hour (0.25C) configurations. Charging generally occurs during low-demand or high solar generation periods, while discharging is scheduled during evening peak demand hours. Recent Indian BESS projects have shown tariffs ranging from ₹2.2–₹4.5/kWh for standalone systems and ₹4–₹6/kWh for solar-integrated storage applications. Regulatory frameworks by CERC emphasize 85% round-trip efficiency and availability-based compensation mechanisms.

III. CASE STUDY: SOLAR + BESS INTEGRATION (INDIA)

A typical daily solar power generation profile of a 20 MW solar power plant under variable weather conditions is depicted in Figure 2 . The scaled values of solar power output shown in figure 2 are modeled using beta distribution to capture the stochastic nature of solar irradiance [18]. Scheduled solar power generation curve under varying climatic conditions is also shown in Figure 3. In the Indian power system, most states operate within a permissible deviation band of ±10% of the available capacity for scheduled generation. Deviation Settlement Mechanism (DSM) charges are computed for each 15-minute time block when the actual generation deviates beyond this prescribed limit. Grid balancing in India is primarily achieved through DSM penalties imposed on generators for over- or under-generation. In contrast, European power systems largely adopt a market-based balancing mechanism, where transmission system balance is maintained through ancillary service markets. Additionally, renewable energy (RE) generators in these systems are typically granted "must-run" status, ensuring priority dispatch irrespective of market conditions. Most of the State Electricity Regulatory Commissions (SERCs) in India use the following error formula for DSM calculation.

$$\% \, Error = \frac{Actual\ MW - Scheduled\ MW}{Available\ capacity\ (MW)} \times 100$$

System Description:

- Solar Plant Capacity: 20 MW
- Contract Rate- $4000 Rs/MWh$
- BESS rating- $4MW$

TABLE II. DSM CHARGES

DSM band	DSM Charge (Under Injection)	DSM Charge (Over Injection)
0-10%	@ Contract rate	@ Contract rate
10-15%	@ 110% of Contract rate	@ 90% of Contract rate
>15%	@ 200% of Contract rate	Nil (No Money will be paid)

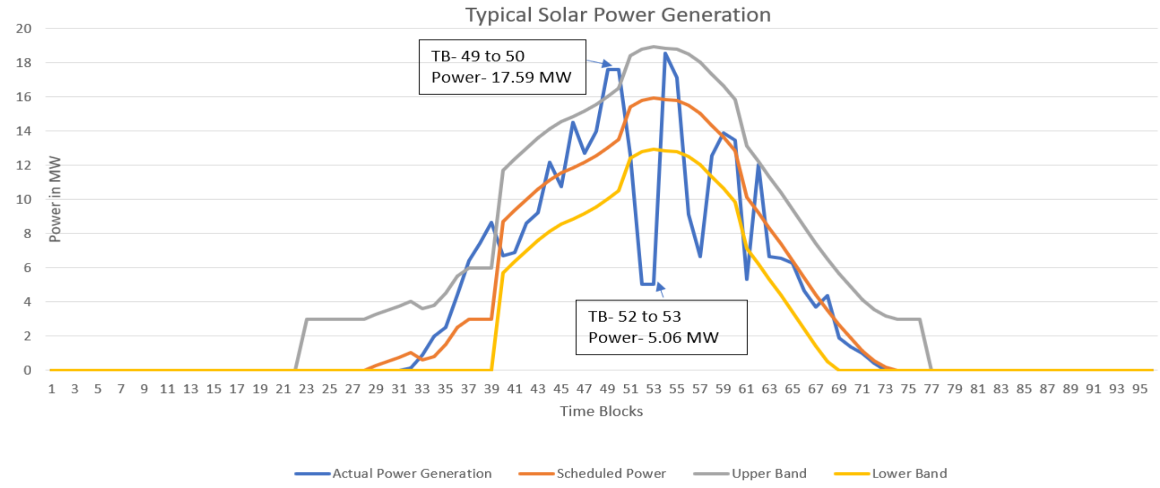

Fig. 2. Solar Power Generation

A. DSM Charges Without BESS (Over Injection)

Time Block- 49 to 50

Available capacity = 20 MW

Scheduled Power = 13.53 MW

Actual Power = 17.59 MW

Contract rate = 4 $Rs/kWHr = 4000Rs/MWh$

$$Error = \frac{17.59-13.53}{20} \times 100 = 20.3\%$$

TABLE III. DSM CALCULATION FOR OVER INJECTION

DSM band	**Quantum of Power**	**Energy in block**	**DSM**	**DSM calculation (Rs.)**
0-10% of available	10% of 20= 2MW	$2 \times \frac{1}{4} = 0.5MWh$	@ CR	$0.5 \times 4000 = 2000$
10-15% of available	5% of 20= 1MW	$1 \times \frac{1}{4} = 0.25MWh$	@90% of CR	0.25×0.9×4000= 900
>15%	5.3% of 20= 1.06MW	$1.06 \times \frac{1}{4} = 0.265MWh$	Nil	0
DSM for over injection in one time block (49 to 50)				**2900/-**

Payment based on scheduled power = $13.53 \times \frac{1}{4} \times 4000 = 13530\ Rs./-$

Actual receivable = Payment as per scheduled power + DSM= $13530 + 2900 = 16430\ Rs/-$

Actual energy supplied = $17.59 \times \frac{1}{4} = 4.3975MWh$

Payment based on actual generation = $4.3975 \times 4000 = 17590/-$

Commercial Loss= Payment based on actual generation- Actual receivable = $17590 - 16430 = 1160/-$

Actual energy generation= 4.3975×1000 = 4397.5kWh or 4397.5 Units

Loss per Unit = $1160/4397.5 = 0.2638 Rs. per\ unit$

B. DSM Charges Without BESS (Under Injection)

Time Block- 52 to 53

Available capacity = 20 MW

Scheduled Power = 15.79 MW

Actual Power = 5.06 MW

Contract rate = 4 $Rs/kWHr = 4000 Rs/MWh$

$$Error = \frac{15.79 - 5.06}{20} \times 100 = 53.65\%$$

TABLE IV. DSM CALCULATION FOR UNDER INJECTION

DSM band	Quantum of Power	Energy in block	DSM	DSM calculation (Rs.)
0-10% of available	$10\%\ of\ 20 = 2MW$	$2 \times \frac{1}{4} = 0.5MWh$	@ Contract rate	$0.5 \times 4000 = 2000$
10-15% of available	$5\%\ of\ 20 = 1MW$	$1 \times \frac{1}{4} = 0.25MWh$	@ 110% of Contract rate	$0.25 \times 110\%(4000) = 1100$
> 15 %	$38.65\%\ of\ 20 = 7.73MW$	$7.73 \times \frac{1}{4} = 1.9325MWh$	@ 200% of Contract rate	$1.9325 \times 200\%(4000) = 15460$
DSM for under injection in one time block (54 to 55)				**18560/−**

Scheduled Energy = $15.79/4 = 3.9475\ MWh$

C.R. = $4000\ Rs/MWh$

Payment based on scheduled power = $3.9475 \times 4000 = 15790/-$

Actual receivable = Payment based on schedule – DSM Charge = $15790 - 18560 = Rs. -2770/-$

Payment based on actual generation = $5.06 \times \frac{1}{4} \times 4000 = 5060/-$

Commercial Loss = Payment based on actual generation – Actual receivable = $5060 - (-2770) = 7830/-$

Per unit loss calculation

Actual energy generation = $5.06 \times \frac{1}{4} \times 1000 = 1265\ kWh\ or\ 1265\ unit$

Loss per unit = $\frac{7830}{1265} = 6.18\ Rs.Per\ Unit$

C. Combining A & B

Total commercial loss (OI + UI) = $1160\ + 7830 = \ 8990/-$

Actual energy generation (OI + UI) = $4397.5 + 1265\ = \ 5662.5\ Unit$

Total loss per unit (OI + UI) = $8990/5662.5 = \ 1.587 Rs/unit$

D. Calculation with BESS

Total energy quantum during over injection= $0.5 + 0.25 + 0.265 = \ 1.015\ MWh$

Total energy quantum during under injection = $0.5 + 0.25 + 1.9325\ = 2.6825\ MWh$

TABLE V. BESS SPECIFICATION

Parameter	Value
Solar Plant Capacity	$20\ MW$
BESS Rating	$4\ MW$
Round-trip Efficiency	85%
Charging Duration	$2\ Hours$
Initial SOC	20%
Maximum SOC	100%
Over-injection Energy Available	$1.015\ MWh$
Under-injection Energy Requirement	$2.6825\ MWh$
Tariff Range	$₹4/kWh$

- BESS Energy Capacity

  Since BESS rating is: 4 MW for 2 hours

  Energy capacity:

  $E\ = P\ \times t\ = \ 4\ \times\ 2\ = \ 8MWh$

- Available Capacity for Charging

  Initial SOC = 20%

  Stored energy initially:

  $E_{initial} = 0.20 \times\ 8\ = \ 1.6MWh$

  Available empty capacity = $8\ -\ 1.6\ = \ 6.4\ MWh$

  Actual Energy Stored from Over-Injection

Available excess energy: 1.015 MWh

Considering 85% efficiency:

$E_{stored} = 1.015 \times 0.85 = 0.86275 MWh$

Thus, actual stored energy: 0.863MWh

Updated SOC energy: = $1.6 + 0.863 = 2.463\ MWh$

Updated SOC percentage:

$SOC = (2.463/8) \times 100 = 30.79\%$

$SOC = 30.8\%$

- Energy Available for Discharge

Stored usable energy after charging: $= 0.863\ MWh$

Delivered energy considering efficiency:

$E_{delivered} = 0.863 \times 0.85 = 0.733 MWh$

Thus, energy delivered to grid: 0.733 MWh

Discharging Duration at Rated Power

BESS rated power: 4 MW

Discharge duration: $t = 0.733/4 = 0.183\ hours = 11 minutes$

- Comparison with Under-Injection Requirement

Under-injection energy deficit: 2.6825 MWh

Energy support available from BESS: 0.733 MWh

Remaining deficit: = 2.6825 - 0.733= 1.9495 MWh

Thus BESS can compensate: 27.3% of under-injection energy.

When the Battery Energy Storage System (BESS) is charged exclusively from surplus generation of the co-located Solar PV plant without drawing power from the utility grid, no separate charging tariff is generally applicable. The stored energy is treated as renewable energy subject to compliance with energy accounting and metering regulations. However, if grid power is utilized for charging the BESS, applicable retail/open access tariffs and associated network charges become applicable. The energy discharged from the Battery Energy Storage System (BESS), when charged exclusively from surplus Solar PV generation, is generally treated as dispatchable renewable energy. The applicable tariff during discharge depends on the contractual and regulatory framework, including composite $Solar + BESS$ tariff structures, time-of-day tariffs, or market-based energy settlement mechanisms.

TABLE VI. BESS PARAMETERS VALUE

Parameter	Results
Total BESS Capacity	$8\ MWh$
Initial Stored Energy	$1.6\ MWh$
Excess Energy Available	$1.015\ MWh$
Actual Energy Stored	$0.863\ MWh$
Updated SOC	30.8%
Energy Required for Full Charge	$6.514\ MWh$
Energy Delivered to Grid	$0.733\ MWh$
Discharge Duration @ 4 MW	$\sim 11\ minutes$
Under-Injection Compensation	27.3%

- DSM calculation with BESS (11+4minutes)

  Quantum of energy required – Quantum of energy supplied= $2.6825 - 0.733 = 1.9495\ MWh$

  Quantum of power= $1.9495 \times 4 = 7.798MW$

  Old quantum without BESS= $10.73MW$

  New quantum applicable for DSM= $10.73 - 7.798 = 2.932MW$

TABLE VII. DSM CALCULATION WITH BESS (PART A)

DSM band	Quantum of Power	Energy in block (11minutes)	DSM	DSM calculation (Rs.)
0-10% of available	$10\%\ of\ 20 = 2MW$	$2 \times \frac{11}{60} = 0.366MWh$	@ Contract rate	$0.366 \times 4000 = 1466.66$
10-15% of available	$4.66\%\ of\ 20 = 0.932MW$	$0.932 \times \frac{11}{60} = 0.171MWh$	@ 110% of Contract rate	$0.171 \times 110\%(4000) = 751.8$
DSM for under injection during first 11 minutes of time block (54 to 55)				$\mathbf{2218.4/-}$

For next 4 minutes DSM charges will be applicable for $10.73MW$

TABLE VIII. DSM CALCULATION WITH BESS (PART B)

DSM band	Quantum of Power	Energy in block (4 minutes)	DSM	DSM calculation (Rs.)
0-10% of available	$10\%\ of\ 20 = 2MW$	$2 \times \frac{4}{60} = 0.133MWh$	@ Contract rate	$0.133 \times 4000 = 533.33$
10-15% of available	$5\%\ of\ 20 = 1MW$	$1 \times \frac{4}{60} = 0.067MWh$	@ 110% of Contract rate	$0.067 \times 110\%(4000) = 293.33$
> 15 %	$38.65\%\ of\ 20 = 7.73MW$	$7.73 \times \frac{4}{60} = 0.5153MWh$	@ 200% of Contract rate	$0.5153 \times 200\%(4000) = 4122.67$
DSM for under injection during 4 minutes of time block (54 to 55)				$\mathbf{4949.32/-}$

Total DSM $= 2218.4 + 4949.32 = 7167.72 = Rs.7168/-$

Scheduled Energy for one-time blocks = $\frac{15.79}{4} = 3.9475MWh$

C.R. = 4000 Rs/MWh

Scheduled Receivable (OI+UI) = $15790 + 13530 = Rs.29320$

Actual Receivable:

Payment based on schedule (OI+UI) – DSM Charges = $(15790 + 13530) - 2218.4 - 4949.32 = Rs.22152$

Payment based on actual generation (OI+UI) = $17590 + 5060 = Rs.22650/-$

Commercial Loss = $22650 - 22152 = Rs.498$

Per unit loss calculation:

Actual energy generation (OI+UI) = $4397.5 + 1265 = 5662.5\ Unit$

Loss per unit = $\frac{498}{5662.5} = 0.087\ Rs.Per\ Unit$

IV. Results and Discussion

BESS impact analysis is presented in Table IX. A significant improvement is observed in both per-unit losses and commercial losses. DSM charges during the over-injection period are reduced to zero in the presence of BESS, as all excess energy is utilized for charging the BESS. During the under-injection period, DSM penalties are calculated in two stages within a single time block. For the first 11 minutes, the energy stored in the BESS is utilized to compensate for the power deficit, and DSM is calculated accordingly. During the remaining 4 minutes, the BESS becomes fully discharged, and DSM is calculated based on the prevailing deficit condition. The total DSM penalty during under-injection with BESS operation is reduced to Rs. 7,168 compared to Rs. 18,650 without BESS

% improvement in penalty = $\frac{1.587-0.087}{1.587} \times 100 = 94.5\%$

% improvement in commercial loss $= \frac{8990-498}{8990} \times 100 = 94.46\%$

TABLE IX. BESS IMPACT ANALYSIS

Metric	Without BESS	With BESS	Improvement
DSM Over Injection Charge (Rs.)	2900	0	↓100%
DSM Under Injection Charge (Rs.)	18560	7168	↓61.4%
Commercial Loss (Rs.)	8990	498	↓94.5%
Loss per Unit (Rs./kWh)	1.587	0.087	↓94.5%

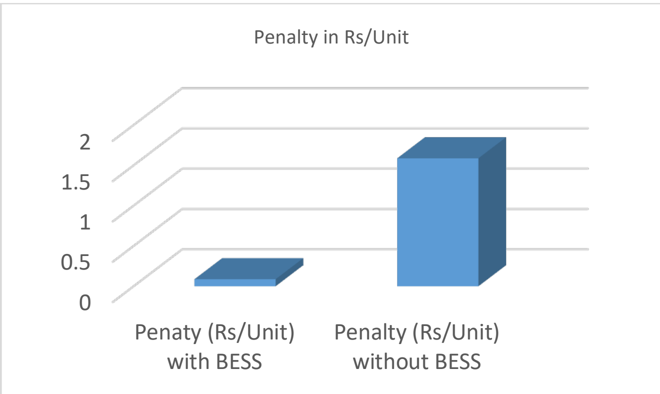

Fig. 3. Penalty in Rs/Unit

The integration of a 4 MW / 8 MWh BESS significantly reduces DSM penalties by absorbing excess generation during over-injection and supplying energy during under-injection conditions. The total DSM charges are reduced, thereby improving commercial viability and reducing loss per unit generation.

V. CONCLUSION

With the recent BESS advanced technological innovation an exponential growth will be observed in this sector and BESS will become the integral part of the power system. For RE generators the BESS makes zero deviation between scheduled and actual power. Technical and economical aspect of integrated BESS with a grid connected Solar PV generator under Indian DSM framework have been investigated in this paper. The proposed study considers one time block of over injection and one time block for under injection for DSM calculation with and without BESS and a significant improvement have been observed DSM penalty and grid stability. The total per loss is reduced to 0.087 Rs/Unit to 1.587 Rs/Unit and 94.5% improvement in commercial loss. A 4MW/8MWh BESS effectively handled the surplus energy during over injection and deficit of energy during under injection. The study shows that integration of BESS with solar energy generator enhances the energy utilization, improves scheduling accuracy, minimizes DSM penalties and increases power system flexibility. High capital cost, battery degradations, optimal sizing and siting, are the major challenges in BESS deployment.

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