# Synthetic Inertia for BESS Integrated on the DC-Link of Grid-Tied PV Inverters

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***Abstract*—The significant mechanical inertia of the rotor in a synchronous generator is crucial for facilitating the cooperative grid forming capability of multiple such generators on the transmission and distribution network. This paper demonstrates that the DC link capacitance in a PV inverter is the analogous form of inertia for such a system, albeit having much smaller magnitude. Furthermore it proposes using storage integrated on the DC link to synthesize extra inertia by programming the storage power electronics controller to achieve an emulated capacitance. Inertia added to distributed energy resources (DERs) in this manner is the first step towards mitigating the power quality issues arising from increased renewable penetration on the network. Demonstration of the acquired inertia dynamics and verification of the required controller design is shown through a detailed simulation model.**

***Keywords—Inertia; Synchronous Generators; PV Inverter; BESS; Emulated Capacitance***

## I. Introduction

Impact of high penetration of distributed energy resources (DERs) on the power quality of the distribution network is well known. As long as renewable (solar, wind, etc.) penetration levels had been low, as they were during the early adoption stages, the controllers for their power electronics interface could afford to assume a stiff unmovable grid. Put another way they mostly behaved as controlled current sources (Fig 1). But even then as renewable dispatch migrated from the medium voltage to the low voltage network and became more granular, ill effects started to become more pronounced [1-3]. Those ill effects manifest in the voltage, frequency, and harmonics and even affect overall system stability [4-5]. The brute force approach to resolve this power quality problem induced by DER's starts by obtaining complete global knowledge of the status of the whole network, coupled with securing capacity to centrally command all resources with minimal delay. Such a solution might resolve the problem, however would require humongous computational resources along with high throughput bidirectional communication channels to and from every single resource. This naturally does not scale well, if at all, as the number of DER's increases [6].

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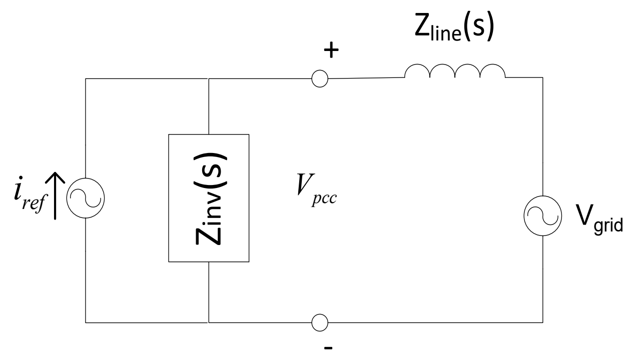


Fig. 1. Current source equivalent model of single DER without perfect disturbance rejection or infinite grid.

### A. Classical Control of Grid-Tied DERs

The classical techniques for controlling PV inverters for DERs present to the grid as ideal current sources. Typically those current sources are synchronized to the fundamental component of the voltage waveform at the point of common coupling ($v_{pcc}$) while rejecting any disturbances arising there. The synchronizing allows injection of real and/or reactive currents into the grid and is typically achieved by a Phase-Locked-Loop (PLL).

However, rejection of grid disturbances can never be perfect, therefore some output impedance $Z_{inv}$ will be present at the output of the DER as shown in Fig. 1 (the norton equivalent circuit form). This output impedance at the grid connected interface is determined by the particulars of the controller design such as controller type, bandwidth, inverter stage switching frequency and output filter (L, LC or LCL).

Also the grid varies in stiffness and is generally not infinite. The measure of the stiffness of the grid is the magnitude of $Z_{line}$, where an infinite grid implies $|Z_{line}| = 0$. Grid weakness coupled with less than perfect disturbance rejection degrades the overall stability of the system. Stability turns out to be dependent on $Z_{line}/Z_{inv}$ as follows,

$$\frac{i_{out}}{i_{ref}} = \frac{v_{pcc}}{v_{grid}} = \frac{1}{1+\frac{Z_{line}}{Z_{inv}}} \tag{1}$$

At lower penetration levels $Z_{line}/Z_{inv} \ll$ and the control loops for a single DER can be designed to obtain reasonable performance. But clearly higher penetration levels will cause the equivalent $Z_{inv}$ to decrease in magnitude, degrading power quality and ultimately causing the aggregate system stability to collapse.

### B. Traditional Control of Centralized Synchronous Machine Based Generation

The traditional electrical transmission and distribution network was historically organized around centralized energy generation from Synchronous Machines. The control of a multitude of such machines at different power plants distributed over a wide geographical area, was designed in a way that achieves synchronous operation and load sharing. Fig. 2 outlines how energy flows in such a setup, sourced from energy stores such as fossil fuels, geothermal or hydro. The energy is then stored in the rotating mass of the rotor, which acts as a large reservoir for that energy due to its substantial mass. Finally energy flows to the electrical network after passing through the stator inductance.

Load sharing was attained by programming frequency-power droop curves into the governor control for individual machines as demonstrated in Fig. 3. This whole control scheme and the attainment of regions of stable synchronous operation was feasible, despite lack of fast local controllers and high throughput communication links, mainly due to the very large inertia in the rotating masses of the aforementioned machines. It can be shown [9] that the natural frequency of such a system can be quantified by linearization to be:

$$\Delta\delta = A\,\mathrm{Sin}\left(\sqrt{\frac{P_s}{M\,S_B}}\,t\right) \tag{2}$$

Where $\Delta\delta$ is the drift in the power angle, $P_s$ is the synchronizing power coefficient, M is the angular momentum of the rotor and $S_B$ is the VA rating of the machine. Note that the typically large value of M makes the natural frequency of the machine low and therefore easy to stabilize against network disturbances. In addition the sizable stator inductance also plays a role in slowing energy transfer from the rotor to the electrical network and manifests a naturally occurring Volt-Var droop output characteristics. In summary all the aforementioned emergent small signal dynamics tend to naturally support the grid.

So this alternate, potentially simpler, and more scalable approach involves adopting the existing grid forming techniques historically developed for multiple large power plants down into the domain of PV inverter DER control. Those techniques are standardized as the so called "Large Generator Interconnection Procedures" or LGIP. Efforts were made to emulate the stator inductance component [3], because normal filter inductance in embedded PV DERs would be too bulky if designed to match the values found in typical machine stators. This sort of emulation can be considered to be the introduction of "Electromagnetic Inertia".

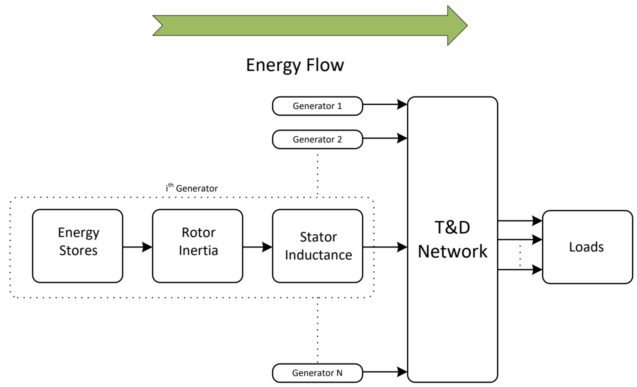


Fig. 2. Energy flow from generation to load in a typical transmission and distribution electromechanical system.

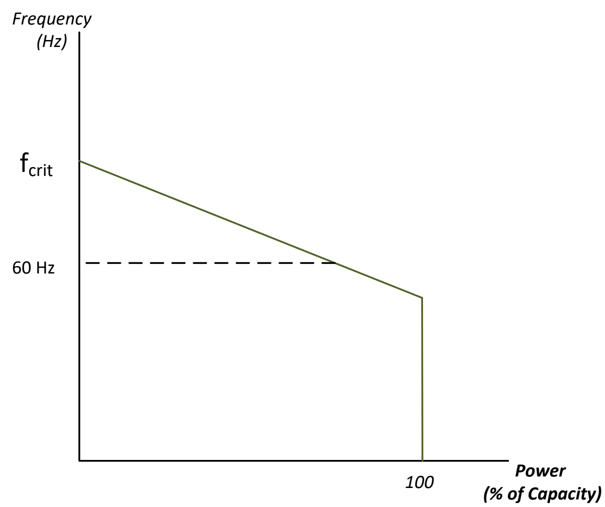


Fig. 3. Typical Frequency droop curve for each generator in a synchronous region of operation.

This paper instead proposes designing the controllers of the power electronics interfaces to emulate the mechanical inertia component in DERs. However, unlike electromagnetic inertia, mechanical inertia cannot be completely virtualized through controller design alone, and incorporation of energy storage is needed to achieve that. The dominant electrical energy storage technology for the grid is Battery Energy Storage Systems (BESS) that are either directly connected to the AC line or connected to the DC link of a PV inverter. This work's focus is on synthesizing inertia for the later.

## II. Proposed Inertia Synthesis On The Dc Link

The kinetic energy stored in the rotor of a synchronous machine is quantified by,

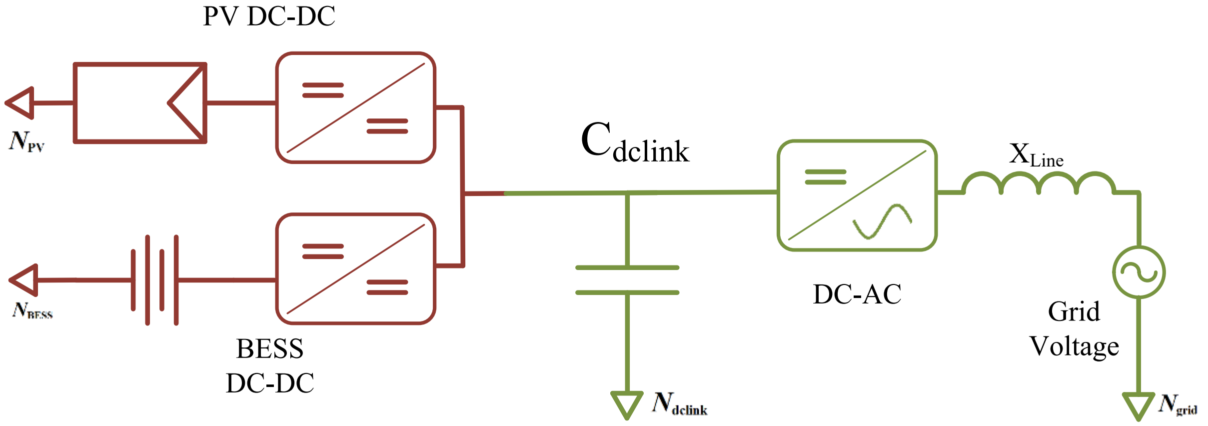


Fig. 4. Architecture of a DER consisting of a PV harvesting and optimization DC-DC stage, BESS DC-DC stage and inverter stage connected to the grid.

$$E_{kinetic} = \frac{1}{2}\frac{4I}{p^2}\omega_e^{\,2} \tag{3}$$

With $I$, $p$ and $\omega_e$ being the moment of inertia, the number of poles of the machine and the electrical angular frequency, respectively. The term $4I/p^2$ is a constant value dependent on the mass, size and geometrical orientation of the rotor. Energy flows from the chemical stores (such as fossil fuels) to the rotor, stator inductance and then the electrical network. Equation (3) shows that the frequency of the electrical system is much less sensitive to disturbances in the power flow if the inertia is significant, and indeed it is. Multiple generators cooperate to maintain synchronous operation across the transmission and distribution system through frequency droop control, which essentially links the frequency of the system to the percentage utilization of the nameplate capacity of every single generator, allowing seamless load sharing.

Fig 4 outlines one typical architecture of a PV and storage based DER. This system is quite analogous to the synchronous machine one described above, with solar insolation playing the role of fossil fuels, and energy flowing all the way to the electrical network.

The key analogy is that of the energy stored in the DC link capacitance to the energy stored in the rotor of the synchronous machine. Examining,

$$E_{dc} = \frac{1}{2}C_{dclink}V_{dc}^{\,2} \tag{4}$$

Demonstrates that $C_{dclink}$ is equivalent to $4I/p^2$ of equation (3), while the dc link voltage is equivalent to the angular velocity. In every way the DC link capacitance is the inertia of the DER system, therefore one immediate conclusion is this form of inertia is miniscule compared to the mechanical sort due to expense and technical limitations. Table I underscores how miniscule this capacitance inertia is by listing a sampling of inertia constants (Energy stored divided by VA rating) for some machines with a sample PV DER design.

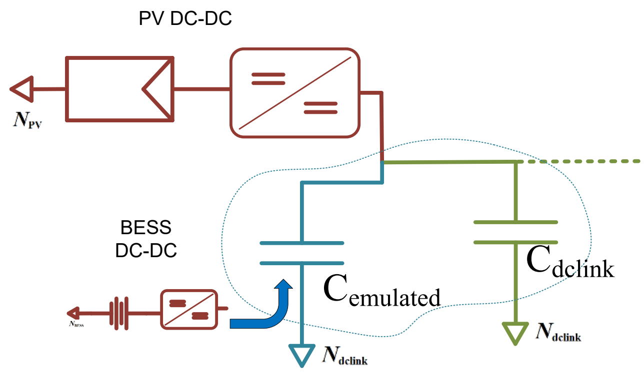


Fig. 5. Adding inertia to DER system through capacitor emulation in the BESS DC-DC converter.

TABLE I. INERTIA CONSTANTS FOR MACHINES AND PV DER

| System | $H_{sys}$ (s) |
|---|---|
| Steam turbines | 4-9 s |
| Gas turbines | 3-4 s |
| Hydro turbines | 2-4 s |
| Synchronous compensator | 1-1.5 s |
| PV DER (10 kVA, 400V bus, 10mF) | 0.08 s |

This default inertia can be beefed from energy stored in the BESS, which is connected through a DC-DC converter stage directly to the DC bus. The mechanism proposed to achieve that objective is to program the controller of the output stage of the BESS so it emulates a capacitor in its dynamics (Fig 5). This means the magnitude of the injected current from BESS to DC link bus should be proportional to the rate of change of the bus voltage.

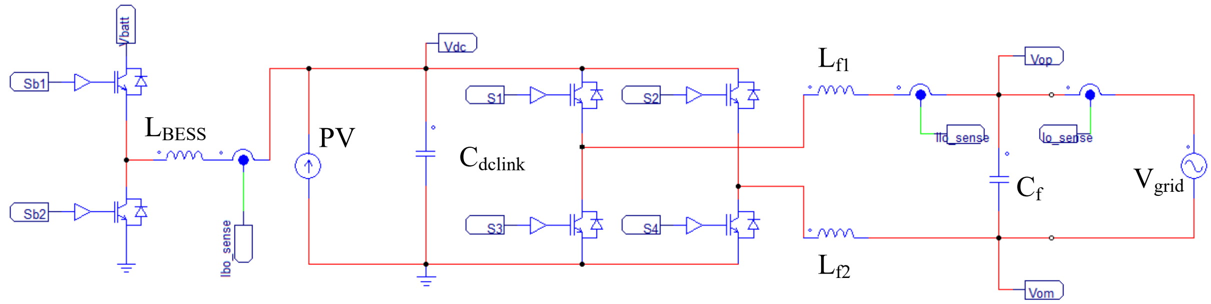


Fig. 6. PSIM model of DER system consisting of a 2-level inverter connected to a grid and a buck DC-DC stage for the BESS.

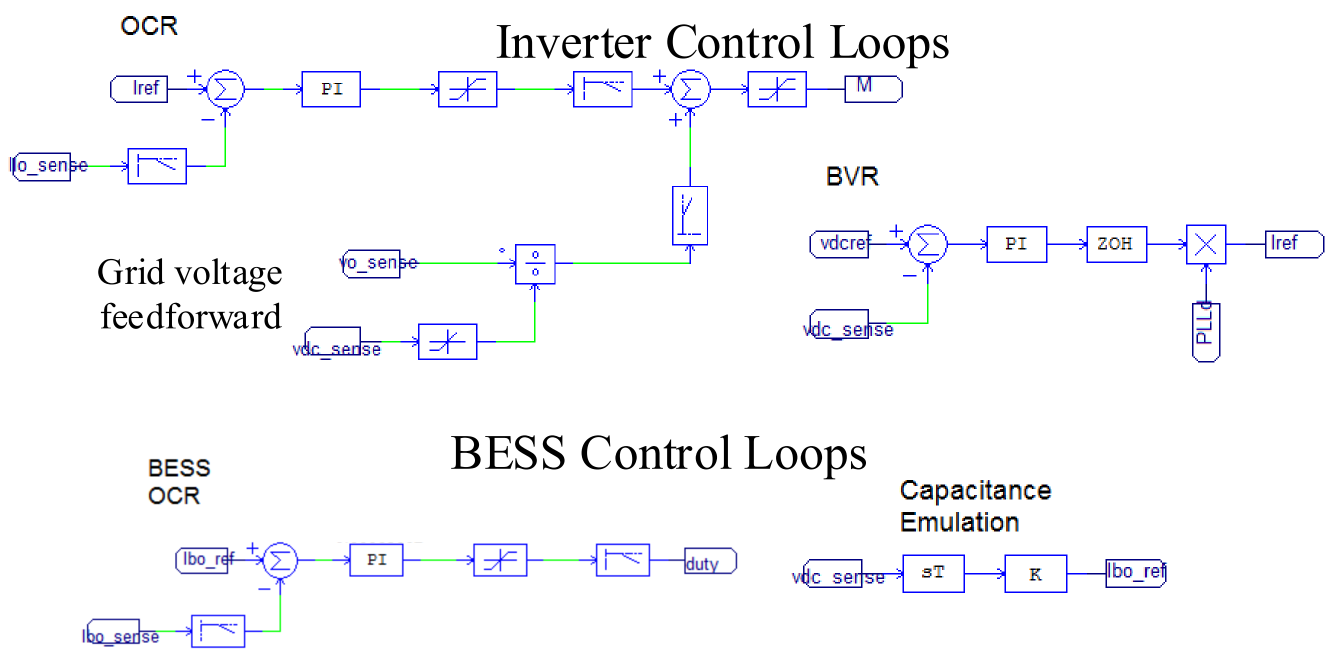


Fig. 7. Control loops for inverter and BESS DC-DC converter.

The introduced emulated capacitor is excess tunable inertia appended to the system. It is limited only by the rated capacity of the BESS DC-DC converter and the robustness of the controller algorithm in terms of stability and disturbance rejection.

## III. Controller Design and Simulation

Design of the proposed controller, and verification that it does indeed increase inertia is achieved through a simulation model developed in PSIM. Fig 6 details the BESS and inverter topologies used: a simple current mode buck converter for the BESS and 2-level full-bridge inverter for grid tie. All the necessary regulation loops have been design and tuned: the output current regulation loops for both BESS and inverter, the DC link voltage regulation loop and the BESS capacitance. A snapshot of the control loops implementation in PSIM is shown in Fig 7. A simulation run has been executed based on the parameters outlined in Table II. Effect of increased inertia was recorded at the 120 Hz power pulse frequency induced by the single phase inverter stage, which manifested as a decrease in the DC link voltage ripple by 75% (Fig 8 and 9).

TABLE II. Simulation Parameters of DER System

| Quantity | Value |
|---|---|
| Inverter rating | 8 kW |
| Grid voltage | 240V, 60 Hz |
| Inverter output filter inductors ($L_{f1}$, $L_{f2}$) | 50 µH |
| BESS output stage inductance ($L_{BESS}$) | 250 µH |
| DC link voltage | 400 V |
| BESS input voltage | 460V |
| DC link capacitance | 10 mF |
| BESS emulated capacitance | 30 mF |
| PV system insolation | 8 kW |
| BESS system rating | 5 kW |
| Switching frequency | 25 kHz |

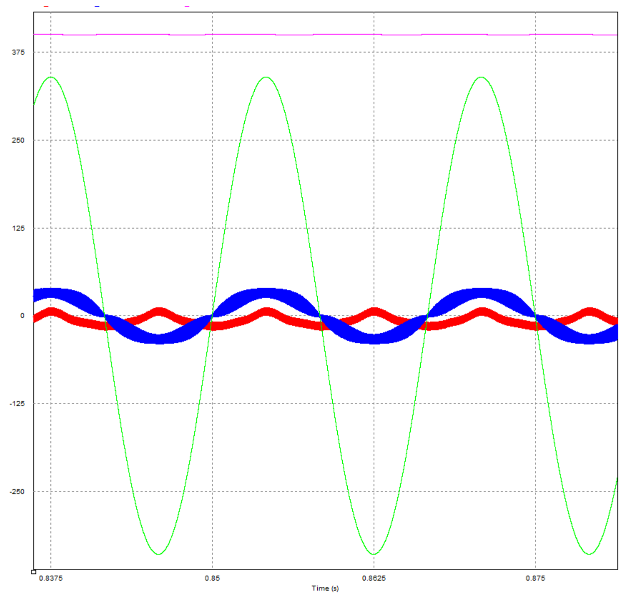


Fig. 8. Simulation results: Grid voltage (green), inverter output current (blue), BESS injected current (red) and DC link voltage (pink).

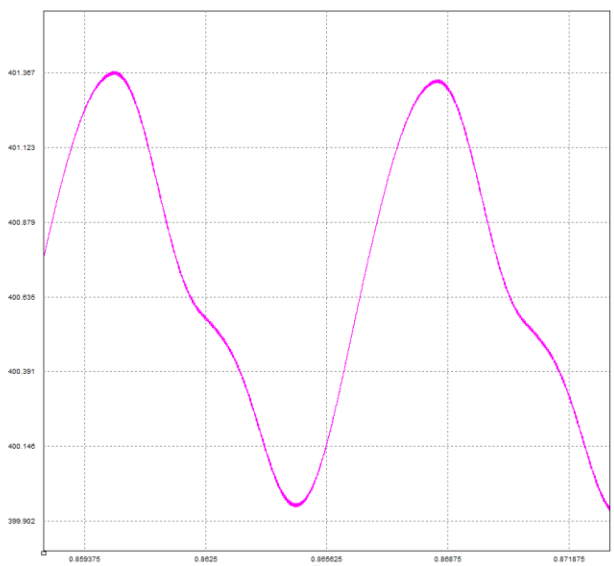


Fig. 9. Detail of 120 Hz ripple in DC link voltage. Increased inertia is demonstrated by reduction of peak to peak ripple to 1.4V, from 5.2V

## IV. Conclusions And Future Work

The need for synthetic inertia for PV and storage based DERs was argued in this work, and a viable controller design was proposed. The design has been validated in simulation for this digest. Future work includes further analysis of control corner cases, determining stability analytically, and implementation on a hardware prototype.


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