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LVRT of Grid Connected PV System with Energy Storage

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Abstract: A grid-connected PV system consists of solar panels, power conversion units, power balancing unit and grid link equipment. The installations of grid-connected DG systems have experienced a significant increase in the past few decades. Low Voltage Ride-Through (LVRT) is one of the most dominant grid connection requirements to be met by PV power generation systems. With increasing penetration of DG, the fault ride through (FRT) capability of DG inverter poses major concern as the failure may lead to serious power system issues and also blackout. This paper presents an improved PV based grid connected system with Maximum Power Point Tracking (MPPT) and energy storage system in such a way that the DG power conversion unit remains connected to grid even during fault conditions as long as conditions specified by modern grid standards are satisfied.

Keywords: Low voltage ride through, energy storage, fault ride through, battery energy storage system, distributed generation, photovoltaic, renewable energy systems.

1. INTRODUCTION

The installations of DG systems along with grid-tied systems, have experienced a major increase in the past few decades. More capacity is expected for the future power grid. This thriving scenario also raises concerns about the availability, quality and reliability of the whole power grid. Consequently, grid codes and standards are continuously being revised to host more energy in the grid. With this increased penetration of DG systems into grid, fault tolerance of these DG systems became one of major concerns as the sudden tripping of DG from grid during faults results in serious problems such as voltage flickers, power outages and may even cause blackout. Hence high power DG systems must be considered as conventional systems and they need to support grid even during fault conditions.

Till now various strategies have been developed for fault ride through of wind energy based DG systems as they constitute more power [1], [2]. Various solutions such as crowbar circuit, DC Chopper, Series dynamic braking resistor are proposed for LVRT of wind energy based DG systems. But nowadays size and number of solar projects are increasing and grid interconnection issues become increasingly important. Also these projects are expected to increase in future as the installation of this type of systems are encouraged by governments. When the level of solar penetration is low, the ability of a solar plant to impact the grid is minimal, but as solar power continues to expand, the potential for grid impact increases. Hence, with the increasing penetration of PV based DG systems, low voltage ride through (LVRT) and dynamic voltage support (DVS) of grid connected PV systems are gaining significance. Various solutions for LVRT are discussed in [4]-[6].

The LVRT standard of India given by Central Electricity Authority (CEA) [3] is shown in Figure 1.

Where, V_T/V_N is the ratio of actual voltage to the nominal voltage.

In [4], LVRT is achieved by controlling the input power to DC link capacitor by controlling the firing angle of boost converter when overvoltage appears across DC link. In this method, the system deviates from maximum power point during low voltage ride through. In [5], LVRT is achieved by controlling the input

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to capacitor by discharging the excess power input by connecting a resistor parallel to DC link through a switch when the voltage across DC link is greater than the reference voltage. In this method also the system deviates from maximum power point during fault ride through. Controlling the input to DC link deviates the system from MPP. Hence the efficiency of PV system decreases. However this is for a small period. For controlling the output voltage across DC link the system need not deviate from maximum power point. Hence, a novel strategy is developed to control output voltage of DC link by using energy storage.

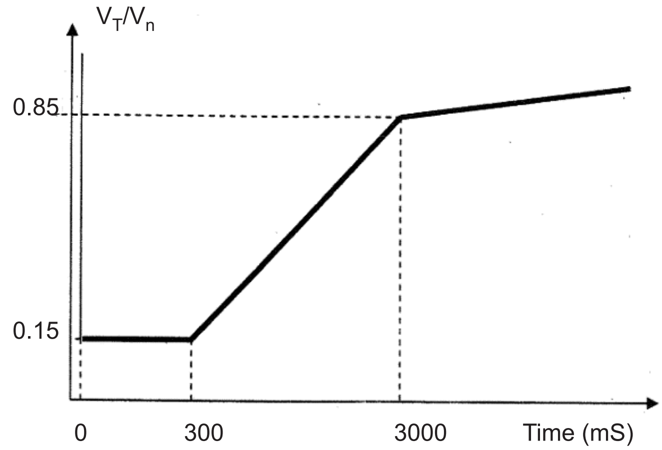

Figure 1: LVRT specification

2. MATHEMATICAL MODEL OF PV MODULE

The solar cell is made up of the *pn*-junction diode which is used for the conversion of light into electricity. A PV cell can be mathematically represented by using Single diode model [7].The mathematical modelling of the PV array is shown in the following figure, in the form of an equivalent circuit that includes diode and ground leakage currents [9].

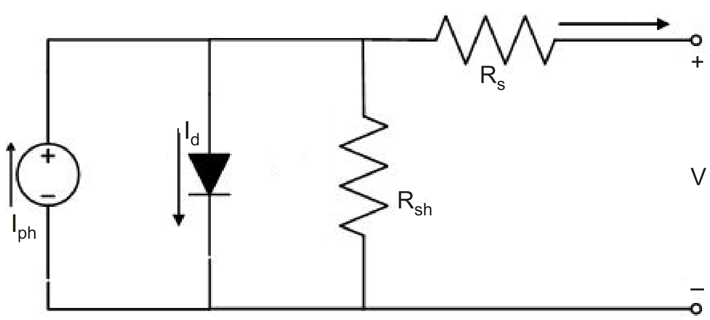

Figure 2: DC Equivalent Circuit of PV Module

Where,

I_{ph} – Photo current of cell

I_D – Diode current

R_s – Internal series resistance

The open circuit voltage (V_{OC}) of the PV cell is given by:

$$V_{oc} = V + IR_{pa}$$

The diode current is given as:

$$I_d = I_o\left(e^{\frac{QV_{oc}}{A\,kT}} - 1\right)$$

Where,

I_o – Saturation current of diode

Q – Electron charge = 1.6×10^{-19} C

K – Boltzmann constant = 1.38×10^{-23} J/°K

Module photo current is given by

$$I_{ph} = I_{sc} + K_i (T - 298) \times \lambda/1000$$

Module reverse saturation current is

$$I_{rs} = I_{sc}/[e^{(Q\,V_{oc}/N_s\,kAT)} - 1]$$

The module saturation current I_O varies with the cell temperature, which is given by

$$I_o = I_{rs}\left[\frac{T}{T_r}\right]^3 e^{\left[\frac{Q \times E_{go}}{Bk}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right]}$$

The current output of PV module is:

$$I_{pv} = N_p \times I_{ph} - N_p \times I_o\left[e^{\left(\frac{Q \times (V_{pv} + I_{pv}R_s)}{N_s\,kAT}\right)} - 1\right]$$

Where,

I_{PV} – PV module output current (A)

V_{PV} – PV module output voltage (V)

T – Operating temperature of module in Kelvin

T_r – Reference temperature = 298 K

I_{ph} – light generated current in PV module (A)

I_o – PV module saturation current (A)

Q – Electron charge = 1.6×10^{-19} C

K – Boltzmann constant = 1.38×10^{-23} J/°K

A = B – Ideality factor of diode = 1.6

R_S – PV module series resistance

I_{SC} – Short-circuit current of PV module at 25°C and 1000 W/m^2

K_i – Short-circuit current temperature coefficient at I_{sc}

λ – PV module illumination (W/m^2)

E_{go} – Band gap for silicon = 1.1 eV

N_S – Number of cells connected in series

N_P – Number of cells connected in parallel

3. MPPT

The output of PV module is not constant. Hence PV system has irregular V-I characteristics and has unique maximum power point. The V-I and P-V characteristics of a PV cell are shown in Figure 3 and Figure 4.

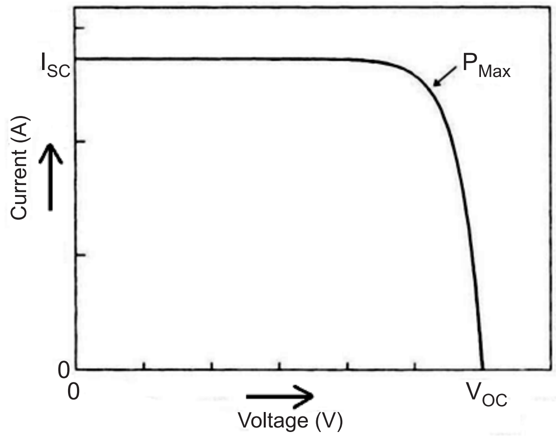

Figure 3: V-I Characteristics of PV cell

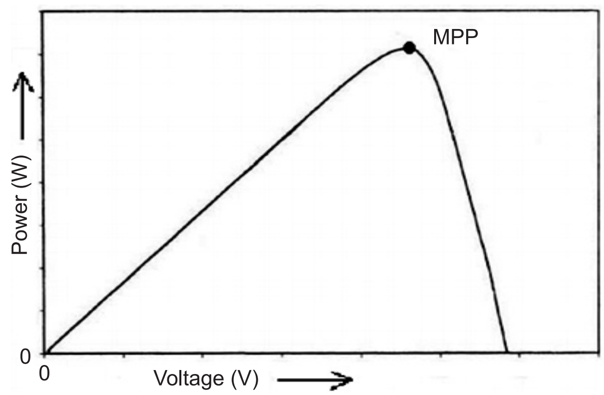

Figure 4: P-V Characteristics of PV cell

With respect to changing weather conditions we need to track maximum power output of PV array. In this work, maximum power point tracking is done by using perturb and observe (P&O) algorithm [8] as it is simple and fast in execution. This algorithm compares previous and present powers and voltages and adjusts the duty cycle accordingly. The flowchart of P&O algorithm is shown in Figure 5.

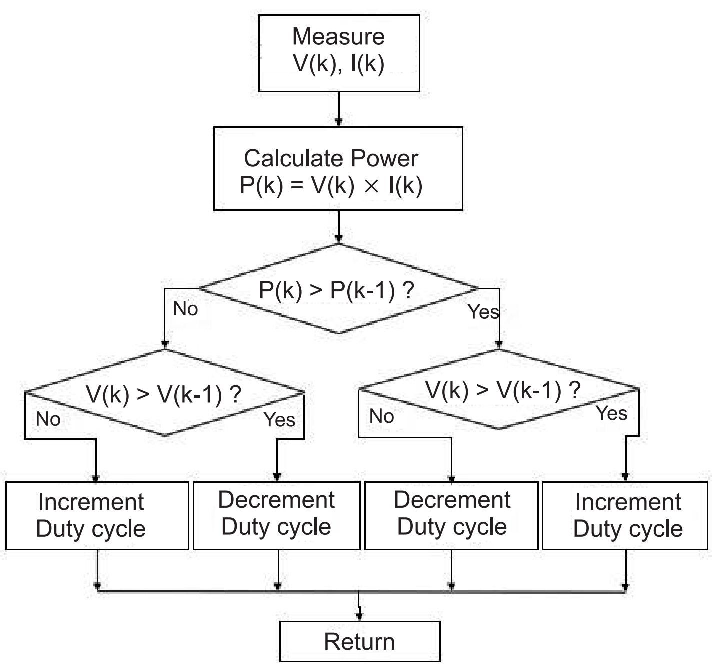

Figure 5: Flowchart of Perturb and Observe algorithm

As the output of PV module is not constant a DC/DC converter should be used. Hence, a boost converter is used for this purpose. The circuit diagram of boost converter is shown in Figure 6.

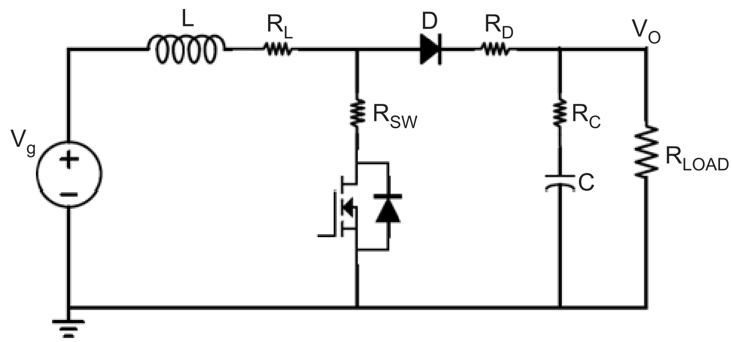

Figure 6: Circuit diagram of boost converter

The boost converter is designed according to its design equations. The values that are obtained by solving design equations are L = 5 mH and C = 24 mF. The output voltage is maintained at 500 V DC.

4. FAULT RIDE THROUGH

In general all the DGs operate in grid voltage following mode. If there are grid derived voltage fluctuations or fault, then these DGs gets disconnected from grid. But in the present scenario, with high penetration of DGs these systems should be connected to grid as conventional generators rather than distributed generating systems even during fault conditions. When there is a fault on grid, then DG systems gets disconnected from grid. This will remove a large amount of generation from grid. This sudden disconnection of DGs impose a heavy load on conventional generators and this leads to serious power system issue and finally result in blackout. Hence, modern grid codes also state that the DGs should have low voltage ride through capability.

LVRT enables the DG inverter to remain connected to grid and supply power even during low voltage on grid side without any damage to power electronic converters connected to DG. LVRT broadens voltage sag tolerances and prevents sudden disconnection of DGs from grid upto some extent.

5. PROPOSED SYSTEM

The proposed system consists of a 200KW PV system along with a battery energy storage system (BESS) connected to grid through a circuit breaker. Battery is connected to DC link through a bidirectional DC/DC converter. The proposed system implements low voltage ride through by using battery energy storage system and circuit breaker control. The block diagram of the proposed system to implement LVRT is shown in Figure 7.

The controller tracks maximum power point and operates boost converter accordingly. It also senses the voltage across DC link and switches the bidirectional DC/DC converter accordingly. It also switches circuit breaker according to the specifications and grid voltage.

The control to bidirectional DC/DC converter is given such that if the voltage at DC link is within the limits then the bidirectional DC/DC converter is in OFF condition or else it is in ON condition

During normal operation, the voltage across DC link is constant and hence the bidirectional DC/DC converter is in off condition unless the voltage at DC link goes beyond the limits. During fault condition over voltage appears across DC link and the controller detects this and operates bidirectional DC/DC converter in buck mode and sends extra charge available at DC link to charge the battery through bidirectional DC/DC converter. If the voltage across DC link is lower than required voltage, then the controller operates bidirectional DC/DC converter in boost mode and the DC link gets charged from battery.

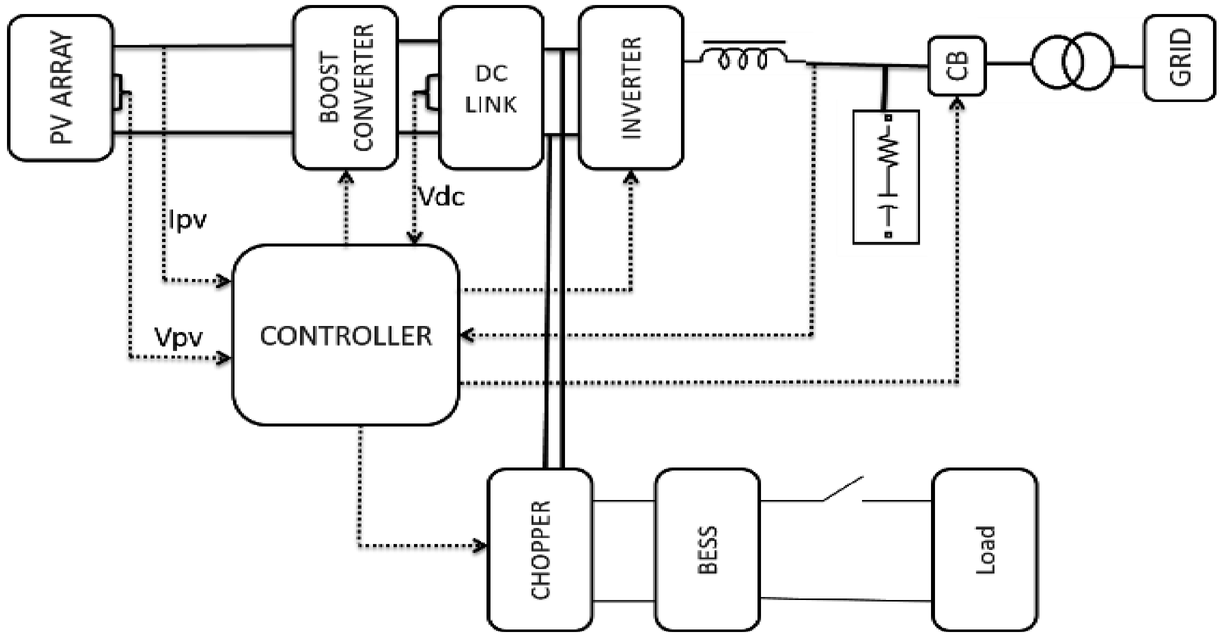

Figure 7: Block diagram of proposed system

The controller senses grid voltage and takes ratio of grid voltage and nominal voltage. If this ratio is within the specified limits mentioned by CEA then the system remains connected to grid or else gets disconnected.

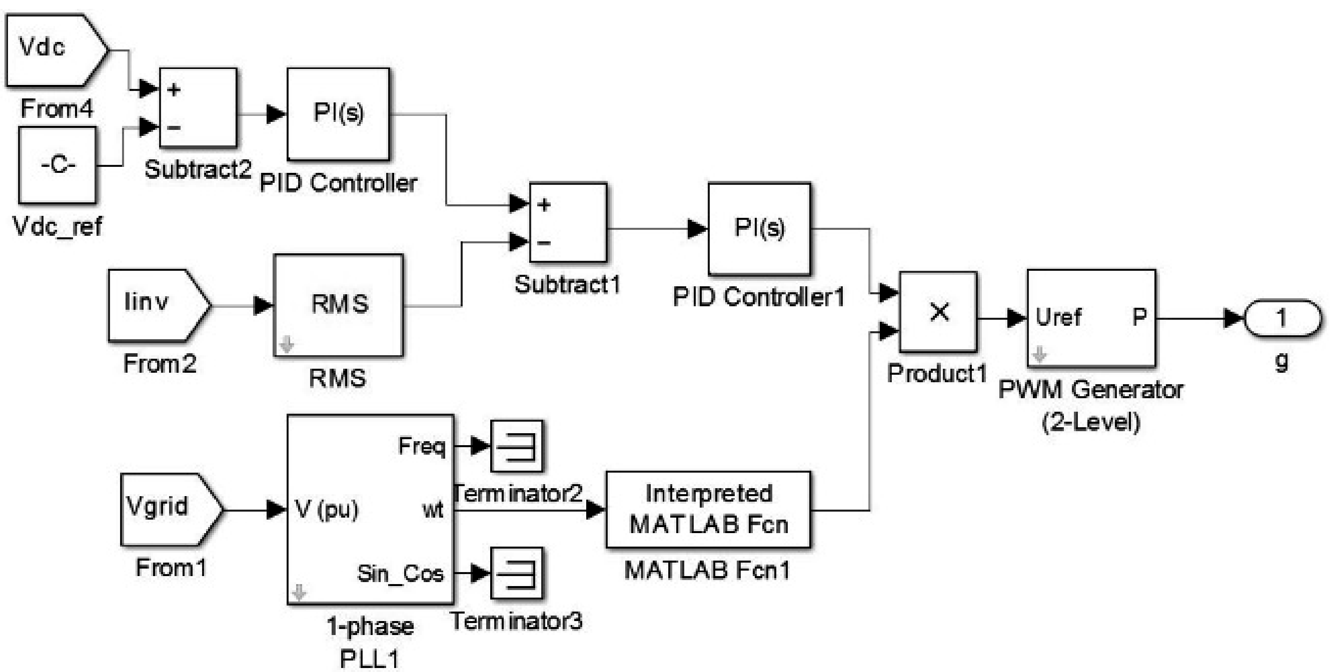

Figure 8: Inverter Control

Figure 8 shows the control method employed to synchronize the system with grid. Constant dc link voltage control is used. Current reference is derived from the DC link voltage. Current from inverter is compared against reference current and it is given to PI controller to derive reference voltage. Phase locked loop is used to track angle from grid voltage. The reference voltage is multiplied with sin of the angle derived from PLL. This signal is sent to pulse width modulation to generate firing pulses for inverter.

6. RESULTS

Figure 9 shows the voltage from PV panel before tracking maximum power point.

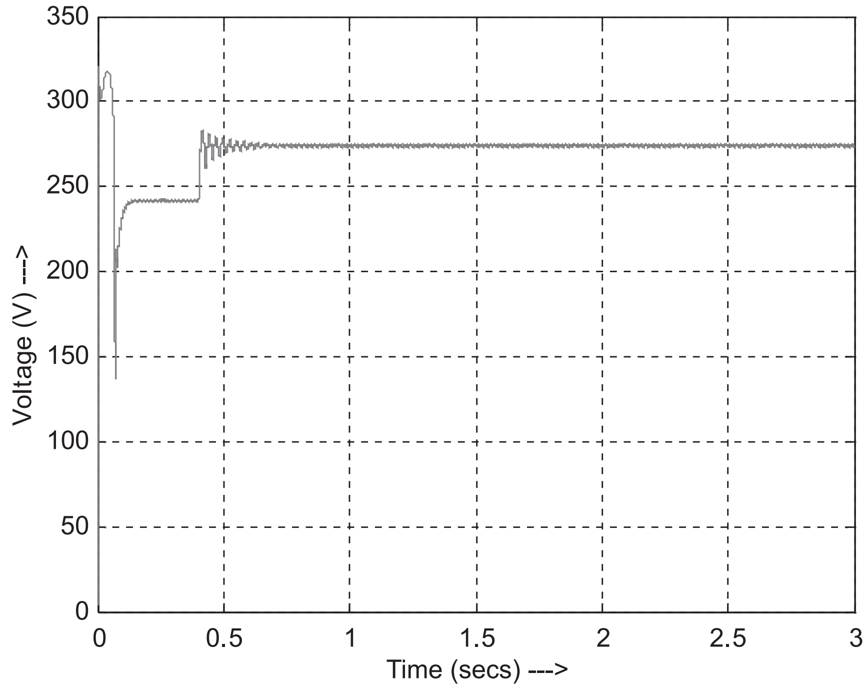

Figure 9: DC voltage from PV panel before MPPT

Figure 10 shows the output DC voltage at DC link after tracking maximum power point.

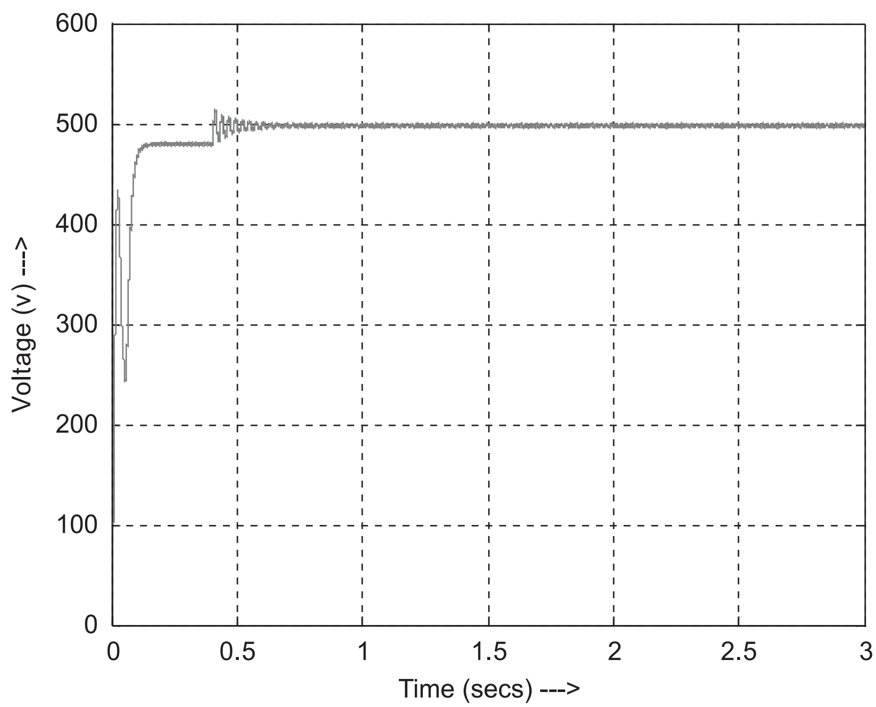

Figure 10: DC link voltage after MPPT

Figure 11 shows the output power from PV system after tracking maximum power point.

From the above figures we can say that the PV system works at maximum power point after MPPT and the output voltage is maintained constant.

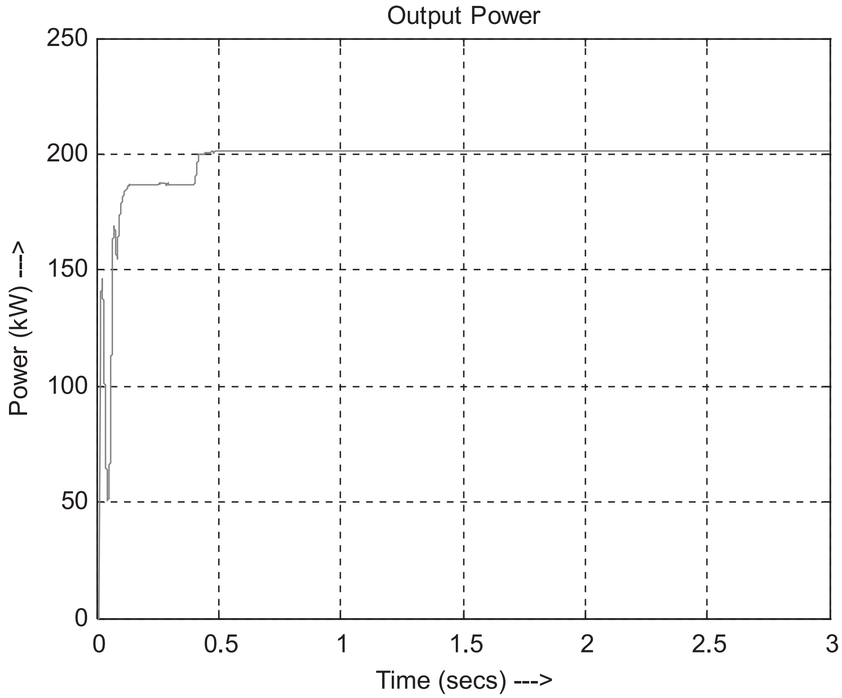

Figure 11: Output power after MPPT

Figure 12 shows real power sent by the system without battery energy storage system and Figure 13 shows real power sent by the system with battery energy storage system.

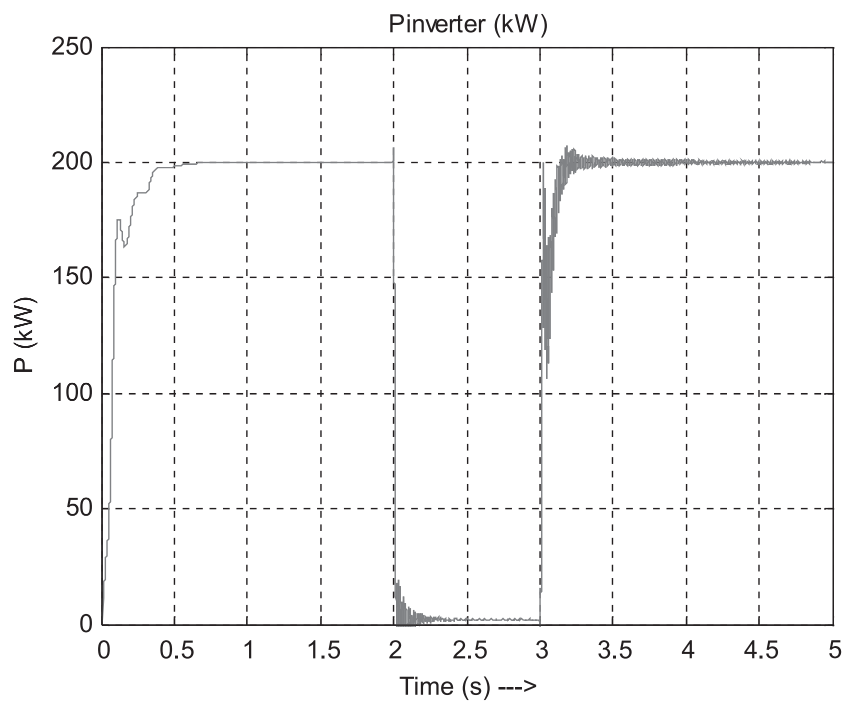

Figure 12: Real power sent by inverter (without BESS)

For grid tied PV system, a fault is created for a period of one second. Before occurrence of fault and after clearance of fault, the system supplied 200KW. But during fault condition, the system without BESS doesn't supply real power during fault condition whereas the proposed system supplied real power during fault condition also. This shows that the DG remains connected even during fault period without any damage and supports grid by sending real power.

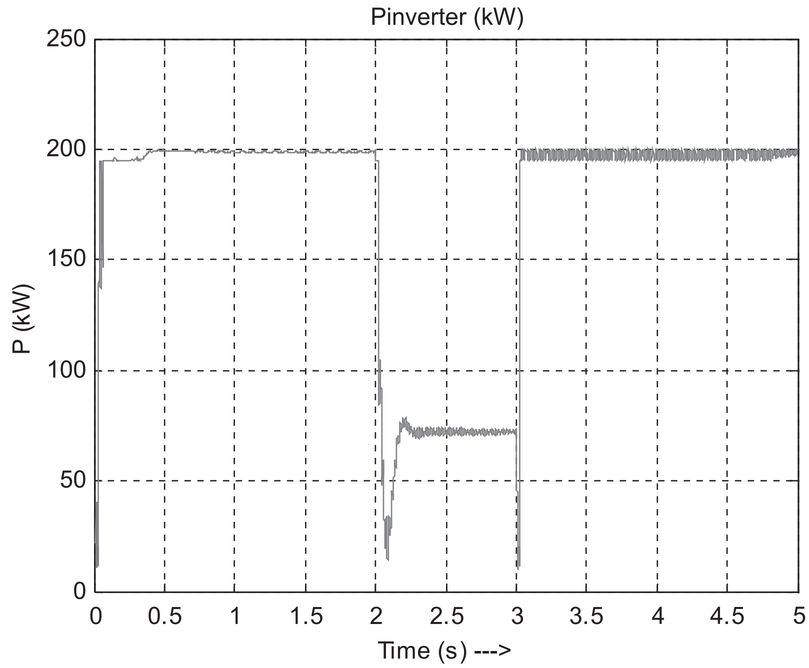

Figure 13: Real power sent by inverter (with BESS)

Figure 12 shows the voltage across DC link of the system without battery energy storage system.

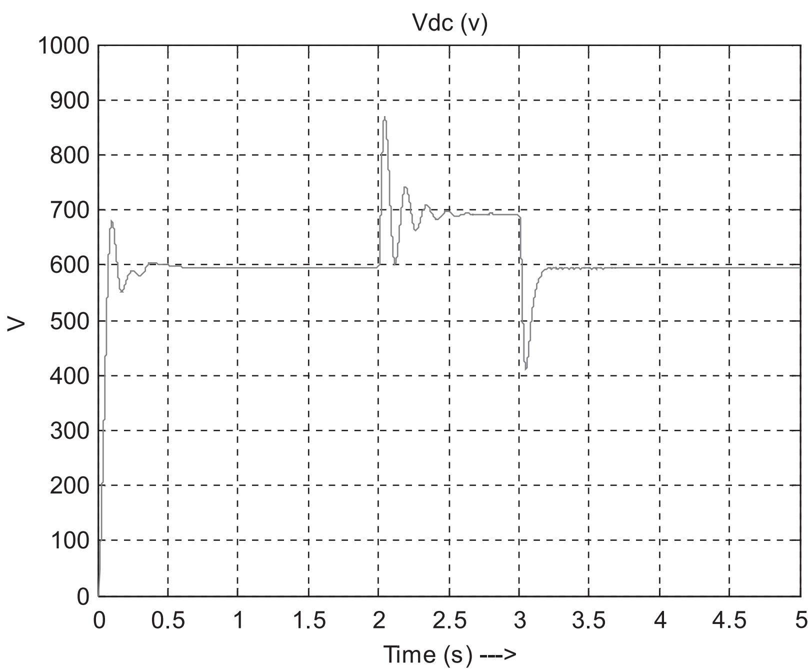

Figure 14: Voltage across DC link (without BESS)

The voltage at DC link is maintained within limits during pre-fault and post fault conditions. But during fault the voltage at DC link raised to a high value (900V). This can damage converter systems.

Figure 13 shows the voltage across DC link of the system with battery energy storage system.

This shows that the battery energy storage system maintains the voltage across DC link within limits (500V to 600V) even during fault conditions. Hence, the system can remain connected to grid without getting damaged even during fault conditions as long as conditions specified by modern grid standards are satisfied.

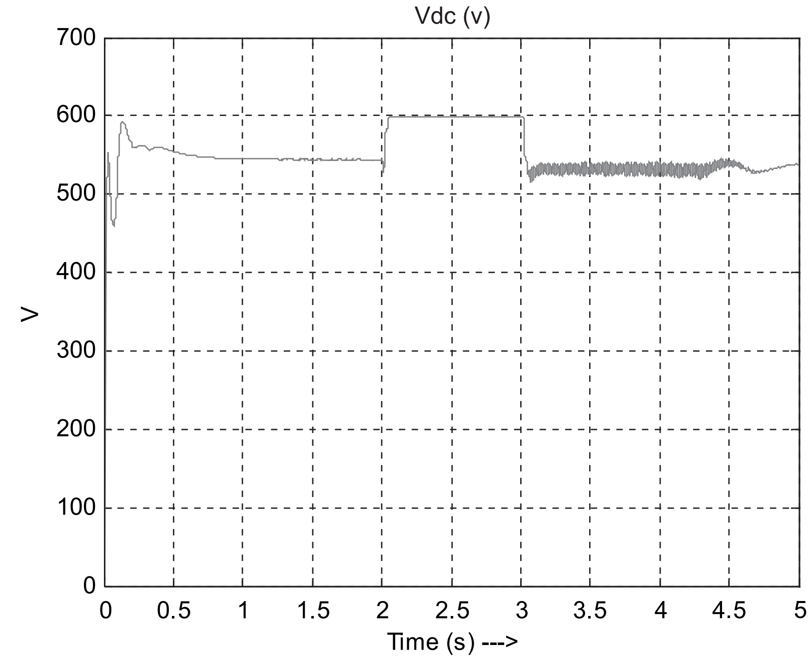

Figure 15: Voltage across DC link (with BESS)

Figure 14 shows the state of charge of the battery used in battery energy storage system.

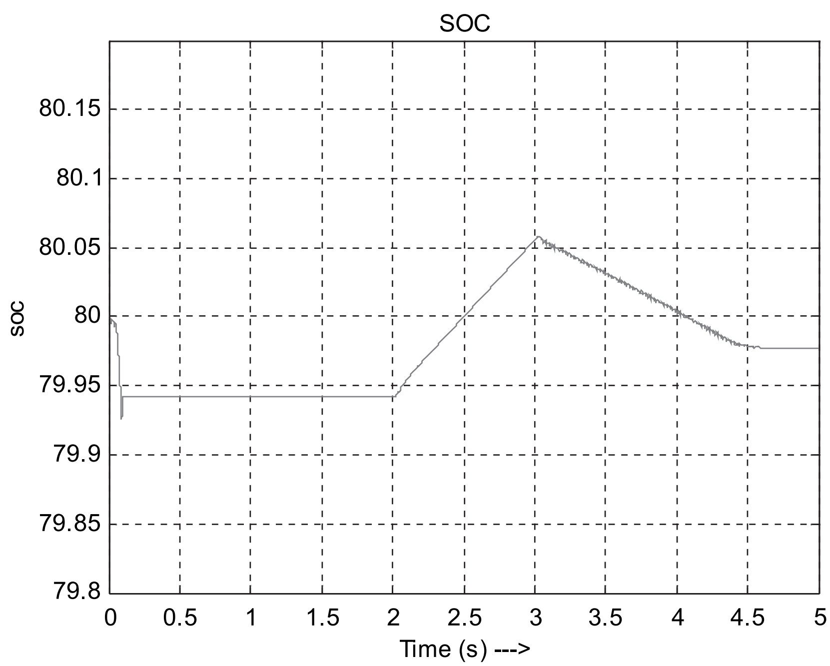

Figure 16: State of charge (SOC) of battery

When the system starts, the voltage across DC link is zero and hence BESS supplies to charge DC link. Hence, there is slight decrease in state of charge of BESS. Once the DC link gets fully charged BESS stops supplying to DC link. From this point the state of charge is constant until fault occurs. When fault occurs and the voltage across DC link increases beyond its limit, then BESS draws extra power. Hence, the state of charge increase. After fault due to flicker, the voltage across DC link decreases beyond its minimum limit and BESS again supplies until DC link gets fully charged. Hence, there is a slight decrease in state of charge. This shows that the BESS maintains the voltage across DC link within the limits.

Figure 15 shows the reference voltage given to C.B controller and the operation of C.B.

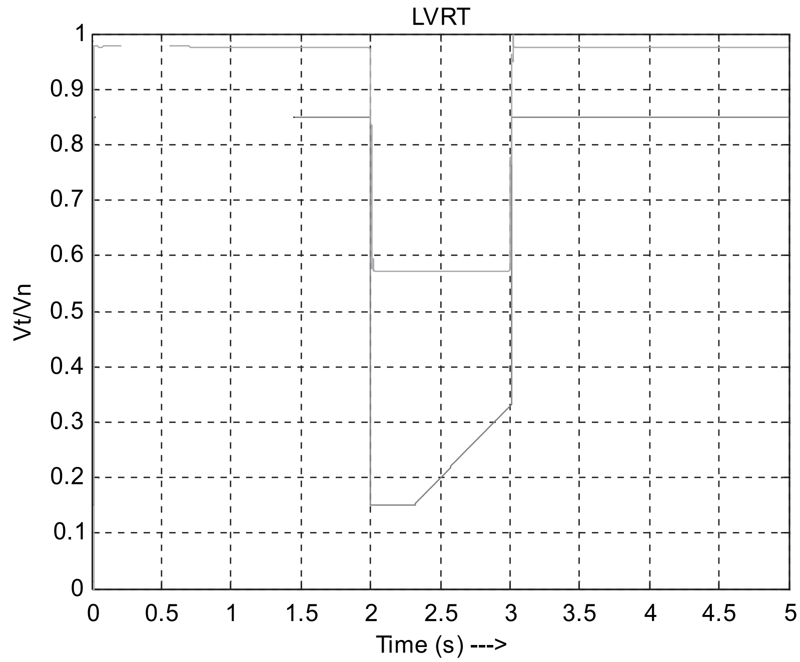

Figure 17: Reference voltage given to C.B controller

In the above figure, the top line represents grid voltage (V_T/V_N ratio) and the second graph (bottom graph) represents the specification given by CEA. This second signal is given as reference and the first signal is compared against the second in CB controller. As the ratio (first signal) doesn't violate the specification, the system remains connected to grid. This shows that the DG system remains connected to grid as long as the ratio satisfies the specifications and gets disconnected when violated.

7. CONCLUSION

LVRT is a common phenomenon during the faults of micro grid connected to the mega grid. This LVRT can be achieved by controlling voltage at DC link capacitor. The voltage variations at the link capacitor can be kept within the desired limits by using bidirectional DC/DC converter.

Thus, the proposed system implements LVRT without compromising efficiency of PV system. It also supports grid by sending active power during faults also. The C.B disconnects the system from grid if the fault conditions are not satisfied as specified by modern grid codes.

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