

Stand-Alone Pv Power Generation With Flexible System Architecture

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Abstract: A standalone photovoltaic (PV) system with energy storage requires a complex control architecture to take into account the various operating modes. This paper presents a flexible architecture of a PV power conditioning system with energy storage is executed. It consists of boost converter, a single-phase inverter, and bidirectional DC/DC converter connected to the PV side of the boost converter. The boost converter regulates the dc-link bus-voltage. The bidirectional DC/DC converter used for battery charge/discharge control and PV maximum power point tracking. The multi loop PI controller used to control the operation of DC to DC converter. In this system there is no change in controller configuration when the storage disconnects.

Index Terms: Energy storage, flexible stand-alone, photovoltaic (PV), PV system, multi loop PI controller.

I. Introduction

NOWADAYS, solar energy is considered to be one of the most effective resources, attracting much attention due to its ubiquity and sustain ability . Stand-alone photovoltaic system (SPVS) is one of the popular applications in photovoltaic(PV) generation and has highly practical values in off-grid areas. Such areas are categorized as micro grid, including remote areas, desert and border-outpost moveable military equipment, street light systems, etc.. However, the power generation is significantly influenced by the light intensity and the temperature. In addition, PV cells cannot store the energy inside; thus, an energy storage device is normally required to balance the energy of the PV systems.

In such types of distributed-sourced microgrid systems, the multiple connection issues of the SPVS to grid have been considered previously and some solutions using droop control methods have been provided. In the design procedure of the individual SPVS architecture, one of the major concerns is the need of a high output dc-voltage bus (400 Vdc) inside the individual SPVS to supply the following inverter from the low voltage power sources. Since a commercialized battery bank voltage is relatively low, such as 12, 24, or 48 V, a power conditioning unit (PCU) is required to interface the battery to dc-link bus with high step-up ratios. This issue has led to many multiple stage PCU topologies.

A conventional topology used widely for an SPVS, including an energy storage device connected with the dc link through a bidirectional dc–dc power converter was proposed [see Fig. 1 (a)]. This power converter acts as a step-up converter when the stored energy flows from the battery bank to the dc-link bus (discharging mode) and as a step-down converter when the energy flows from the dc link to the battery bank (charging mode). The controller regulates the dc-link voltage and another dc–dc converter associated with PV source performs an maximum power point tracking (MPPT) operation for the PV source. As aforementioned, because the dc-link bus voltage is usually very high (for most applications), the bidirectional dc–dc converter needs to have a high step-up gain along with a high efficiency. It is difficult to achieve the high efficiency and the high gain simultaneously in conventional bidirectional dc–dc converters due to the losses in semiconductor devices, leakage inductance.

Another traditional stand-alone PV system architecture is that whereby the energy storage device (battery) is placed between the first dc/dc and the dc link, or the battery is interfaced with the dc link by the second dc/dc converter [see Fig. 1 (b)] . In case without the second dc/dc converter, the first dc/dc converter performs MPPT while the dc/ac inverter regulates the ac output voltage. Despite the advantages of this configuration (such as reducing the number of power converters), it also has some disadvantages such as a high-voltage battery, which leads to stacking up of the multiple battery modules. Furthermore, the battery current is uncontrollable; thus, when the load changes abruptly, it often damages the battery due to the large transient current. Also, there can be a small cycle of charging and discharging in the battery from the consistent power flow during the operation, which causes a serious reduction of battery lifetime. In order to overcome these drawbacks, the secondary dc/dc converter is normally added to this configuration. However, the battery is still involved in energy conversion, affected by load disturbance directly, which could seriously affect the battery life-time and utilization. Recently proposed topology of an SPVS is classified as a three-port converter as shown

in Fig. 1(c). The main advantages of this topology are the low voltage stress across the active switches, the low input current ripple, etc.

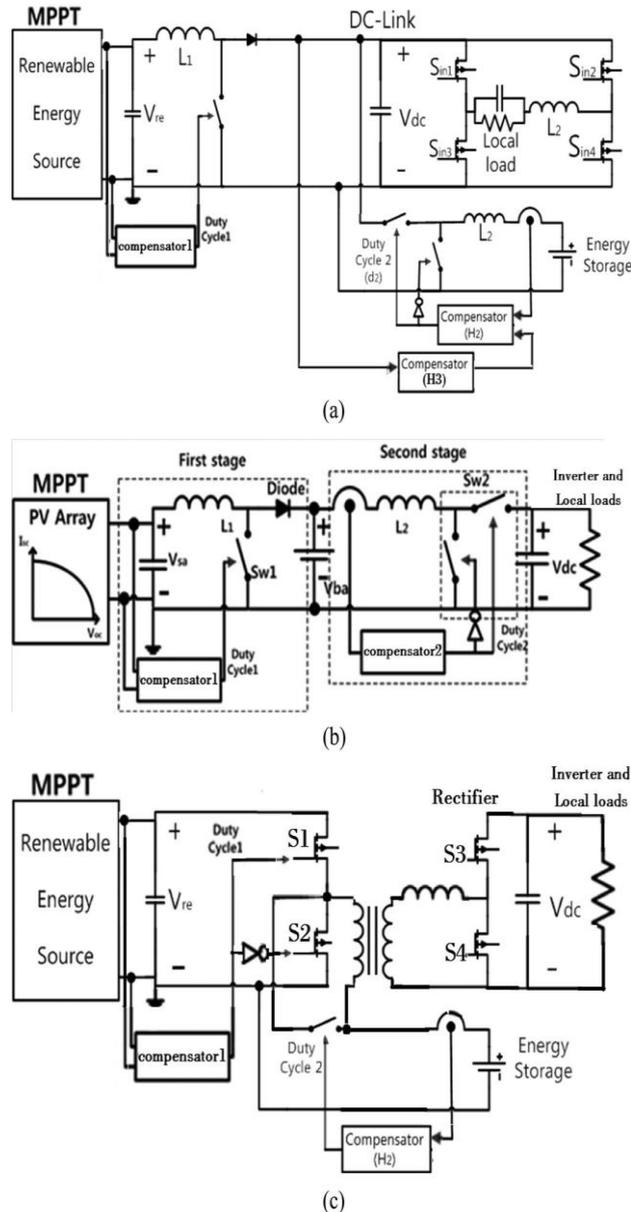


Fig. 1. Convectional circuits of the SPVS proposed in previous literature.

(a) Stand-alone PV power generation an energy storage device connected with dc link. (b) Stand-alone PV power generation an energy storage device connected between first and second converters. (c) Stand-alone PV power generation used three port converter.

However, the architecture and the control method are quite complex and the control architecture is difficult to instantaneously adapt for multiple mode variation. In addition, a multiport ac link, as an alternative configuration for SPVS, is a configuration that utilizes many high-frequency switches, which leads to low efficiency of the overall system. Main advantages of this topology are the low voltage stress across the active switches, the low input current ripple, etc. However, the architecture and the control method are also quite complex and the control architecture is difficult to instantaneously adapt for multiple mode operation, as well.

In this paper, a flexible system configuration for an SPVS with an energy storage device is proposed. The principle of the proposed architecture and its advantages and operating modes are described in Section II. The PV modeling, control strategy of the converters and single phase inverter are analyzed in Section III. An analysis of the strategy of the boost converter and bidirectional DC to DC converter using Proportional integral (PI) method is presented in Section IV. Finally, the numerical simulation and experimental results of the 500-W test bed are presented in Section V.

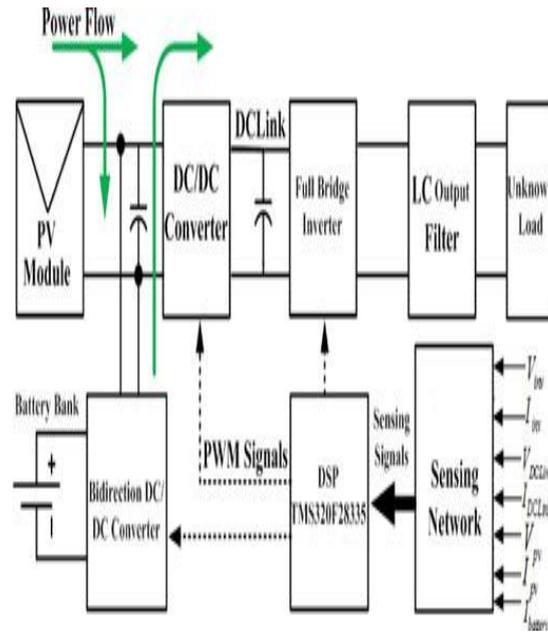


Fig. 2 Block diagram of the SPVS

II. Proposed Pv-Storage System Architecture

The proposed SPVS is shown in Fig. 2 and consists of a PV panel, batteries, two converters, and a single-phase dc/ac inverter. The boost converter (BC) is used to maintain the dc link voltage, while the charging or discharging mode of the bidirectional dc/dc converter is applied to track the MPPT of the PV array when the available PV power is insufficient to meet the load. Therefore, the two dc/dc converters in the system need to be coordinated by an upper level controller.

This configuration provides a flexible smooth operation for the system, since the role of the main PV power stream and that of the storage subsystem are clearly separated from each other. The system could work with and without battery both, without any major mode change in the local controllers, which is preferable from industrial point of view. The proposed system architecture makes the switch between the different modes of operation smooth and simple without the need for supervisory controller. Furthermore, this arrangement provides more flexibility in choosing the battery's nominal voltage with a reasonable step-up ratio. It also stores the excess PV energy in the battery to balance the system and supplies the instantaneous peak power demand. One of the main concerns in the previous architecture is the battery voltage, which needs stacking up of multiple packs to enhance the voltage range. Actually, the stacking up requires a balancing circuit, a so-called charge balancer, which makes the system structure more complicated, resulting in an undesirable configuration in terms of the size and cost competitiveness. Also, some safety issues are observed, whereby the high-voltage dc lines can cause fatal damage to the human body since the battery is alive even during the main power system turn-off. Therefore, the proposed scheme is more desirable for the PV-storage combination system. In the previous section, it has already been seen that the battery voltage in the conventional schemes should be greater than 100 V because of a fundamental characteristic that the bidirectional converter (BDC) should discharge the battery energy to 400 V dc link.

TABLE I
SUMMARY OF OPERATION MODES

Modes	Power Condition	Battery Condition	PV Condition
I	$P_{MPP} < P_{load}$	discharging	MPPT
II	$P_{MPP} < P_{load}$	Fully discharged	Non-MPPT
III	$P_{MPP} > P_{load}$	Charging	MPPT
IV	$P_{MPP} > P_{load}$	Fully charged	Non-MPPT
V	$P_{MPP} = 0, P_{bat} = P_{load}$	Discharging	Non-MPPPT

Five flexible operation modes are possible for the proposed scheme. These modes depend on the power producing and energy-storing conditions, as follows.

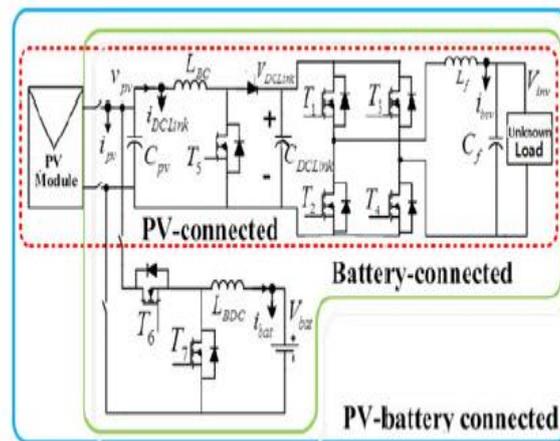
Mode I—PV-storage connected (PMPP < Pload): The PV is not enough to meet load demand, so the battery bank is discharged to meet the load demand. The BDC discharges the stored energy to the input of PV PCS, and the BC enhances PV voltage up to the 400 V dc link.

Mode II—PV-connected (PMPP < Pload): If the battery becomes fully discharged, or when the battery bank is removed, the system enters the non-MPPT mode or under voltage lockout and shuts down.

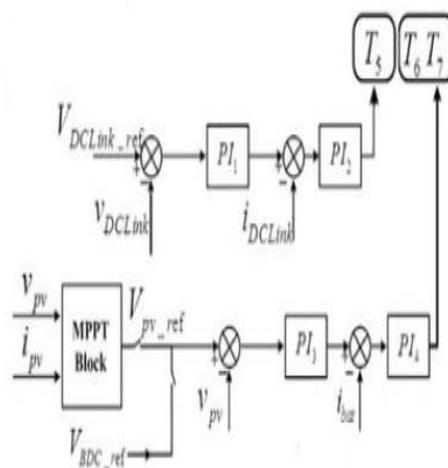
Mode III—PV-storage connected (PMPP > Pload): The harvested power exceeds the load and the battery is charged with the excess power, until the battery is fully charged. Electric power can flow from the PV source to the load as well as charge the battery.

Mode IV—PV-connected (PMPP > Pload): If the battery is fully charged, the battery bank should be disconnected from the PV power conditioning system. The MPPT must be disabled (non-MPPT), and the PV voltage reference is set at constant to hold the CPV voltage, providing the load-power tracking.

Mode V—Battery-connected (nighttime): When PV sources do not produce sufficient power for the load, for example, at night or on a cloudy day, the PV modules are disconnected from the power conditioning system. Pload is provided only by the battery through cascading the BC, BDC, and full-bridge inverter. Such a cascaded operation makes it possible to step up the voltage from 24 Vdc, given by the battery bank, up to 400 Vdc to feed the dc/ac inverter and the load.



(a)



(b)

Fig. 3. Circuit diagram of the overall system configuration of the SPVS.

(a) Power stage. (b) Control strategy.

In this paper, a multi loop proportional-integral (PI) controller is presented. The multi loop PI is used to control the operation of the dc/dc converters due to its robustness and good performance with any type of unknown arbitrary load.

This system has a number of advantages. First, the flexibility for various types of operating modes, with and without energy storage, is strongly guaranteed without the control configuration change. Second, the system can be applied even with a single 24 V commercial battery without any extra connection.

III. Bidirectional Dc-Dc Converter

Energy storages in general uses bidirectional DC-DC converter for charging and discharging applications may be either in half-bridge or full-bridge arrangement of semi-conductor switching devices. The buck type of converter has energy storage on the high voltage side, whereas boost type of converter has energy storage on the low voltage side.

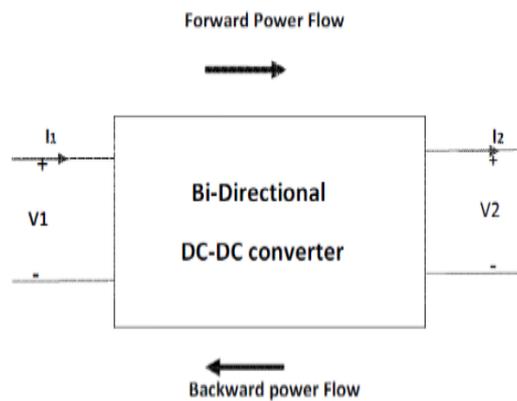


Fig.4. General block diagram of bidirectional DC-DC converter

The concept of power flow in both directions for a bidirectional dc-dc converter is the operation of switching devices that realize current flow in each way. Bidirectional dc-dc converters are developed from two unidirectional semiconductor switching devices such as MOSFET, Transistors and IGBT power switches constructed with parallel diodes. These parallel diodes serve double-sided power flow. Even though there are many topologies of bidirectional dc-dc converter; basically they are divided into two types such as an isolated bidirectional DC-DC converters and non-isolated bidirectional DC-DC converters based on the isolation material between input and load.

IV. Boost Converter

A Boost converter is a switch mode DC to DC converter in which the output voltage is greater than the input voltage. It is also called a step up converter. The name step up converter comes from the fact that analogous to a step up transformer the input voltage is stepped up to a level greater than the input voltage. By the law of conservation of energy the input power has to be equal to output power (assuming no losses in the circuit).

$$\text{Input power } (P_{in}) = \text{output power } (P_{out})$$

Since $V_{in} < V_{out}$ in a boost converter, it follows then that the output current is less than the input current. Therefore in a boost converter

$$V_{in} < V_{out} \text{ and } I_{in} > I_{out}$$

The main working principle of a boost converter is that the inductor in the input circuit resists sudden variations in input current. When the switch is OFF the inductor stores energy in the form of magnetic energy and discharges it when the switch is closed. The capacitor in the output circuit is assumed large enough that the time constant of the RC circuit in the output stage is high. The large time constant compared to the switching period ensures a constant output voltage $V_o(t) = V_o(\text{constant})$.

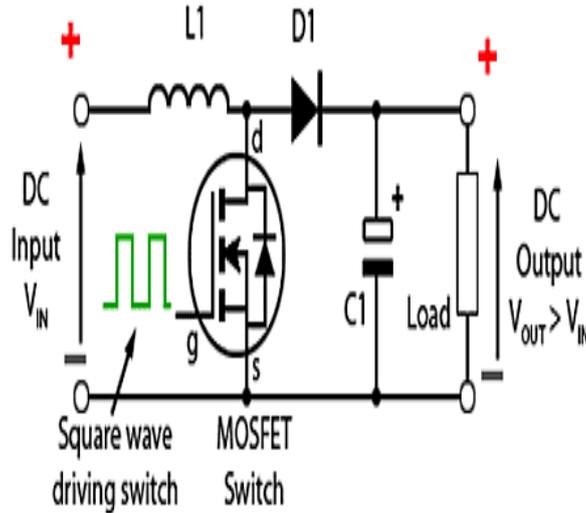


Fig.5.Circuit diagram of boost converter

The boost converter can be operated in two modes: Continuous conduction mode in which the current through inductor never goes to zero i.e. inductor partially discharges before the start of the switching cycle. Discontinuous conduction mode in which the current through inductor goes to zero i.e. inductor is completely discharged at the end of switching cycle.

V. Single Phase Inverter

In this four switches (in 2 legs) are used to generate the ac waveform at the output. Any semiconductor switch like IGBT, MOSFET or BJT can be used. Four switches are sufficient for resistive load because load current I_o is in phase with output voltage v_o . However this is not true in case of RL load where the I_o is not in phase with v_o and diodes connected in anti-parallel with switch will allow the conduction of the current when the main switch is turned off. These diodes are called as feedback diodes since the energy is fed back to the dc source.

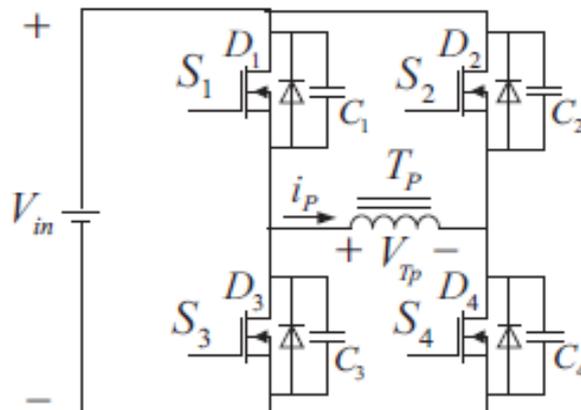


Fig.6. Single phase inverter

In full bridge inverter, when T1, T2 conduct the output voltage is V_s and when T3, T4 conducts the output voltage is $-V_s$. The switches T1, T2 conducts for period of $0 < t \leq T/2$ and the switches T3, T4 conducts for period of $T/2 < t \leq T$ where 'T' is the time period of the gate pulses to the devices. The frequency of output ac voltage can be varied by varying the T of the gate signal.

The root mean square (rms) value of output ac voltage:

$$V_o = \left(\frac{1}{T} \int_0^T V_s^2 dt \right)^{1/2} = V_s$$

TABLE II
CIRCUIT PARAMETERS

Parameter	Value
$V_{PV} (max)$	100 V
$I_{PV} (max)$	4 A
R_{eq}	25 Ω
V_{bat}	24 V
L_{BDC}	1.8 mH
C_{PV}	2200 μF
L_{BC}	1.8 mH
C_{dc_link}	1300 μF
f_{sw}	20 kHz

VI. Proportional Integral (Pi) Controller

In this paper PI controller was used in the Bidirectional DC to DC converter and Boost converter. The PI controller is most widely adopted in industrial application due to its simple structure, easy to design and low cost. Despite these advantages, the PI controller fails when the controlled object is highly nonlinear and uncertain.

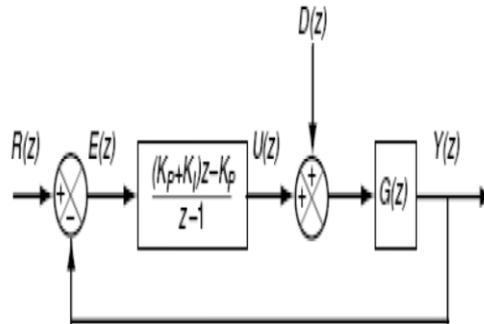


Fig.7. Block diagram of pi controller

PI controller will eliminate forced oscillations and steady state error resulting in operation of on-off controller and P controller respectively. However, introducing integral mode has a negative effect on speed of the response and overall stability of the system. Thus, PI controller will not increase the speed of response. It can be expected since PI controller does not have means to predict what will happen with the error in near future. This problem can be solved by introducing derivative mode which has ability to predict what will happen with the error in near future and thus to decrease a reaction time of the controller. PI controllers are very often used in industry, especially when speed of the response is not an issue.

The controller output in this case is

$$u(t) = K_p \cdot e(t) + K_i \int e(t) dt$$

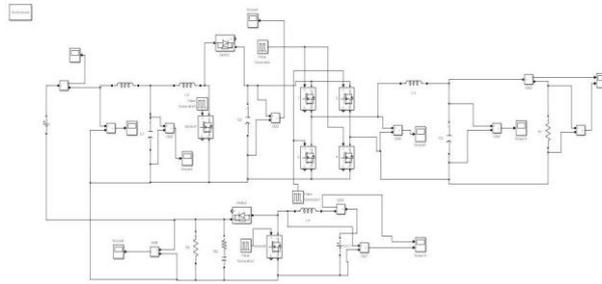
This type of compensation is introduced by using a controller which produces an output signal consisting of two terms, one proportional to the actuating signal and the other proportional to its integral. Such a controller is called proportional plus integral controller or PI controller.

VII. Experimental Results

A) Open Loop:

It consists of PV, boost converter (BC), a single phase inverter, bidirectional DC to DC converter connected to the PV side of the BC and LC filter, resistive load. There are five flexible operation modes. These modes depend on the power producing and energy storing condition, as follows.

Mode 1



The PV generate about 20V. The voltage from the bi-directional converter 24V is boosted to 100V. In this mode BDC acts as the boost converter. The 20V from PV and 100V from the BDC are given to the boost converter which converts 120V to 400V. Then 400V from then boost converter is given to the inverter which covert DC to AC 400V. The AC voltage is passed to the LC filter which eliminates harmonic and the pure sine wave obtain is given to resistive load.

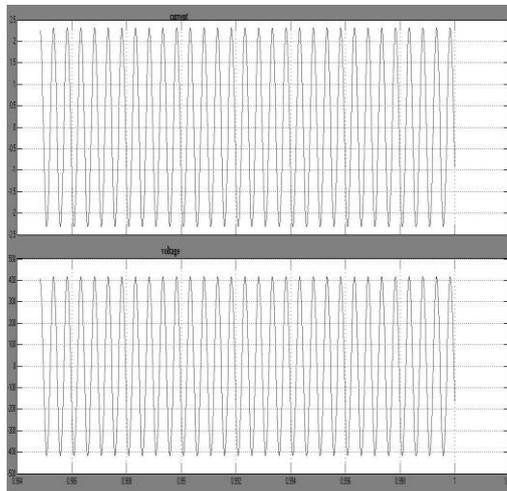
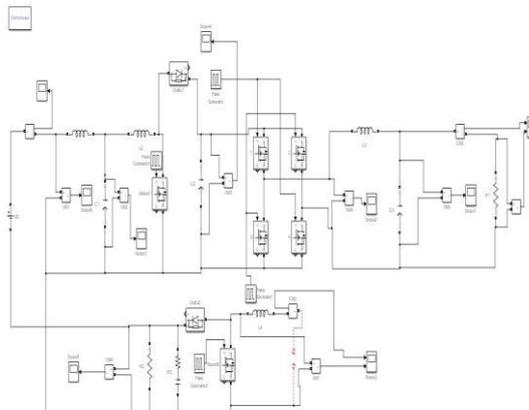


Fig.8. Voltage and current waveform for openloop mode 1

Mode 2



Due to fully discharge of voltage from the BDC, it gets disconnected from the circuit. Therefore 20V from the PV alone is given to the boost converter. It boost 20V to 80V. The 80V is given to the inverter and the processes continuous as in mode 1.

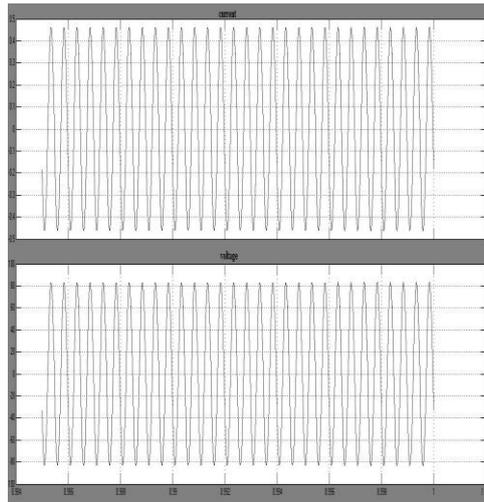
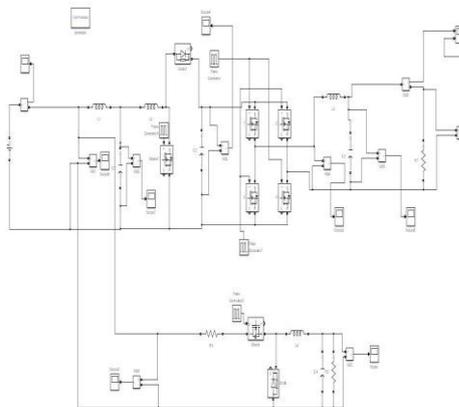


Fig.9. Voltage and current waveform for openloop mode 2

Mode 3



The generate 100V from PV is given to the BDC converter and gets charged. In this mode it acts as the buck converter which converts high voltage to low voltage. The 100V from PV is given to the boost converter which provides 400V. Then 400V from boost converter is given to the inverter which converts DC to AC 400V. The AC voltage is passed to the LC filter which eliminates harmonic and pure sine wave obtain is given to resistive load.

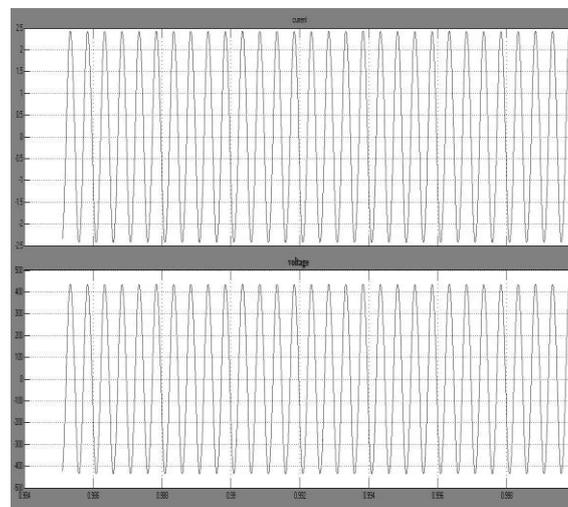
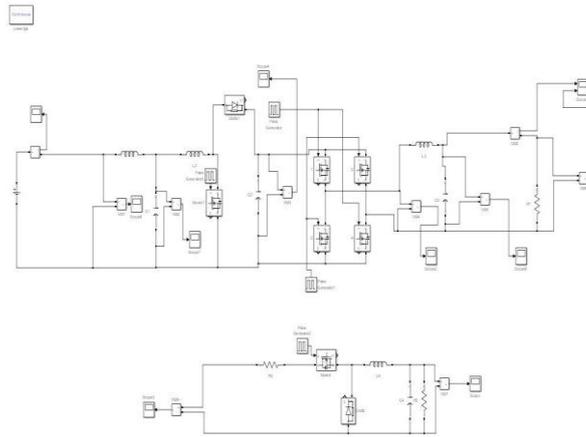


Fig.10. Voltage and current waveform for openloop mode 3

Mode 4



In mode 4 as BDC was fully charged it gets disconnect from the circuit. The generated 100V from PV is given to the boost converter and the output of 400V is obtain. The 400V is given to the inverter which converts DC to AC. The AC voltage is passed to the LC filter which eliminates harmonic and pure sine wave obtain is given to resistive load.

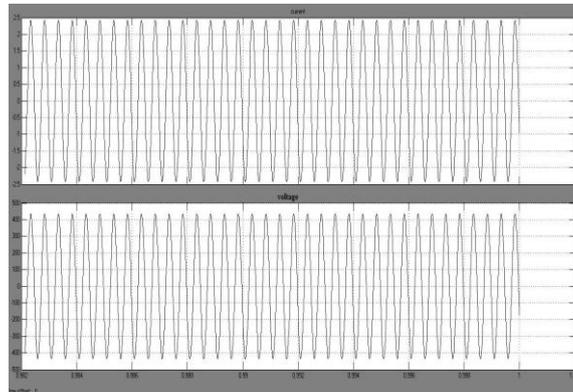
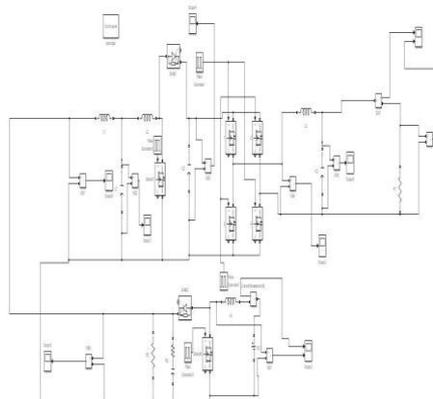


Fig.11. Voltage and current waveform for openloop mode 4

Mode 5



When PV sources do not produce sufficient power for the load, for example, at night or on a cloudy day, the PV modules are disconnected from the power conditioning system. Therefore the voltage is obtain from

the BDC converter that acts as the boost converter which boost 24V to 100V and it is again given back to the BC which converts 100V to 400V. Then 400V from the BC is given to the inverter which convert DC to AC 400V. The AC voltage is passed to the LC filter which eliminates harmonic and the pure sine wave obtain is given to resistive load.

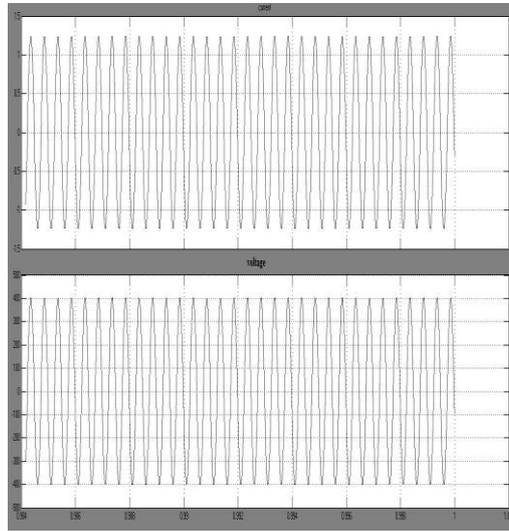
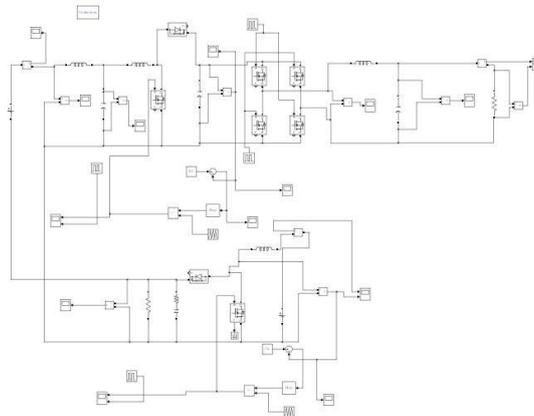


Fig.12. Voltage and current waveform for openloop mode 5

B) Closed Loop:

It consists of PV, boost converter (BC), bi-directional DC to DC converter (BDC), single phase inverter, LC filter and resistive load. Additionally multiloop PI controller are used. The PI controller are connected at the output of BDC and BC. There are five modes operation.

Mode 1



The PV generate about 20V. The voltage from the BDC 24V is boosted to 100V. The output is controlled by means of PI controller are used. In this mode BDC acts as the BC. The 20V from PV and 100V from the BDC are given to the BC which converts 120V to 400V. The 400V is controlled by means of PI controller are used. Then 400V from the BC is given to the inverter which convert DC to AC. The AC voltage is passed to the LC filter which eliminates harmonic and pure sine wave obtain is given to resistive load.

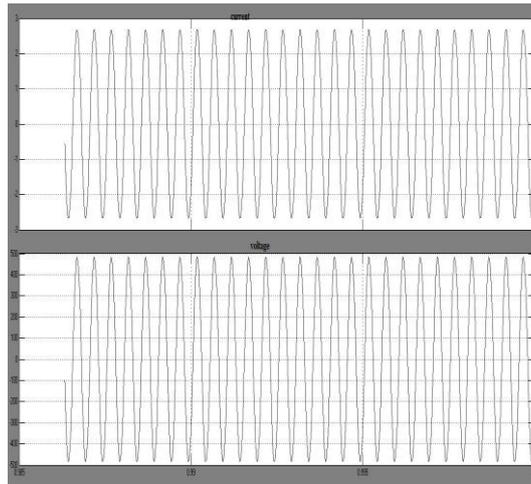
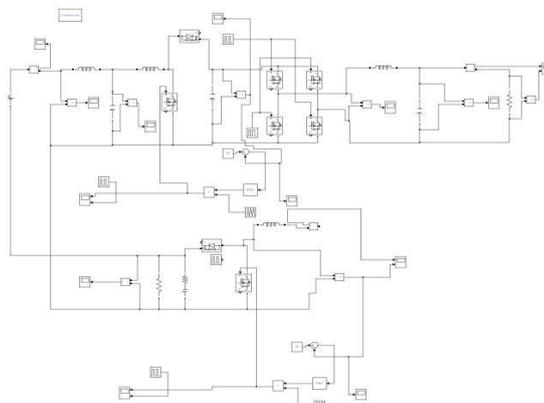


Fig.13.Voltage and current waveform for close-loop mode 1

Mode 2



Due to fully discharge of voltage from the BDC,it gets disconnected from the circuit.Therefore the 20V from the PV alone is given to the BC.It boost 20V to 140V.The output is controlled by means of PI controller are used.The 140V is given to the inverter and the processes continuous as in mode 1.

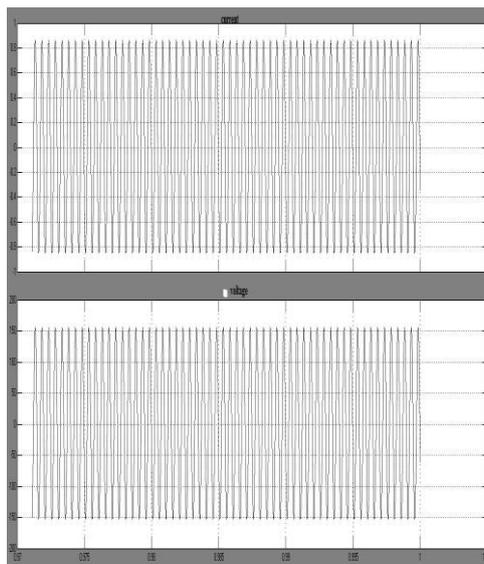
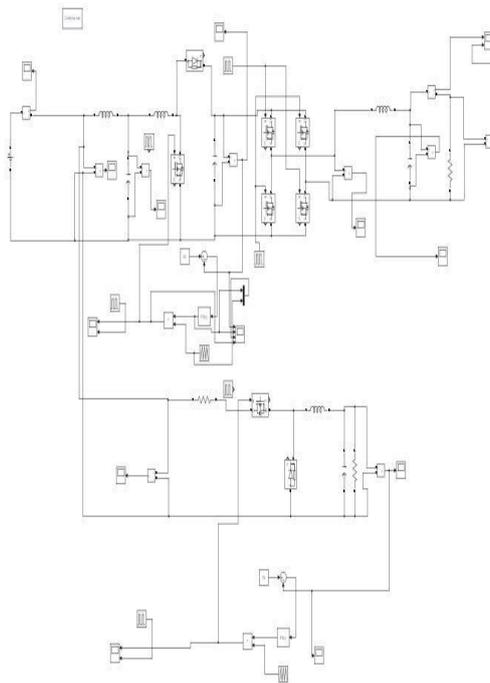


Fig.14.Voltage and current waveform for close-loop mode 2

Mode 3



The generate 100V from PV is given to the BDC converter and gets charged. In this mode it acts as the buck converter which converts high voltage to low voltage. The output is controlled by means of PI controller are used. The 100V from PV is given to the BC which provide 700V. The 700V is controlled by means of PI controller are used. Then 700V from the BC is given to the inverter which convert DC to AC. The AC voltage is passed to the LC filter which eliminates harmonics and pure sine wave obtain is given to resistive load.

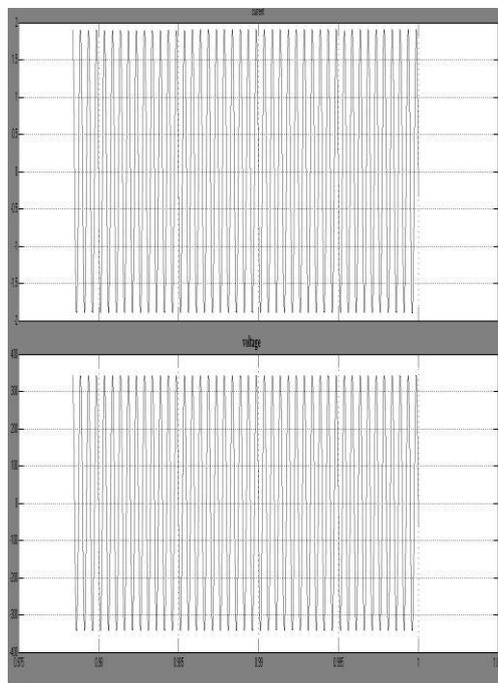
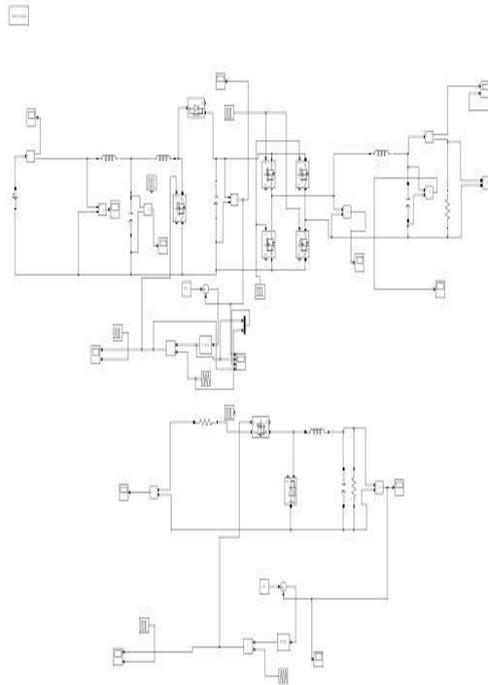


Fig.15. Voltage and current waveform for close-loop mode 3

Mode 4



In mode 4 as BDC was fully charged it gets disconnect from the circuit. The generated 100V from PV is given to the BC and the output of 400V is obtain. The output is controlled by means of PI controller are used. The 400V is given to the inverter which convert DC to AC. The AC voltage is passed to the LC filter which eliminates harmonics and the pure sine wave obtain is given to resistive load.

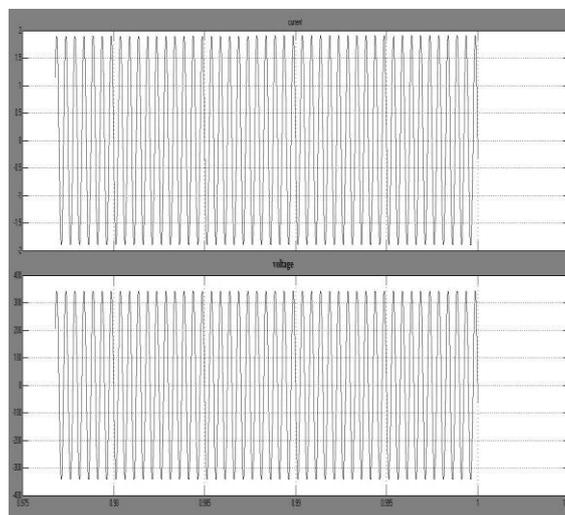
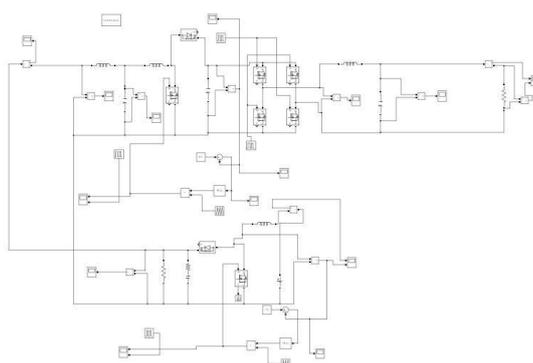


Fig.16. Voltage and current waveform for close-loop mode 4

Mode 5



The PV does not generate power during night and rainy seasons. Therefore the voltage is obtained from the BDC that acts as the BC which boosts 24V to 100V and it is again given back to the BC which converts 100V to 400V. The both outputs are controlled by means of PI controllers. Then 400V from BC is given to the inverter which converts DC to AC. The AC voltage is passed to the LC filter which eliminates harmonic and pure sine wave obtained is given to resistive load.

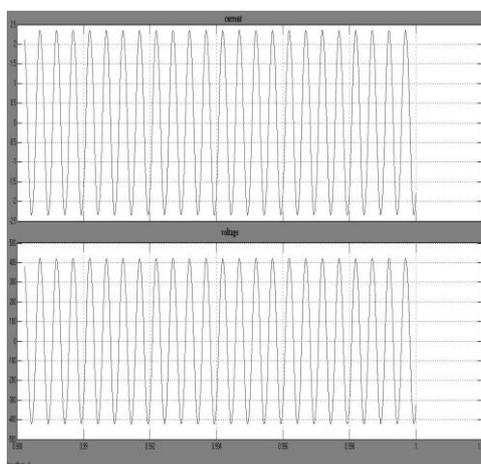


Fig.17. Voltage and current for close-loop mode 5

VIII. Conclusion

In this project presented, dynamic-response analysis and the controller-design procedure of the flexible SPVS. Both dc/dc converters are successfully controlled in a variable operation condition, and the control strategy achieves fast and accurate control of the inverter output voltage, even with nonlinear loads and step-load changes. From the proposed control architecture of the PV-storage system, multiple operating modes such as PV-only, storage only, and PV-storage coupled are allowed without any instantaneous control configuration changes. The experimental tests are verified by utilizing a 36-V battery bank; actually, the SPVS can also operate well when associated with a 24 V commercial single battery. The proposed topology, along with its control strategy, is very practical because of the flexibility of the configuration, and the controlling strategy of the bidirectional dc/dc converter and dc/ac inverter is simple and strong. As a result, it is compatible with a conventional PV or battery systems without any control configuration modification. This topology is highly promising for a commercial product of PV conversion systems.

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