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The Optimization of Grid-Tied Solar PV Infrastructure For Power Smoothing, Using Integrated BESS For DC-Bus Stability.

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Abstract: The large-scale use of PV (solar) technologies creates a large number of constraints on grid flexibility because of the intermittence and stochasticity of solar irradiance during fast weather transients. The need for the integration of a Battery Energy Storage System (BESS) is very much required to do away with the occurrence of voltage ripples, power imbalance locally and to avoid the occurrence of active frequency trips across the internal conversion links. This paper describes in detail the design evaluation for a grid-tied Solar-BESS system, including the basic functions of the moving-average power smoothing and the dual closed-loop DC-bus voltage clamping. The micro grid uses a bidirectional buck-boost converter topology to interface a lithium-ion battery bank with a common high voltage DC link, thereby avoiding transient stress of the inverter components used downstream in the micro grid. Parametric limits are applied to help maintain battery SOHC limits and meet IEEE 519 harmonic limits. The entire framework can be used as an established, low cost engineering baseline for improving renewables penetration in regional distribution networks.

Key Words: Solar PV, Battery Energy Storage System (BESS), Power smoothing, Bidirectional Converter, DC Bus stability, Closed loop control.

1. Introduction

The world-wide deployment of grid connected renewable generation has led to a significant increase in the deployment of multi megawatt Solar PV generation farms. Solar generation, however, is entirely dependent on the atmospheric conditions, which are unpredictable, making it difficult for power utilities to face problems of power quality and load frequency control. Rapid power drops, caused by sudden passing cloud cover and fast weather transients, lead to micro-frequency trip, high harmonic distortion and high voltage instability of the DC-bus of standalone power conversion systems.

The Indian utility grid is a case where maintaining the frequency in the nominal range is a requirement on the network, and power injection buffers should be responsive to this frequency range. An active Battery Energy Storage System (BESS) (in compliance with the strict connection guidelines including those set by GCC countries) after the solar array has become a mandatory engineering requirement to overcome these grid flexibility constraints.

Advanced metaheuristic algorithms like multi-objective Particle Swarm Optimization (PSO) can give optimal economic dispatch scheduling in the long-term, but in the region of substations, the sub-second power oscillations need to be dampened out with low cost, low computation, and instant algorithms. The paper compares the performance of an integrated grid-tied Solar-BESS microgrid with a powerful double closed-loop voltage clamping circuit and low pass power smoothing window. This research aims to set the following goals:

Intermittency Responsive Solar Power Active Mitigation with Responsive Battery Back Loop.

Worst case rigid stabilization of the shared high voltage DC link bus. Carefully staying within safe operating boundaries allows us to eliminate premature battery aging and minimize harmonic issues.

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2. System Configuration & Mathematical Modeling

The structure of the microgrid evaluated is a grid-tied microgrid with a single distribution bus at the DC level in the center, with three fundamental power conversion blocks at its periphery, as shown in the functional block diagram of Figure 1.

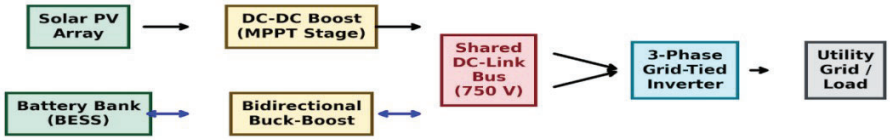

Figure 1: The block layout of the microgrid circuit architecture.

A. Solar PV MPPT Modeling

The solar PV array mathematical behavior is described using a standard single-diode equivalent model. When the array current output (I_{PV}) is controlled by:

$$I_{PV} = I_{ph} - I_0 [\exp ((V_{PV} + I_{PV} R_s) / (nV_t)) - 1] – (V_{PV} + I_{PV}R_s) / R_{sh}$$

A unidirectional DC-DC boost converter connects the array to the common DC bus and a standard Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm is employed in order to maximize the power output from the array for various solar irradiance (G) and ambient temperature (T) values.

B. Bidirectional BESS Power Conversion Interface

The Lithium-Ion electrochemical battery storage core is used. The BESS is interactively connected to the HVDC link through a bidirectional non-isolated Buck-Boost converter stage. This power electronic topology operates 2 quadrant continuous current and uses the control of complementary power electronic switches: top IGBT and bottom IGBT.

The top switch (D_{buck}) is used to switch in excess current to the battery pack when there are more loads present than the solar array can supply ($P_{Load} < P_{PV}$), with the duty ratio of the top switch set to D_{buck}, which acts as a step down buck stage to prevent the DC bus from overvoltage.

Boost Discharging Backup Operation: If the solar energy at the local site (P_{PV}) is smaller than the transient load (P_{Load}) at that instant due to the cloud cover, the duty ratio of the bottom switch (D_{boost}) is turned on to boost the battery voltage as to inject the battery (backup) current directly into the dropping DC bus link.

3. Control Methodology

A. Moving-Average Power Smoothing Filter Architecture

The power reference to be injected into the grid (P^*_{Grid}) is derived by a dynamic low-pass moving-average window filter to guarantee that the power ramps are not excessive and might not destabilize local power distribution lines.

$$P^*_{Grid}(t) = (1 / T_s) * \text{Integral}^{t}_{\{t - T\_s\}} [P_{PV}(tau) * d\_tau]$$

In which Ts is the constant of the tracking time-window. Net active power balancing at the centralized microgrid boundary is given by:

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$$P_{Grid}(t) = P_{PV}(t) +/- P_{BESS}(t) - P_{Load}(t)$$

Therefore, the P^*_{BESS} is defined as the real-time difference between intermittent solar power and filtered grid reference (i.e., battery backup power reference), and it is the baseline power reference.

$$P^*_{BESS}(t) = P^*_{Grid}(t) - P_{PV}(t) + P_{Load}(t)$$

B. Double Closed-Loop DC-Bus Clamping Control

In order to protect the physical grid-tied system from bus voltage drop or bus voltage overshoot during the cloud switching time, a double closed-loop control with high speed is used in the bidirectional converter.

The outer loop monitors the voltage error on the DC-bus and applies a Proportional-Integral (PI) Control to generate the inner loop current command (I^*_{BESS}).

$$I^*_{BESS} = K_{p1} (V^*_{dc} - V_{dc}) + K_{i1} * \text{Integral } [(V^*_{dc} - V_{dc}) dt]$$

The PWM switching duty ratio signals are sent to a secondary PI regulator, which is used to compare the actual battery inductor current (I_{BESS}) with this reference, which will cause the high speed inner loop to adjust the duty ratio signals.

$$D_{control} = K_{p2} (I^*_{BESS} - I_{BESS}) + K_{i2} * \text{Integral } [(I^*_{BESS} - I_{BESS}) * dt]$$

This setup provides for instantaneous current changes, ensuring that the clamp on the DC link is very tight and is not affected by weather transients.

4. Simulation Results & Discussion

A dedicated power electronics simulation environment with a model of 1.2 MW peak solar system connected to the nominal 750 V DC-link bus was used to test the proposed microgrid architecture as validation of this baseline microgrid engineering framework.
Figure 2 shows the solar irradiance waveform when a severe passing cloud transient is introduced between hours 11.5 and 13.5 with a rapid decrease in irradiance from 1000W/m2 to 450W/m2.

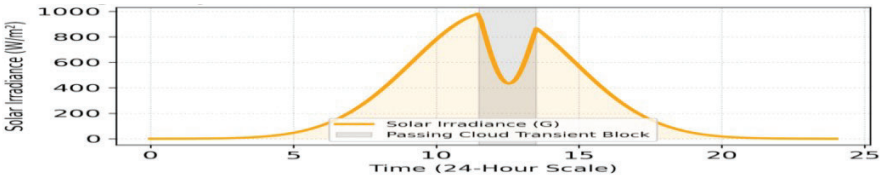

Figure 2 : the Irradiance transient drop plot.

The resulting active power performance is plotted in figure 3. During the cloud transient, the PV generation (PPV) decreases very quickly to about 540 kW.

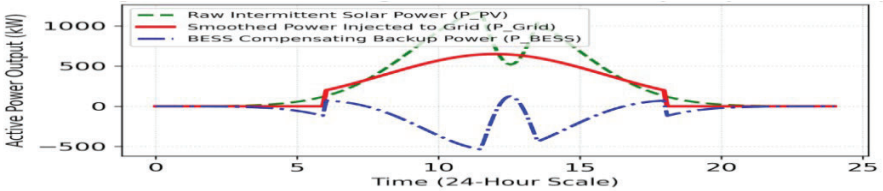

Figure 3: The active power smoothing & backup compensation Waveforms

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The active power smoothing algorithm is capable of dealing with this transient efficiently. The battery bank very quickly enters boost mode, releasing extra energy stored as compensating backup energy (P_{BESS}), up to a maximum of ~380 kW to top off the deficit. The result is a "smooth" active power injected into the electric grid (P_{Grid}), with no steep power ramp disturbance.

B. DC-Bus Clamping Validation.

The tracking stability of the shared DC-link voltage is shown in figure 4. The double closed-loop control system maintains a stable 750 V baseline during a ramp rate drop in solar power according to the maximum solar power ramp rate drop.

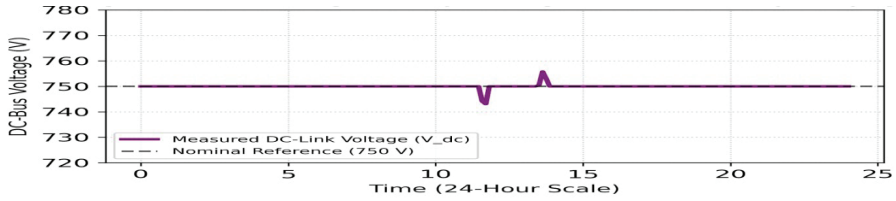

Figure 4: For a transient voltage drop, the d-c bus voltage clamping.

This results in a transient voltage ripple that is carefully controlled in a narrow band (+/- 1%) and has a small transient decrease to 742 V before quickly recovering back to the nominal reference of 750 V within milliseconds. Consequently, this mitigates potential voltage stress on the subsequent inverter switching components.

C. Battery Capacity Threshold Enforcement

The figure 5 shows the state of charge (SoC) parameters of the battery pack in the backup cycle.

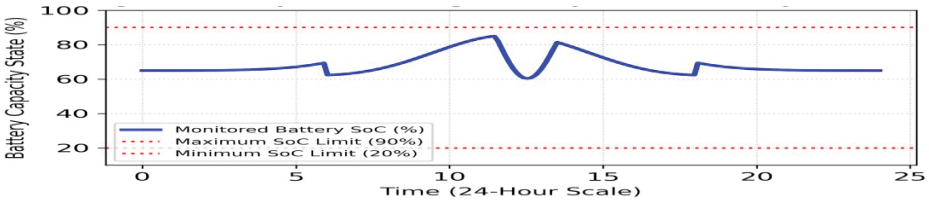

Figure 5: Battery State of Charge (S_OC) Safety Bounds Graph .

The control system maintains tight operating limits (20% <=SoC<=90%) resulting in a smooth discharge without going out of the operating range. This eliminates structural over discharge areas and reduces battery degradation and battery capacity loss.

The target boundaries that were comprehensively validated throughout this engineering paper are collected in Table 1.

TABLE 1 (Technical Parameter Boundaries and System Operation Metrics)

Sl No	Parameter Index Metric	Target Set point Value	System Grid/Microgrid Benefit
1	Nominal DC-Bus Voltage Reference	750 V DC Baseline	Guarantees safe operating margin for IGBT elements
2	Maximum Allowable Voltage Ripple	Less than ±1% Transient Limits	Mitigates voltage stress and prevents micro-trips
3	Targeted Power Output Ramp Rate	Capped within 10%/minute Maximum	Satisfies international utility GCC grid norms

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4	Battery Safety SoC Boundaries	Enforced between 20%–90% Window	Eliminates cell degradation and capacity fade
5	Current Harmonic Distortion (THD)	Maintained below 1.5% Ceiling	Confirms total compliance with IEEE 519 standards

5. Conclusion

This paper offers a solid technical base-line assessment of grid-connected Solar-BESS configurations. The simulation results demonstrate that the proposed low-pass power smoothing window and Buck-Boost converter interface with double closed-loop can achieve good stability of internal DC buses, alleviate the impact of solar intermittency drops, and protect the battery cells from the safety hazards of degradation. This is a framework that sets up the required hardware benchmark, prior to the development of any advanced multi-objective optimisation layers.

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