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A Novel Topology for Controlling a Four Port DC-DC Boost Converter for a Hybrid PV/PV/Battery Power System

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Abstract

This paper proposes a four port three input-dc-dc boost converter for hybridising two photovoltaic systems and a storage medium. Three unidirectional ports are utilised to interface the converter with the two input sources and the output load. A bidirectional port interfaces the converter with the storage system. The two sources individually or simultaneously supply the load and charge the battery. The proposed technique employs only four independently controlled switches with different duty ratios. The regulated dc output can be obtained by controlling these four switches and tracking the maximum power of the two photovoltaic systems. Three different modes of operation of converter influenced by the state of battery are presented. The proposed system is validated and verified by simulation performed in MATLAB under various operating conditions.

Keywords: *photovoltaic (PV) cell, hybrid alternative energy sources, dc-dc boost converter, perturb and observe algorithm*

1. Introdution

As per the present scenario, power from the fossil fuels (coal, lignite, oil, gases) are depleting and the trend is to develop green or renewable based energies which does not cause any pollution to the environment. In this paper Photovoltaic (PV) energy is used which finds much attractive owing to its noiseless and clean electric power generation. But this majorly depends on the environmental aspects such as sun's irradiation level and temperature, which cannot be suffice throughout the day for power generation, hence energy storage medium is employed and hybridised to form a promising energy supplying systems. Batteries are the storage mechanism which improves the system capacity by smoothing the output power, increasing the start-up transitions and dynamic characteristics to increase the peak power capacity [1, 2]. When compared with the single sourced system, hybrid systems provide a high quality, reliable, and efficient power this is because of the bidirectional capability of the storage element. Various traditional methods have been used to integrate different power sources to form a hybrid system which can be classified into ac-coupled systems [3, 4]. The major short comings of these systems are complex system topology, power losses, cost expensive and bulk in size. Nowadays traditional topology systems are replaced with multi input converters. When comparing the single port system, integrated multi-port system can interface several power sources and storage devices, multi port converters have an advantage of lower cost, compact size, and better dynamic performance, centralised control, bidirectional power flow capacity for the storage element and higher reliability. Systematic approach of generating MICs is introduced in [5], where the pulsating voltage source and pulsating current source cells are proposed for deriving MICs. Chen *et al* [6] deals with the hybridisation of PV and wind power sources in a unified structure. Another basic research on MICs deals with two types of MICs [7]: first type in which only one power source is allowed to transfer energy to the load at a time, and in second type all the sources supply energy to the load either individually or simultaneously. In [8] a three port bidirectional converter with three active full bridges, two resonant tanks and high frequency transformers are proposed where higher system gain and switching losses are reduced due to soft switching behaviour. MICs are proposed based on the structure of dc-dc

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converters [9], the dc-dc converters in [10] is useful for combining various input sources which is of different power capacity. When operating DC-DC converters for solar applications under hard switching increases the switching losses and decreases the efficiency, hence soft switching method is used as in [11]. The three input dc-dc converter which is proposed in [12] has the capability of configuring various topologies (buck, boost, buck- boost) along with the bi-directionality of battery. Power switches with lower voltage rating and lower turn on resistance is used to reduce the conduction losses [13]. A novel single-stage MPPT controller is used for rapid tracking of the PV array's maximum power point. The proposed algorithm in this paper [14] reduces oscillation, resulting in significantly improved tracking. Suntio *et al* [15] focuses on the control system of the multiple-input power electronic converter. Two powerful and practical methods for maximum power point tracking of PV systems are investigated and compared in [8], the optimal MPPT methodology strongly depends on matching load and tracker characteristics. Control strategy of various renewable resources with digital control techniques are employed in [16]. Figure 1 shows the proposed integrated four port converters which are controlled by a single converter. This topology reduces the volume and system cost of the central controller. The proposed switching strategy of the converter allows the converter control by duty ratios under various operating modes.

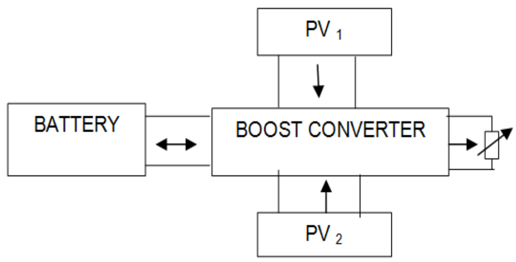

Figure 1. Functional Diagram of the Proposed Methodology

The organisation of this paper is as follows: The principal of operation are discussed under section II. The operation modes of the converters are detailed in section III. The simulations performed for validating the proposed methodology are explained in section IV and section V provides the conclusions and future scopes of the proposed work.

2. Principle of Operation

This section introduces a novel technique for a three port boost converter utilising a two PV source and a storage element. Figure 1 shows the control methodology of the proposed technique. It has three unidirectional ports, two ports coupling the input sources PV_1 and PV_2 with the boost converter and one coupling the converter with the load. A bidirectional port couples the converter with the storage element. The current source converter is utilised for stepping up both the PV sources voltage. Four MOSFET switches are employed here and are controlled with four different duty ratios, enabling to control the power between the hybrid system and the load. An interesting feature in this methodology is that the power can be delivered simultaneously to the load by the two PV systems, as well as charging and discharging of the battery through the sources can be done. The major advantage of this method is that the four switches are operated at different duty cycles, thereby the summation of duty cycle restriction is eliminated and it results in high output voltage gain. The presence of inductor L_1 and L_2 makes the input sources to be two current sources which results in drawing smooth currents from the input sources. Diodes D_1 and D_2 acts in a complementary manner with the switches S_1 and S_2, Similarly diodes D_3 and D_4 acts in a complementary manner with the switches S_3 and S_4. Depending on the exploitation state of the battery three operating modes are stated for the proposed converter and all the three modes are operated with four different duty ratios of the switches whose summation gives stable duty ratio range under various circumstances.

3. Operation Modes of the Converter

The proposed three input boost converter interfacing two PV systems is as shown in Figure 2.

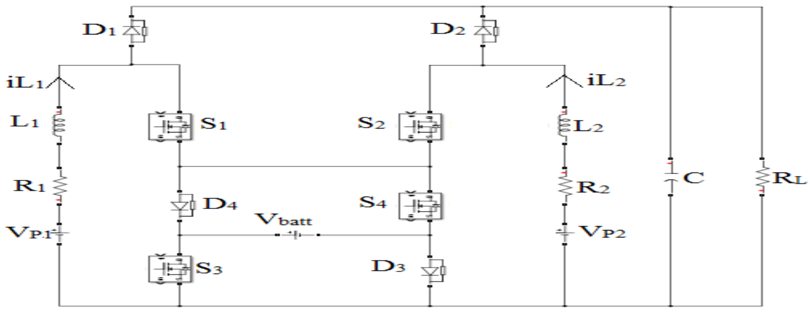

Figure 2. Circuit topology of the proposed system

The two PV sources are given by v_1 and v_2. The load resistance is R_L. S_1, S_2, S_3 and S_4 are the four MOSFET switches. These switches are controlled for changing the power flow direction by changing the duty cycles of the switches d_1, d_2, d_3 and d_4 respectively. It has to be noted that the duty cycles are completely independent. The two diodes D_1 and D_2 acts opposite with the two switches S_1 and S_2. When the switches S_3 and S_4 are ON, the diodes D_3 and D_4 are blocked as they are reverse biased by the battery voltage.

Depending upon the power utilisation from the battery three modes of operation are defined:

1) Both the sources are supplying load without battery
2) Both the sources and the battery is supplying load
3) Both the sources are supplying the load and charging the battery

Before performing the analysis of different modes of the converter some of the assumptions are made:

1) Switches are assumed to be ideal.
2) Magnetizing inductance is kept large so as maintain the current flow across the inductance constant.
3) Capacitors are large enough to maintain the voltage across it constant.
4) Conductor is assumed to be operated in CCM mode.

3.1. First Mode of Operation

In this mode, only the v_1 and v_2 supply the load. The battery is neither charged nor discharged. When battery is not considered the inductor currents of PV_1 and PV_2 can pass only through two path of conduction, S_4-D_3 and S_3-D_4 respectively. The first path is considered for this operating mode. Hence the switch S_3 is OFF and S_4 is made ON. Thus three different switching states can be obtained according to the requirement and are tabulated in Table 1.

Table 1. Switching States of mode 1

Switching State	Duty Cycle	S1	S2	S3	S4
State 1	$0 < t < d_1T$	ON	ON	OFF	ON
State 2	$d_1T < t < d_2T$	OFF	ON	OFF	ON
State 3	$d_2T < t < T$	OFF	OFF	OFF	OFF

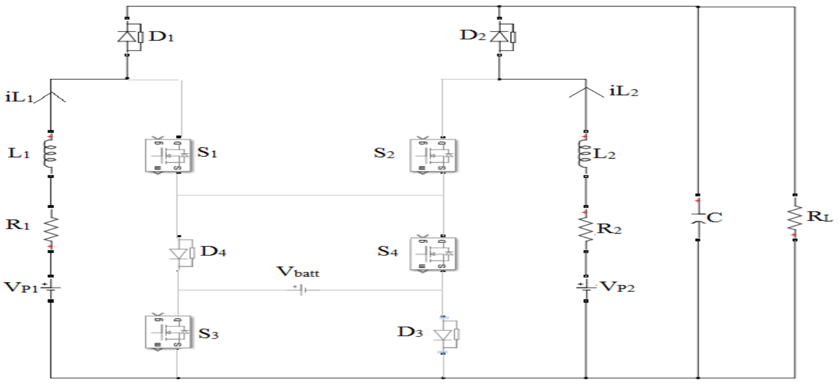

Figure 3. First operating mode

The voltage and current balance theory [17] is applied and the following expressions are obtained for the converter.

$$L_1 : v_0 = \frac{v_1 - r_1 i_{L1}}{1 - d_1} \quad (1)$$

$$L_2 : v_0 = \frac{v_2 - r_2 i_{L2}}{1 - d_2} \quad (2)$$

$$C : (1 - d_1)Ti_{L1} + (1 - d_2)Ti_{L2} = T\frac{v_0}{R_L} \quad (3)$$

$$I_{batt}=0; \quad P_{batt}=0 \quad (4)$$

It can be seen that the battery current and power delivered by the battery is zero. Thus it can be said that only the two sources are delivering power to the load.

3.2. Second Mode of Operation

In this operating mode the power to load is delivered by both the sources and the battery. If the battery has to deliver power to the load both the switches S_3 and S_4 has to be turned ON. Thus the power discharge from the battery depends on switches S_1 and S_2, with specific duty cycles d_1 and d_2. Mathematically it can be represented as follows:

$$P_{batt.dis}^{max} = v_B[d_1 i_{L1} + d_2 i_{L2}] \quad (5)$$

In one switching period four switching states can be obtained in this mode of operation, given in Table 2.

Table 2. Switching States of mode 2

Switching State	Duty Cycle	S1	S2	S3	S4
State 1	$0 < t < d_4T$	ON	ON	OFF	ON
State 2	$d_4T < t < d_1T$	ON	ON	OFF	OFF
State 3	$d_1T < t < d_2T$	OFF	ON	OFF	OFF
State 4	$d_2T < t < T$	OFF	OFF	OFF	OFF

The voltage and current balance theory is applied and the following expressions are obtained for the converter.

$$L_1 : v_0 = \frac{v_1 - r_1 i_{L1} + d_4 v_B}{1 - d_1} \quad (6)$$

$$L_2 : v_0 = \frac{v_2 - r_2 i_{L2} + d_4 v_B}{1 - d_2} \tag{7}$$

$$C : (1 - d_1)Ti_{L1} + (1 - d_2)Ti_{L2} = T\frac{v_0}{R_L} \tag{8}$$

$$i_{batt} = d_4(i_{L1} + i_{L2}) \tag{9}$$

$$P_{batt} = v_B d_4(i_{L1} + i_{L2}) \tag{10}$$

The d_4 is used to regulate the output power voltage by the battery discharge, whereas the sources are made to deliver the reference power by d_1 and d_2.

3.3. Third Mode of Operation

In this mode the power to the load is supplied by the two sources as well the charging of the battery is accomplished. The condition for charging the battery can be given when S_3 and S_4 are OFF, turning ON S_1 and S_2 will charge the battery through D_4 and D_3. Hence, the maximum charging power of the battery must be considered and it is given by:

$$P_{batt.cha}^{max} = -v_B[d_1 i_{L1} + d_2 i_{L2}] \tag{11}$$

Four switching states are possible in one switching period, and are given in Table 3.

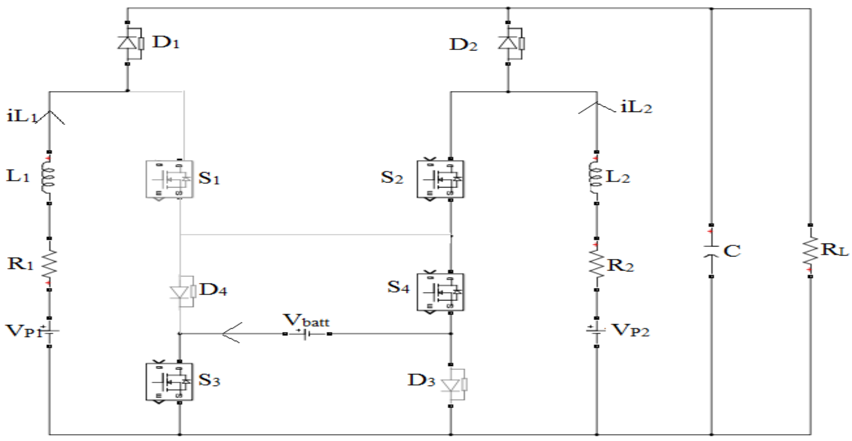

Figure 4. Second operating mode

Table 3. Switching States of mode 3

Switching State	Duty Cycle	S1	S2	S3	S4
State 1	$0 < t < d_3T$	ON	ON	ON	OFF
State 2	$d_3T < t < d_1T$	ON	ON	OFF	OFF
State 3	$d_1T < t < d_2T$	OFF	ON	OFF	OFF
State 4	$d_2T < t < T$	OFF	OFF	OFF	OFF

The voltage and current balance theory is applied and the following expressions are obtained for the converter:

$$L_1 : v_0 = \frac{v_1 - r_1 i_{L1} - (d_1 - d_3)v_B}{1 - d_1} \tag{12}$$

$$L_2 : v_0 = \frac{v_2 - r_2 i_{L2} - (d_2 - d_3)v_B}{1 - d_2} \tag{13}$$

$$C: (1-d_1)Ti_{L1} + (1-d_2)Ti_{L2} = T\frac{v_0}{R_L} \quad (14)$$

$$i_{batt} = -(d_1 - d_3)i_{L1} - (d_2 - d_3)i_{L2} \quad (15)$$

$$P_{batt} = -v_B[(-d_3)(i_{L1} + i_{L2}) + d_1 i_{L1} + d_2 i_{L2}] \quad (16)$$

This mode of operation can be accomplished only when the two sources generate power in excess than the load power. Also the charging can be accomplished only when d_3 regulates the output voltage. Thus d_1 and d_2 are used to regulate the power from sources and d_3 charges the battery through the power that is generated in excess.

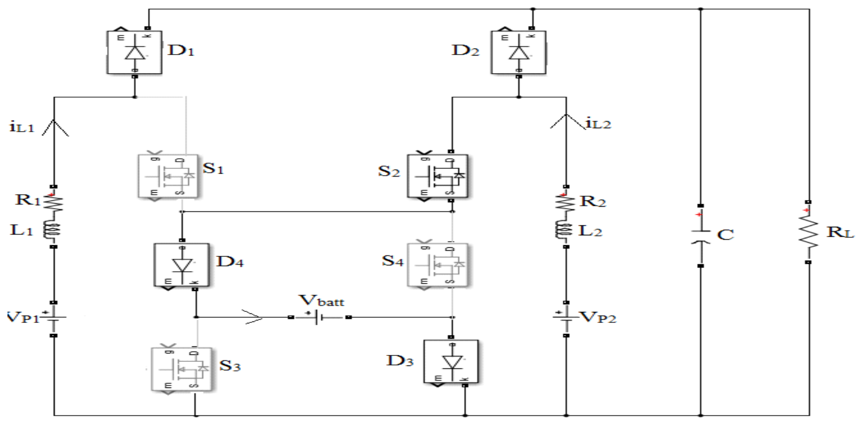

Figure 5. Third operating mode

4. Simulation Results

The proposed methodology is verified by simulating the converters in MATLAB environment. All the three modes of operation are performed in the simulation package. A resistive load of power 2.5 kW is chosen at the DC link. The regulated output voltage of the converter is 350V. Two PV systems of peak power 2.5 kW are chosen to assure reliable supply to the load. The discharge power of the battery is selected at 1 kW. The two PV cells are modelled to provide the peak power. In the simulation, the PV system is modelled and the output characteristics are depicted for the PV sources are as shown in the Figure 6 and 7 respectively. To extract a maximum power from the PV source perturb and observe MPPT algorithm has been used, the output characteristic of PV source is obtained under the irradiation level of 1000 w/m^2 respectively. Determination of maximum operating point of PV source under MPPT is achieved by periodic control method.

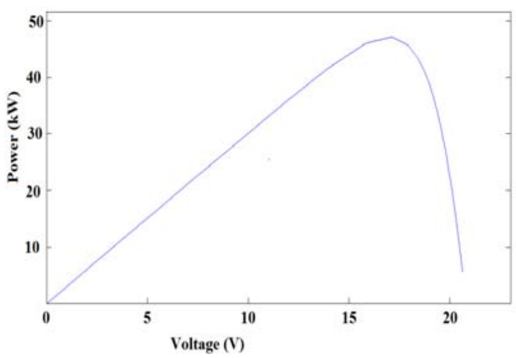

Figure 6. P-V Characteristics of Solar Panel

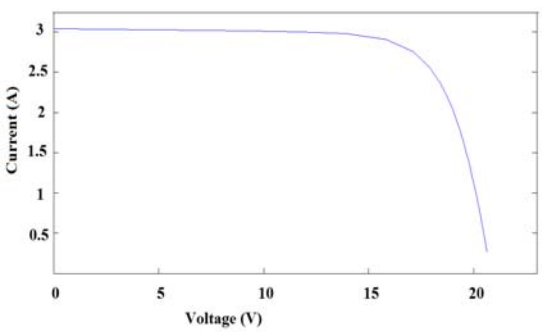

Figure 7. I-V Characteristics of Solar Panel

The maximum power tracked by MPPT algorithm is found to be 47KW. The P-V and I-V curve are as shown in the Figure 6 and Figure 7, it is noted that the solar cell acts as a constant current source at low operating voltages and acts as a constant voltage source under low operating current.

The simulation is made to run for 6 seconds to evaluate the performance of the converter under all the three modes. Simulation results of dc-link voltage which is efficiently regulated in all the three stages are as depicted in the Figure 9 and 10. Furthermore the duty ratios which regulate PV source, battery power are illustrated in the Figure 8.

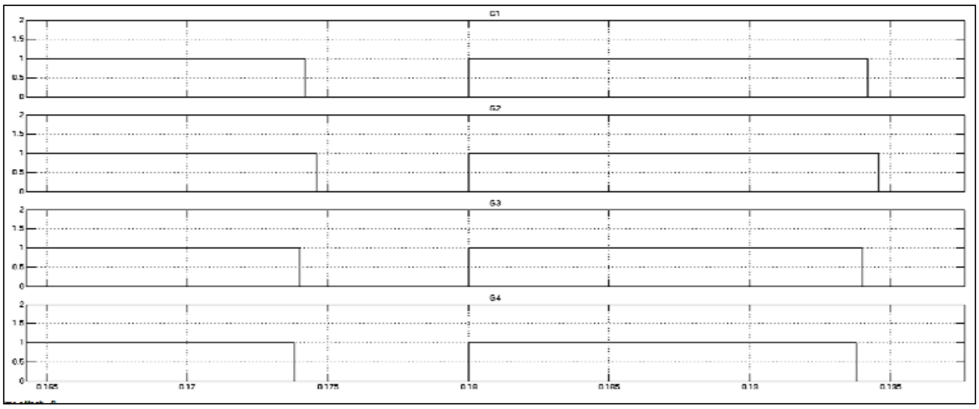

Figure 8. Switching Pattern

The simulation in performed in three stages and all the stages are discussed in detail below. The output results obtained for the overall performance of the converter under three stages remains same and it is as shown in the Figure 9 and 10

First simulation stage: This stage is made to run for initial two seconds (0<t<2s).during this stage of operation there is no need for battery since the load power is shared by both PV sources. The control is obtained by adjusting the duty ratio of the switches d_3=0 and d_4=1 which allows the battery contribution to be zero. This mode of operation is conducted during peak periods for maximum utilisation of solar power.

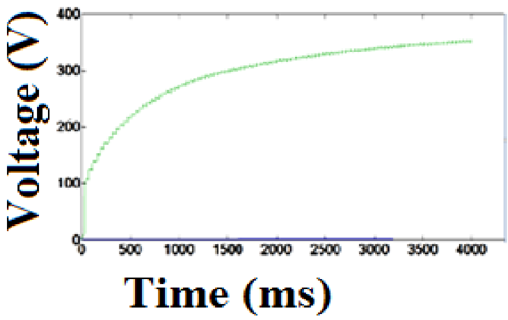

Figure 9. Output Voltage Plot

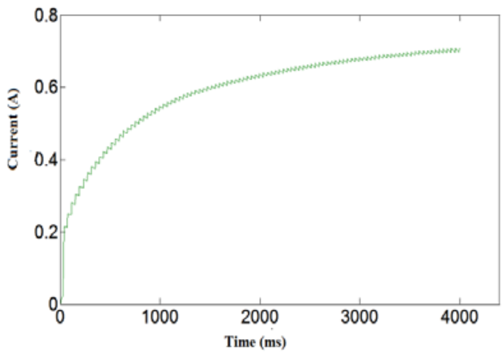

Figure 10. Output Current Plot

Second simulation stage: This stage is made to run for time period (2s<t<4s).during this stage of operation there is a need of battery contribution since power delivered by PV sources will be low enough to contribute the load requirement. The power shortage existed in the system will be contributed by battery. The controlling mechanism which assists this mode of operations depicts the duty ratio as shown in Figure 8. The duty ratio set for this corresponding mode in MATLAB environment is as show below:

D_1 =71%
D_2 =73%
D_3 =70%
D_4 =69%

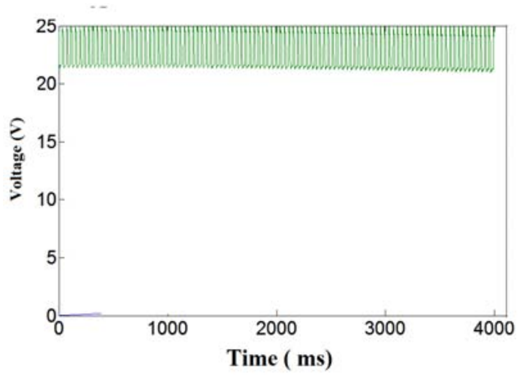

Figure 11. Battery Voltage

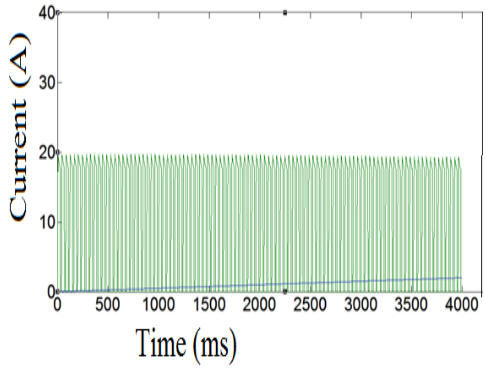

Figure 12. Battery Current

Third simulation stage: This stage is made to run for time period (4s<t<6s). During this stage of operation battery charging is made to be performed and this is done by the excess PV power available during the operation of the converter without upsetting the actual performance. This mode is advisable to be performed during excess sunlight.

The efficiency obtained by the converter in all the modes is depicted as in fig 13. It is found that the converter under various circumstances attains the efficiency of 80%.

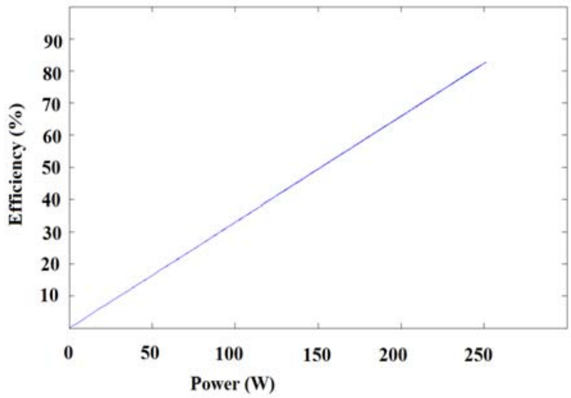

Figure 13. Efficiency Curve

5. Conclusion and Future Work

A four port dc-dc converter for a hybrid PV/PV/ battery system is proposed in this paper. The power flow is controlled by the four independently operated switches. Based on the state of the battery, three modes of operation of the converter are observed. Applying the voltage-second current-second balance theory, the mathematical model of the converters is realised. The proposed model was validated by the MATLAB simulation. The proposed system was found to be more economical, since the number of inductors used is considerably reduced and low voltage batteries and super capacitors can be effectively implemented. The proposed methodology is investigated under the PV system, it can also be utilised for other alternative energy sources.

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