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A REVIEW OF HYBRID CONVERTERS FOR DC-BASED RENEWABLE ENERGY NANOGRID SYSTEMS

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ABSTRACT

Hybrid converters produce AC and DC output simultaneously in single stage from single DC input. These types of hybrid converters play an important role in DC-based renewable energy nanogrid applications which can feed AC and DC loads at the same time. Conventional two stage conversion in DC nanogrid uses dedicated DC-DC converter and DC-AC converter with DC input that may be supplied from solar panel, fuel cell etc. and suffers from shoot through problem, reduced EMI immunity and reduced reliability. On the other hand, the component count is less in hybrid converters, increases the reliability due to the inherent shoot-through protection, and also, eliminates the need of dead time circuitry. Various modified PWM techniques are applied to obtain the required DC and AC output. This paper presents the review of various hybrid converters for DC nanogrid systems.

Keywords: boost derived hybrid converter, buck-boost derived hybrid converter, boost derived multilevel hybrid converter, DC nanogrid, solar, inverse Watkins–Johnson converter.

1. INTRODUCTION

Smart residential power systems involve the use of nanogrid structures extensively [1]. These systems use conventional or renewable energy sources and feed AC and DC loads with the help of power converters [2]. DC nanogrid architecture is shown in Figure-1 which has a single dc input provided by either by PV panel, battery, fuel cell etc. feeding both AC and DC loads. Dedicated DC-DC converter and DC-AC converter based architecture is shown in Figure-1 (a) and single converter supplying both AC and DC loads called as hybrid converter is shown in Figure-1 (b). The hybrid converter has advantages such as compact size, high reliability due to the short circuit capability, no need of dead time circuitry and high EMI immunity which makes it suitable for systems supplying DC and AC loads. As an example, a hybrid converter can feed a LED lamp and an AC fan simultaneously in a single stage from a single DC input. Renewable energy sources are often used in smart residential systems to provide green and clean energy. Conventionally, the system consists of a boost converter and DC-AC converter, which may be a Voltage Source Inverter (VSI) for supplying DC and AC loads as shown in Figure-1 (a). Topologies with higher gains are needed to obtain step up operation according to the requirements [3]. Hence, various single stage boost converters are investigated for hybrid converters which are capable of supplying AC and DC loads at the same time. Dead time circuitry is needed in conventional VSIs to avoid shoot-through. Misgating turn on of the switches that are present in the same inverter leg due to spurious noise signals or electromagnetic interference (EMI) causes damage to the switches. Hence, VSI when used in residential applications to be provided with proper protection against EMI or other spurious signals due to compactness of the system. The unwanted condition of shoot-through caused by EMI is mitigated in Z-source inverter (ZSI) [4]. In ZSI, both the switches of the inverter leg can be turned on at the same time which is called the shoot-through state due to the input impedance network in ZSI. To achieve higher gain, extended boost ZSI [5] is proposed in Z-source topology.

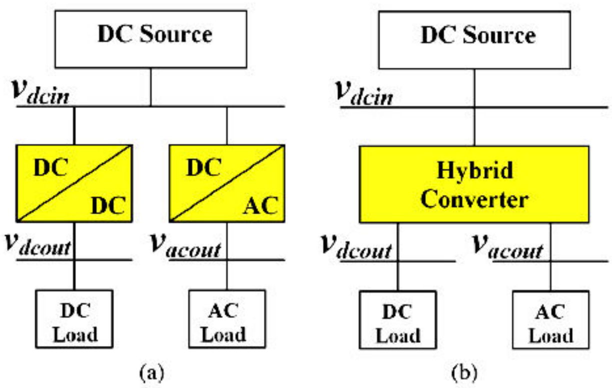

Figure-1. DC Nanogrid architecture feeding AC and DC loads (a) Architecture based on separate DC-AC and DC-DC converters (b) Architecture of hybrid converter.

But, ZSI is not suitable for supplying both AC and DC loads together. Two capacitors in ZSI has to be coordinated across them with identical loads, otherwise causes dynamic instability [6]. Hence, hybrid converters are proposed to obtain single stage conversion feeding AC and DC loads simultaneously with the advantages of small size, more reliability because of shoot through protection, high EMI immunity, and no need of dead time circuitry. The outline of this paper is as follows. In Section II, the hybrid topologies are presented and their basic operational characteristics and PWM techniques are briefly discussed. Section III explains the closed loop operation of hybrid converters. Section IV includes the conclusions of this paper.

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2. HYBRID CONVERTER TOPOLOGIES

A. Switched boost inverter (SBI) based on inverse Watkins-Johnson (IWJ) converter topology

The output voltage is lower or higher when compared to the input voltage in ZSI because of the inductor-capacitor impedance included between the input voltage and the VSI. ZSI also has high EMI immunity and allows shoot-through operation. But, ZSI cannot supply both AC and DC loads at the same time. Hence, hybrid converter based on inverse Watkins–Johnson (IWJ) topology shown in Figure-2 called Switched Boost Inverter (SBI) shown in Figure-3 is presented. in [7].

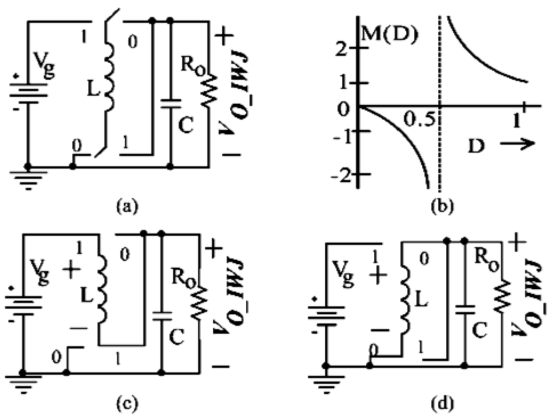

Figure-2. (a) Circuit diagram of IWJ converter (b) conversion ratio (c) IWJ in D.Ts period and (d) IWJ in D'.Ts period.

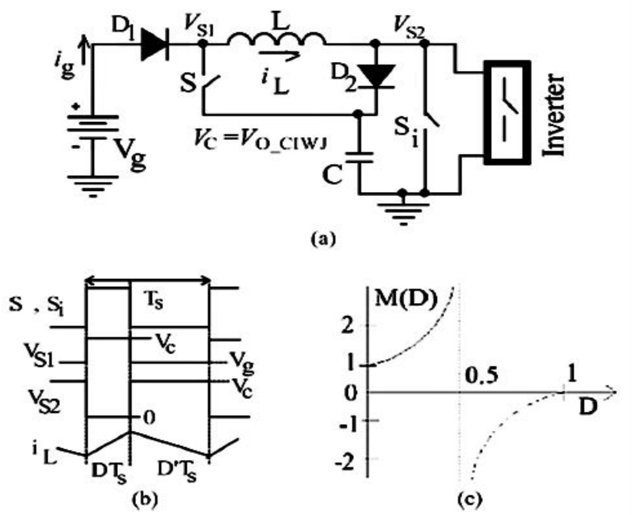

Figure-3. (a) Circuit diagram of SBI (b) Important waveforms and (c) Conversion ratio.

SBI has two switches and one set of LC filter other than VSI, but could supply both AC and DC loads simultaneously, and has the advantages of ZSI like buck-boost operation and allowing shoot-through condition of the switches in the inverter to provide EMI immunity.

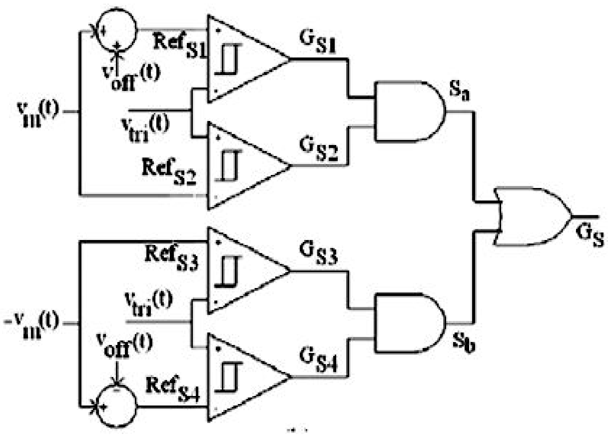

Figure-4. PWM control strategy of SBI.

PWM signals of SBI are obtained by the modification of conventional unipolar PWM technique. The modification is done to include shoot-through interval. The change incorporates an addition of shoot-through period in the PWM signals. The control strategy of SBI is presented in Figure-4. The reference signals Ref SN (N = 1 - 4) is compared with triangular carrier signals Vtri(t) to produce the gating signals GSN (N = 1 - 4). From GS1 and GS2, GS3 and GS4, the two shoot-through periods Sa and Sb are obtained which are added to obtain gate signal Gs. The DC nanogrid based on SBI is shown in Figure-5. The circuit of SBI supplying AC and DC loads and the two stage conversion topology are shown in Figure-6 and Figure-7 [8].

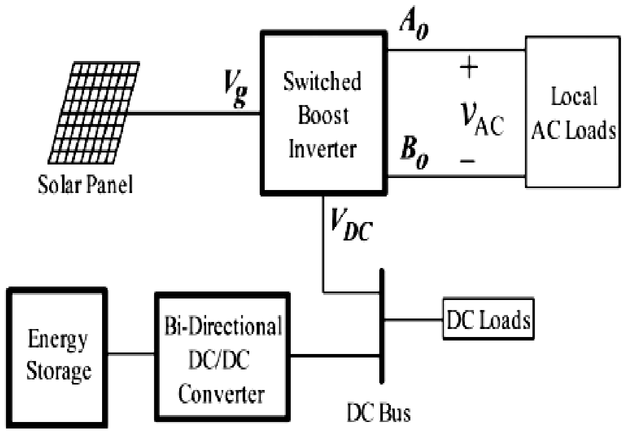

Figure-5. SBI based DC nanogrid.

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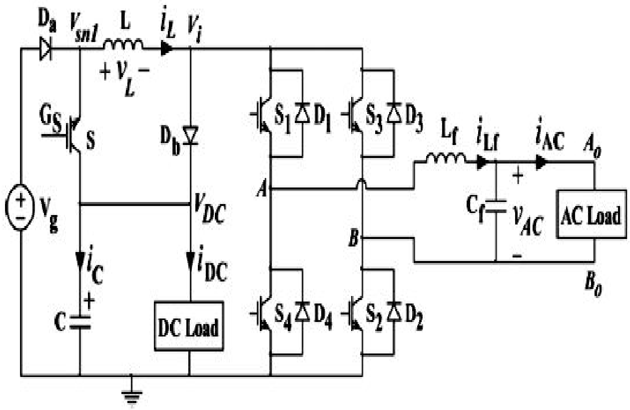


Figure-6. SBI feeding both AC and DC loads.

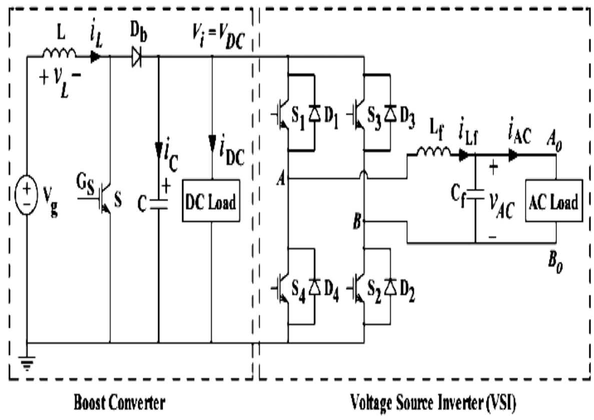


Figure-7. Conventional two stage conversion system: Boost converter cascaded with VSI.

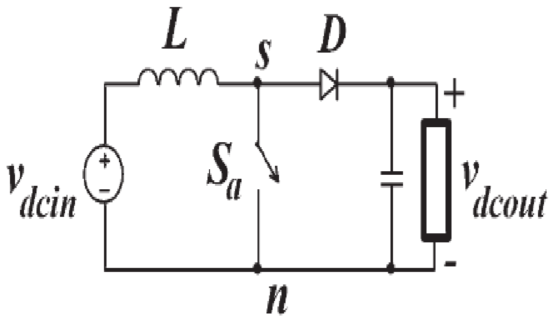
However, the SBI has certain advantages and limitations when compared to the two stage conversion system which is discussed below in Table-1. [8].

Table-1. Comparison of two stage conversion and SBI.

Parameter	Two stage conversion	SBI
Dead time circuit	**Needed**	**Not needed**
EMI noise immunity	Less	Better
Reliability	Less	High
Extreme duty cycle operation	D>= 0.75 and switching frequency less and increased filter size	D = 0.5 and hence switching frequency can be high and decreased filter size
Voltage stress of switching devices	Switch S, S_1, S_2, S_3, S_4has V_{DC}	Switch S has V_{DC} – Vg, and S_1, S_2, S_3, S_4has V_{DC}
Maximum conversion ratio	2.12	2
Control variables	Duty Cycle D, Modulation Index M	Duty Cycle D, Modulation Index M
Number of Devies	Active switches-5 Diodes-5 Inductors-2 Capacitors-2	Active switches-5 Diodes-6 Inductors-2 Capacitors-2

B. Boost derived hybrid converter (BDHC)

In order to reduce the number of switches, the BHDC [9] shown in Figure-8 (b) is developed from boost converter shown in Figure-8 (a), which is a step-up converter based on two-switch configuration. Number of components is less in BHDC compared to IWJ converter [7]. Each of the four bidirectional switches (Q1–Q4) of BDHC comprises the Switch Si and antiparallel diode Di. Turning on the switches in the same leg (Q1, Q4 or Q2, Q3) simultaneously which is to be strictly avoided shoot-through operation in VSI results in boost operation in BDHC. This is same as turning "on" of the switch "Sa" in conventional boost converter. Modified unipolar sine-PWM switching scheme is used to control the AC output voltage.



(a)

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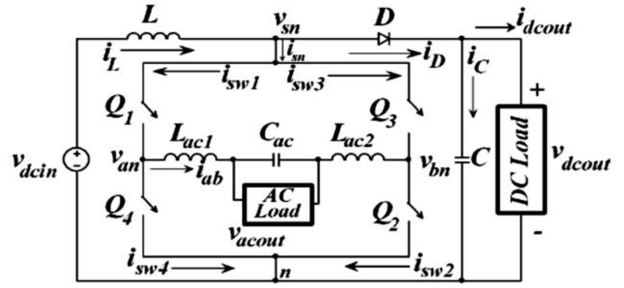

(b)

Figure-8. (a) Conventional boost converter (b) BHDC.

The BHDC operation can be demonstrated in three intervals. In Interval I - Shoot-through (ST) interval, Q2 and Q3 or $Q_1$and Q_4 are kept on at the same time. Diode D will be in the reverse biased condition. The current in the inverter will be flowing through the bridge network.

In Interval II - Power (P) interval, both the switches Q_3, Q_4 or Q_1, Q_2 are switched ON. Through Q1-Lac1-Cac-Lac2-Q2 or Q3-Lac2-Cac-Lac1-Q4 network, the inverter current flows. The inductor L gets charged from the input voltage V_{dcin} and feeds the capacitor C_{ac} and AC load during this interval. The diode also conducts during this interval. Therefore, the charging inductor supplies energy to the output capacitor C_{dc} and DC load.

In Interval III - Zero (Z) interval, all the switches are turned OFF and the inverter current will be circulating. During this interval, the current through the inductor L continues to flow through the diode D, capacitor C and DC load that then flows back to the source. It can be seen that the capacitor voltage has to be higher than the source voltage V_{dcin} at the load side.

Switching scheme proposed in [10] is used for the PWM control scheme of BDHC. Modified Unipolar sine PWM strategy is employed to BDHC. In this scheme, shown in Figure-9 (a), switches on the same leg are turned on at the same time to realize shoot-through. Only one leg switches are turned on in this switching strategy. Turning on all the switches to realize shoot-through is another alternative shown in Figure-9 (b) and is presented in [11] and [12], but it is associated with more losses. The comparison of BHDC with conventional architectures is listed in Table-2.

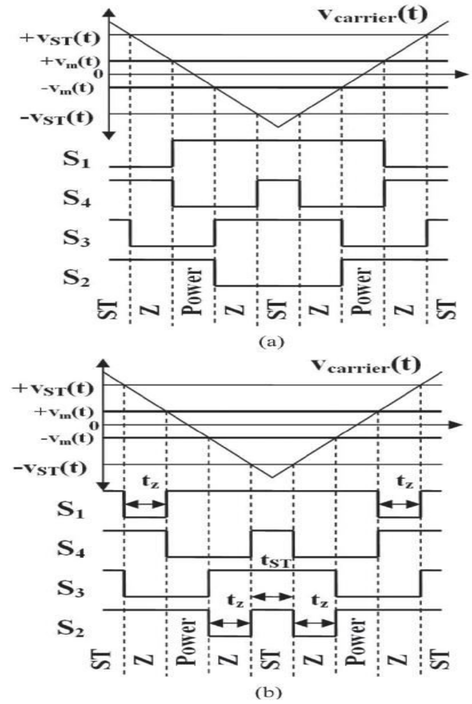

Figure-9. (a) PWM scheme and (b) variant of PWM scheme.

Table-2. Comparison of BDHC with other conventional converters.

	Separate Boost and VSI (Fig. 2(a))	**Boost-cascaded VSI** (Fig. 2(b))	**BDHC** (Fig. 3(b))
Total no. of switches	6	6	5
DC gain	$\frac{1}{(1-D_{st})}$	$\frac{1}{(1-D_{st})}$	$\frac{1}{(1-D_{st})}$
Peak AC voltage	$M_a.V_{dcin}$	$\frac{M_a V_{dcin}}{(1-D_{st})}$	$\frac{M_a V_{dcin}}{(1-D_{st})}$
Range of M_a	$0 \le M_a \le 1$	$0 \le M_a \le 1$	$0 \le M_a \le (1-D_{st})$
Dead-time requirement	Yes	Yes	No
Control Degree of freedom	2	2	1 (2 limited)
Control elements	5	5	4

C. Current-fed switched inverter based hybrid topology

A hybrid converter based on Current Fed Switched Inverter (CFSI) is shown in Figure-10, which is presented in [13] feeds both DC and AC loads at the same time from one input DC source making it fit for DC nanogrid systems, and also, has high boosting voltage. The AC bus is realized between the nodes A_0 and B_0 at voltage V_{AC} and the DC bus is realized between the nodes V_{s2} and V_{s3} at the voltage V_{DC}.

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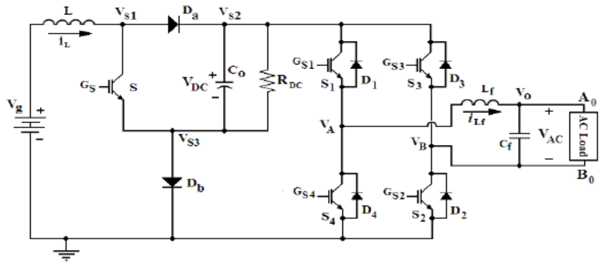

Figure-10. Hybrid converter based on CFSI.

Simplified hybrid CFSI topology is shown in Figure-11 (a). The inverter is denoted by switch S_i in order to obtain the relationship between converter input (V_g) and inverter input voltage (V_{DC}). Diodes D_a and D_b are in off condition, switches S and S_i are switched on in the D interval or shoot-through interval. Inductor current is zero and capacitor C_o is charged to input voltage Vg before the switching signals are started. In the D interval or shoot-through interval, diodes D_a and D_b are reverse biased because they are in parallel with C_o, switches S and Si are switched to the on condition, and source voltage V_g will be charging the inductor L, whereas, during the D′ interval, switches S and S_i are switched off that makes diodes D_b and D_a to be forward biased. The inductor will be discharging now to the load via the inverter. The critical waveforms of CFSI hybrid topology in simple form is shown in Figure-11 (b).

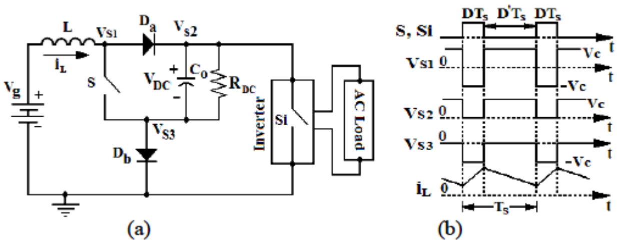

Figure-11. (a) CFSI hybrid topology in simple form (b) Critical waveforms.

D. Buck-boost derived hybrid converter (BBDHC)

In all the hybrid converters discussed above, the output DC voltage is higher than the input DC voltage normally and buck-boost action is carried out at the inverter side. Some applications such as Laptop chargers, LEDs, mobile phones etc. require output DC voltage lesser than the input DC voltage [14].

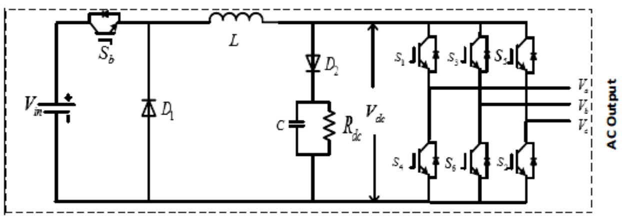

Figure-12. Circuit diagram of BBDHC.

In buck-boost derived hybrid converter (BBDHC) shown in Figure-12, it is possible to have buck-boost action of output DC voltage and buck action of output AC voltage. Also, during large load variation or low duty cycle, as the current through the inductor crosses the load current at the AC side, it saturates as shown in Figure-13. The Non-Zero Discontinuous Conduction Mode (NZ-DCM) is defined as the mode during which the inductor current will be constant and satisfactory operation of converter is not obtained during this period. In BBDHC, AC operation under standalone condition is also impossible.

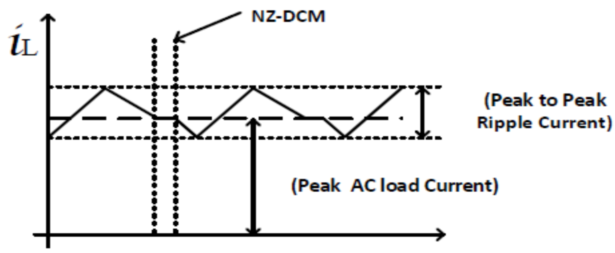

Figure-13. NZ-DCM for high variation in the load.

To overcome the limitation of BBDHC, Modified BBDHC (MBBDHC) shown in Figure-14 is proposed in [14]. During standalone operation or DCM, the switch, S, plays a major role and the current is made to flow in the reverse direction. But, in the Forced Continuous Current Mode (FCCM), in MBBDHC, complemented shoot-through pulses control the switch S. During NZ-DCM, turning ON of switch S is done that makes the flow of current through it. The energy is fed to the DC link by the capacitor and suppresses the ripple voltage. The antiparallel switch conducts during standalone operation and ensures stability of the operation. Figure-15 indicates the various operating modes of the BBDHC and MBBDHC. From Figure-15 (c), FCCM operation shows absence of dip in the voltage of dc link, negative diode current and triangular inductor current. Therefore, the MBBDHC has ability to supply simultaneous AC and DC loads and AC or DC load. The comparison of MBBDHC with boosted converter is shown in Table-3.

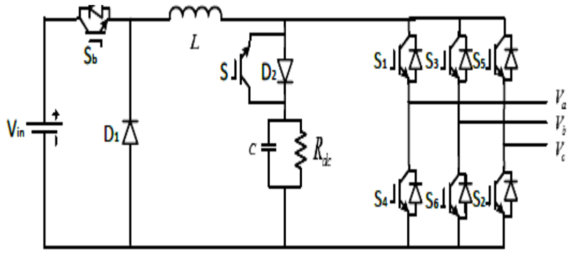

Figure-14. Circuit diagram of MBBDHC.

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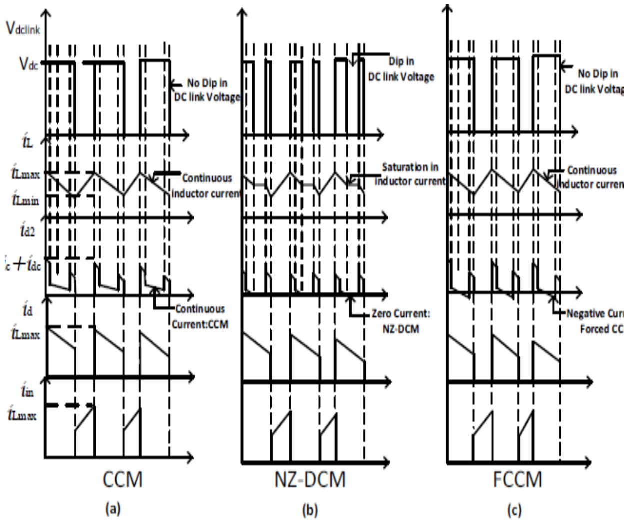

Figure-15. (a) BBDHC-operation in CCM (b) BBDHC-operation in NZ-DCM (c) MBBDHC-operation in FCCM.

Table-3. Comparison of MBBDHC with boosted converters.

	BDHC	SBI	L-ZSI	MBBDHC
DC Gain	$\frac{1}{1-d}$	$\frac{1}{1-2d}$	$\frac{1+d}{1-d}$	$\frac{d}{1-d}$
Peak AC Voltage	$\frac{mV_{in}1}{1-d}$	$\frac{mV_{in}1}{1-2d}$	$\frac{mV_{in}1+d}{1-d}$	$\frac{mV_{in}d}{1-d}$
modulation index	$0 \leq m \leq 1-d$	$0 \leq m \leq 1-d$	$0 \leq m \leq 1-d$	$0 \leq m \leq 1-d$
Dual Output	Yes	Yes	Yes	Yes
Dead time	No	No	No	No
Max Degree of Freedom	2	2	2	2
EMI Immunity	Yes	Yes	Yes	Yes
Power Conversion Stage	One	One	One	One
Capacitor Life Time	High	High	High	High
Buck voltage at DC terminal	No	No	No	Yes
NZ-DCM	Yes	Yes	Yes	No
Standalone AC	No	Yes(restricted range)	No	Yes

E. Boost derived multilevel hybrid converter (BDMHC)

The advantages of multilevel inverter are near sinusoidal output voltage waveform, reduced electromagnetic interference and lower harmonic distortion [15]. The BDHCs are connected in series to generate separate DC outputs and near sinusoidal multilevel output at the AC side for high power solar PV system that is called as Boost Derived Multilevel Hybrid Converter (BDMHC) as shown in Figure-16, which can feed DC and multilevel AC loads at the same time [16].

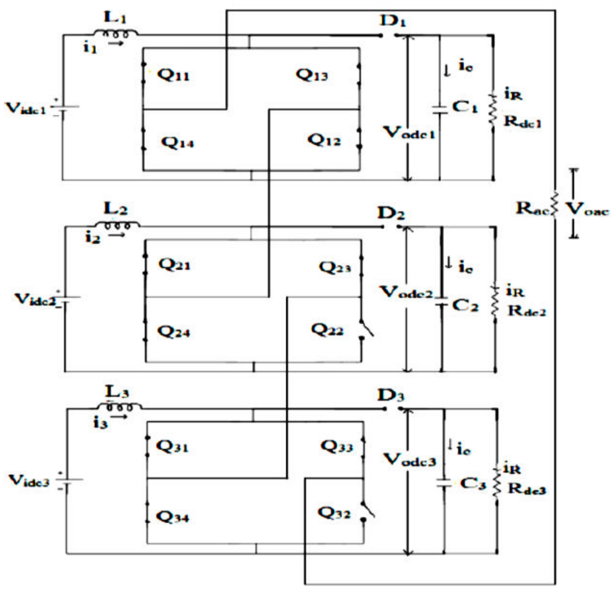

Figure-16. BDMHC-equivalent circuit.

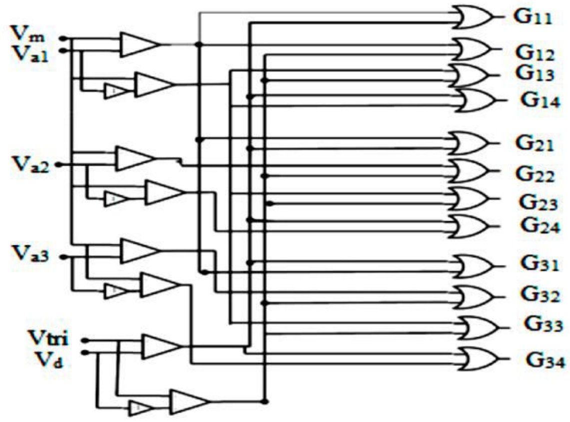

Figure-17. Gate pulses generation of BDMHC.

The sinusoidal wave is compared with three constant DC signals V_{a1}, V_{a2}, V_{a3}, that keep up the level in the phase output at the AC side, and a DC signal, V_d, is compared with the triangular carrier pulse, V_{tri}, that varies the boosting interval of the BDMHC are combined to obtained gate pulses. The signals obtained individually for boosting and inverting modes are added logically, as shown in the Figure-17 to obtain G11 to G14, G21 to G24, G31 to G34 gate pulses.

3. CLOSED LOOP OPERATION OF HYBRID CONVERTERS

The architecture for closed loop control of the BDHC is shown in Figure-18. DQ reference frame control [3], [8] is used for the control scheme of AC output. The gate signals (GS1, GS2, GS3, GS4) of the BDHC switches are generated by controller. The AC voltages (V_{acout}) and dc voltage (V_{dcout}) are regulated to their references $v*_{dcout}$ and ($v*_d$, $v*_q$), respectively by the controller. Two different loops for control of AC as well as DC voltages are used.

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The AC and DC outputs are maintained constant at the desired value individually using M_a and D_{st} as control variables when the changes in the DC controller is quicker when compared to the AC controller. An outer voltage loop and inner current loop is used in AC voltage control system. Another type of control that can be applied to BDHC is using One Cycle Control (OCC), which is presented in [17] has advantages such as high voltage gain and efficiency.

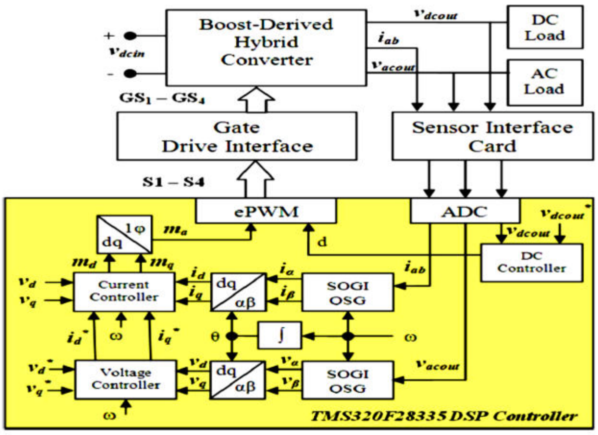

Figure-18. Architecture for closed loop control of BDHC.

4. CONCLUSIONS

Hybrid converters are single stage converters that feed AC and DC loads simultaneously and has the advantages such as compact size, high reliability due to the short circuit capability, no need of dead time circuitry and high EMI immunity that fit it appropriate for DC-based renewable energy nanogrid systems. SBI and BDHC have advantages like ZSI, but can feed both AC and DC loads unlike ZSI. Component count is less in BDHC compared to SBI. Current-Fed Switched Inverter based hybrid converter has high boosting output voltage and can operate in either buck or boost mode and also suitable for DC Nanogrid applications. In BBDHC, NZ-DCM operation results in large THD of around 10% whereas it is lowered to the THD of 2% by FFCM operation in MBBDHC. Also, in MBBDHC, using FFCM, standalone AC operation and the DC voltage regulation can be achieved. BDMHC is suitable for high power residential applications supplying multilevel AC output and the DC output simultaneously.

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