A Survey on Maximum Boost Control of Diode-Assisted Buck–Boost VSI through Least Switching Frequency by SVPWM Method

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ABSTRACT: *Diode-assisted buck–boost voltage-source inverter achieves high voltage gain by introducing a switch-capacitor based high step-up dc–dc circuit between the dc source and inverter bridge. As for the unique structure, various pulse width modulation (PWM) strategies are developed with regard to the chopped intermediate dc-link voltage. This research study paper is analyzing the modulation principle of three-phase VSI and PWM techniques to achieve the instantaneous maximum utilization of intermediate dc-link voltage, as well as to reduce the switching frequency of power devices in diode-assisted buck–boost VSI.*

KEYWORDS: *Buck-Boost converter, PI controller, SPWM, SVPWM, Minimum switching frequency, closed loop control.*

I. Introduction

GIVEN the efficiency and environmental benefits of emerging solar and fuel cell technology, the distributed generation systems based on the renewable energy sources have rapidly developed in recent years [1]–[3]. In photovoltaic (PV) systems, it is difficult to realize a series connection of the PV cells without incurring a shadow effect [3]. Fuel cells and lightweight battery power supply systems are promising in future hybrid electric vehicle, more-electric aircraft and vessel. However, the obvious characteristic of these dc sources is low voltage supply with wide range voltage drop.

Power electronic interface has to regulate the amplitude and frequency to obtain required high ac utility voltage. These applications raise stringent requirements for power converters such as low cost, high efficiency and wide range voltage buck–boost regulation ability. Traditional voltage-source inverter (VSI) can only perform buck voltage regulation.

Thus, various novel and improved dc–ac topologies with buck– boost capability as well as the related control methods have been proposed to solve the issues [4]–[19].Traditional two-stage VSI shown in Fig. 1 obtains the required output voltage by introducing dc–dc boost circuit in the front. In view of additional power conversion stage increasing cost and lowering efficiency, a family of Z-source inverter [4]–[6] introduces a unique impedance network between the dc source and the inverter bridge.

It achieves the desired output voltage that is larger than the available dc source voltage by adopting shoot-through (ST) operation mode. Z-source inverter provides a potential cheap and single-stage power conversion. However, the ST state limits the modulation index and accompanies large ST current. Literature [7] makes comparison between traditional VSI and Z-source inverter based on electric vehicle driver system. The results reveal that Z-source inverter demonstrates low cost and high efficiency under relatively low voltage boost ratio range (1–2).

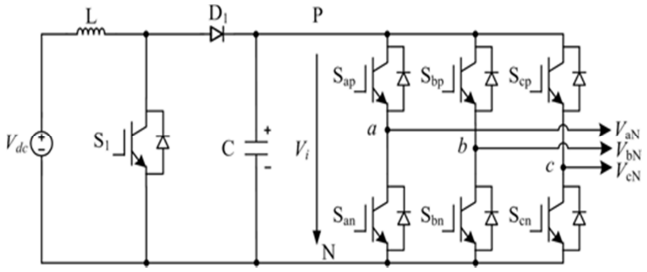

Figure 1: Conventional Two-Stage Buck–Boost VSI

Although both of them can boost output voltage to any desired value without upper limitation in theory, the degradation of efficiency and increasing requirement of switching devices are prominent under high voltage gain. Literature [8] proposed diode-assisted buck–boost VSI and related modulation strategy. It extends voltage gain and avoids extreme boost duty ratio by introducing a switch-capacitor based high step-up dc–dc circuit between the dc source and inverter bridge.

The diodes are naturally conducting to perform capacitive charging in parallel and discharging in series to achieve high voltage gain. In view of chopped intermediate dc-link voltage, the front boost circuit and inverter bridge needs coordinate control. The existing typical modulation strategy in [8] just utilizes intermediate dc-link voltage for ac output in the duration when the two capacitors are connected in series. Therefore, it has the drawback of relatively low dc-link voltage utilization.

In order to increase voltage gain as well as to reduce voltage stress of switching devices, Zhang and Liu [9] proposed the improved PWM strategy to further utilize the intermediate dc-link voltage for ac output in the duration.

II. Literature Review

W. Li and X. He.[1] “The photovoltaic (PV) grid-connected power system in the residential applications is becoming a fast growing segment in the PV market due to the shortage of the fossil fuel energy and the great environmental pollution. A new research trend in the residential generation system is to employ the PV parallel-connected configuration rather than the series-connected configuration to satisfy the safety requirements and to make full use of the PV generated power. How to achieve high-step-up, low-cost, and high-efficiency dc/dc conversion is the major consideration due to the low PV output voltage with the parallel-connected structure.

The limitations of the conventional boost converters in these applications are analyzed. Then, most of the topologies with high-step-up, low-cost, and high-efficiency performance are covered and classified into several categories. The advantages and disadvantages of these converters are discussed. Furthermore, a general conceptual circuit for high-step-up, low-cost, and high-efficiency dc/dc conversion is proposed to derive the next-generation topologies for the PV grid-connected power system. Finally, the major challenges of high-step-up, low-cost, and high-efficiency dc/dc converters are summarized.

This paper would like to make a clear picture on the general law and framework for the next-generation non-isolated high-step-up dc/dc converters”.

Y. P. Siwakoti, F. Z. Peng, F. Blaabjerg, P. C. Loh, and G. E. Town,[2] “Impedance networks cover the entire of electric power conversion from dc (converter, rectifier), ac (inverter), to phase and frequency conversion (ac-ac) in a wide range of applications. Various converter topologies have been reported in the literature to overcome the limitations and problems of the traditional voltage source, current source as well as various classical buck-boost, unidirectional, and bidirectional converter topologies.

Proper implementation of the impedance-source network with appropriate switching configurations and topologies reduces the number of power conversion stages in the system power chain, which may improve the reliability and performance of the power system. The first part of this paper provides a comprehensive review of the various impedance-source-networks-based power converters and discusses the main topologies from an application point of view.

This review paper is the first of its kind with the aim of providing a "one-stop" information source and a selection guide on impedance-source networks for power conversion for researchers, designers, and application engineers. A comprehensive review of various modeling, control, and modulation techniques for the impedance-source converters/inverters will be presented in Part II."

Y. P. Siwakoti, F. Z. Peng, F. Blaabjerg, P. C. Loh, G. E. Town, and S. Yang, [3] "Impedance-source networks cover the entire spectrum of electric power conversion applications (dc-dc, dc-ac, ac-dc, ac-ac) controlled and modulated by different modulation strategies to generate the desired dc or ac voltage and current at the output. A comprehensive review of various impedance-source-network-based power converters has been covered in a previous paper and main topologies were discussed from an application point of view. Now Part II provides a comprehensive review of the most popular control and modulation strategies for impedance-source network-based power converters/inverters.

These methods are compared in terms of theoretical complexity and performance, when applied to the respective switching topologies. Further, this paper provides as a guide and quick reference for researchers and practicing engineers in deciding which control and modulation method to consider for an application in a given topology at a certain power level, switching frequency and demanded dynamic response".

Y. Zhang and J. Liu, [4] "This paper explorers modulation strategies for diode-assisted buck-boost voltage source inverter and the relationship of voltage transfer ratio versus modulation index. Two kinds of improved pulse-width modulation strategies with high dc link voltage utilization are presented to obtain maximum voltage gain at given modulation index and minimize the voltage stress at the same time.

The operation principle and realization of the proposed modulation strategies, the relationship of voltage gain versus modulation index and voltage stress versus voltage gain are analyzed in details. Simulation results are given to verify the theoretical analysis and demonstrate good performance of the improved pulse width modulation strategies."

M. Shen, J. Wang, and F. Z. Peng, [5] "This paper proposes two constant boost-control methods for the Z-source inverter, which can obtain maximum voltage gain at any given modulation index without producing any low-frequency ripple that is related to the output frequency and minimize the voltage stress at the same time. Thus, the Z-network requirement will be independent of the output frequency and determined only by the switching frequency. The relationship of voltage gain to modulation index is analyzed in detail and verified by simulation and experiments."

S. Kwak and J.-C. Park,[6] "This paper proposes a predictive control method with zero-sequence voltage injection to efficiently reduce the switching losses of three-phase voltage source inverters (VSIs). In the proposed predictive control method, three-phase future voltage references modified by a zero-sequence voltage injection are generated to clamp one of the three legs with the largest load current. Furthermore, the future zero-sequence voltage, which is produced online with the future voltage and current references in every sampling period, optimally adjusts the clamping duration on each leg, depending on the load angle.

In addition, the proposed method selects the zero vectors on the basis of the polarity of the future zero-sequence voltage to reduce the switching losses. Using a predefined cost function, the proposed predictive control scheme chooses one optimal voltage state closest to the future voltage references modified by the zero-sequence voltage injection. Therefore, the proposed predictive control method can perform load current control and minimize the switching losses of the VSI under any load condition regardless of the load angle."

C. Charumit and V. Kinnares, [7]"In this paper, various types of discontinuous space vector pulse-width modulation techniques for a three-leg voltage source inverter supplying balanced two-phase loads are proposed.

The main objectives of the paper are to analyse switching loss characteristics associated with semiconductor devices and to reduce output current ripple by dealing with various types of zero space vector time in each switching sequence. Capabilities of reductions in switching losses and current ripple for both balanced and unbalanced output phase voltages at high modulation index and load power factor angle of 30° lagging are focused.

The validity of the proposed techniques is verified by simulation and experimental results in terms of voltage spectrum, current waveforms, and reductions in switching losses, and output current ripple at high modulation index when compared to a continuous space vector pulse-width modulation technique.

M. Shen, Q. Tang, and F. Z. Peng, [8] this paper proposes an average model for the Z- source inverter with inductive load using state space averaging. Based on this model, a controller is designed using gain scheduling by continuously varying the control gains according to the operating point. The average model is verified by simulation results. The validity of the controller is proved by experimental results.

P. C. Loh and D. M. Vilathgamuwa, [9] the newly proposed Z-Source inverter has been proven in the literature to exhibit both steady-state voltage buck and boost capabilities using a unique LC impedance network coupled between the power source and converter circuit. This paper now presents transient modeling and analysis of a voltage-type Z-source inverter. These aspects are found to be challenging and they need to be carefully investigated before attempting to design advanced control algorithms for controlling the Z-source inverter. Through detailed analysis, the paper identifies several phenomena on the dc and ac-sides of the inverter, which would result in the inverter having a non-minimum-phase transient response.

The dc-side phenomenon is associated with the Z-source impedance network, which is shown through small-signal and signal-flow-graph analyses to be having a right-half-plane zero in its control-to-output transfer function. Also, the ac-side phenomenon is shown through space vector analysis to depend on the time intervals of inverter states used for reconstructing the desired inverter output voltage. Based on the ac vectorial analysis, a method for improving the inverter transient response is also presented. Last, simulation results obtained using a switching-functional model and experimental results obtained using a laboratory prototype are presented for validating the described theoretical concepts.

C.-K. Cheung, S. C. Tan, C. K. Tse, and A. Ioinovici, [10] “The energy-efficiency issue of switched-capacitor converters is still a controversial topic that requires a more in-depth discussion. In this paper, we address the issue by dividing the analysis of the entire efficiency problem into two parts. In the first part, the efficiency of a capacitor-charging RC circuit under different aspects (partial charging, full charging, at zero capacitor voltage, at nonzero capacitor voltage, etc.) will be conducted.

The efficiency analysis of a capacitor-discharging RC circuit with a resistor, capacitor, and paralleled resistor-capacitor loads will be covered. A complete evaluation of the overall efficiency is then performed in terms of both the charging and discharging efficiencies. Based on the analysis, some design rules useful for developing high-efficiency switched-capacitor converters is suggested. Additionally, it is shown that the belief that quasi-switched-capacitor converters are lossier than switched-capacitor converters is a common misconception.

III. PV Array and VSI

As In order to interconnect the renewable sources (PVA) to the grid system a conversion is required to convert the DC to three phases AC. The three phase AC has to be in synchronization with the grid in parameters of voltage, frequency and phase. The VSI (Voltage source Inverter) is a three legged six IGBT switch inverter, where the DC side is connected to PVA and the three phase AC side connected to the grid through LC filter. The LC filter is connected to damp out the generated harmonics form the VSI avoiding the harmonics into the grid.

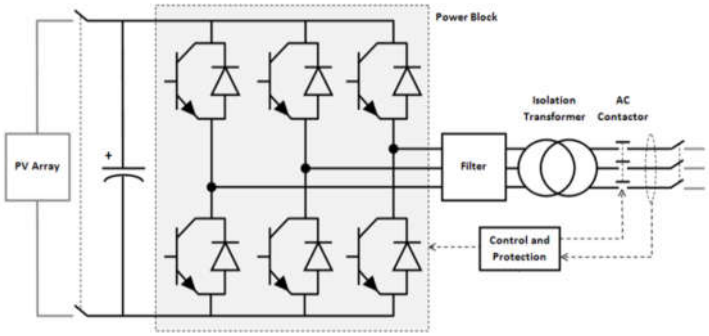

Figure 2: VSI Connected to Grid using RES

Any disruption in the switching of the VSI while connected to the grid system may also disrupt the grid voltage increasing the vulnerability of equipment connected to the system. It is very mandatory to maintain the switching of the VSI with optimal control techniques.

There are many control techniques that can control the VSI producing six pulses for each and every IGBT. The control techniques are:

1) SRF (synchronous reference frame) theory
2) id iq theory
3) IRP (Instantaneous reactive power) theory

All the above techniques use different PWM techniques which can be

a) Sinusoidal PWM
b) Space Vector PWM
c) Hysteresis current loop control

The controller senses the voltages and currents at the source side and also the load side generating reference values for the generation of pulses to VSI. The grid system contain linear and non-linear loads, the effect of non-linear loads is higher than the linear loads. As the non-linear load works on DC an AC to DC converter is used with the help of power electronic switches. Load is only inductors or resistors; we do not have any capacitor loads.

The total impedance of the load connected to the AC to DC converter introducing harmonics in the system creating a severe problem of PQ balancing. These load current harmonics caused by the power electronic devices can be compensated through the APF (Active Power Filter) with RES by injecting required active and reactive power.

The compensation reduces emphasize on main source increasing the power factor and improving the power quality. The operational cost of the APF is very less as RES is interconnected for the compensation to the grid.

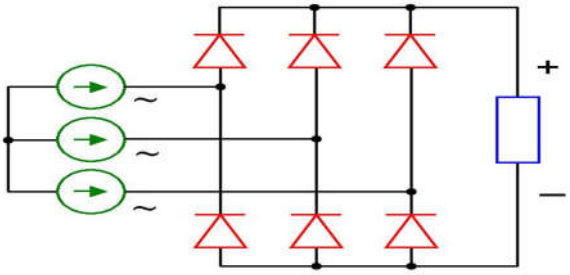

Figure 3: Rectifier of Non-Linear Load

The main aim of grid system is to incorporate the renewable sources into the grid with maximum penetration and to replace the conventional sources with the renewable sources. The VSI should be controlled effectively using optimum control techniques with less conduction losses to utilize the power from the renewable sources and inject active power, with reactive power compensation and reduction of harmonics in the grid system. The load flow can be controlled by controlling the modulation index of the fundamental reference waveform of the VSI.

In this report we introduce a new topology to control the VSI interconnection to the grid and mitigate the voltage harmonics and unbalanced voltages. In the design we also mitigate voltage sags and swells and control the load profile. There are many types of loads in the electrical grid system some of them are purely active power loads and some are combination of active and reactive power.

The active power loads are considered to be pure resistive loads for which the power factor is almost unity. Loads having inductance with resistance are considered to be impedance loads which consume both active and reactive powers. According to the electrical grid the loads are bifurcated as;

1) Industrial loads
2) Commercial loads
3) Domestic loads

4) Agricultural loads

Industrial loads are considered to be the most critical loads as they are the highest consuming loads in the total grid system, as it includes manufacturing industries, crushing mill, and boilers etc., which consume a high reactive power form the source. Due to this high consumption if reactive power from the source the power factor of the system drops to a low value i.e. between 0.5 & 0.8.

Due to the drop in the power factor the source introduces harmonics in the transmission line where the harmonics are distributed to the other distribution lines inducing the harmonics into other loads which is caused by the industrial load. It is very important to maintain the power factor of the distribution line and also to reduce the THD caused by the other critical loads. A simple phasor diagram with impedance load is shown below.

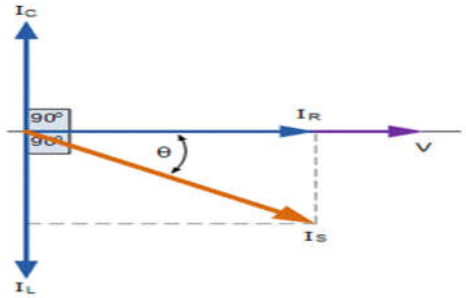

Figure 4: Phasor Diagram of Impedance Load

The normal (d-axis) is considered as the reference phasor or the angle of the supply voltage (V) assuming the angle as 0deg. The phasor I_R is the resistance current which is in phase with the voltage and the relative angle between the voltage and the current I_R is 0deg. There is also an imaginary axis (q-axis) with positive and negative vectors, where the positive vector is capacitor current (I_C) and negative vector is considered as inductor current (I_L).

The two vectors are 90deg phase shifted from the voltage vector with leading and lagging angles as capacitive and inductive currents respectively. When the load angle is 0deg the power factor is calculated as Cos (θ) which is '1' called as unity power factor. Unity power factor is the ideal power factor where the apparent power is same as that of the active power and also never achieved. Now, with the capacitive current (I_C) the angle is 90deg leading where the power factor with the above give equation is '0' zero power factor leading and the inductive current (I_L) with 90deg lagging is calculated as '0' zero power factor lagging.

The resultant current (I_S) with an impedance load which includes resistive and inductive elements has an angle of 'θ' relative to the voltage (V) vector and the current (I_S) vector. The power factor reduces gradually when the '–q-axis' component vector increase i.e. inductive load increases. It is very essential to maintain the power factor in a range of '0.9-1' so as to maintain the power quality.

In order to compensate the angle between the voltage and the load current vector a capacitive loads has to be added into the system. The capacitive loads has a '+q-axis' vector which compensates the '–q-axis' component vector reducing the angle between the voltage vector and load current vector. The compensation load phasor diagram is shown in fig. 5.

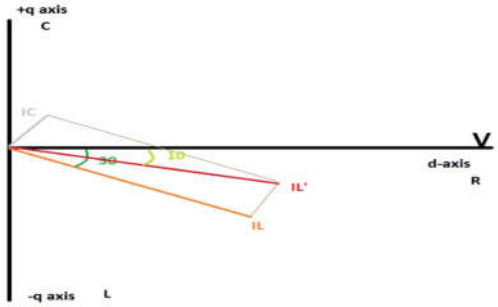

Figure 5: Compensation Phasor Diagram

Where, V= Voltage vector
I_L = load current vector
I_C = capacitor current
I_{RL}'= resultant load vector

As we can clearly see in the above figure the angle between the voltage reference vector and the load is 30 degree calculating the power factor as 0.866. A compensating current (I_C) is introduced by adding a capacitor load reducing the relative angle between the load vector from the voltage vector to 10degree increasing the power factor to 0.98.

Adding to the above load issues we also have sag and swell of voltage problems where swell is considered most critical problem in the entire electrical engineering. Sags may not cause immediate damage to the system but it causes insipient damage to the equipment. Swells are caused when large loads in the range of megawatts are suddenly disconnected from the distribution system. It can be elaborated as when the distribution system is feeding large loads high currents flow in the lines, but when this large load is disconnected the consumption current is reduced immediately in the line.

In order to maintain the apparent power in the distribution line the voltage increases suddenly creating a voltage swell in the system. This effect is called Ferranti effect. The increased voltage may be 125-150% to the nominal voltage value which can be eliminated with either circuit breakers or FACTs devices such as DVR or UPQC.

On the other hand the sags are created when a large load is suddenly connected to the distribution system. Due to the sudden adding of large load the current in the line is increased suddenly and as we discussed above to maintain the apparent power the voltage now will be decreased and sag is created. The system is said to be in sag when the voltage level goes below 95% of the nominal value.

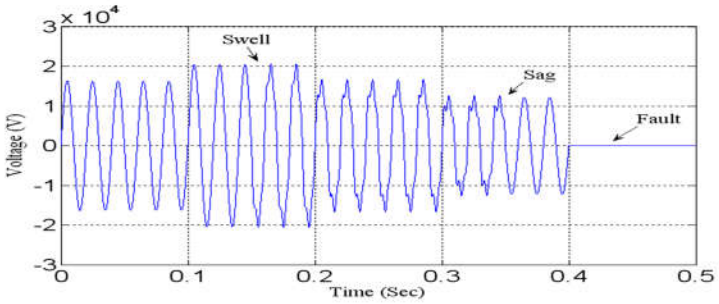

Figure 6: Voltage Profile with Sag, Swell & Harmonics

Apart from the above mentioned load types there are also sub types to these modules, they can be

i) Balanced loads
ii) Un-balanced loads
iii) Linear loads
iv) Non-linear loads
v) Critical loads
vi) Sensitive loads

The balanced loads are very rear loads which can be only utilized in industrial or agricultural load demands. These include three phase motors and furnaces, where the current in all the three phases will be equal making it a balanced load. Coming to un-balanced loads, the current in each phase of the grid can never be determined as the loads which are connected are independent to each other.

The independent loads have independent demand of power leads to unpredictable current flow in each phase. Whereas, the linear loads are which operate on AC as a supply to it. There will be no conversion taking place to run these loads either three phases or single phase. And the non-linear load use power electronic devices to convert AC to DC and is used as a supply to the load generating harmonics into the distribution line. This load is one of the most power qualities disrupting load in the grid system. Critical and sensitive loads are basic loads which get easily damaged with any change in voltage and current profiles.

With all the different types of loads mentioned above we can clearly understand that the non-linear unbalanced loads are the critical loads which introduce harmonics, sags & swells in the system with which the power is at its minimum quality and with the linear balanced loads the system is ideal and the quality of the power is at its maximum. During the transmission of power the three lines with phase R Y & B have to be always balanced so as to maintain the electro-magnetic forces between the lines to be balanced. In order to do this Delta Δ connection has to be used and to reduce the harmonic content on the load side Star Y connection has to be used for unbalanced operation of loads with a neutral point.

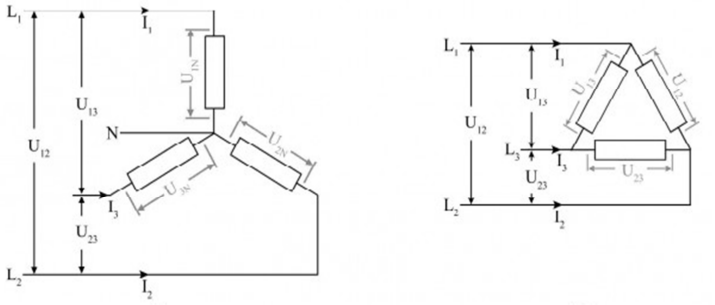

Figure 7: Delta and Star Connection of Loads

IV. PWM Techniques

a) Sinusoidal PWM Technique

The pulse width modulation technique is generally used for the conversion of DC to AC waveforms. A full bridge inverter with six IGBTs can be used to convert DC to three phases AC. Each phase has to be phase shifted to each other by 120^0 and has to be in synchronization with the grid to which it is being connected. The pulses are to be given to the IGBTs are generated with a reference or fundamental waveform compared with a triangular waveform.

The fundamental waveform has the frequency of the grid and the triangular or carrier waveform has higher frequency to create a modulation signal. The diagram of the fundamental and the carrier waveform are shown below in figure below. Six pulses are formed by applying NOT gates to the three pulses produced by the comparison of the fundamental and carrier waveforms. The generated pulses are fed to the VSI (Voltage source Inverter) with G1 G2 G3 G4 G5 and G6 switches. A simple construction of VSI is shown in figure;

The rating of IGBT is taken as
Internal resistance Ron = 0.001 ohms
Snubber resistance Rs = 100 k-ohms
Snubber capacitance Cs = 1F

Due to the impedance load the load current gets ceased during sudden switch OFF of the IGBT switch and generates high voltage peaks in the output voltage. To avoid this anti-parallel diode is attached to the switch (IGBT) so that the inductor current from the impedance load can pass through the diode.

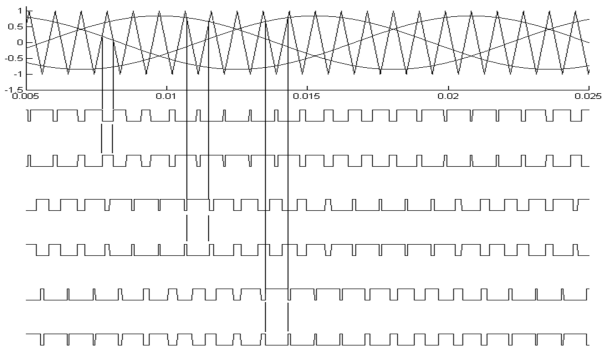

Figure 8: Generation of Pulses With Respect to Reference Fundamental Waveforms

The higher the carrier frequency the lower the harmonics developed by the inverter. To eliminate the minimum harmonics we also use LC filter to filter the higher order harmonics from the three phase AC voltage waveforms. The three sinusoidal fundamental waveforms are generated as;

$V_a = V_m \sin(wt)$
$V_b = V_m \sin(wt - 2\pi/3)$
$V_c = V_m \sin(wt + 2\pi/3)$

Where, V_m maximum voltage

The modulation index in PWM waveform is controlled by controlling the amplitude of the fundamental waveform. By reducing amplitude of the sinusoidal wave the space between the pulses is increased reducing the amplitude of the PWM waveform. The phase of the reference wave considered decides the phase of the PWM waveform.

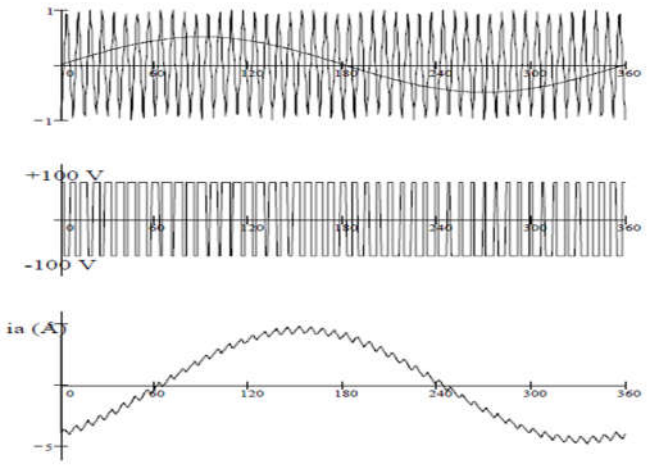

Figure 9: Effect of Change in Amplitude of Sinusoidal Waveform

b) Space Vector PWM Technique

Space vector PWM technique is an advancement of sinusoidal PWM as the pulses produced by digital switching of the fundamental waveform. Considering six switch operation we divide the VSI into two parts as upper part and lower part. The upper part contain the switches S1 S3 & S5 leaving the lower part of the VSI with S2 S4 & S6.

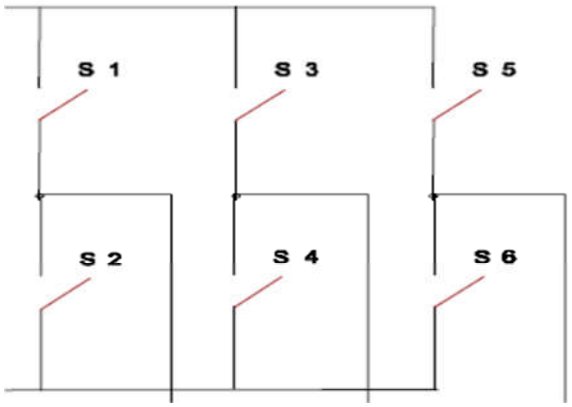

Figure 10: Switch Assigning of VSI

The states of the switches are either to be ON of OFF i.e., two states. The number of possible switching states is given as $2^3 = 8$. The 8 switching states are given below.

TABLE 1: Switching States

SWITCH	S1	S3	S5
1ST MODE	0	0	0
2ND MODE	0	0	1
3RD MODE	0	1	0
4TH MODE	0	1	1
5TH MODE	1	0	0
6TH MODE	1	0	1
7TH MODE	1	1	0
8TH MODE	1	1	1

In the above mentioned 8 switching modes the first and the last are completely OFF and ON which is not applicable. We only consider the six states from 1st to 6th eliminating 0 and 7th mode.

The last three switching states are the compliment of first three switching states, which concludes that we have to only generate the three switching states ie., 1st 2nd and 3rd. The other switching states i.e., 4th 5th and 6th are generated by applying a NOT gate to the previous modes. A simple hexagonal representation of switching patter in showed below which can be called as Space vector Trajectory.

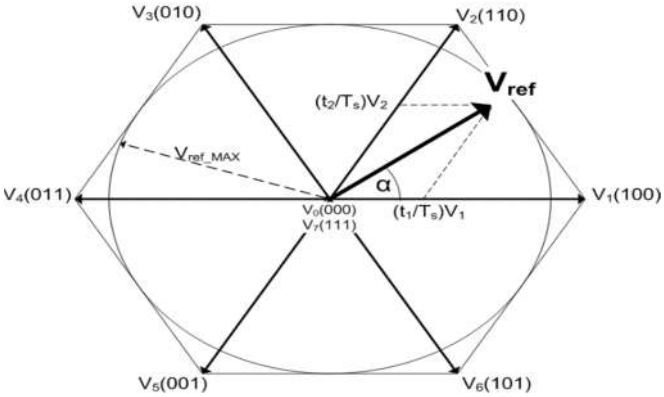

Figure 11: Space Vector Trajectory

The signal generation of space vector is compared to the triangular waveform to generate three PWM pulses to which NOT gates are given to get the other three pulses. The control signal of space vector PWM is given blow.

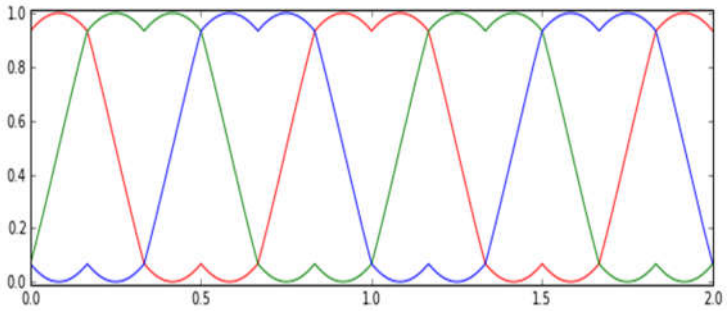

Figure 12: Control Signals of Space Vector PWM

c) Hysteresis Control Technique

Compared to traditional PWM techniques the hysteresis loop controller is flexible and easy to control. The operation of this control is simple and fast in response. The pulses in hysteresis control are generated by comparing the source

current to the reference current generated by the unit vector templates. The unit vector templates with PLL reference 'wt' are give as;

$V_a = V_m \sin(wt)$
$V_b = V_m \sin(wt - 2\pi/3)$
$V_c = V_m \sin(wt + 2\pi/3)$

The block diagram of the hysteresis loop control is give below

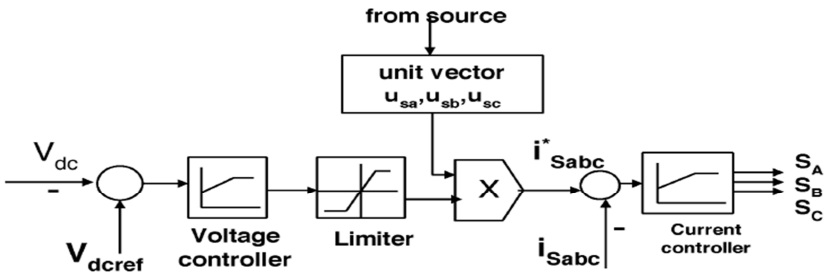

Figure 13: Hysteresis Control

The comparison output of the two currents (reference current & measured current) is given to relay which has a hysteresis band. The upper limit and the lower limit of the hysteresis controller is manually set to a certain value which can be +h & -h. When the error value is more than the upper limit, HIGH signal is produced ie., '1' and when the error value goes below the lower limit, LOW signal is generated ie., '0'.

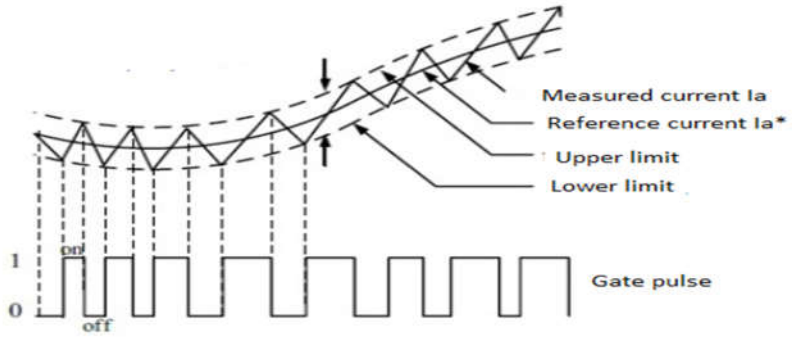

Figure 14: Hysteresis Band

Conclusion

The research study is analyzing the modulation principle of three-phase VSI and PWM techniques to achieve the instantaneous maximum utilization of intermediate dc-link voltage, as well as to reduce the switching frequency of power devices in diode-assisted buck–boost VSI.

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