Review on DC-to-DC Boost Converter Control Topologies of Renewable Energy Applications

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ABSTRACT

This paper reviews the various control strategies used for Dc-Dc boost converter applied with renewable energy systems, like photovoltaic array module and wind energy system. Boost converters are in prime position for lifting up the lower voltage level collected from renewable energy sources (RES), such as fuel cells and solar panel, to cope up the required level of the grid voltage. Useful control techniques are required for assuring circuit efficiency, stability and reliability under different condition. This paper classifies control methods into conventional method and advanced methods. Each method's benefits, drawbacks and suitability for dynamic and unbalanced renewable energy supply. Distinct concentration is provided for real-time adaptability, fast response and minimized power losses vital for improving renewable energy system applications.

Keywords: boost converter, renewable energy, control techniques, photovoltaic array

I. INTRODUCTION

The increasing global attention on renewable energy sources such as solar, wind, and fuel cells is required to fulfil the necessity to lessen the effect of climate change and dependency on fossil fuels. Renewable energy systems are now acute components of modern power grids, offering clean and sustainable electric power generation. Yet, the essential inconsistency and intermittency of renewable energy sources present significant contest for integration into electrical system specially in terms of power quality and stability. To fulfil these challenges Dc-Dc converters, particularly boost converters are applied to adjust and step up the flexible, low voltage output from renewable energy sources to a higher more stable voltage level for grid connection or direct load supply. The presentation and proficiency of these converters are highly dependent for the control approaches used to manage their operation under varying conditions

Dc-Dc boost converter shows an important role in renewable energy applications by lifting up lower voltage DC output from energy sources like solar panel, fuel cells etc. which produce output voltage that varies depending on environmental conditions such as solar irradiance and temperature. The control methods used in these converter circuits defines how effectively they can respond to these variations, keeping high efficiency, stability and fast dynamic response.

Conventional control methods, like voltage mode control and current mode control have been extensively applied in boost converter circuits for their simple and easy implementation. Though, these circuits often face problem with the maintenance of stability and efficiency under quickly changing condition of renewable energy sources. In present years, a variety of advanced control techniques have been implemented to overcome the prior difficulties of conventional methods. Sliding mode control deals robustness in contradiction of parameter variations due to external changes developing it appropriate for applications with varying inputs such as solar or wind energy sources[1-5]. Fuzzy logic control and artificial neural networks have been employed for their advantages to grip non-linarites and offer adaptive control techniques without demanding a detailed mathematical model of the structure [6-10].

The irregular and vibrant characteristics of renewable energy sources has directed to the progress of more refined control methodologies, with model predictive control (MPC), which calculates future system nature to maximize converter performance in real time world [10-15]. More advanced control methods applying machine learning are now most popular, as they optimize adaptability and efficiency from system behaviour and maximize the control methods over time [16-20]. Furthermore, hybrid control methods, which pool the parameters of different control methods, are being used to control the usefulness of each method and lessen their individual limitations [21-25].

This paper delivers a broad analysis of the up-to-date methods used in Dc-Dc boost converters for green energy applications. By matching traditional and advanced control topologies, this review targets the balances the complexity, cost, efficiency and real-time compliance [26-34].

II. DIFFERENT TECHNOLOGIES

Conventional boost converter topologies: They are traditional methods of Dc-Dc conversion in applications used to lift up the voltage, generally used in renewable energy systems, automotive and power controlling circuits. The fundamental boost converter, with its components like, an inductor, switch, diode and capacitor shown in Fig.1proficiently step up the input voltage but it has the limitations in high power applications due to bigger switching losses and the size of the inductor[1-2]. Various strategies, such as interleaved and cascaded boost converters are presented to enhance efficiency and reduce voltage stress on components [3-4]. For example, interleaved boost converter engages parallel phases for sharing the amount of current which will further reduce ripple and inductor size for improvement of thermal performance [6-7]. On contrast, cascaded converters achieve higher gains with a multi stage structure with added complexity and reliability issues[8-9]. With advancement of the topologies like, coupled inductor and switched capacitor topologies where minimizations of size of passive components have implanted [10-11]. In spite of improvements, traditional topologies still face challenges related to control stability and efficiency at changing loads, emphasizing the present need for improved designs in dynamic environments like renewable energy system.

Conventional Boost Converter Circuit Analysis: A Dc to Dc boost converter is a scheme that alters fixed voltage to adjustable voltage as output. The synchronized output voltage from a Dc to Dc converter depends on the pulse width and the switching frequency of the semiconductor switch or duty ratio of the converter as shown in equation (1), as in

$$D_c = T_{on} / T_t$$

Where D_c is the duty cycle of the proposed converter, T_{on} is the ON time period of the switch. and

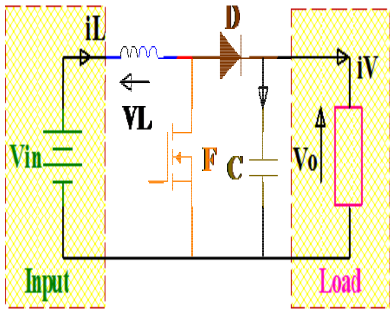

Fig.1: Structure of Boost Converter

T_t is the total time period of a single pulse. The circuit illustration of the boost converter using power MOSFET as a transferring device is shown in Fig 1. It comprises of an inductor linked in series after which a power MOSFET is joined in parallel with the positive and negative terminals respectively. A diode is connected in series with the load after the power MOSFET which also acts as the switch by automatically forward biasing and reverse biasing. A capacitor in parallel is placed at the load side for removing ripples in the output voltage.

Operation: Mode I(0<t<Ton) The switch is in closed position and the diode is turned off

The ON/OFF semiconductor switch, F (Power MOSFET) alternatively connects and disconnects the load from the source at a rapid rate. The semiconductor switch (Power MOSFET) is turned ON and OFF by controlling the gate signal using Pulse Width Modulation (PWM). Let T_{On} and T_{Off} be the time period for which the switch S remains closed and open respectively. Once the power MOSFET is switched ON as shown in Fig 2, the inductor current (I_L) starts increasing and it will charge with a polarity according to the direction of the flow of supply current as shown above during period Ton. The inductor current rises linearly from minimum to maximum value. The diode is reverse biased due to voltage in the capacitor which appears across the cathode (anode is at zero potential due to the conducting power MOSFET). Thus, the reverse biased diode will isolate the load from the supply. If the capacitance is very high, the capacitor supplies a constant load current.

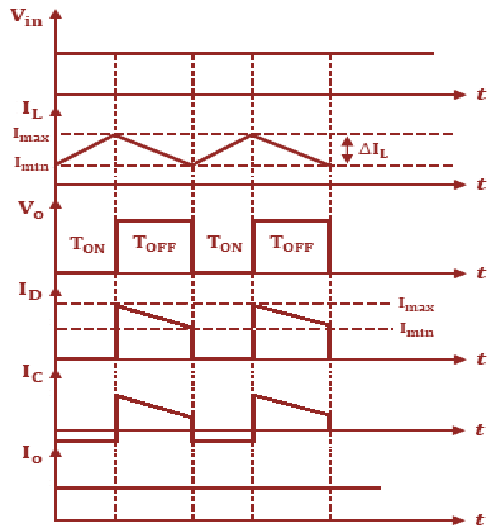

Fig.2. Voltage and current waveform of Boost converter

Mode II(T_{On}<t<T) The switch is turned off, but the diode is turned on

Now when the power MOSFET is switched OFF shown in Fig 3, the supply current which was flowing through the inductor, and power MOSFET will now flow through the inductor, diode, capacitor and load.

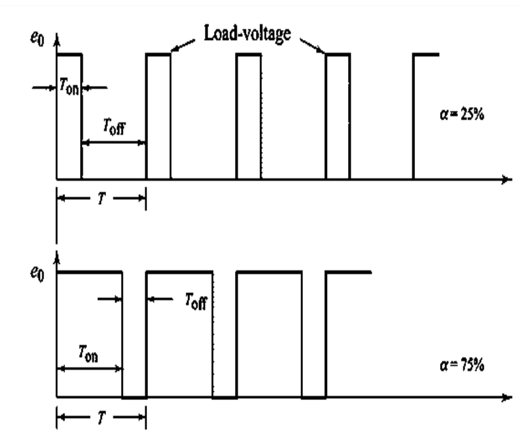

Fig.3.(a) & (b) Time Ratio or Pulse Width Modulation Control [17]

When the power MOSFET is switched OFF, the charged inductor will start discharging with reversed polarity due to which the diode gets forward biased. The load now receives a voltage from the supply along with the inductor voltage (i.e., $V_{In} + V_L$) and the capacitor will be charged.

The inductor current will fall linearly until the power MOSFET is turned ON again. Therefore, it is observed that the load receives a voltage (average value) greater than the input voltage, hence the name boost. The associated voltage and current waveforms for the operation of the boost converter are shown in Fig.2.

On applying KVL to the circuit when MOSFET is in ON state, we will get,

$$V_{L1} - V_{In} = 0$$

$$\therefore V_{L1} = V_{in} \quad (1)$$

On applying KVL to the circuit when MOSFET is in OFF state, we will get, $\therefore V_{L1} - V_0 + V_{In} = 0$

$$\therefore V_{L1} = V_0 - V_{in} \quad (2)$$

The energy supplied to the inductor during the ON period of MOSFET is given as,

$$\therefore E_{On} = \text{inductor volage} \times \text{inductor current} \times T_{On}$$

$$\therefore E_{On} = V_{in} ((I_{m1} + I_{m2})/2)\, T_{On} \quad (3)$$

Where I_{m1}, I_{m2} are minimum and maximum value of inductor current.

Also, the energy supplied by the inductor throughout the OFF period of MOSFET is given as,

$$E_{Off} = \text{inductor voltage} \times \text{inductor current} \times T_{Off}$$

$$\therefore E_{Off} = (V_0 - V_{in})((I_{min} + I_{max})/2)\, T_{Off} \quad (4)$$

$$\text{For a lossless circuit } E_{On} = E_{Off} \quad (5)$$

$$\therefore Vin\, ((I_{m1} + I_{m2})/2)\, Ton = (V_0 - V_{In})((I_{m1} + I_{m2})/2)\, T_{Off}$$

$$\therefore (V_{In})\, ((I_{m1} + I_{m2})/2)\, T_{On} = (Vo - Vin)(I_{m1} + I_{m2})/2)T_{Off}$$

$$\therefore (V_{In})\, T_{On} = V_0\, T_{Off} - V_{In}\, T_{Off}$$

$$\therefore V_0 = V_{In} \; (T_{On} / T_{Off}) \quad (6)$$

$\therefore$Duty cycle, $D = T_{On}/(T_{On}+ T_{Off})$

We know that $T = T_{On}+ T_{Off}$

$$\therefore D = T_{On} / T \quad (7)$$

$$\therefore V_0 = (1/(1-D)) \; V_{In} \quad (8)$$

The average value of output voltage, V_0 can be controlled by periodic on and off of the switches. The two types of control strategies for operating the switches are employed in DC choppers. They are [17]:

(1) Time-Ratio Control (TRC), and
(2) Current Limit Control.
(1). Time-Ratio Control (TRC)
In the time-ratio control, the value of T_{On}/T_t is varied. This can be done in two ways. They are variable frequency method and constant frequency method.

In constant frequency topology the on time T_{On}, is varied but the chopping frequency f_c ($f_c = 1/T$, and hence the chopping period T) is kept constant. This control strategy is also called as the pulse-width modulation (PWM) control. Fig.3 describes the principle of pulse-width modulation. As shown, chopping period T is constant. In Fig. 3(a), $T_{On} = (¼)T_t$, so that duty cycle, D = 25%. In Fig. 3 (b), $T_{On} = (3/4)T_t$, so that duty cycle, D = 75%. Hence, the output voltage V_0 can be varied by varying the on-time T_{On}.

In variable frequency system control scheme, the chopping frequency f_c is varied and either (a) ON-time, T_{On}, is kept constant or (b) OFF-time, T_{Off}, is kept constant. This type of control strategy is also called as frequency modulation control. In the principle of frequency modulation chopping period T_t is varied but on-time T_{On} is kept constant. The output voltage waveforms are shown for two different duty cycles.

2) Current Limit Control

In current limit control strategy, the chopper is switched on and off so that the current in the load is maintained between two limits. When the current exceeds upper limit, the chopper is switched off. During off period, the load current freewheels in the circuit and decreases exponential. When it reaches the minor limit, the chopper is switched on. Current limit control is promising either with constant frequency or with constant T_{On}. The current limit control is used only when the load has energy storage features. The reference values are the load current or load-voltage. Since the chopper operates between arranged current limits, discontinuity cannot occur. The difference between the I_{0max} and I_{0min} , adopts the switching frequency. The ripple of the load current can be lessen if the difference between the I_{0max} and I_{0min} limits is minimum. This in turn increases chopper frequency thereby increasing the switching losses.

III. ADVANCED CONTROL TECHNIQUES

1. Maximum Power Point Tracking (MPPT)

By applying MPPT algorithms, such as Perturb and Observe (P&O) , Incremental Conductance(IC) are essential in renewable energy system such as PV arrays, in which power output is delicate for environmental issue. P&O is extensively used for its easiness, but drawbacks are oscillation around the Maximum Power Point (MPP) during steady state condition [10].Incremental Conductance provides more accuracy but computational power requirement is high [11]. Presently, Fuzzy Logic Control (FLC) is applied for MPPT in systems with quickly varying inputs [12].

2. Sliding Mode Control (SMC)

Sliding Mode Control (SMC) is a robust control method that is compatible for systems with huge uncertainties, like wind energy system. SMC confirms stability and optimal performance even during quickly changing environmental conditions [13-14]. Still, SMC often shows high-frequency oscillations which can decrease the efficiency of converter [15]. Different methods have been proposed to minimize the issue [16].

3. Model Predictive Control (MPC) provides

Implementation of MPC shows outstanding presentation by predicting future system performance and optimizing the control inputs consequently. This allows MPC particularly appropriate for high performance renewable systems [17]. In other words for its high computational cost limits its applications in small-scale systems [18].

4. AI-Based Control Techniques

Artificial Intelligence (AI) techniques, like Neural Networks (NN), Genetic Algorithms (GA) and Fuzzy Logic have been popular for their ability for handling non-liner and complex system dynamics [19].

5. Neural Networks (NN)

Neural Networks applies data from system performance and adjust control techniques in real-time, making them highly working for systems using random inputs [20]. As NN-based control provides greater adaptability, its complexity and computational requirements can pose challenges, especially in real time applications [21].

6. Genetic Algorithms (GA)
The controllers with GA based cam maximize control parameters using simulation of natural selection and are operative to find total solutions for non-linear systems [22]. However converter performance can be improved using GA .

IV. EMERGING TRENDS AND CHALLENGES

1. Wide Band gap (WBG) Semiconductors
The incorporation of wide band gap semiconductors like Gallium Nitride (GaN) and Sillicon Carbide (SiC) have considerably improved the efficiency of converter and switching speed [24]. These new materials allow operation in high frequency region, lessen losses due to compact design, creating them more suitable for renewable energy applications [25]. Still , they face new challenges, like managing electromagnetic interference (EMI) and controlling high frequency switching losses [26].

2. Energy Storage Integration
By growing demand of energy storage system (ESS), like batteries and super capacitors, the requirement for bi-directional Dc-Dc converters have increased [27]. These converters must competently use the power flow in both directions means charging and discharging mode of the system [28].

V. CONCLUSION

DC-DC boost converters are indispensable in renewable energy applications, playing a vital role in stepping up low voltages for grid integration and energy storage. Classical control techniques, such as PID and VMC, offer simplicity and ease of implementation but are inadequate for highly dynamic environments like those seen in renewable energy systems. Advanced control techniques, including MPPT, SMC, and MPC, provide better performance in such variable conditions. Emerging AI-based control strategies further enhance the efficiency and adaptability of boost converters. Additionally, the integration of wide bandgap semiconductors and energy storage systems presents new challenges and opportunities for future research in this field.

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AOI: 10.11234.2024.0004