ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Website: www.ijareeie.com

Vol. 7, Issue 3, March 2018

Studying the Effect of DC- DC Over-Modulation on the Output Voltage of Three-Phase Single-Stage Inverter

Sabari M[1], Inba Arasi M[2]

Department of Electrical and Electronics Engineering, Mahendra College of Engineering, Namakkal District,

Mallasamudram Tamil Nadu, India

ABSTRACT: Abstract Voltage boosting is very essential issue in renewable-energy fed applications. The classical two-stage power conversion process is typically used to interface the renewable energy sources to the grid. For better efficiency, single-stage inverters are recommended. In this paper, the performance of single-stage three-phase grid-connected boost inverter is investigated when its gain is extended by employing over-modulation technique. Using of over-modulation is compared with the employment of third order harmonic injection. The latter method can increase the inverter gain by 15% without distorting the inverter output voltage. The performance of extended gain grid-connected boost inverter is also tested during normal operation as well as in the presence of grid side disturbances. Simulation and experimental results are satisfactory.

KEYWORDS: Boost Extended gain, Over-modulation, Third harmonic injection

I. INTRODUCTION

The voltage source inverter (VSI), current source inverter (CSI), and Z-source inverter are the prevalent converter topologies proposed for grid-connected renewable energy systems. The voltage source inverter (VSI) is the workhorse of the power converter industry [1]. Its widespread use and versatile applications span most industrial and commercial sectors. One of the characteristics of the topology is the stepped down nature of its output voltage. If one is to consider the application of this topology in grid-connected renewable energy applications, such a characteristic emerges as an important design factor. In such applications, the low output voltage typical of renewable sources such as photovoltaic and fuel cell systems requires proper boosting in order to meet grid interface requirements. A two-stage power conversion process is thus typically used. Using an intermediate DC–DC boost converter is one means of achieving the required voltage boost. This adds significant complexity and hardware to the power conversion system [2–8]. Alternatively, a bulky low frequency output transformer to boost the inverter output voltage may be used.

A CSI boosts the input DC voltage to the AC voltage without the boost DC–DC converter stage. The converter power switches should have a reverse voltage blocking capability or series connected diodes with the switches. These semiconductor devices should be able to carry the full input DC current [8–10]. Ref. [11] provides a detailed comparative evaluation of VSIs and CSIs for grid interfaces in distributed and renewable energy systems.

The Z-source inverter is considered a combination of the VSI and the CSI. It can be employed to achieve inverting and buck/boost function in only a single stage. With a specific impedance network of capacitors and inductors, the Z-Source inverter employs the shoot-through states by gating both upper and lower switches in the same phase legs to boost the DC voltage without adding a DC–DC converter [12–15]. Buck–boost capability, intrinsic short circuit protection due to the Z-source arrangement, and improved EMI are considered advantages of the ZSI over the CSI and VSI.

Single-phase DC–AC boost converters [16–18] can also be used to connect renewable energy sources to the grid. In [16], a new single-phase voltage source inverter was described. It can generate an output AC voltage larger than the input DC voltage depending on the reference duty cycle [16, 17]. Fig. 1a shows a block diagram of the single-phase boost inverter. Blocks A and B represent DC–DC converters. These converters produce a dc-biased sine wave

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output so that each block only produces a unipolar voltage. The modulation of each converter is 180 out of phase with the other, which maximizes the voltage excursion across the load. The load is connected differentially across the converters. Thus, whereas a dc bias appears at each end of the load with respect to ground, the differential DC voltage across the load is zero.

A single-stage three-phase boost inverter is proposed in [18] with reference to its possible use in distributed power generation and emphasizing its impact on the overall power quality and dynamic performance.

II. BOOST INVERTER PRINCIPLE OF OPERATION

Each phase in the three-phase boost inverter consists of two IGBTs, one inductor, and one capacitor as shown in Fig. 1. There is a common point for the capacitors (O), which is connected to the negative terminal of the DC supply. The load is connected to the inverter terminals creating another common point (N), which is electrically isolated from the capacitors' common point.

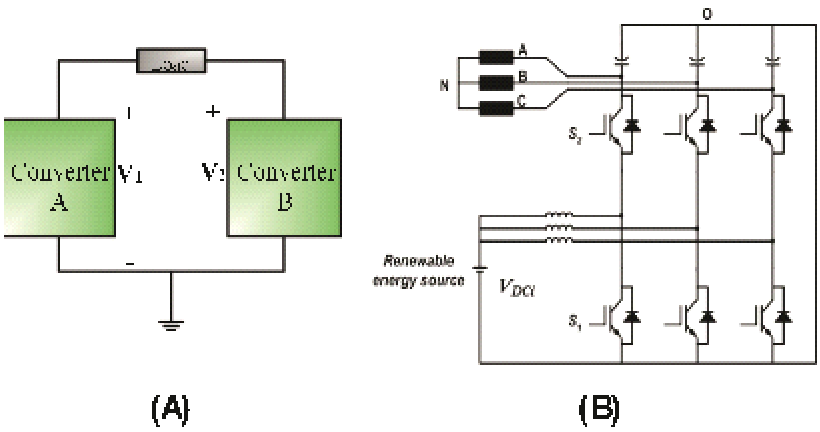

Figure 1 (a) Single-phase boost inverter block diagram and (b) three-phase boost inverter.

The capacitor reference voltage is composed of two components:

- AC component (v_{aco}): the AC component of each capacitor is of equal magnitude but with a mutual phase shift of 120 as shown in (1).
- DC component (V_{DCo}): the DC component should be the same for all phases and greater than or equal to the sum of the AC component peak (V_{aco}) and the DC input voltage

The load terminals are trapped between the capacitors connected to the upper IGBTs as shown in Fig. 1. This connection eliminates the DC component present in the voltage between the capacitors and the common point (O) from the output line voltage and consequently the output phase voltage. Eq. (2) shows the converter output line voltages with eradicated DC components

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$$\begin{aligned} v_{AO}(t) &= V_{DCo} + V_{aco}\sin(\omega t) \\ v_{BO}(t) &= V_{DCo} + V_{aco}\sin\left(\omega t - \frac{2\pi}{3}\right) \\ v_{CO}(t) &= V_{DCo} + V_{aco}\sin\left(\omega t + \frac{2\pi}{3}\right) \end{aligned} \quad (1)$$

$$\begin{aligned} v_{AB}(t) &= v_{AO}(t) - v_{BO}(t) = \sqrt{3}V_{aco}\sin\left(\omega t + \frac{\pi}{6}\right) \\ v_{BC}(t) &= v_{BO}(t) - v_{CO}(t) = \sqrt{3}V_{aco}\sin\left(\omega t - \frac{\pi}{2}\right) \\ v_{CA}(t) &= v_{CO}(t) - v_{AO}(t) = \sqrt{3}V_{aco}\sin\left(\omega t + \frac{5\pi}{6}\right) \end{aligned} \quad (2)$$

III. THREE-PHASE SINGLE-STAGE INVERTER

This paper presents a study about the power injection of grid connected photovoltaic plants when there are non-linear loads connected to the point of common coupling. The smart grid scenario suggests that the photovoltaic energy should take care not only about the active power, but also about the reactive power. The study compares the last year's criteria of injecting the maximum active power, with the expected tendency of providing reactive power in an active filter way for avoiding currents harmonics in the grid. The topology used is a traditional three-phase inverter controlled by a power balance technique through a synchronous hysteresis band. First of all, a power injection system that do not care about the loads connected into the grid is developed, then the loads are taken into account to improve the grid operation by supplying them. Both configurations are implemented in a prototype to compare the results via experimental tests.

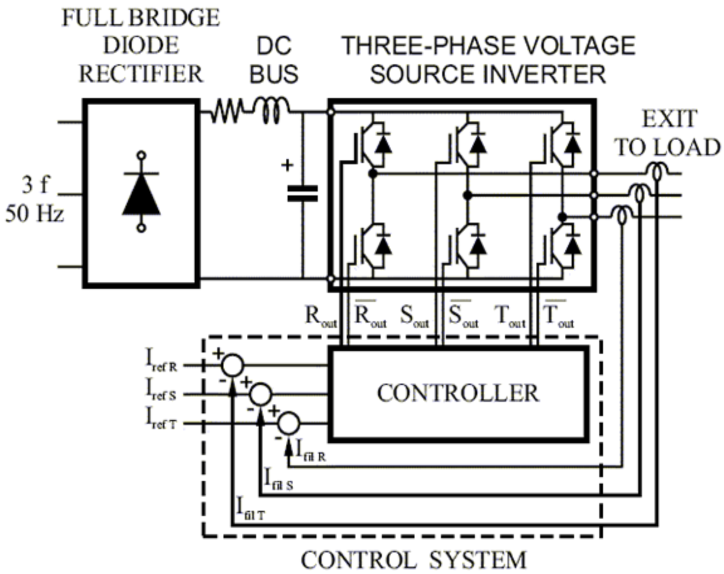

Figure: 2 three phase inverter single stage inverter

The basic mathematics and principles of three-phase electricity. For information on where, how and why three-phase is used, In electrical engineering, **three-phase** electric power systems have at least three conductors carrying current voltages that are offset in time by one-third of the period. A three-phase system may be arranged in delta (Δ) or star (Y)

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(also denoted as wye in some areas). A wye system allows the use of two different voltages from all three phases, such as a 230/400 V system which provides 230 V between the neutral (center hub) and any one of the phases, and 400 V across any two phases. A delta system arrangement only provides one voltage magnitude, however it has a greater redundancy as it may continue to operate normally with one of the three supply windings offline, albeit at 57.7% of total capacity. Harmonic current in the neutral may become very large if non-linear loads are connected.

Total harmonic distortion

The effect of modulation index variation and over-modulation on the THD of the output voltage is studied in this section, and

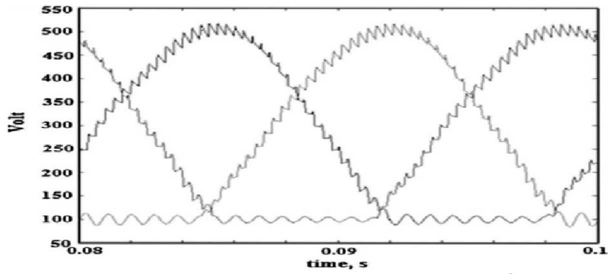

Figure: 3 Capacitors' voltage at M = 1.65 and switching frequency of 3 kHz.

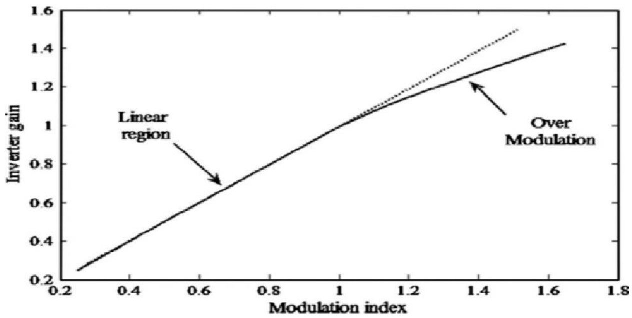

Figure 4 Modulation index versus inverter gain.

The results are tabulated in Table 3. Assuming that V_{DCi}= 100 V, L = 200lH, C = 100 lF, V_{DCo}= 250 V, and switching frequency is 3 kHz. Fig. 11 shows the relation between modulation index and inverter gain. Fig. 12 shows the

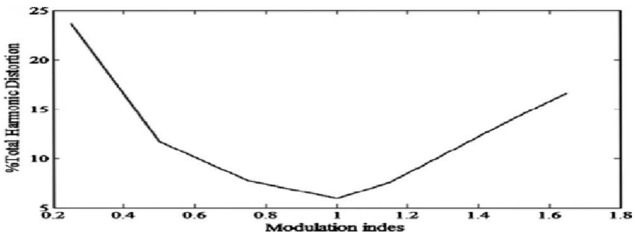

Figure 5 Modulation index versus output voltage %THD.

Relation between modulation index and %THD of the output voltage. From the results shown in these figures, it is clear that for a desired AC component, it is recommended to operate the three-phase boost inverter at unity modulation index to avoid high THD values. This can be done by adjusting $V_{DCo}$to equal the sum of the desired $V_{aco}$and V_{DCi}.

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IV. THIRD ORDER HARMONIC INJECTION.

Table 3 Effect of modulation index variation.

Modulation index	Inverter gain	THD (%)
0.25	0.25	23.7
0.5	0.5	11.7
0.75	0.7479	7.72
1	0.9942	5.93
1.15	1.113	7.59
1.25	1.181	9.41
1.5	1.338	14.07
1.65	1.426	16.59

Operating in the over-modulation region results in distorted output. Alternatively, third harmonic injection can be used as a means to extend the inverter gain to 1.15 without adding more stress on switches or distorting the output voltage waveform. The main disadvantage of this method compared to over-modulation is its limited gain. Third harmonic injection is commonly used to extend the linear range of the conventional VSIs, producing a flat-topped modulating signal, and hence better DC-link utilization.

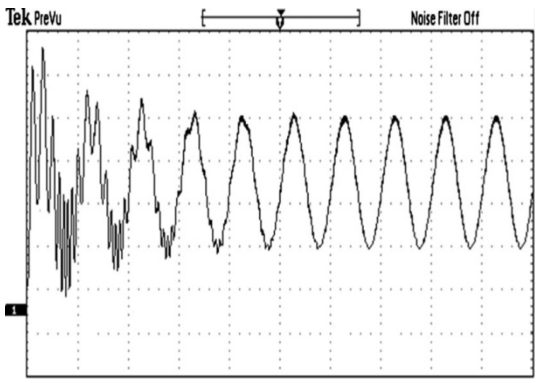

Figure 6Capacitor voltage (20 V/Div, 20 ms/Div).

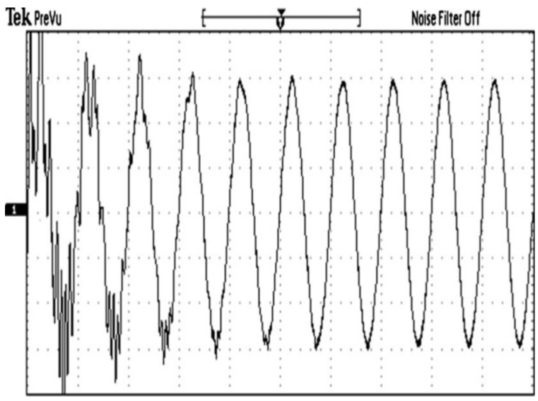

Figure 7Inverter output voltage (10 V/Div, 20 ms/Div).

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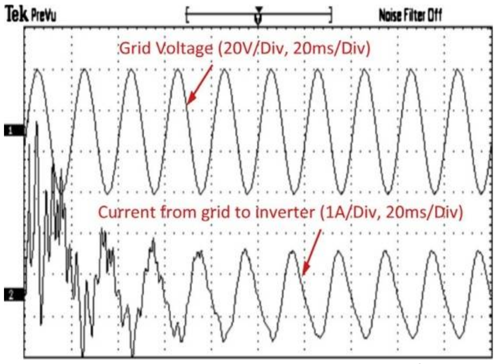

Figure 8Channel 1: grid voltage, channel 2: current from grid to inverter.

V. CONCLUSION

This paper addresses a three-phase boost inverter suitable for a single-stage connection of renewable energy sources to the grid. The converter possesses the benefits of reduced hardware requirements and an improved gain. The main contributions of the paper can be briefly summarized in three main points as follows:
(1) The effect of modulation index variation on THD of the output voltage is studied.
(2) Employing over-modulation technique and third order harmonic injection to extend the gain of the boost inverter.
(3) The performance of the extended gain converter in normal operation as well as during disturbances was evaluated. Simulation results supported by experimental verification show the effectiveness of the grid-connected boost inverter during normal operation well as in the presence of grid side disturbances.

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