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Implementation of Control Strategies for Optimum Utilization of Solar Photovoltaic Systems with Energy Storage Systems

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Abstract- Solar Photovoltaic (SPV) system primarily based on autonomous system have advanced as a promising solution to the problem of electrification in areas where the network is now not available. The main challenges in designing such systems are as follows: 1) extraction of maximum power from PV system under fast varying irradiance; 2) extraction of high voltage gain with DC-DC converter; 3) development of efficient power management scheme between SPV and Energy Storage System (ESS). As multiple objectives must be satisfied, existing schemes for autonomous systems require a minimum of three conversion steps, which leads to significant reduction in the reliability and efficiency of the system. The above issues are addressed with different control strategies. For extraction of maximum power a modified non iterative Incremental Conductance MPPT method is developed to generate a fine tuned duty cycle for sudden change in irradiance and regulates that always the intersection point of load line and I-V curve represents Maximum power point (MPP). High voltage gain DC-DC converter generally required for industrial applications and can be achieved by high duty ratio which cause reverse recovery problem and voltage stress on power switches. To overcome this problem a soft switch interleaved boost converter (SSIBC) is proposed which is operate on zero current switching to turn ON active switches and it can achieve high voltage gain for lower duty ratios. Lead acid battery is an energy storage device which is used in SPV systems. Finally to achieve power management, variable DC bus voltage based algorithm is developed with super capacitor (SC) and battery (BAT) as ESS. The capability of the proposed control strategies is tested and validated under various scenarios

Keywords battery protection, high voltage gain DC-DC converter, stand alone solar pv system, energy storage system, power management scheme.

1. Introduction

The performance and efficiency of medium and large scale Photovoltaic (PV) plant mainly depends on power conversion process through power electronic converter interfaced between PV plant and the distribution grid or load. The power conversion system used in the existing Solar PV (SPV) plant involves high cost and reduced efficiency, due to more than one power conversion stage [1]. The existing single stage power conversion system has low voltage gain, common mode leakage current problem and requires more number of PV panels to get the desired output. Moreover the output power from PV plant is intermittent which affects the reliability of supply and performance of power converters [2]. The fluctuating power leads to the harmonic injection into the grid, and affects real and reactive power flow resulting in the reduction of efficiency of the power conversion system. To overcome the above problems and to improve the performance of PV power conversion system this research work develops a multistage DRSS and SDC algorithms to enhance the performance of PV systems This research work also investigates Maximum Power Point Tracking (MPPT) for PV system. MPPT controller is used to extract the maximum available power from PV plant, so that efficiency of PV system can be increased. In this research work power electronic based MPPT controller is used [3-5]. The conventional MPPT algorithms have large oscillations due to continuous perturbation, sluggish response and low efficiency due to ripple in the output voltage and require more number of sensors during the sudden changes in irradiance condition. To minimize the above shortcomings a new MPPT algorithm has been developed with slope detection method and variable step perturbation and observation algorithms[6, . The performance of the proposed algorithm is investigated and compared with variable step incremental conductance and based on step change in irradiance condition, efficiency, ripple and response time.

2. Problem Statement and Objectives of Research Work

The solar-powered system introduces a variety of issues based on climate conditions. These problem formulations are listed as follows: 1) the conductance of solar cell was non-linearly fluctuating with climatic changes, which had produced in false Maximum Power Point. To overcome this problem modified Incremental Conductance MPPT method is developed to generate a fine tuned duty cycle and regulates that always the intersection point of load line and I-V curve represents MPP under fast varying irradiance; 2) Normally a DC-DC boost converter can provide a high voltage with high duty ratio but this voltage gain is limited by inductor, capacitor and main switches in the converter. Another problem with high duty ratio is reverse recovery problem which increases the switching losses; 3) there will be wide variations in DC bus voltage in standalone PV system and mismatch power between generation and demand. To overcome this problem hybrid ESS (super capacitor + battery) is connected in parallel with PV system and a high efficient variable DC bus voltage based power management algorithm is proposed between PV, SC, BAT and utility grid.

3. Proposed Control Strategies

3.1. *Modified Incremental Conductance MPPT under fast varying irradiance:*

To extract the maximum power from solar PV systems MPPT technique is used. A number of MPPT methods are there to track maximum power with high efficiency under constant irradiance such as P&O [7-11], INC [12-15], PSO [16-19], ANN [20-23] [32], Open circuit voltage, short circuit current etc. Among above methods P&O, INC methods are most popular.

Between PV module and load a DC-DC converter is connected and duty cycle of the DC-DC converter always regulated to operate the PV system at maximum power point (MPP). Figure 1 show the conventional INC method algorithm, which operates with high efficiency under steady irradiance. In this method the slope of the P-V curve is used to vary the duty cycle of converter to get maximum voltage [6, 23-25]. The MPP can be determined by methods for the use of the connection between *dI/dV* and – *I/V*. On the off chance that DP/DV is negative then MPPT is lies on the correct part of current capacity and if the MPP is high caliber the MPPT is on left side. The condition of IC strategy is

$$\frac{dP}{dV}=\frac{d(V*I)}{dV}=I\frac{dV}{dV}+V\frac{dI}{dV} \tag{1}$$

$$\frac{dP}{dV}=1+V\frac{dI}{dV} \tag{2}$$

MPP is reached when $\frac{dP}{dV}=0$

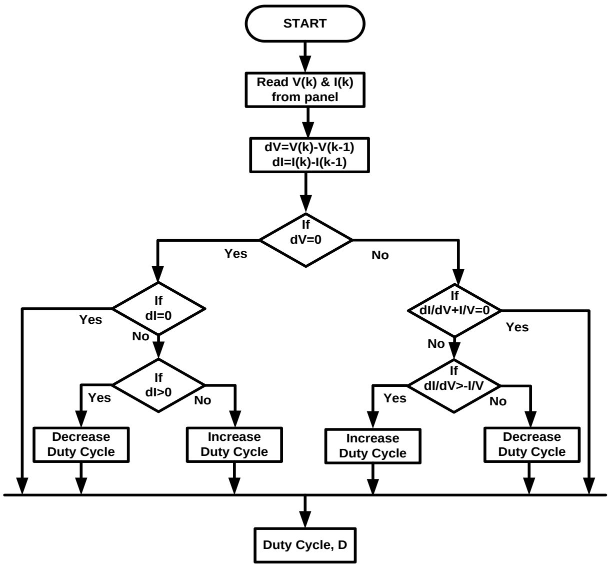


Figure 1. Conventional INC MPPT Algorithm.

For varying irradiance the response of fixed step size is slow. So, variable step size is proposed which decreases the step size and convergence of MPP is slow when it reaches to near the peak of P-V curve. A modified INC algorithm is proposed to increase the converging speed with fast varying irradiance [30, 31].

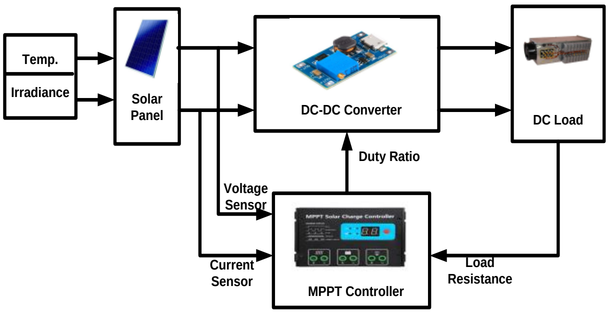


Figure 2. Block diagram of proposed DC/DC converter with modified INC Algorithm.

The fast acting MPPT method used the relation between load line and MPP locus. Figure 3 shows the I-V curves at different irradiance with MPP line which is approximately a straight line. When PV system is fed to load; load line is imposed on the I-V curve as shown in figure 3. The intersection point of the load line and I-V curve represents the MPP.

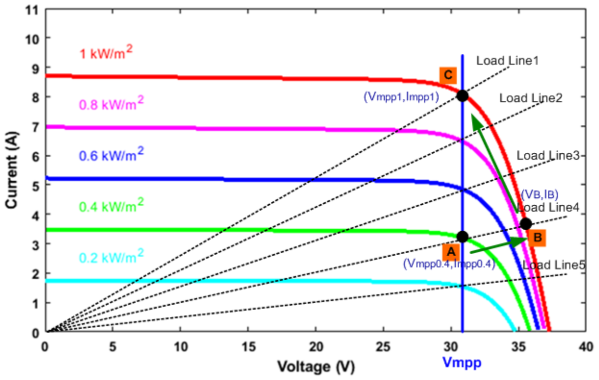


Figure 3. I-V curves at different irradiances with load line and MPP line.

The relation between the input output voltage and currents for a DC-DC converter is represented by

$$V_{input} = \frac{1-D}{D} V_{output} \tag{3}$$

$$I_{input} = \frac{D}{1-D} I_{output} \tag{4}$$

Divide (3) and (4) we get

$$R_{input} = \frac{(1-D)^2}{D^2} R_{output} \tag{5}$$

From (5) it is noticed that duty cycle can be regulated to force the input resistance of the converter to be varied until the load line cuts the I-V curve at MPP.

Equation (5) can be written as

$$\frac{D^2}{(1-D)^2} = \frac{R_{output}}{R_{input}} \tag{6}$$

Load resistance can be calculated at any operating MPP by substituting the duty cycle, PV voltage and PV current in (6)

$$D = \frac{\sqrt{\frac{I_{PV}}{V_{PV}} R_{load}}}{1+\sqrt{\frac{I_{PV}}{V_{PV}} R_{load}}} \tag{7}$$

Instead of $\frac{dP}{dV} = 0$ it is consider as *dI/dV+I/V<0.06* and calculated the duty ratio for different conditions as shown in figure 4

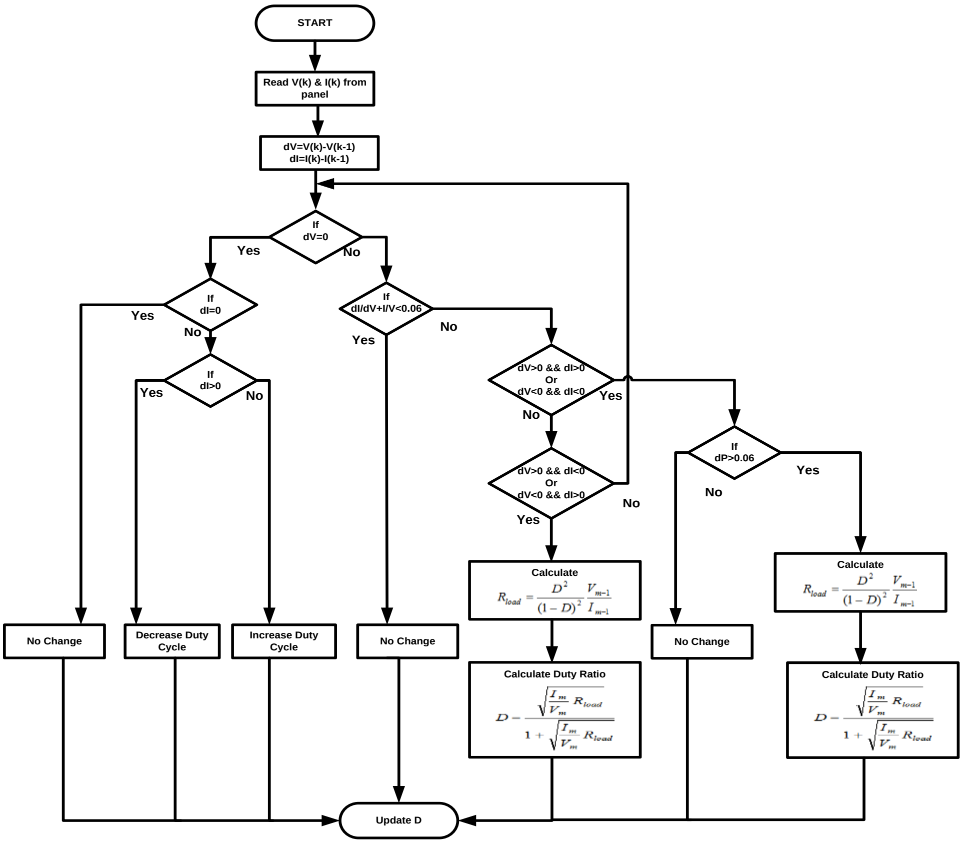


Figure 4. Proposed modified INC MPPT method under fast varying irradiance

Initially if the PV module is operating at 200 W/m^2 and load line 1, the operating MPP is at point A as shown in figure 3. Then if the solar radiation is increased to 800 W/m^2, load line 1 cuts the I-V curve at point B, which is far away from the MPP of 800W/m^2, point C. The new MPP is calculated by using the equation (7)

Where I_{PV} is the short circuit current at increased radiation, V_{pv} always operates at V_{MPP} of previous point (V_{pv} at point A).

The simulation results for conventional and proposed MPPT method is shown in figure 5 and figure 6. In simulation a variable irradiance is of 500 W/m^2 from 0 to 0.3 , 1000 W/m^2 from 0.3 to 0.6; 800 W/m^2 from 0.6 to 0.8; 600 W/m^2 from 0.8 to 1 is considered as shown in fig 5,6 (a). A variable DC voltage is absorbed for low value of irradiance and it never reaches to steady sate in figure 5(b). In figure 6(b) it is observed that voltage reaches to steady state in a fraction of seconds and getting a constant DC voltage.

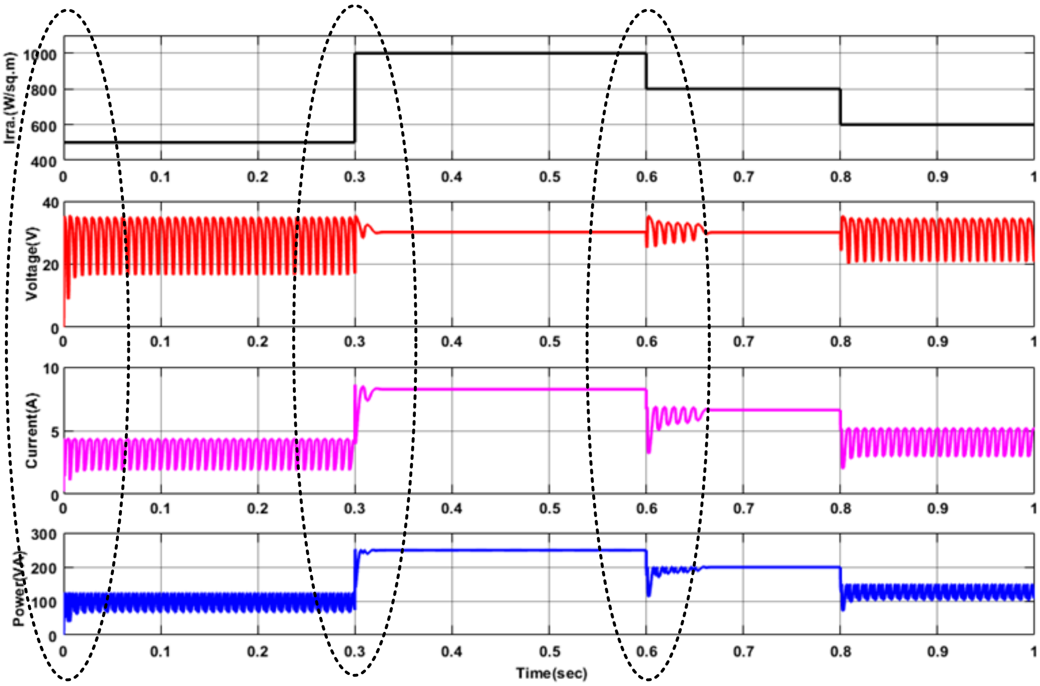


Figure 5. Simulation results for conventional INC MPPT method under fast varying irradiance

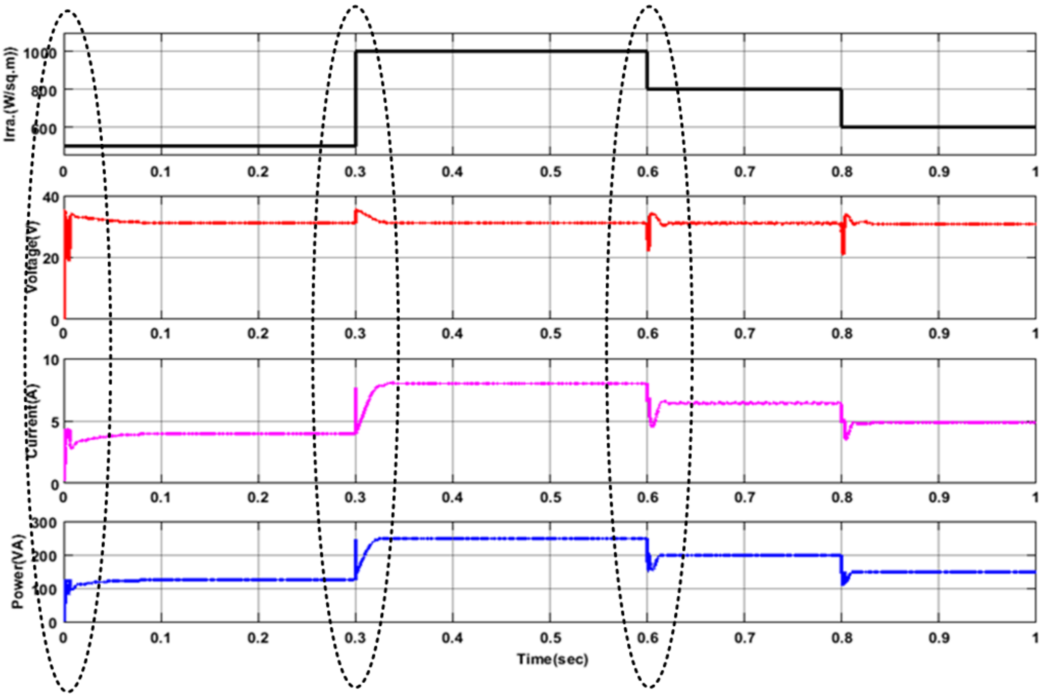


Figure 6. Simulation results for proposed modified INC MPPT method under fast varying irradiance

The proposed modified INC method shows better response for fast varying irradiance and the steady state oscillations is also reduces which improves the dynamic performance of the overall system.

3.2. High Voltage Gain with Soft Switch Interleaved Boost Converter:

The block diagram of Soft switch interleaved boost convert for high voltage gain shown in figure 7.

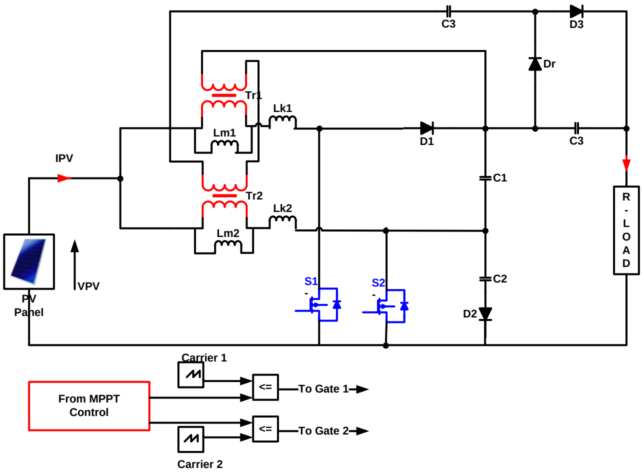


Figure 7. Proposed Block diagram of SSIBC for high voltage gain applications

This is operated in 4 modes of operation and the switches are operated in any one of the three ways

Table 1. Switching sequence for proposed SSIBC

S.No	S1	S2
1	ON	ON
2	ON	OFF
3	OFF	ON

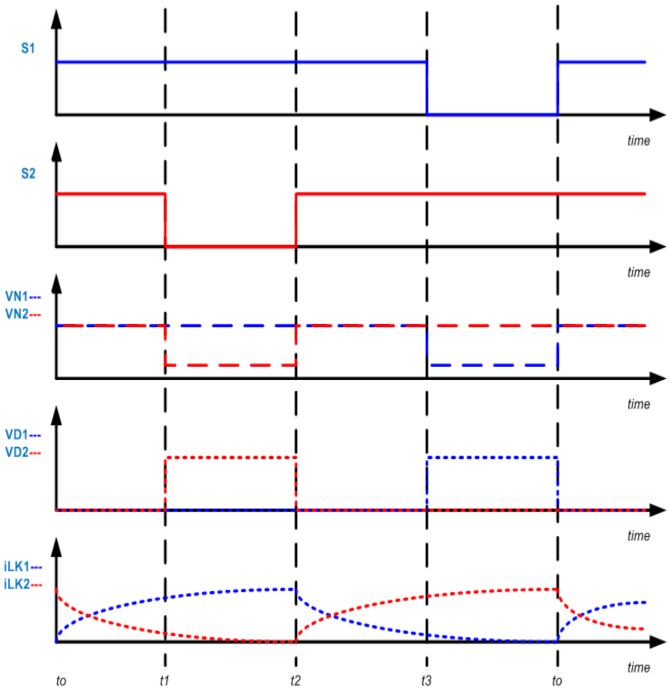
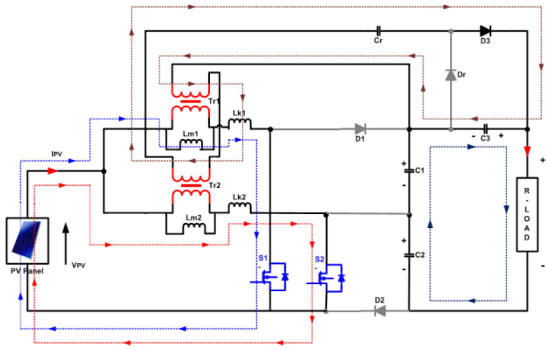
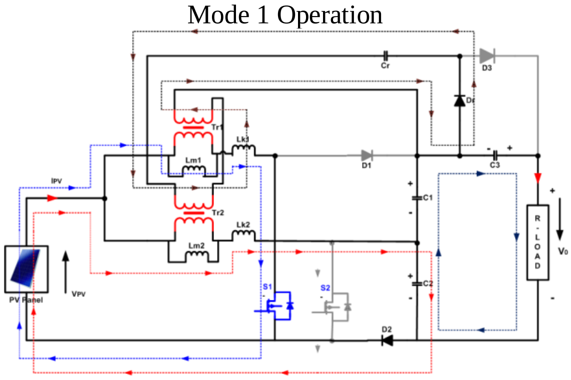


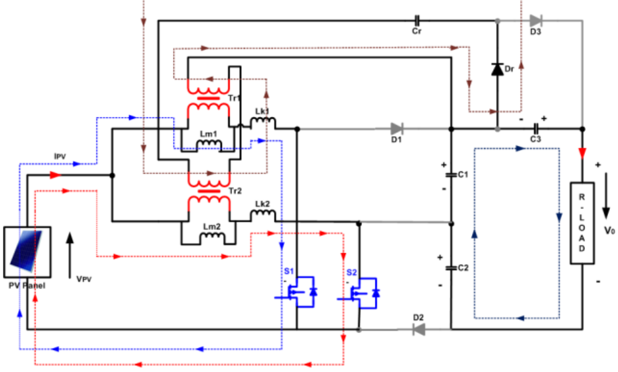
Figure 8. Switching sequence of proposed SSIBC DC-DC Converter



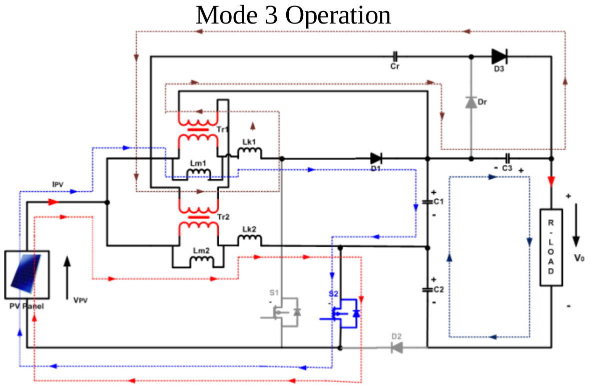
Mode 1 Operation



Mode 2 Operation



Mode 3 Operation



Mode 4 Operation

Figure 9. Operating modes of SSBIC in different modes (Mode I to Mode IV)

Mode1 of Operation: In this mode S1 is ON and S2 is in ON position due to L_{K2}. All the diodes are in OFF state expect D_3. The current falling rate through $D_3$is controlled by the inductance which reduces the reverse recovery problem. The output voltage is given by

$$V_0 = V_{c1} + V_{c2} + V_{c3} \tag{8}$$

Mode 2 of Operation: During this mode S2 is in OFF and diodes D_2 and D_r is turn ON. Leakage inductance discharges to C_2 through D_2. When the total energy of L_{k2} discharges completely to C_2 and the L_{m2} still discharge energy to secondary side charging the capacitor C_r through D_r.

Voltage across LM1 is given by

$$V_{LM1} = kV_{PV} \tag{9}$$

Voltage across LM2 is given by

$$V_{LM2} = k[V_{PV} - V_{C2}] \tag{10}$$

Voltage across regenerative capacitor Cr is s given by

$$V_{Cr} = V_{S1} - V_{S2} \tag{11}$$

Above equation is rewritten as

$$V_{Cr} = kNV_{C2} \tag{12}$$

Mode 3 of operation : During this mode S2 is in ON position with ZCS condition ad S1 remains in On position. Current flowing through Dr is controller by Lk1 and Lk2 which minimizes the diode reverse recovery problem

$$V_0 = V_{c1} + V_{c2} + V_{c3} \tag{13}$$

Mode 4 of operation: Duting this mode S1 is turn OFF ans S_2 remain in ON condition. V_PV, L_{m1}, L_{k1} release their energy to C_1 via S_2 Energy stored in Lm1 is transferred to sec. side of transformer. The current through sec. sides in series flows to the capacitor C3and load through D_3

Voltage across LM1 is given by

$$V_{LM1} = k[V_{PV} - V_{c1}] \tag{14}$$

Voltage across LM2 is given by

$$V_{LM2} = kV_{PV} \tag{15}$$

Voltage across regenerative capacitor C3 is s given by

$$V_{C3} = V_{Cr} + V_{S2} - V_{S1} \tag{16}$$

Above equation is rewritten as

$$V_{C3} = kN[V_{C1} + V_{c2}] \tag{17}$$

Voltage gain expression is given by

$$M = \frac{V_0}{V_{PV}} = \frac{2}{1-D}[1+N] \tag{18}$$

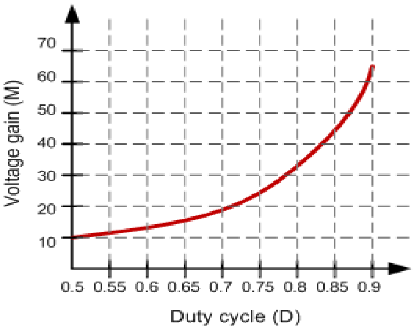


Figure 10. Voltage gain vs Duty cycle

Figure 10 shows the relation between the voltage gain and duty cycle from equation (18) it is clearly indicates that for increase in the duty ratio the gain value is linearly increases.

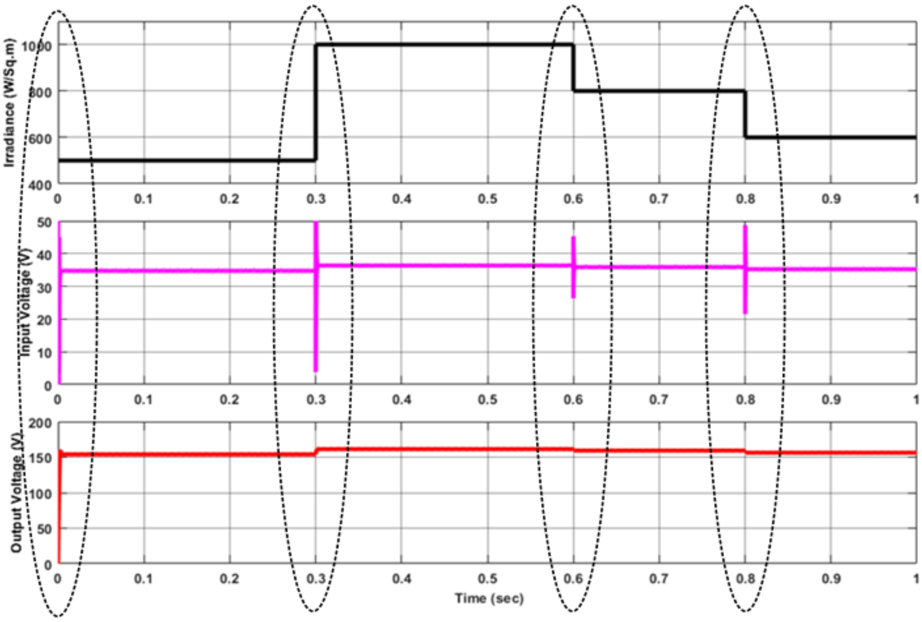


Figure 11. Simulation Response under changes in irradiance and Load
(a)Irradiance; (b) Voltage at PV Terminals; (c)Voltage at output of DC-DC Converter

Conclusion for the proposed SSIBC converter is achieved high voltage gain at medium duty ratios. The voltage stress on the main switches are reduced there by switching losses are reduced and avioded reverse recovery problem.

3.3. High Efficient variable DC bus voltage Power management scheme in DC microgrid:

Due to the deformities of the method for the conventional grid power supply, microgrid plays a major role.. At present, DC microgrid is a successful answer for coordinate sustainable power sources which are DC power supply with DC loads. Because of the temperamental yield of the Distributed Energy Resources in a DC microgrid there will be a wide changes of DC transport voltage and there will be issue of the force unbalance in the microgrid [24] [26-28]. A Novel energy management scheme is for DC microgrid is proposed. Figure 12 shows the block diagram of proposed energy management.

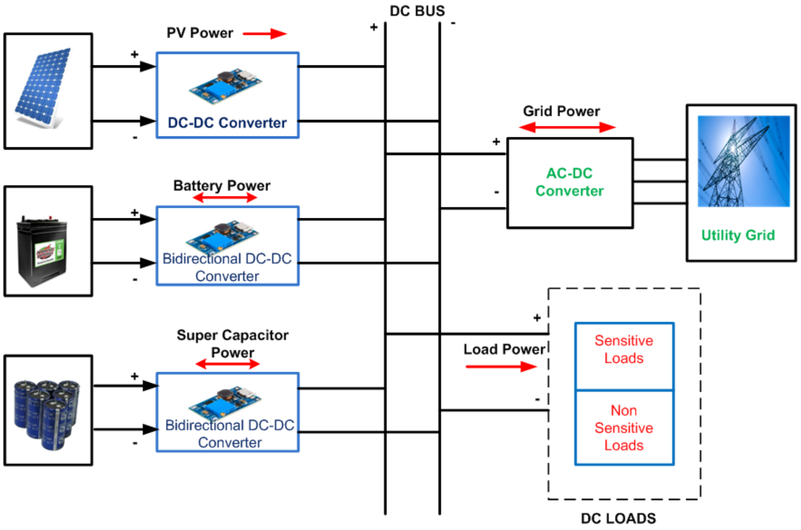


Figure 12. Block Diagram for power management strategy in a hybrid DC microgrid

The control methodology separates the DC bus voltage into seven stages by six basic voltages (as shown in figure 13) which are utilized as the speaks to of intensity states and as per the range which the bus voltage has a place with the activity method of the system can be consequently judged and switched unreservedly. The proposed system comprises of Primarily PV source, Energy Storage System (battery and super-capacitor) and Grid. Power management is mainly depends on the State Of Charge (SOC) of battery and SC. The SOC of the SC is given by equation (19)

$$SOC_{SC} = \frac{\frac{C_{SC}V_{SC}^{2}}{2}}{\frac{C_{SC}V_{SC\_RATED}^{2}}{2}} X100\% = \left(\frac{V_{SC}}{V_{SC\_RATED}}\right)^{2} X100\% \qquad (19)$$

The SOC of the battery value at time *(t+Δt)* depends on the *SOC of battery* value at time *t*, and the energy absorbed or released by the battery bank during the time period Δ*t*. It can be expressed as follows

$$BAT_{SOC}(t+\Delta t) = BAT_{SOC}(t) + \frac{1}{C_{B} X 3600 X V_{B}(t)} \int_{t}^{t+\Delta t} P_{BAT}(t)dt \qquad (20)$$

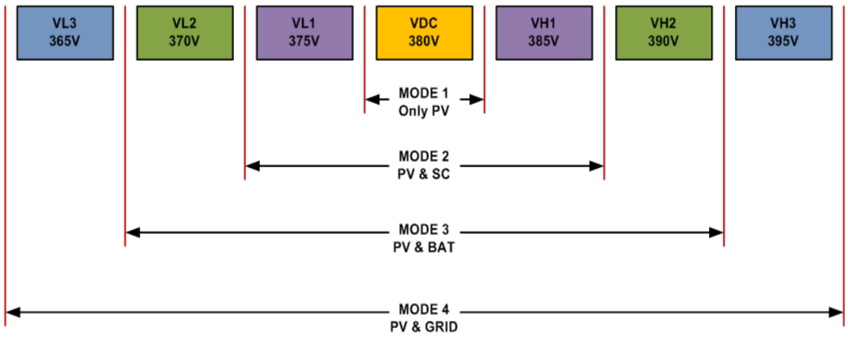
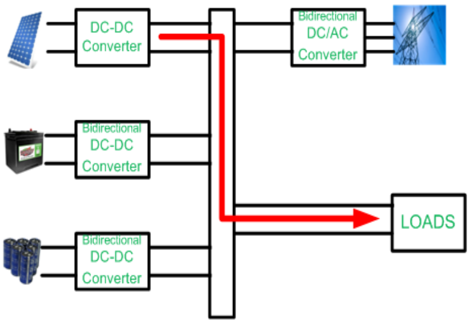


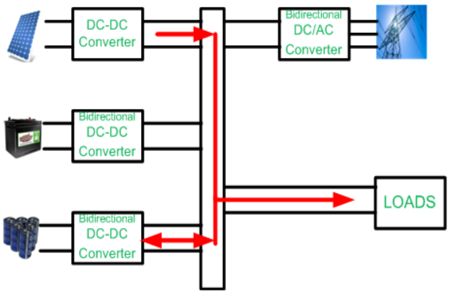
Figure 13. Modes of operation in power management strategy in a hybrid microgrid

Table 2. Shows the different modes of operation in DC microgrid

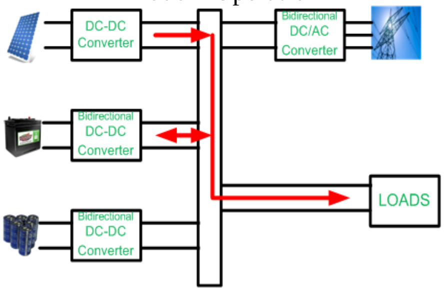
Mode Name	Power Condition	DC Bus Voltage Range	DC Bus Regulation	Power Supply Sources
Mode I	$P_{PV}=P_{Load}$	$V_{L1}<V_{DC}<V_{H1}$	PV System	PV System only
Mode II	$P_{PV}+P_{SC}=P_{Load}$	$V_{L2}<V_{DC}<V_{L1}$	SC System	PV & SC System
	$P_{PV}-_{SC}=P_{Load}$	$V_{H1}<V_{DC}<V_{H2}$	SC System	PV & SC System
Mode III	$P_{PV}+P_{BA}=P_{Load}$	$V_{L3}<V_{DC}<V_{L2}$	Battery System	PV & Battery System
	$P_{PV}-P_{BA}=P_{Load}$	$V_{H2}<V_{DC}<V_{H3}$	Battery System	PV & Battery System
Mode IV	$P_{PV}+P_{AC}=P_{Load}$	$V_{DC}<V_{L3}$	Utility System	PV & Utility System
	$P_{PV}-P_{AC}=P_{Load}$	$V_{H3}<V_{DC}$	Utility System	PV & Utility System



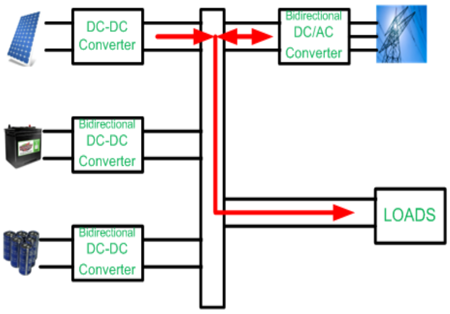
Mode 1 Operation



Mode 2 Operation



Mode 3 Operation



Mode 4 Operation

Figure 14. Operating modes of Power management system in different modes (Mode 1 to Mode 4)

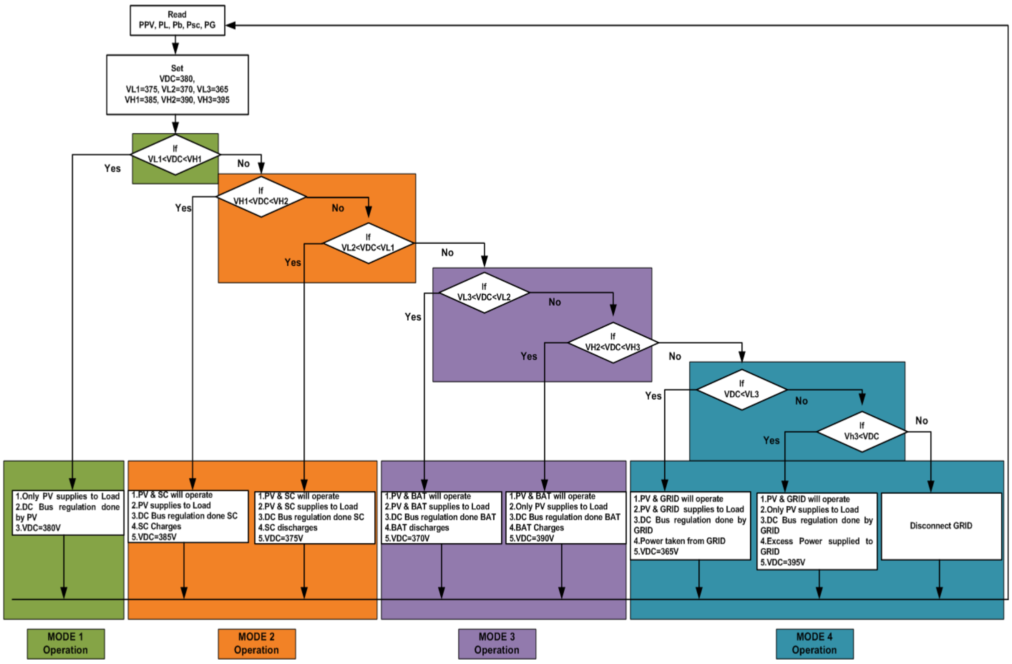


Figure 15. Variable DC bus voltage based power management Algorithm

Mode 1: $V_{L1}<V_{DC}<V_{H1}$. In this mode, the DC bus voltage is regulated only by the PV generation, which means the generated PV power just matches the demands. The bus voltage fluctuates at the reference value in a small range. At the same time, the other converters are in the standby state. The power flow is shown in mode 1 in figure 14.

Mode2: $V_{L2}<V_{dc}<V_{L1}$ or $V_{H1}<V_{dc}<V_{H2}$. When the, power of PV cells keeps changing with irradiation and ambient temperature or the load fluctuates severely, the generated PV power and the local load will not match. When this case happens, super-capacity will be used to maintain the constant DC bus voltage due to the mismatch between the generated PV power and the demands

Mode3: $V_{L3}<V_{dc}<V_{L2}$ or $V_{H2}<V_{dc}<V_{H3}$. The mode 1 and mode 2 have their working section where the DC bus ranges from VL2 to VH2. When the voltage is up to VH2, it represents that the super-capacity is full and the generated PV power is still more than the load demand. When this case happens, the surplus power will be inverted to the utility grid. When the voltage is down to VL2, it means that the discharge of super-capacity reaches the limit and the generated PV power is still less than the demand. Then, the insufficient power will be transported to DC microgrid from the main grid.

Mode 4: $V_{DC}<V_{L3}$ or $V_{H3}<V_{DC}$. When the utility grid fault or grid-tied converter failure, the DC microgrid will change to islanding mode.

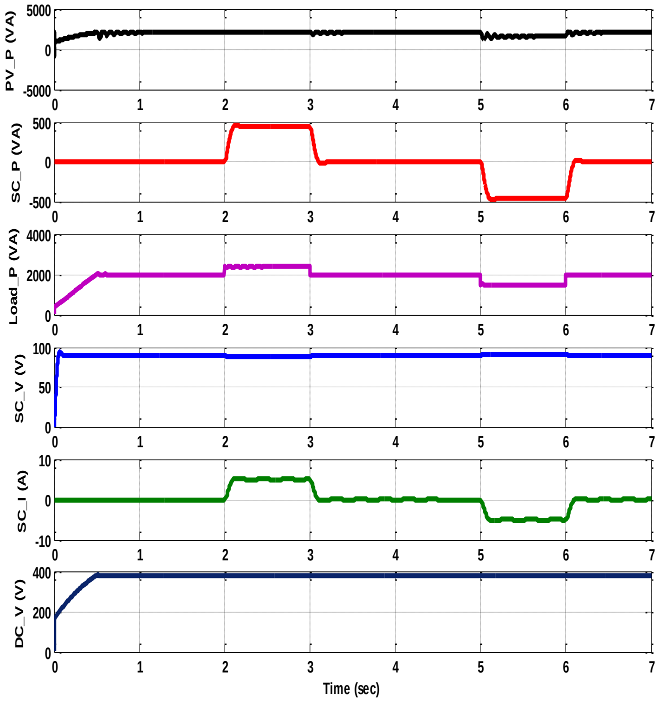


Figure 16. Transition between Mode I and Mode II: (a) PV Power, (b) SC Power, (c) Load Power, (d) SC Voltage, (e) SC current, (f) DC bus voltage

Figure 16 shows the simulation results of the proposed power management algorithm between mode 1 and mode 2. From time period of 0 to 2 load is 2kw and it is operating in mode 1, from 2 to 3 load is increased by 0.4kw. this power is supplied by SC and operating in mode 2. From time period 5 to 6 load is decreased to 1.6 kw the extra power supplied from PV is used to charge the SC.

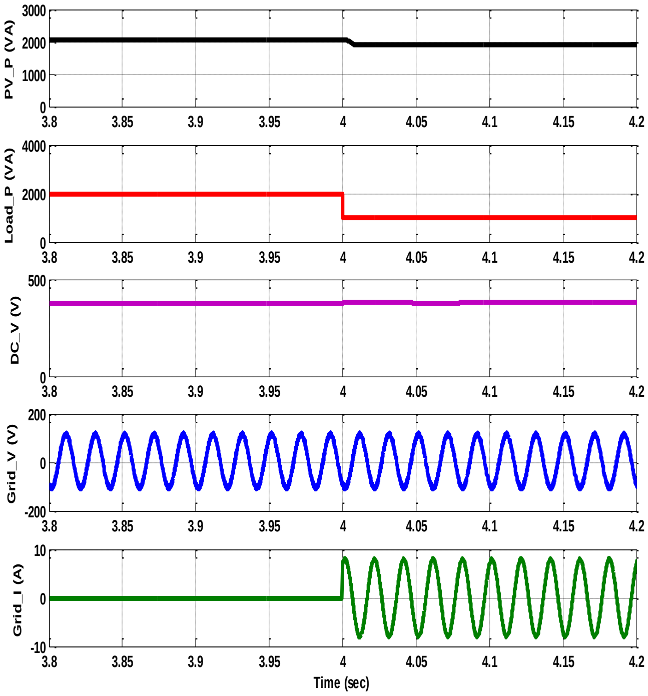


Figure 17. Transition between Mode I and Mode IV: (a) PV Power, (b) Load Power, (c) DC bus voltage, (d) Grid voltage, (e) Grid current

Figure 17 shows the simulation results of the proposed power management algorithm between mode 1 and mode 4. From time period of 4 the grid is supplying to the load as explained in mode 4.

The proposed power management system include: (i) DC Bus voltage is utilizes to operate in different modes of operation. (ii) Full Active control HESS is actualized to empower the EMS to deal with the force trade. The proposed framework can upgrade the unwavering quality and adaptability of the system

4. Conclusion

A DC microgrid with energy storage system is investigated with different control strategies. First a new MPPT method is proposed to track the maximum power under fast varying solar irradiance. Since the proposed MPPT is not an iterative method, directly it tracks the MPP when there is change in the irradiance or in load. The results show that operation of proposed system reduces the steady state oscillations is also reduces which improves the dynamic performance of the overall system. For Second problem is SSIBC is proposed and it is operating in different modes of operation. The results show that proposed SSIBC converter is achieved high voltage gain at medium duty ratios. The voltage stress on the main switches are reduced there by switching loaaes are reduced and avioded reverse recovery problem. Finally variable DC bus voltage based full active HESS power managemnt algorithm is proposed which operates the overall system in steady sate inder different loading conditions.

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