A High Step-Up Three-Port Dc–Dc Converter for Stand-Alone PV/Battery Power Systems

1.Bandaru Naveen,navennsri555@gmail.com, 2.C.Balachandra Reddy, cbcredyy202@gmail.com, 3.Dr.B.Ravindranath Reddy,Bumanapalli_brreddy@yahoo.co.in,4. Dr.M.Suryakalavathi, munagala12@yaho.com

Abstract- **The proposed topology includes five power switches, two coupled inductors, and two active-clamp circuits. The coupled inductors are used to achieve high step-up voltage gain and to reduce the voltage stress of input side switches. Two sets of active-clamp circuits are used to recycle the energy stored in the leakage inductors and to improve the system efficiency. The operation mode does not need to be changed when a transition between charging and discharging occurs. Moreover, tracking maximum power point of the PV source and regulating the output voltage can be operated simultaneously during charging/discharging transitions. As long as the sun irradiation level is not too low, the maximum power point tracking (MPPT) algorithm will be disabled only when the battery charging voltage is too high. Therefore, the control scheme of the proposed converter provides maximum utilization of PV power most of the time. As a result, the proposed converter has merits of high boosting level, reduced number of devices, and simple control strategy. Simulation results are verified by MATLAB/SIMULINK.**

Index Terms—Boost–flyback converter, high step-up, photovoltaic system, voltage multiplier module.

I. INTRODUCTION

This project addresses dynamic modeling and control of a grid-connected wind–PV–battery hybrid system with versatile power transfer. The hybrid system, unlike conventional systems, considers the stability and dispatch-ability of its power injection into the grid. The hybrid system can operate in three different modes, which include normal operation without use of battery, dispatch operation, and averaging operation.

In order to effectively achieve such modes of operation, two modified techniques are applied; a modified hysteresis control strategy

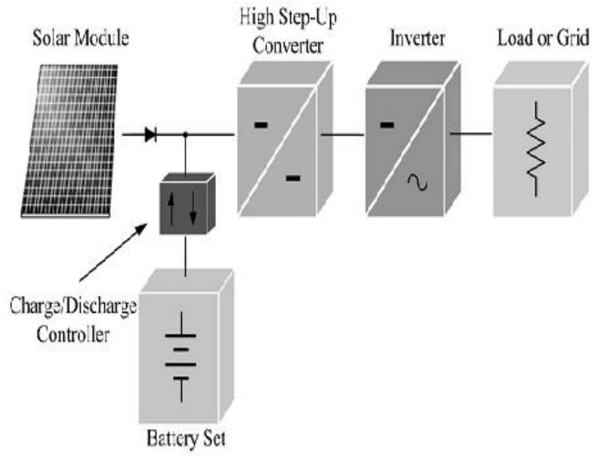


Fig. 1. Typical photovoltaic system.

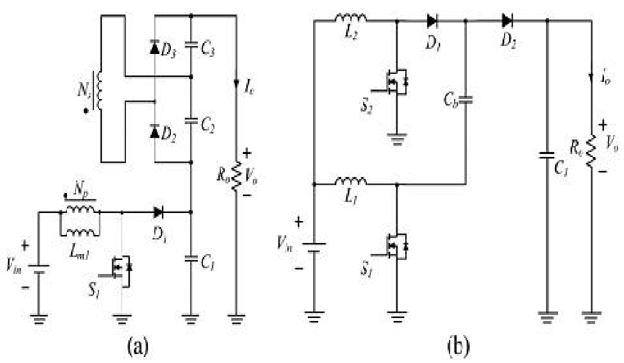


Fig. 2. High step-up techniques based on a classical boost converter. (a) Integrated flyback–boost converter structure. (b) Interleaved boost converter with a voltage-lift capacitor structure.

for a battery charger/discharger and a power averaging technique using a low-pass filter. The concept and principle of the hybrid system and its supervisory control are described. Classical techniques of maximum power tracking are applied in PV array and wind-turbine control. Dynamic modeling and simulations were based on Power System Computer Aided Design/Electromagnetic Transients Program for DC (PSCAD/EMTDC), power-system transient-analysis software. The program was based on Dommel's algorithm, specifically developed for the simulation of high-voltage direct current systems and efficient for the transient simulation of power system under power-electronic control.

Theoretically, conventional step-up converters, such as the boost converter and flyback converter, cannot achieve a high step-up conversion with high efficiency because of the resistances of elements or leakage inductance. Thus, a modified

boost–flyback converter was proposed , and many converters that use the coupled inductor for a considerably highvoltage conversion ratio were also proposed Despite these advances, conventional step-up converters with a single switch are unsuitable for high-power applications given an input large current ripple, which increases conduction losses. Thus, numerous interleaved structures and some asymmetrical interleaved structures are extensively used. The current study also presents an asymmetrical interleaved converter for a high step-up and high-power application.Modifying a boost–flyback converter, shown in Fig. 2(a), is one of the simple approaches to achieving high step-up gain; this gain is realized via a coupled inductor. The performance of the converter is similar to an active-clamped flyback converter; thus, the leakage energy is recovered to the output terminal. An interleaved boost converter with a voltage-lift capacitor shown in Fig. 2(b) is highly similar to the conventional interleaved type.

It obtains extra voltage gain through the voltage-lift capacitor, and reduces the input current ripple, which is suitable for power factor correction (PFC) and high-power applications.

The advantages of the proposed converter are as follows:

1) the converter is characterized by a low input current ripple and low conduction losses, making it suitable for highpower applications;

2) the converter achieves the high step-up voltage gain that renewable energy systems require;

3) leakage energy is recycled and sent to the output terminal, and alleviates large voltage spikes on the main switch;

4) the main switch voltage stress of the converter is substantially lower than that of the output voltage;

5) low cost and high efficiency are achieved by the low rDS(on) and low voltage rating of the power switching device.

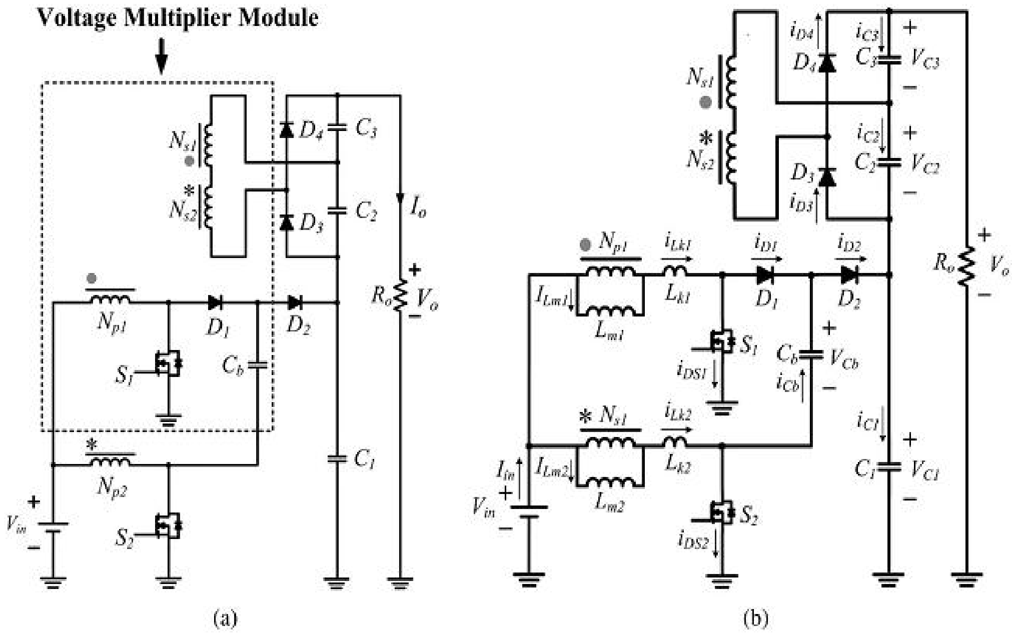


Fig. 3. (a) Proposed high step-up converter with a voltage multiplier module. (b) Equivalent circuit of the proposed converter.

II. OPERATINGPRINCIPLEDESCRIPTION

The proposed high step-up converter with voltage multiplier module is shown in Fig. 3(a). A conventional boost converter and two coupled inductors are located in the voltage multiplier module, which is stacked on a boost converter to form an asymmetrical interleaved structure. Primary windings of the coupled inductors withNp turns are employed to decrease input current ripple, and secondary windings of the coupled inductors withNs turns are connected in series to extend voltage gain. The turns ratios of the coupled inductors are the same. The coupling references of the inductors are denoted by " .“and " ▫ ”inFig.3. The equivalent circuit of the proposed converter is shown in

Fig. 3(b), whereLm1 andLm2 are the magnetizing inductors, Lk1andLk2represent the leakage inductors,S1andS2denote the power switches, Cb is the voltage-lift capacitor, and nis defined as a turns ratioNs/Np. The proposed converter operates in continuous conduction mode (CCM), and the duty cycles of the power switches during steady operation are interleaved with a 180◦ phase shift; the duty cycles are greater than 0.5. The key steady waveforms in one switching period of the proposed converter contain six modes, which are depicted in Fig. 4, and Fig. 5 shows the topological stages of the circuit. Mode1[t0,t1]:Att=t0, the power switches S1 andS2 are both turned ON. All of the diodes are reversed-biased. Magnetizing inductorsLm1 andLm2 as well as leakage inductors Lk1 andLk2 are linearly charged by the input voltage source Vin.

Mode 2 [t1,t2]:Att=t1, the power switch S2 is switched OFF, thereby turning ON diodesD2 andD4. The energy that magnetizing inductorLm2 has stored is transferred to the secondary side charging the output filter capacitorC3. The input voltage source, magnetizing inductorLm2, leakage inductor Lk2, and voltage-lift capacitor Cb release energy to the output filter capacitorC1 via diodeD2, thereby extending the voltage onC1.

Mode 3 [t2,t3]:Att=t2, diode D2 automatically switches OFF because the total energy of leakage inductorLk2has been completely released to the output filter capacitorC1. Magnetizing inductor Lm2transfers energy to the secondary side charging the output filter capacitorC3via diodeD4untilt3.

Mode 4 [t3,t4]:Att=t3, the power switch S2 is switched ON and all the diodes are turned OFF. The operating states of modes 1 and 4 are similar.

Mode 5 [t4,t5]:Att=t4, the power switch S1 is switched OFF, which turns ON diodesD1 andD3. The e nergy stored in magnetizing inductorLm1 is transferred to the secondary side charging the output filter capacitorC2. The input voltage source and magnetizing inductorLm1 release energy to voltage-liftcapacitorCb via diodeD1, which stores extra energy inCb.

Mode 6 [t5,t0]:Att=t5, diode D1 is automatically turned OFF because the total energy of leakage inductorLk1has been completely released to voltage-lift capacitorCb. Magnetizing inductor Lm1 transfers energy to the secondary side charging the output filter capacitorC2via diodeD3 until t0.

The calculated voltage gain and efficiency with different copper resistances are shown in Fig. 11, andrL11 andrL21 are defined asrL. The other parameters in (33) are set as follows:

1) input voltage Vin :40V;

2) Turns ration:1;

3) load Ro : 200Ω

4)on-resistances of switchesrDS1andrDS2: 0.021Ω;

5) resistances of diodesrD1,rD2,rD3, and rD4:0.01Ω;

6) forward bias of diodesVD1,VD2,VD3, and VD4:1V;

7) copper resistances of secondary windings of coupled inductorsrL12andrL22=rLat a turns rationof 1.

Fig. 11 reveals that efficiency and voltage gain are affected by various coupled inductor winding resistors and duty cycle, and that efficiency is decreased by the extreme duty ratio.

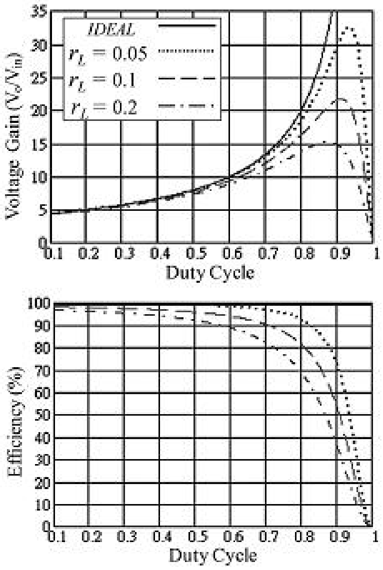


Fig. 11. Calculated voltage gain and efficiency with different copper resistances.

TABLE I
PERFORMANCE COMPARISON OF INTERLEAVED HIGH STEP-UP CONVERTERS

High step-up interleaved converter	Converter in [33]	Converter in [30]	Proposed Converter
Voltage gain	$\frac{2}{1-D}+nD$	$\frac{2(n+1)}{1-D}$	$\frac{2(n+1)}{1-D}$
Voltage stress on switch	$\frac{V_o}{2+nD(1-D)}$	$\frac{V_o}{2(n+1)}$	$\frac{V_o}{2(n+1)}$
The highest voltage stress on diodes	$\frac{2V_o}{2+nD(1-D)}$	$\frac{(n+0.5)V_o}{n+1}$	$\frac{nV_o}{n+1}$
Quantities of diodes	4	6	4
Quantities of cores	3	2	2
Quantities of secondary side windings	1	2	1

TABLE II
CONVERTER COMPONENTS AND PARAMETERS

Components	Symbols	Parameters
Magnetizing inductances	L_{m1}, L_{m2}	133 μH
Leakage inductances	L_{k1}, L_{k2}	1.6 μH
Turns ratio	$n\ (N_s/N_p)$	1
Power switches	S_1, S_2	IRFP4227
Diodes	D_1, D_3, D_4	FCF06A-40
	D_2	BYQ28E-200
Capacitors	C_b, C_2, C_3	220 μF
	C_1	470 μF

III. DESIGN ANDEXPERIMENT OF THEPROPOSEDCONVERTER

A prototype of the proposed high step-up converter with a 40-V input voltage, 380-V output voltage, and maximum output power of 1 kW is tested. The switching frequency is 40 kHz, and the corresponding component parameters are listed in Table II for reference. The design consideration of the proposed converter includes components selection and coupled inductors design, which are based on the analysis presented in the previous section. In the proposed converter, the values of the primary leakage inductors of the coupled inductors are set close as possible for current sharing performance. Due to the performances of high step-up gain, the turns rationcan be set 1 for the prototype circuit with a 40- V input voltage, 380- V output to reduce cost, volume, and conduction loss of winding.

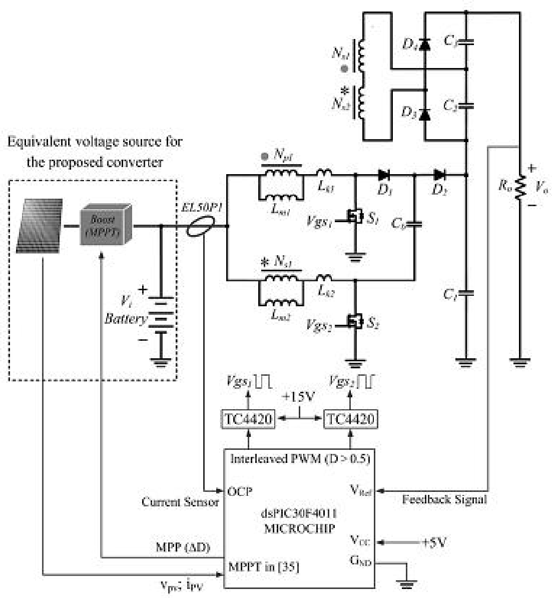
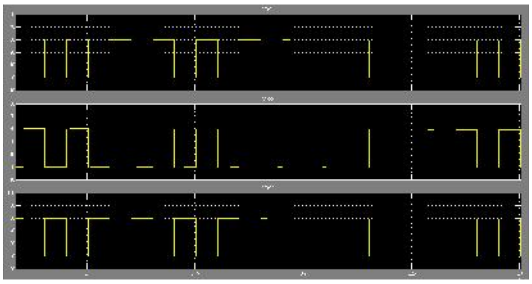
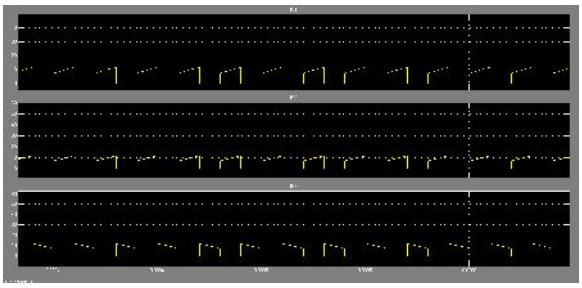


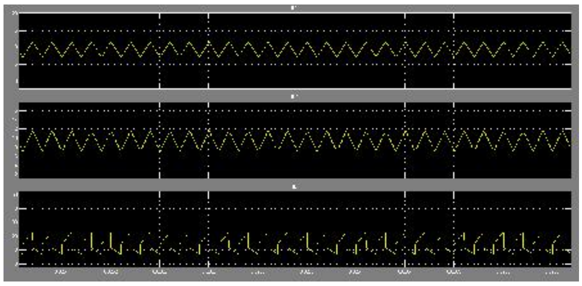
Fig. 12. Control strategy for the proposed converter.

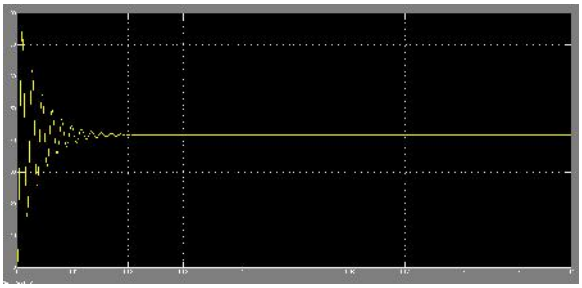
Thus, the copper resistances which affect efficiency much can be decreased. The value of magnetizing inductorsLm1 andLm2 can be design based on the equation of boundary operating condition, which is derived from

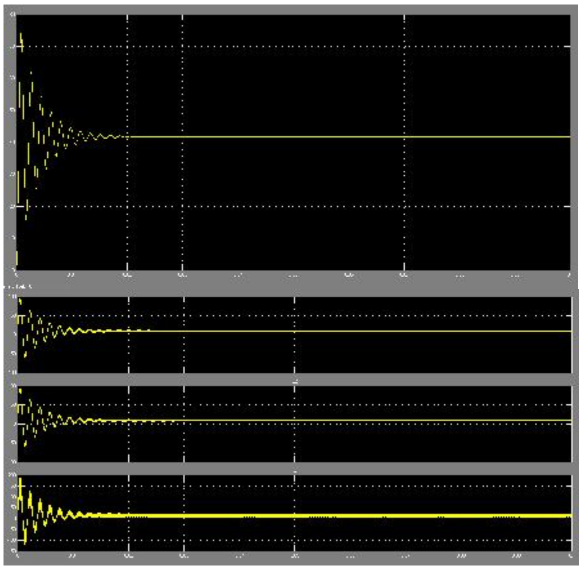
$$L_{m(\text{critical})} = \frac{D(1-D)^2 R_o}{2(n+1)(2n+2)f_s}$$











IV. CONCLUSION

This paper has presented the topological principles, steadystate analysis, and experimental results for a proposed converter. The proposed converter has been successfully implemented in an efficiently high step-up conversion without an extreme duty ratio and a number of turns ratios through the voltage multiplier module and voltage clamp feature. The interleaved PWM scheme reduces the currents that pass through each power switch and constrained the input current ripple by approximately 6%. The experimental results indicate that leakage energy is recycled through capacitorCb to the output terminal. Meanwhile, the voltage stresses over the power switches are restricted and are much lower than the output voltage (380 V). These switches, conducted to low voltage rated and low on-state resistance MOSFET, can be selected. Furthermore, the fullload efficiency is 96.1% atPo =1000 W, and the highest efficiency is 96.8% at Po =400 W. Thus, the proposed converter is suitable for PV systems or other renewable energy applications that need high step-up high-power energy conversion.

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BandaruNaveen, received B.Tech degre in Electrical Enginering, where he is currently working towards M.Tech degree in Power Electronics.His area of interests includes A High Step-Up Three-Port Dc–Dc Converter For Stand-Alone Pv/Battery Power Systems.

Mr. C.Balachandra Reddy received M.Tech degree in Electrical Engineering from NIT Warangal,now doing as a Ph.D Research Scholor at JNTU Hyderabad, in His area of interests Power quality issues in wind power generation.

Dr.B.Ravindranath Reddy ,He working as a Deputy Excutive Engineer JNTU Hyaderad.

Dr.M.Suryakalavathi,she is working as profesor in EEE department at JNTU Hydearabad.