Department of Electrical and Electronics Engineering

The Design and Analysis of Large Solar PV Farm Configurations With DC-Connected Battery Systems

HARIPRASAD N LTVE18EE132 Roll No: 31

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Contents

Introduction

- PV energy installations are growing fastly for both residential applications and for utility-sized power plants.
- Solar PV generation is intermittent in nature.
- BESS are expected to play a significant role in the integration of renewable energy sources into the future electric grid.

Objective

- To calculate the curtailed solar energy due to inverter rating limitations.
- To develop a sizing approach for the battery.
- Integrate battery to the dc link of the PV inverter via a dc–dc converter.

Curtailment

- Reduce in extent or quantity; impose a restriction on.
- Act of reducing or restricting energy delivery from a generator to the electrical grid.
- Reasons for curtailment are;
  - DC/AC ratio of a PV system
  - wide oversupply
  - local transmission constraints

Inverter Limitation

- DC/AC ratio of a PV system
- The dc rating for utility-scale PV is typically higher than its ac-rated capacity for multiple reasons
- Power is curtailed during periods of surplus irradiance

BESS

- Battery Energy Storage System (BESS)
- BESS are rechargeable battery systems that store energy from solar arrays and provide that energy to electric grid.
- Ramp Rate
  - Ramp rate indicates the rate at which storage power can be varied.
  - usually expressed either as % per minute or MW per minute.

Integrating BESS

- Conventional system with multiple dc-dc converters
  - increase the system complexity and reduce its overall efficiency
- BESS connected to the grid via independent inverter
  - less efficient,PV dc-ac converter needs to have similar ratings as the PV array
- Proposed system configuration - single dc–dc converter
  - capable of simultaneously operating as a charge controller and a MPPT device.

Topologies

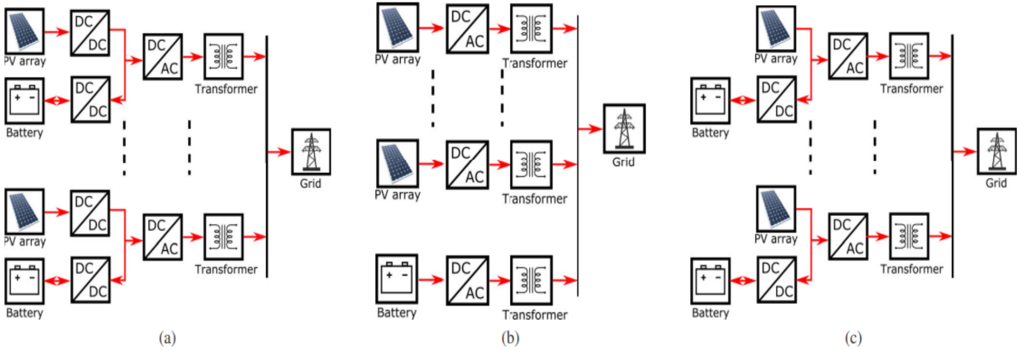

Figure: (a) Conventional system with multiple dc-dc converters ,(b) BESS connected to the grid via independent inverter, (c) proposed system with single dc-dc converter .

Proposed system

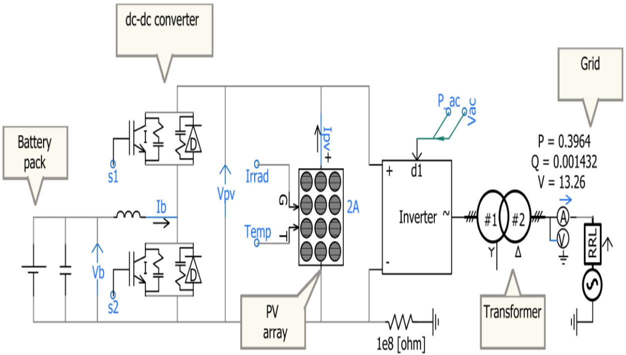

Figure: The power circuit diagram in the PSCADTM/EMTDCTM software environment

Block Diagram

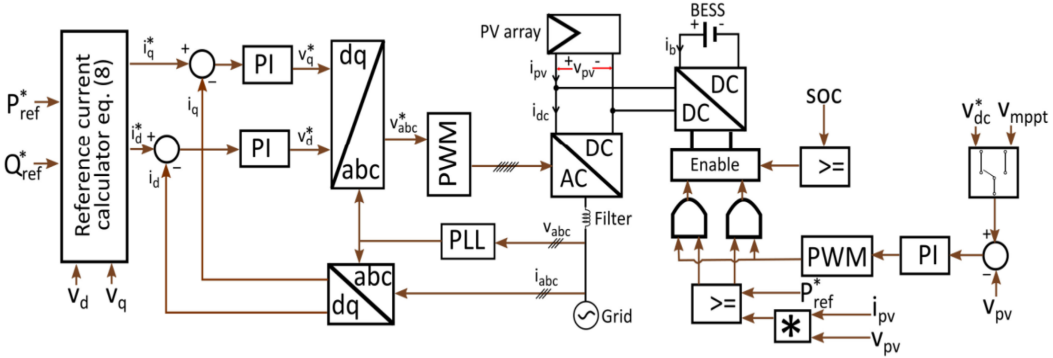

Figure: Proposed system schematic and configuration control scheme

Working

- System is capable of operating in different modes
- Allows the power sources to operate effectively and independently of one another.
- The inverter employs a voltage-oriented control scheme

$$i_d^* = \frac{2}{3}\frac{P_{\mathrm{ref}}^*}{v_d}, \qquad i_q^* = \frac{2}{3}\frac{Q_{\mathrm{ref}}^*}{v_q}$$

Figure: active and reactive current components

Mode 1

- Battery charges with the surplus available power.
- The battery dc–dc converter is operated in buck (charging) mode.
- Ensures MPPT stability

$$i_{b(c)} = \frac{\left(i_{\mathrm{pv}} - i_{\mathrm{dc}}\right)}{\left(V_{\mathrm{MPPT}} - V_{\mathrm{pv}}\right)\left(K_{ps} + \frac{K_{is}}{s}\right)}$$

Figure: converter current during charging

Block Diagram

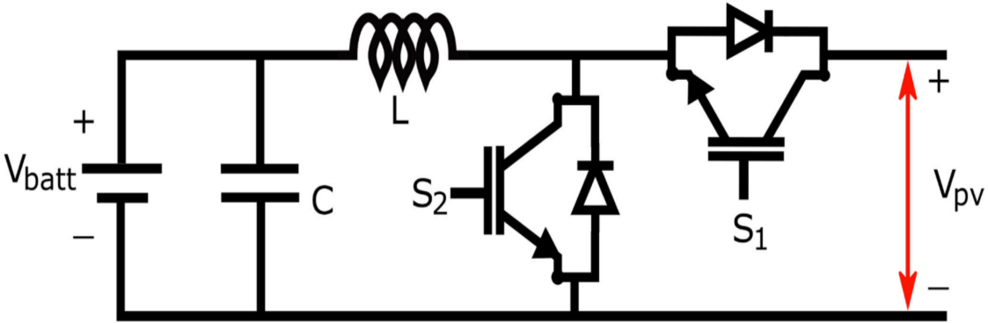

Figure: Buck/Boost Converter

Mode 2

- The dc–dc converter is operated in boost mode.
- PV array is operating at MPP while the battery supplies the deficit power.
- The battery may also be operated as an independent BESS storage system.

$$i_{b(d)} = \frac{\left(i_{dc} - i_{pv}\right)}{\left[1 - \left(V_{MPPT} - V_{pv}\right)\left(K_{ps} + \frac{K_{is}}{s}\right)\right]}$$

Figure: converter current during discharge

Mode 3

- When the battery SOC is beyond operation range or unavailable.
- The setup is operated as a single-stage PV system
- Inverter maintains the PV array at its MPP reference .
- Power will need to be curtailed during periods of excess irradiance.

LGE and KU E.W.Brown Universal solar facility

Figure: Solar Facility.

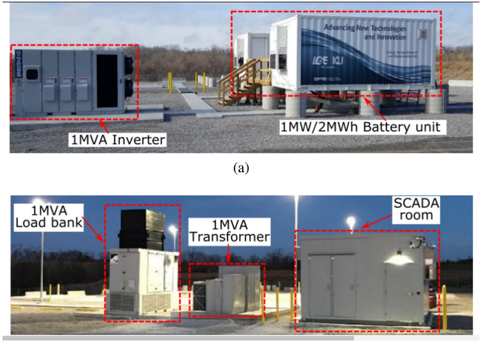

Figure: BESS Setup

Power Generated

- PV system dc output power is represented as a function of its irradiance and cell temperature.

$$P_{\mathrm{dc}S} = \left(\frac{\gamma}{1000} \cdot P_{r1}\right) \times \left(-\frac{0.41}{100} T_{\mathrm{cell}} + 1.1025\right)$$

- The power supplied to the grid (P_{gS}) is expressed as

$$P_{gS} = \begin{cases} P_{\mathrm{dc}S} & P_{\mathrm{dc}S} < P_{r2} \\ P_{r2} & \text{otherwise} \end{cases}$$

Battery Charging

- Power flow in the BESS is described as

$$P_{battS} = \begin{cases} P_{r2} - P_{dcS} & 0 < P_{r2} - P_{dcS} < P_{rb} \\ P_{rb} & P_{r2} - P_{dcS} \geq P_{rb} \\ 0 & \text{otherwise} \end{cases}$$

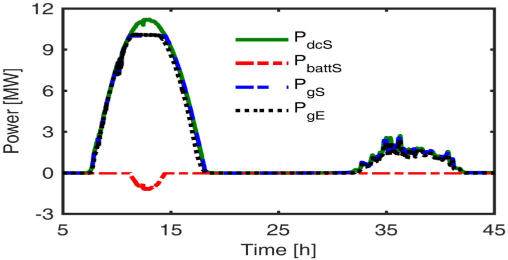

Figure: PV system output power

Curtailed Energy Calculation

- Amount of PV energy curtailed daily varies with different seasons of the year.
- Daily curtailed PV energy in the absence of a dc-connected storage is calculated as

$$\lambda_f = \int_{t0}^{t1} (P_{\mathrm{dc}S} - P_{gS})dt$$

contd.

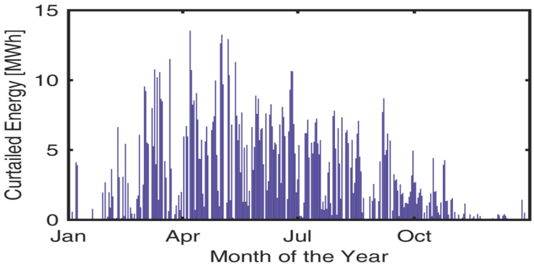

Figure: Daily Curtailed energy

- Annual PV energy curtailed is computed as

$$C_{yr} = \sum_{f=1}^{365} (\lambda_f - E_{bf}), \quad \text{where} \quad E_{bf} \leq E_{rb}$$

Curtailment Observation

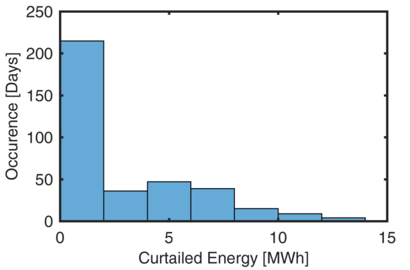

Figure: Daily curtailed power

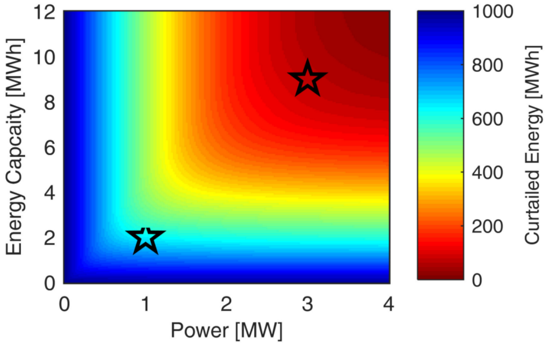

Figure: Annual PV energy curtailed

Sizing the BESS

- Value of C_{yr} was computed for multiple P_{rb} and E_{rb} combinations at 20 kW and 60 kWh intervals.
- 1:3 BESS power to energy ratio is the minimum rating combination.
- Increasing the BESS size above 2 MW/6 MWh does not lead to a significant reduction in the amount of energy curtailed

Field Implemented

- Up to 360 MWh of energy curtailed may be retrieved if a 1-MW BESS capable of storing up to 2 MWh.
- BESS rating is sufficient for satisfactory grid ancillary services;
  - PV power smoothing
  - frequency regulation
  - constant power production
  - Energy arbitrage

Validation

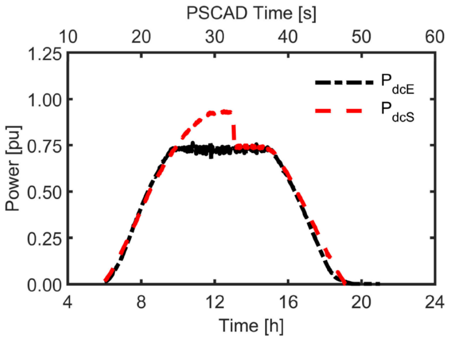

Figure: PV array P_{dc} output

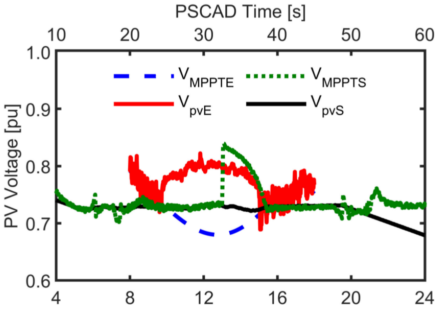

Figure: PV array MPPT reference

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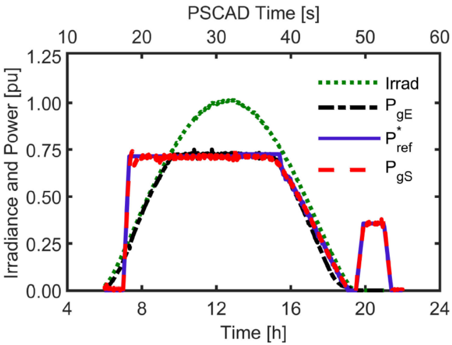

Figure: System output P_{ac}

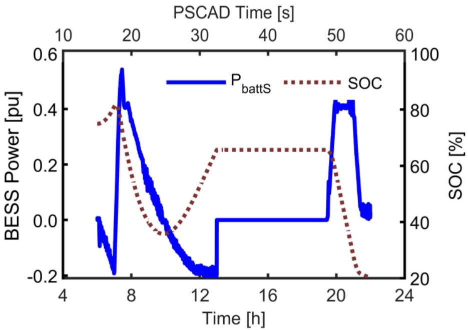

Figure: Battery net power flow SOC

Smoothing PV Power

- The PV smooth output power is

determine the sample mean of the saturated PV output estimated as

$$P_{\text{ref}}^{\text{MA}}(t) = \frac{P_{dcE}(t) + P_{dcE}(t-1) + \cdots + P_{dcE}(t - \Delta + 1)}{\Delta} \quad (14)$$

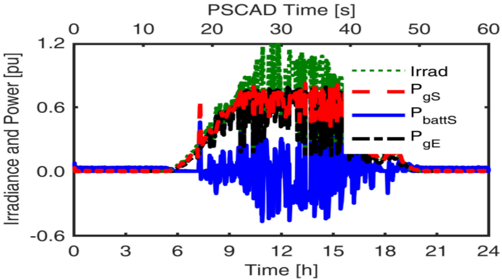

Figure: PV output power smoothing

Capacity Factor

- capacity factor (CF) defined as:

$$CF(\%) = \frac{\int_0^T P_g \, dt}{P \cdot T} \cdot 100,$$

- Increased the PV system capacity factor by approximately 13.3 %.

CONCLUSION

- Battery storage integrated into multi-MW grid-connected PV system through the use of a dc–dc converter.
- A general approach for sizing dc-bus connected batteries is developed.
- An increase in the annual capacity factor of up to 20% is possible with a dc-bus connected battery

References

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Thankyou!