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# A New Hybrid Boosting Converter for Renewable Energy Applications

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**Abstract:** A hybrid boosting converter(HBC) with collective advantages of regulation capability from its boost structure and gain enhancement from its voltage multiplier structure is proposed in this paper. The new converter incorporates a bipolar voltage multiplier, featuring symmetrical configuration, single inductor and single switch, high gain capability with wide regulation range, low component stress, small output ripple and flexible extension, which make it suitable for front-end PV system and some other renewable energy applications. The operation principal, component stress, and voltage ripple are analyzed in this paper. Performance comparison and evaluation with a number of previous single-switch single-inductor converters are provided. A 200-W 35 to 380V second-order HBC prototype was built with peak efficiency at 95.44%. The experimental results confirms the feasibility of the proposed converter.

**Keywords:** Hybrid Boosting, Bipolar, Component Stress.

## I. INTRODUCTION

In recent years, the rapid development of renewable energy system calls for new generation of high gain dc/dc converters with high efficiency and low cost. The front end of "Plug and Play" PV system usually demands step-up converter which is capable of boosting the voltage from 35 to 380Vwith regulation capability due to the low terminal voltage and the requirement of MPPT tracking function for single PV panel. Considering a wind farm with internal medium-voltage dc (MVDC)-grid system, a MVDC converter able to boost the voltage from 1–6 to 15–60 kV is required to link the output of generator-facing rectifier to the MVDC line. Some other energy storage systems such as fuel cell powered system also require high-gain dc/dc converter due to their low voltage level at storage side. In order to achieve high voltage conversion ratio with high efficiency, many high gain enhancement techniques were investigated in the previous publications. Among them, switched capacitor tapped/coupled inductor-based technique transformer based technique voltage multiplier structure or combinations of them attracted significant attentions. Each technology has its unique advantages and limitations. The switched capacitor dc–dc converter can achieve high efficiency but has pulsating current and poor regulation capability. Introduction of resonant switched-capacitor converter can alleviate the pulsating current but does not solve the regulation issue. The tapped-inductor and transformer facilitates gain boosting function but requires snubber circuit to handle leakage problem. The combination of above technologies usually outputs promising circuit features but with excessive number of components. In this paper, gain enhancement technology based on modification of traditional boost converter while maintaining single inductor and single switch is investigated, targeting at simplifying the circuit design, reducing the cost, satisfying the demands of normal high gain applications, and facilitating mass production

## II. HYBRID BOOSTING CONVERTER (HBC)

A hybrid boosting converter (HBC) with collective advantages of regulation capability from its boost structure and gain enhancement from its voltage multiplier structure is proposed in this paper. The new converter incorporates a bipolar voltage multiplier, featuring symmetrical configuration, single inductor and single switch, high gain capability with wide regulation range, low component stress, small output ripple and flexible extension, which make it suitable for front-end PV system and some other renewable energy applications. It combines the advantages of regulation capability of traditional inductor based DC-DC converters and gain boosting ability of switched capacitor converters. It is capable of boosting the input voltage to ten times with single active switch and one inductor while maintaining high efficiency. In addition, the switch stress is low and output voltage has a wide regulation range. A boost converter (step-up converter) is a DC-to-DC power converter steps up voltage (while stepping down current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) containing at least two semiconductors (a diode and a transistor) and at least one energy storage element, a capacitor, inductor, or the two in combination. To reduce voltage ripple, filters made of capacitors (sometimes in combination with inductors) are normally added to such a converter's output (load-side filter) and input (supply-side filter).

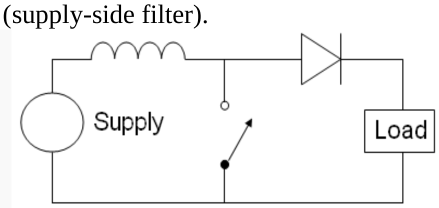



**Fig.1. The Basic Schematic of a Boost Converter. The Switch is Typically a MOSFET, IGBT, or BJT.**

Power for the boost converter can come from any suitable DC sources, such as batteries, solar panels, rectifiers and DC generators. A process that changes one DC voltage to a different DC voltage is called DC to DC conversion. A boost converter is a DC to DC converter with an output voltage greater than the source voltage. A boost converter is sometimes called a step-up converter since it "steps up" the source voltage. Since power must be conserved, the output current is lower than the source current.

**A. History**

For high efficiency, the SMPS switch must turn on and off quickly and have low losses. The advent of a commercial semiconductor switch in the 1950s represented a major milestone that made SMPSs such as the boost converter possible. The major DC to DC converters were developed in the early 1960s when semiconductor switches had become available. The aerospace industry's need for small, lightweight, and efficient power converters led to the converter's rapid development.

Switched systems such as SMPS are a challenge to design since their models depend on whether a switch is opened or closed. R. D. Middlebrook from Caltech in 1977 published the models for DC to DC converters used today. Middlebrook averaged the circuit configurations for each switch state in a technique called state-space averaging. This simplification reduced two systems into one. The new model led to insightful design equations which helped the growth of SMPS. Applications

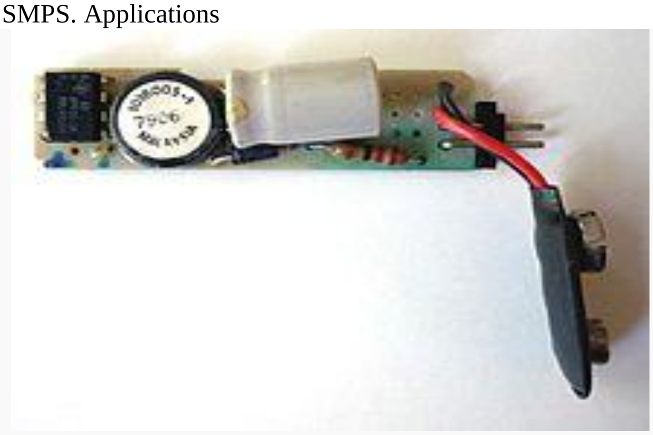


**Fig.2. Boost Converter from a TI Calculator, Generating 9 V from 2.4 V Provided By Two AA Rechargeable Cells**.

Battery power systems often stack cells in series to achieve higher voltage. However, sufficient stacking of cells is not possible in many high voltage applications due to lack of space. Boost converters can increase the voltage and reduce the number of cells. Two battery-powered applications that use boost converters are used in hybrid electric vehicles (HEV) and lighting systems. The NHW20 model Toyota Prius HEV uses a 500 V motor. Without a boost converter, the Prius would need nearly 417 cells to power the motor. However, a Prius actually uses only 168 cells and boosts the battery voltage from 202 V to 500 V. Boost converters also power devices at smaller scale applications, such as portable lighting systems. A white LED typically requires 3.3 V to emit light, and a boost converter can step up the voltage from a single 1.5 V alkaline cell to power the lamp. Boost converters can also produce higher voltages to operate cold cathode fluorescent tubes (CCFL) in devices such as LCD backlights and some flashlights. An unregulated boost converter is used as the voltage increase mechanism in the circuit known as the 'Joule thief'. This circuit topology is used with low power battery applications, and is aimed at the ability of a boost converter to 'steal' the remaining energy in a battery. This energy would otherwise be wasted since the low voltage of a nearly depleted battery makes it unusable for a normal load. This energy would otherwise remain untapped because many applications do not allow enough current to flow through a load when voltage decreases. This voltage decrease occurs as batteries become depleted, and is a characteristic of the ubiquitous alkaline battery.

**B. Circuit Analysis**

**1. Operating**

The key principle that drives the boost converter is the tendency of an inductor to resist changes in current by creating and destroying a magnetic field. In a boost converter, the output voltage is always higher than the input voltage. A schematic of a boost power stage is shown in Figure 1.

- When the switch is closed, current flows through the inductor in clockwise direction and the inductor stores some energy by generating a magnetic field. Polarity of the left side of the inductor is positive.
- When the switch is opened, current will be reduced as the impedance is higher. The magnetic field previously created will be destroyed to maintain the current towards the load. Thus the polarity will be reversed (means left side of inductor will be negative now). As a result, two sources will be in series causing a higher voltage to charge the capacitor through the diode D.

If the switch is cycled fast enough, the inductor will not discharge fully in between charging stages, and the load will always see a voltage greater than that of the input source alone when the switch is opened. Also while the switch is opened, the capacitor in parallel with the load is charged to this combined voltage. When the switch is then closed and the right hand side is shorted out from the left hand side, the capacitor is therefore able to provide the voltage and energy to the load. During this time, the blocking diode prevents the capacitor from discharging through the switch. The switch must of course be opened again fast enough to prevent the capacitor from discharging too much.

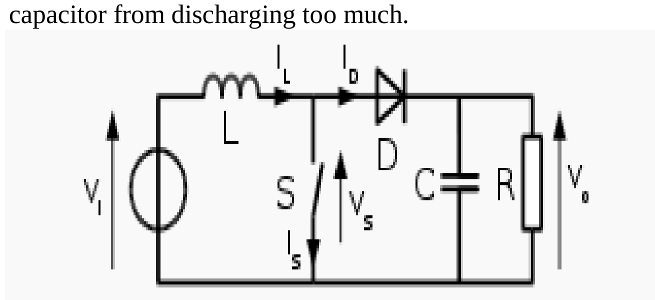



**Fig.3. Boost Converter Schematic**

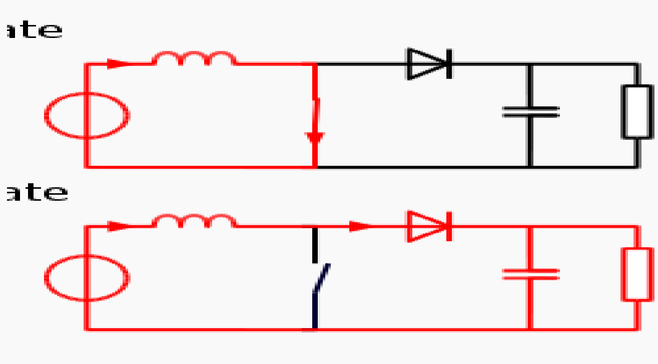


**Fig.4. The Two Configurations of a Boost Converter, Depending on the State of the Switch S.**

The basic principle of a Boost converter consists of 2 distinct states (see figure 2):

- in the On-state, the switch S (see figure 1) is closed, resulting in an increase in the inductor current;
- in the Off-state, the switch is open and the only path offered to inductor current is through the fly back diode D, the capacitor C and the load R. This result in transferring the energy accumulated during the On-state into the capacitor.
- The input current is the same as the inductor current as can be seen in figure 2. So it is not discontinuous as in the buck converter and the requirements on the input filter are relaxed compared to a buck converter.

**C. Renewable Energy Sources (RES)**

Renewable energy is generally defined as energy that is collected from resources which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat. Renewable energy often provides energy in four important areas: electricity, air and water heating/cooling, transportation, and rural (off-grid) energy services. Based on REN21's 2014 report, renewable contributed 19 percent to humans' global energy consumption and 22 percent to their generation of electricity in 2012 and 2013, respectively. This energy consumption is divided as 9% coming from traditional biomass, 4.2% as heat energy (non-biomass), 3.8% hydro electricity and 2% is electricity from wind, solar, geothermal, and biomass. Worldwide investments in renewable technologies amounted to more than US$214 billion in 2013, with countries like China and the United States heavily investing in wind, hydro, solar and bio fuels. Renewable energy resources exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries. Rapid deployment of renewable energy and energy efficiency is resulting in significant energy security, climate change mitigation, and economic benefits.

In international public opinion surveys there is strong support for promoting renewable sources such as solar power and wind power. At the national level, at least 30 nations around the world already have renewable energy contributing more than 20 percent of energy supply. National renewable energy markets are projected to continue to grow strongly in the coming decade and beyond. Some places and at least two countries, Iceland and Norway generate all their electricity using renewable energy already, and many other countries have the set a goal to reach 100% renewable energy in the future. For example, in Denmark the government decided to switch the total energy supply (electricity, mobility and heating/cooling) to 100% renewable energy by 2050. While many renewable energy projects are large-scale, renewable technologies are also suited to rural and remote areas and developing countries, where energy is often crucial in human development. United Nations' Secretary-General Ban Ki-moon has said that renewable energy has the ability to lift the poorest nations to new levels of prosperity. As most of renewable provide electricity, renewable energy deployment is often applied in conjunction with further electrification, which has several benefits: For example, electricity can be converted to heat without losses and even reach higher temperatures than fossil fuels, can be converted into mechanical energy with high efficiency and is clean at the point of consumption.

In addition to that electrification with renewable energy is much more efficient and therefore leads to a significant reduction in primary energy requirements, Renewable energy flows involve natural phenomena such as sunlight, wind, tides, plant growth, and geothermal heat, as the International Energy Agency explains: Renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, or from heat generated deep within the earth. Included in the definition is electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, and bio fuels and hydrogen derived from renewable resources. Renewable energy resources and significant opportunities for energy efficiency exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries. Rapid deployment of renewable energy and energy efficiency, and technological diversification of energy sources, would result in significant energy security and economic benefits. It would also reduce environmental pollution such as air pollution caused by burning of fossil fuels and improve public health, reduce premature mortalities due to pollution and save associated health costs that amount to several 100 billion dollars annually only in the United States.

Renewable energy sources, that derive their energy from the sun, either directly or indirectly, such as hydro and wind, are expected to be capable of supplying humanity energy for almost another 1 billion years, at which point the predicted increase in heat from the sun is expected to make the surface of the earth too hot for liquid water to exist. Climate change and global warming concerns, coupled with high oil prices, peak oil, and increasing government support, are driving increasing renewable energy legislation, incentives and commercialization. New government spending, regulation and policies helped the industry weather the global financial crisis better than many other sectors. According to a 2011 projection by the International Energy Agency, solar power generators may produce most of the world's electricity within 50 years, reducing the emissions of greenhouse gases that harm the environment. As of 2011, small solar PV systems provide electricity to a few million households, and micro-hydro configured into mini-grids serves many more. Over 44 million households use biogas made in household-scale digesters for lighting and/or cooking, and more than 166 million households rely on a new generation of more-efficient biomass cook stoves. United Nations' Secretary-General Ban Ki-moon has said that renewable energy has the ability to lift the poorest nations to new levels of prosperity. At the national level, at least 30 nations around the world already have renewable energy contributing more than 20% of energy supply.

National renewable energy markets are projected to continue to grow strongly in the coming decade and beyond, and some 120 countries have various policy targets for longer-term shares of renewable energy, including a 20% target of all electricity generated for the European Union by 2020. Some countries have much higher long-term policy targets of up to 100% renewable. Outside Europe, a diverse group of 20 or more other countries target renewable energy shares in the 2020–2030 time frame that range from 10% to 50%. Renewable energy often displaces conventional fuels in four areas: electricity generation, hot water/space heating, transportation, and rural (off-grid) energy services, Renewable hydroelectric energy provides 16.3% of the world’s electricity. When hydroelectric is combined with other renewable such as wind, geothermal, solar, biomass and waste: together they make the "renewable" total, 21.7% of electricity generation worldwide as of 2013. Renewable power generators are spread across many countries, and wind power alone already provides a significant share of electricity in some areas: for example, 14% in the U.S. state of Iowa, 40% in the northern German state of Schleswig-Holstein, and 49% in Denmark. Some countries get most of their power from renewable, including Iceland (100%), Norway (98%), Brazil (86%), Austria (62%), New Zealand (65%), and Sweden (54%).

### D. Heating

Solar water heating makes an important contribution to renewable heat in many countries, most notably in China, which now has 70% of the global total (180 GWth). Most of these systems are installed on multi-family apartment buildings and meet a portion of the hot water needs of an estimated 50–60 million households in China. Worldwide, total installed solar water heating systems meet a portion of the water heating needs of over 70 million households. The use of biomass for heating continues to grow as well. In Sweden, national use of biomass energy has surpassed that of oil. Direct geothermal for heating is also growing rapidly. The newest addition to Heating is from Geothermal Heat Pumps which provide both heating and cooling, and also flatten the electric demand curve and are thus an increasing national priority· Transportation Series-connected energy storage modules such as super capacitors (SCs) and lithium-ion batteries cause module voltage imbalances that lead to premature deterioration of modules. Various equalization techniques have been proposed for series-connected energy storage cells/modules to alleviate such voltage imbalances. However, since the conventional topologies consist of numerous switches, sensors, inductors, or transformers, their circuit size, complexity, and costs are prone to increase in proportion to the number of series connections. This paper proposes a single-switch single-inductor equalization charger using a voltage multiplier. Because the proposed equalization charger requires only a single switch and a single inductor to operate, the circuit size and complexity can be dramatically reduced compared to that of conventional topologies. To combine advantages of switched-mode and switched-capacitor (SC) power converters, a series of non-isolated multi-output pulse width modulation converters are developed in this study. This type of converters employs only one inductor and one active switch, which contributes to a simple structure and easy control features. An optimized SC technique is developed for peak current limitation and equivalent resistance reduction for SC units.

## III. PROPOSED GENERAL HBC TOPOLOGY AND ITS OPERATIONAL PRINCIPAL

The proposed HBC is shown in Fig. 2. There are two versions of HBC, odd-order HBC and even-order HBC as shown in Fig. 5(a) and (b). The even-order topology integrates the input source as part of the output voltage, leading to a higher components utilization rate with respect to the same voltage gain. However, they share similar other characteristics and

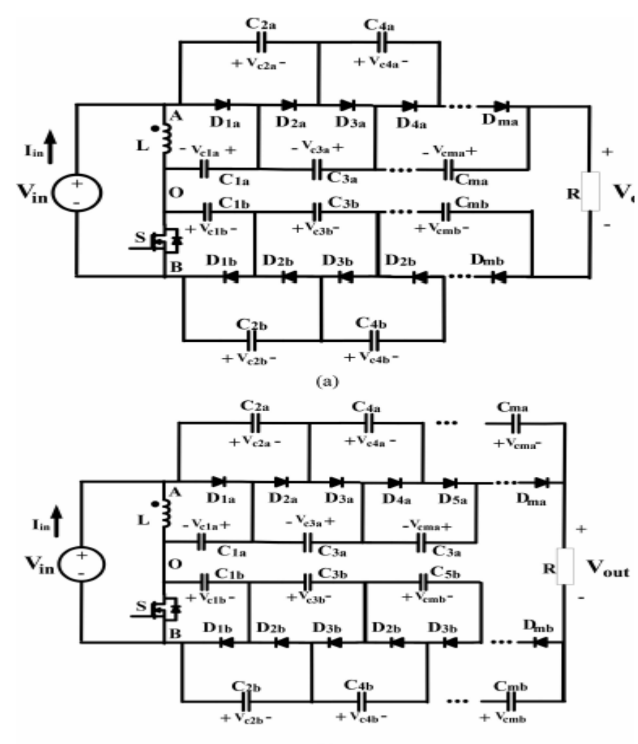



**Fig.5. Proposed General HBC Topology. (a) Odd-Order HBC. (b) Even-Order HBC**.

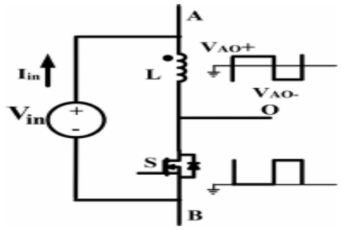



**Fig.6. Inductive Three-Terminal Switching Core.**

Circuit analysis method. Therefore, only even-order topology is investigated in this paper.

**A. Inductive Switching Core**

In a HBC topology, the inductor, switch and input source serve as an "inductive switching core," shown as Fig. 3. It can generate

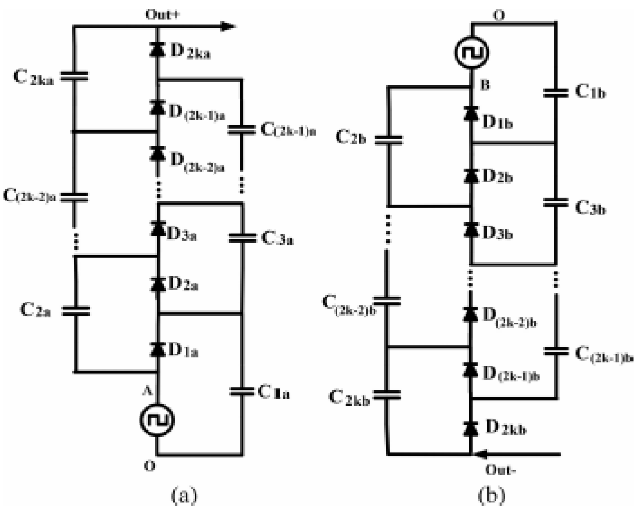



**Fig.7. Bipolar Voltage Multiplier. (a) Positive Multiplier. (b) Negative Multiplier**.

two "complimentary" PWM voltage waveforms at port AO and port OB. Although the two voltage waveforms have their individual high voltage level and low voltage level, the gap between two levels is identical, which is an important characteristic of inductive switching core for interleaving operation.

**B. BVM**

A BVM is composed of a positive multiplier branch and a negative multiplier branch, shown in Fig. 7(a) and (b). Positive multiplier is the same as traditional voltage multiplier while the negative multiplier has the input at the cathode terminal of cascaded diodes, which can generate negative voltage at anode terminal, shown in Fig. 7(b). By defining the high voltage level at input AO as VOA+, the low voltage level as VOA−, and the duty cycle of high voltage level as D, the operational states of the even-order positive multiplier is derived as Fig. 5 and illustrated as following:

**1. State 1 [0, DTs]:** When the voltage at port AO is at high level, diodes Dia (i = 2k − 1, 2k − 3 . . . 3, 1) will be conducted consecutively. Each diode becomes reversely biased before the next diode fully conducts. There are K sub states resulted as shown in Fig. 7(a). Capacitor Cia (i = 2, 4 . . . 2k) are discharged during this time interval. Assuming the flying capacitors get fully charged at steady state and diodes voltage drop are neglected, the following relationship can be derived:

$$V_{c1a} = V_{AO+} \tag{1}$$

$$V_{cia} = V_{c(i+1)a} (i = 2, 4, 6, ..., 2k - 2). \tag{2}$$

**2. State 2[dTs, Ts]:** When the voltage at port AO steps to low level, diode D2k a is conducted first, shown as Fig. 8(b)-(1). Then the diodes Dia (i = 2, 4 . . . 2k − 2) will be turned on one after another from high number to low. Each diode will be turned on when the previous one becomes blocked. Only diode D2ka is conducted for the whole time interval of [0, dTs], since capacitor C(2k−1)a has to partially provide the

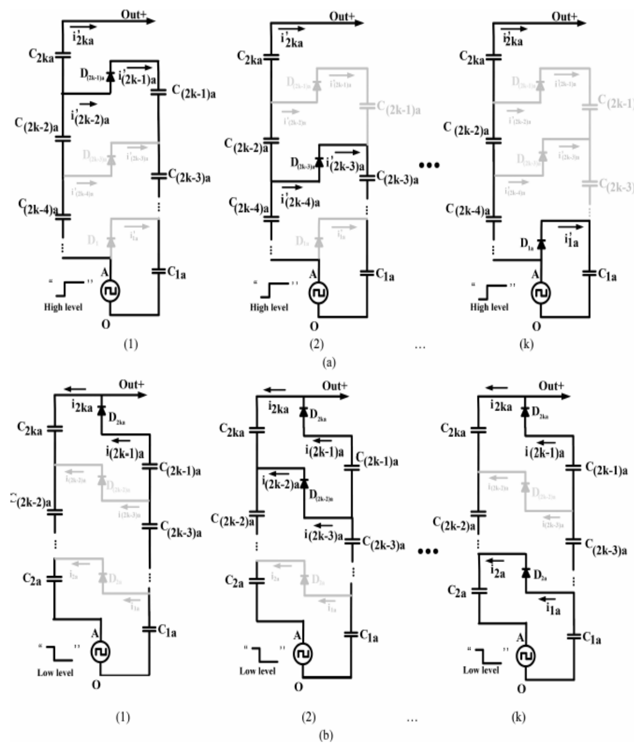


**Fig.8. Operation Modes of Even-Order BVM Positive Branch. (a) State 1[0, Dts]. (b) State 2[Dts,Ts].**

Load current during the whole time interval. Even though not all the diodes are conducted and blocked at the same time, the flying capacitors still have the following relationship by the end of this time interval:

$$V_{c2a} = V_{c1a} - V_{AO-} \tag{3}$$

$$V_{cia} = V_{c(i+1)a} (i = 3, 5, 7, \ldots, 2k - 1). \tag{4}$$

According to charge balance principal, the total amount of electrical charge flowing into capacitors Cia (i = 2, 4, . . . 2k) should equal to that coming out from them in a switching period at steady state, therefore

$$\sum_{i=1}^{k} \int_{0}^{DT_S} i'_{2ia} dt = \sum_{i=1}^{k} \int_{DT_S}^{T_S} i_{2ia} dt. \tag{5}$$

Thus, the capacitor group Cia (i = 2, 4 . . . 2k) can be replaced by an equivalent capacitor C2a(eq).The diode group

Dia (i = 2, 4 . . . 2k) which provides the charging path for C2 a(eq) is equivalent to a single diode C2a(eq) . Similarly, the capacitor group Cia (i = 1, 3, . . . 2k − 1) can be replaced by an equivalent capacitor C1a(eq) and diode group Dia (i = 1, 3, . . . 2k − 1) by D1a(eq) . The final equivalent even-order positive multiplier branch is given as Fig. 6(a). A similar analysis yields the equivalent negative multiplier branch as shown in Fig. 9(b). According to (1)–(4), the voltage of equivalent capacitors C1a (eq) ,C2a (eq) can be expressed as following:

$$V_{c2a(eq)} = k(V_{AO+} - V_{AO-}) \quad (6)$$

$$V_{c1a(eq)} = (k-1)(V_{AO+} - V_{AO-}) + V_{AO+}. \quad (7)$$

For the negative branch shown in Fig. 6(b), the following results can be obtained based on similar analysis:

$$V_{c2b(eq)} = k(V_{OB+} - V_{OB-}) \quad (8)$$

$$V_{c1b(eq)} = (k-1)(V_{OB+} - V_{OB-}) + V_{OB+} \quad (9)$$

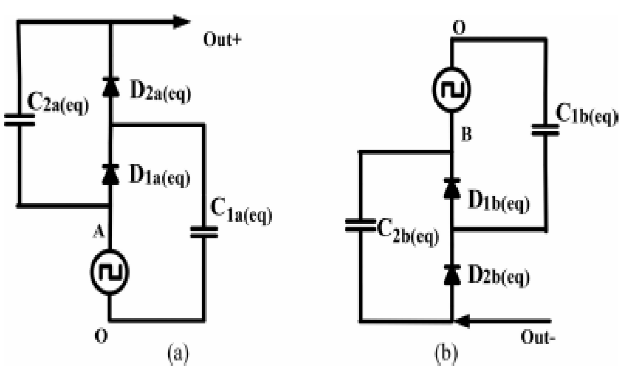



**Fig.9.Equivalent Circuit (a) Even-Order Positive Multiplier. (b) Even-Order Negative Multiplier.**

Where VOB+ is the high voltage level of input port OB and VOB− is the low voltage level.

**3.Equivalent Capacitance Derivation**:Assuming capacitors Cia (i = 1, 2, 3, 2k) have the same capacitance C, in order to derive the equivalent capacitance of C2a (eq) and C1a (eq) in expression of C, a voltage ripple-based calculation method is proposed in this section. Assuming the peak to peak voltage ripple of the flying capacitors can be expressed as ΔVcia (i = 1, 2, 3 . . . 2k), the ripple of equivalent capacitor C2a (eq) isΔV, the following relationship can be approximated:

$$\Delta V = \Delta V_{c2a} + \Delta V_{c4a} + \ldots \Delta V_{c2ka}. \quad (10)$$

In Fig. 5, assuming the average current of i_ ia (i = 1, 2, 3 . . . 2k) during [0, dTs] is (i = 1, 2, 3 . . . 2k) i_ 2ia(on) and the average current of iia (i = 1, 2, 3 . . . 2k) during [dTs, Ts] is iia(off ) (i = 1, 2, 3 . . . 2k), according to charge balance of capacitors Cia (i = 2, 4 . . . 2k), it can be derived that

$$\overline{i'_{ia(\text{on})}} DT_S = \overline{i_{ia(\text{off})}} D'T_S (i = 2, 4, \ldots 2k). \quad (11)$$

At the same time, state 1 gives

$$\overline{i'_{ia(\text{on})}} = \overline{i'_{(i+1)a(\text{on})}} (i = 2, 4, \ldots 2k-2). \quad (12)$$

State 2 gives

$$\overline{i_{ia(\text{off})}} = \overline{i_{(i+1)a(\text{off})}} (i = 1, 3, \ldots 2k-3). \quad (13)$$

Based on the (11)–(13), the following relationship can be obtained:

$$\overline{i_{2a(\text{off})}} = \overline{i_{4a(\text{off})}} = \ldots \overline{i_{(2k-4)a(\text{off})}} = \overline{i_{(2k-2)a(\text{off})}} = \overline{i_{(2k-1)a(\text{off})}}. \quad (14)$$

Based on charge balance of capacitor C2ka, it can be derived that

$$\overline{i_{2(k-1)a(\text{off})}} D'T_S = I_O T_S \quad (15)$$

$$\overline{i_{2ka(\text{off})}} D'T_S = \overline{i'_{2ka(\text{on})}} DT_S = I_o DT_S \quad (16)$$

Where $I_o = \frac{V_{out}}{R}$ .

According to KCL in Fig. 5(b), voltage ripple of capacitors Cia (i = 2, 4 . . . 2k) can be obtained

$$\begin{cases} C\Delta V_{c2a} = (\overline{i_{2ka(\text{off})}} + \overline{i_{2k-2a(\text{off})}} + \ldots \overline{i_{4a(\text{off})}} \\ \qquad + \overline{i_{2a(\text{off})}}) D'T_S \\ C\Delta V_{c4a} = (\overline{i_{2ka(\text{off})}} + \overline{i_{2k-2a(\text{off})}} + \ldots \overline{i_{4a(\text{off})}}) D'T_S \\ \ldots \\ C\Delta V_{c2ka} = \overline{i_{2ka(\text{off})}} D'T_S \end{cases} \quad (17)$$

Where $D' = 1 - D$.

Based on the equations from (14) to (16), the equation group (17) can be reduced to the following expression:

$$\begin{cases} C\Delta V_{c2a} = (k-1+D) I_O T_S \\ C\Delta V_{c4a} = (k-2+D) I_O T_S \\ \ldots \\ C\Delta V_{c2ka} = (0+D) I_O T_S \end{cases}. \quad (18)$$

Substituting (10) to (18), the following equation is derived:

$$C\Delta V = \left(\frac{k(k-1)}{2} + kD\right) I_O T_S. \quad (19)$$

Meanwhile, the following equation can be derived based on discharging stage of equivalent capacitor $C_{2a(eq)}$:

$$C_{2a(eq)} \Delta V = I_O DT_S. \quad (20)$$

Based on (19) and (20), the equivalent capacitor $C_{2a(eq)}$ can be expressed

$$C_{2a(eq)} = \frac{2D}{k(k-1+2D)} C. \quad (21)$$

Similarly, in order to derive the equivalent capacitance of C1a(eq), the following equation can be derived:

$$\begin{cases} C\Delta V_{c1a} = k I_O T_S \\ C\Delta V_{c3a} = (k-1) I_O T_S \\ \qquad \ldots \\ C\Delta V_{c2(k-1)a} = I_O T_S \end{cases}. \quad (22)$$

At the same time, the following equation exists:

$$C_{1a(eq)} \Delta V' = I_O T_S \quad (23)$$

Where $\Delta V' = \Delta V_{c1a} + \Delta V_{c3a} + \ldots \Delta V_{c(2k-1)a}$

Therefore, the expression of C1a (eq) is obtained

$$C_{1a(eq)} = \frac{2}{(k+1)k} C. \quad (24)$$

Because of the symmetry, the equivalent capacitance C1b (eq) and C2b (eq) is given as following:

$$C_{1b(eq)} = \frac{2}{(k+1)k}C \quad (25)$$

$$C_{2b(eq)} = \frac{2D'}{k(k-1+2D')}C. \quad (26)$$

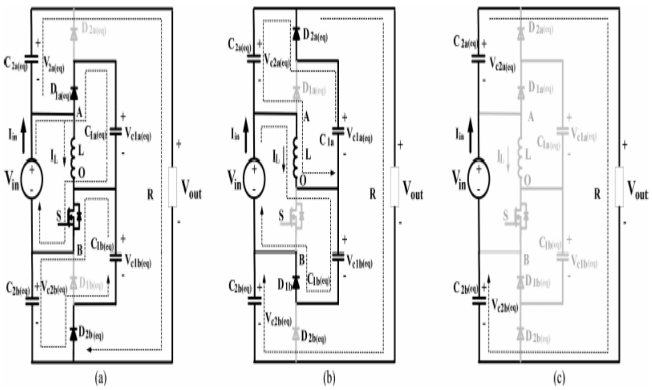



**Fig.10. Three Operation States. (a) State 1[0, DTs]. (b) State 2[DTs, (*D* + *D*1)*T s*]. (c) State 3[(*D* + *D*1)*T s*, *T s*].**

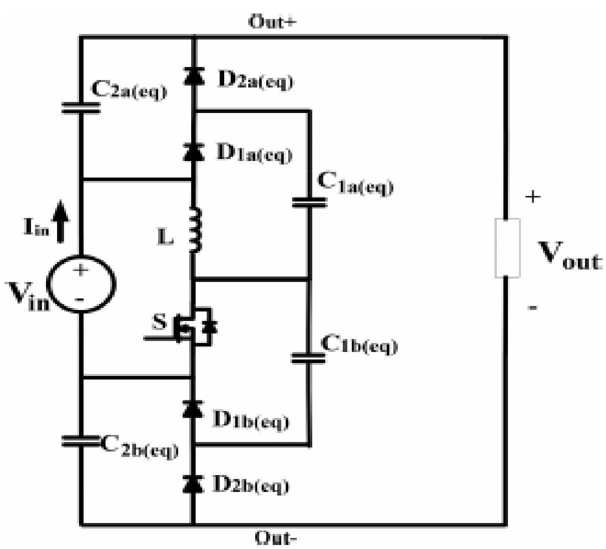



**Fig.11. Equivalent Even-Order HBC**.

The derivation of voltage and equivalent value of the equivalent flying capacitors can facilitate the output voltage calculation and ripple estimation.

### C. Operation Principle of General Basic HBC

Based on the simplification method discussed in previous section, the general even-order HBC in Fig. 12(b) can be simplified to an equivalent HBC circuit, shown as Fig. 10. Careful examination of the topology indicates that the two “boost” like sub circuits are intertwined through the operation of the active switch S. The total output voltage of HBC is the sum of the output voltage of two boost sub circuits plus the input voltage. Three operation states are described as Fig. 11.

**1. State 1[0, DTs]:** In Fig.12(a), switch S is turned on and diodes D1a (eq), D2b (eq) conduct while diodes D2a (eq) and D1b (eq) are reversely biased. The inductor L is charged by the input source. Meanwhile, capacitor C1a (eq) is charged by input source and capacitor C2b (eq) is charged by capacitor C2b (eq). At this interval, the following equations can be derived based on the inductive switching core analysis:

$$V_{\mathrm{AO}+} = V_{\mathrm{in}} \quad (27)$$

$$V_{\mathrm{OB}-} = 0. \quad (28)$$

**2. State 2[DTs,(D + D1)Ts]:** As illustrated in Fig. 7(b),when S is turned off, the inductor current will free wheel through diodesD2a(eq) andD1b(eq).The inductor is shared by two charging boost loops. In the top loop, capacitor C1a(eq) is releasing energy to capacitor C2a(eq) and load at the same time. In the bottom loop, input source charges capacitor C1b(eq) through the inductor L. During this time interval, voltage generated at AO and OB is expressed as following based on inductor balance principal:

$$V_{\mathrm{AO}+} = -V_{\mathrm{in}}\frac{D}{D_1} \quad (29)$$

$$V_{\mathrm{OB}+} = \frac{V_{\mathrm{in}}(D+D_1)}{D_1}. \quad (30)$$

**3. State 3[(D + D1)Ts, Ts]:** Under certain conditions, the circuit will work under DCM operation mode, thus the third state in Fig. 7(c) appeals. At this state, the switch S is kept off. The inductor current has dropped to zero and all the diodes are blocked. The capacitor C2a (eq) and C2a(eq) are in series with input source to power the load. During this time interval, voltage generated at port AO is zero while at OB is Vin.

## IV. RESULTS

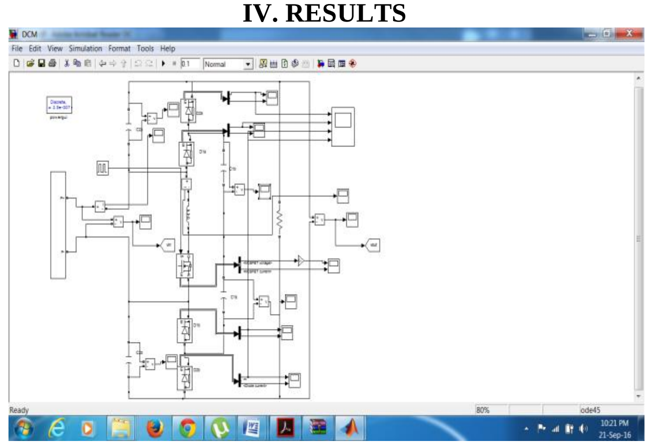
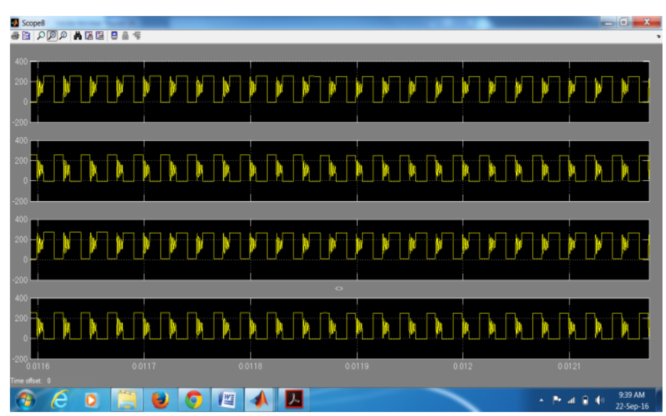
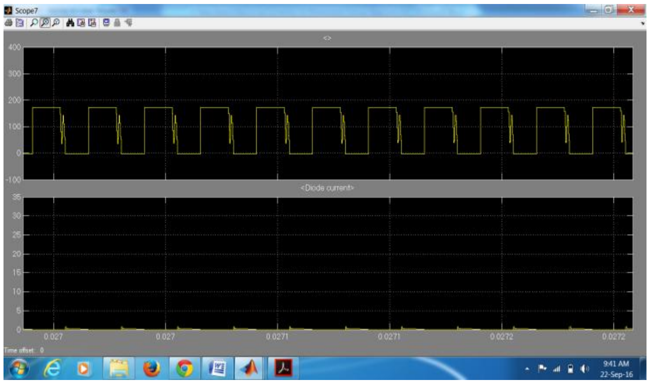


**Fig.12. Simulation Model Circuit.**



**(a)**



(b)

**Fig.13. (a)(b) Simulated Wave Forms**

## V. CONCLUSION

A new HBC composed of an inductive switching core and BVM is proposed in this paper. The proposed converter has the collective advantages of the gain boosting technique from voltage multiplier and voltage regulation capability from boost converter, featuring in nature interleaved operation, wide regulation range, low component stresses, small output ripple, flexible gain extension, and high efficiency. Compared with other high gain boosting technologies such as tapped inductor, multi inductor/ switch method or transformer-based method, the proposed topology has reduced the complexity which is suitable for mass production. Compared with other single switch and single inductor dc–dc converters, it has a better component utilization rate, smaller output ripple and lower component stress. This project provides operation principle, design consideration, and overall comparison with many other similar topologies. A 200-W, 35 to 380 V second-order HBC prototype was constructed which achieved a peak efficiency of 95.44%. This converter is suitable for many renewable energy applications such as the front-end of PV system.

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