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Analysis of Three Phase 3-Level NPC Voltage Source Converter for AC-DC Conversion

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ABSTRACT

The use of power electronic converters influences the generation of harmonics and reactive power flow in power system. Therefore, three-phase multilevel improved power quality AC-DC converters are gaining lot of popularity in power conversion applications. This work deals with critical problem of multilevel structure i.e neutral point potential (NPP) variation. In this paper, a simplified current controlled scheme is presented to ensure unity power factor operation. Neutral point potential (NPP) of three-phase, 3-level NPC AC-DC converter is controlled by modifying control signal in the controller using NPP regulator. An auxiliary circuit is being presented in this paper as an alternative option for controlling the neutral point potential of the converter. Comparison has been carried out between these control techniques in terms of power quality. A complete mathematical model is presented for better understanding of both techniques used for NPP control. The presented control techniques has been verified through simulation investigations and validated

KEYWORDS: *AC-DC converters, Active Front End Converter, Multilevel Converter, Neutral Point Clamped Converter, Unity Power Factor Controller (UPC).*

INTRODUCTION

AC-DC power converters have been widely used in various applications like front end converters in adjustable speed AC drives, High Voltage DC Transmission, Switch Mode Power Supply, utility interface with non-conventional energy source etc. [1]. Traditionally uncontrolled rectifier or SCRs used for AC-DC conversion suffer from some inherent problems like drawing harmonic currents and reactive component of the current from the source and offering highly nonlinear characteristic. Current harmonics generated by these nonlinear loads further result in voltage distortion which is becoming troublesome for the operation of many sensitive equipment and other consumer loads [2-3]. Therefore, high power factor converters (HPFC) has became the inherent part of AC-DC conversion because of its important features like conversion at unity power factor with higher efficiency, reduced size and well regulated dc output [4-8]. But these high power factor converters using high voltage rating devices are having limitations such as large dv/dt, large voltage stress across switching device, large common mode voltage generation, high switching frequency etc. [9-12]. A new age of converters i.e. multilevel structure is gaining lot of popularity because of its excellent performance in terms of improved power quality, less ripple in regulated dc output voltage, reduced voltage stress across switch, reduced dv/dt and low electromagnetic interference with neighbouring communication lines as compared to its counterpart 2-level HPFCs [13-18].

Diode Clamped Multilevel Converter topology which is most widely used topology in multilevel power conversion [9-11], suffers from the problem of unbalanced voltages across dc link capacitors [19]. The voltage equalization of dc link capacitors is the necessary precondition for stable operation of a diode clamped multilevel converters [20].

Several control techniques based on sinusoidal pulse width modulation (SPWM) and space vector pulse width modulation (SVPWM) [21-25] have already been proposed to mitigate this problem. Another way to control neutral point potential in multilevel converters is the use of additional voltage regulators, separate dc sources or additional circuit to balance the voltage across the capacitors [19, 26]. The problem with the auxiliary circuits used for balancing purpose is the extra cost of the switching devices, inductors, capacitors as well as higher switching losses. Literatures are now available for reducing switching losses in multilevel structures [28, 29].

In this paper, unity power factor controller (UPC) is presented to ensure unity power factor operation of three-phase, 3-level NPC AC-DC converter. A comparative study has been carried out between neutral point potential (NPP) regulator in UPC and an auxiliary circuit for controlling the NPP. The aim of this study is to address adverse effects of NPP regulator in UPC to control NPP in terms of power quality. A simple concept based on ping-pong theory to control NPP, is discussed in this paper as an alternative option for balancing of dc link capacitor voltages on the cost of extra hardware and higher losses. The complete working with mathematical modelling of auxiliary circuit based on ping-pong theory is presented. Experimentation is performed on the prototype developed in the laboratory to validate the effective working of controllers.

MAIN CIRCUIT TOPOLOGICAL STRUCTURE OF AC/DC CONVERTER

The circuit topological structure of three phase voltage type AC/DC converter is as shown in Fig. 1. It consists of two parts-main circuit and control circuit (Wang, 2008). The main circuit includes AC side voltage source, the inductance of AC side L, system load resistance R, DC capacitor C and the three phase full bridge converter made up from all control switch device V1-V6 and freewheel diode. The control circuit is mainly composed of control chip which can produce PWM (Pulse Width Modulation) modulating signal and related circuit. The function of control circuit is to provide PWM signal for controlling the cut-off of all control switch device. In Fig. 1, ea, eb, ec are three-phase supply phase voltage, Uao, Ubo, Uco are the three phase output voltage of AC/DC converter AC side and the neutral point 0 is the reference point. Suppose the grid voltage three phases are symmetry and stable, according to Kirchhoff Voltage Law and Fig. 1, system differential equations can be listed as follows:

$$\begin{cases} L\dfrac{di_a}{dt}+Ri_a=e_a-u_{a0} \\ L\dfrac{di_b}{dt}+Ri_b=e_b-u_{b0} \\ L\dfrac{di_c}{dt}+Ri_c=e_c-u_{c0} \end{cases} \tag{1}$$

Transform the Eq. 1 according to Laplace transformation, the three phase transfer function of the three-phase voltage type PWM rectifier abc can be gotten as follow:

$$\begin{cases} \dfrac{i_a(s)}{e_a(s)-u_{a0}(s)}=\dfrac{1}{Ls+R} \\ \dfrac{i_b(s)}{e_b(s)-u_{b0}(s)}=\dfrac{1}{Ls+R} \\ \dfrac{i_c(s)}{e_c(s)-u_{c0}(s)}=\dfrac{1}{Ls+R} \end{cases} \tag{2}$$

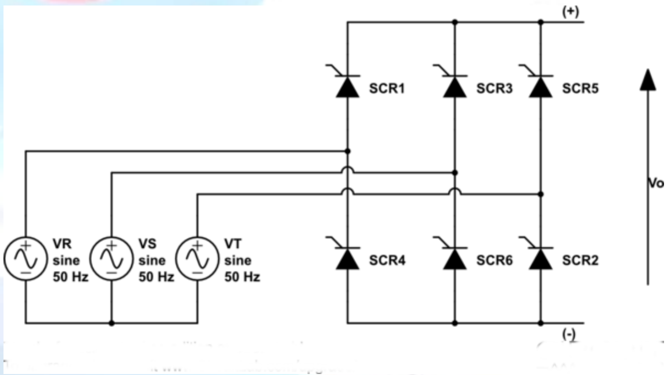


Fig 1: Three Phase Rectifier

3-LEVEL NEUTRAL POINT CONVERTER

A three phase neutral-point clamped active front end 3-level converter is shown in Figure.2. There are four power switches (Sa1, Sa2, S'a1 and S'a2 for phase 'a') in one leg for each phase and each leg is having two clamping diodes (Ds1 & D's1 for phase 'a'). Active front end rectifier is fed by 3-phase AC source connected through boost inductor (Ls). C1 and C2 are the dc link capacitors, midpoint of dc link capacitors and clamping diodes of each leg is connected to the neutral of three phase AC source. Resistance R1 and R2 are connected across the dc link capacitors to include loading effect of active front end converter [30].

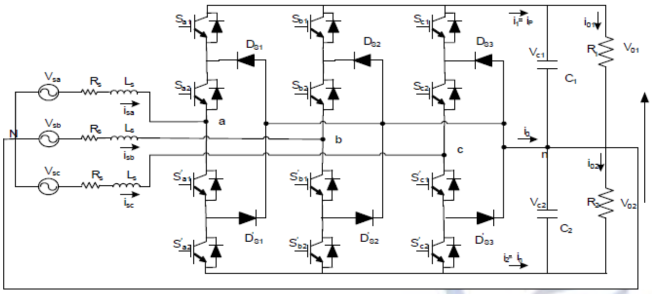


Figure 2. Neutral point clamped active front end 3-level converter

The neutral point clamped inverter is a bidirectional three-level PWM topology, which is widely employed in high power conversion. Fig. 3(a) shows one leg of such inverter. Table 1: Switching states for leg *a* for the npc-based topology in dependency of the input current direction

The dc-link is split into two equal voltages *Uo*/2 that limit the voltage across the switches *Sp,A*, *SA,p*, *SA,n*, and *Sn,A*through the clamping diodes *DMP,A* and *DA,MP* . Point *a* shall be connected to a current source, which is typically an interfacing inductor or an electrical machine. Inverting the drawing direction and considering the power flowing uniquely into the dc-link as shown in Fig. 3(b) causes no current to flow through switches *Sp,A*and *Sn,A*. Therefore, for unidirectional rectifier operation the NPC topology can be reduced to the circuit shown in Fig. 3(c).

Table 1

i_a	$S_{A,p}$	$S_{A,n}$	$u_{a,MP}$	i_{MP}
> 0	—	0	$+U_o/2$	0
	—	1	0	$i_a(> 0)$
< 0	0	—	$-U_o/2$	0
	1	—	0	$i_a(< 0)$

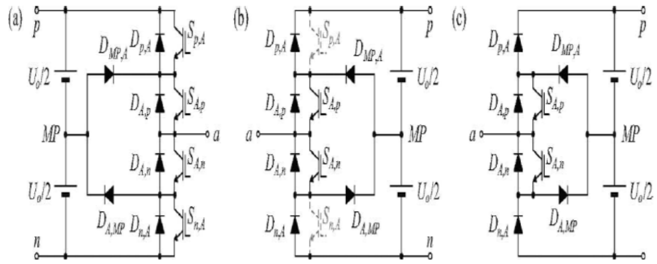


Fig 3: Derivation of an unidirectional rectifier based on the three-level NPC inverter

SIMULATION RESULTS:

In this section, we will test the proposed inverter model on a 2nd power system, a simple AC/DC three-level PWM converter, depicted in Fig. 4. The model, power_3levelSVC.mdl, is again taken from the SimPowerSystems demos[16]. It is composed of a 3-phase inductive source (600V) connected on the AC-side to a 500 kVar capacitor bank and 1 MW load. A 400kW DC-load is fed by a three-level inverter connected on this AC-bus through a transformer and a reactor. The controller tries to regulate the DC voltage to 500V despite load variations (200kW added at T=0.05 sec. form the initial 200kW). Then, at T=0.1 sec, the IGBT pulse are blocked and the inverter goes into rectifying mode. Fig. 5 compares the DC link voltages and transformer input currents between an SPS model running at 5 us and the proposed model (TSB) at 25 us, this last sample time being compatible with current real-time CPU-based simulator technology. They are very similar both in active mode and in rectifying mode (after 0.1 sec.).

Not shown in the result tests is the rectifying to active mode transition. At the time of writing this paper, this transition results in some DC-link over-voltage for this circuit (>20% with regards to the SimPowerSystems reference). The authors are actively working to further improve the model. It must be mentioned that the major usage of the real-time simulator for the inverter-based controller development is made in the active mode.

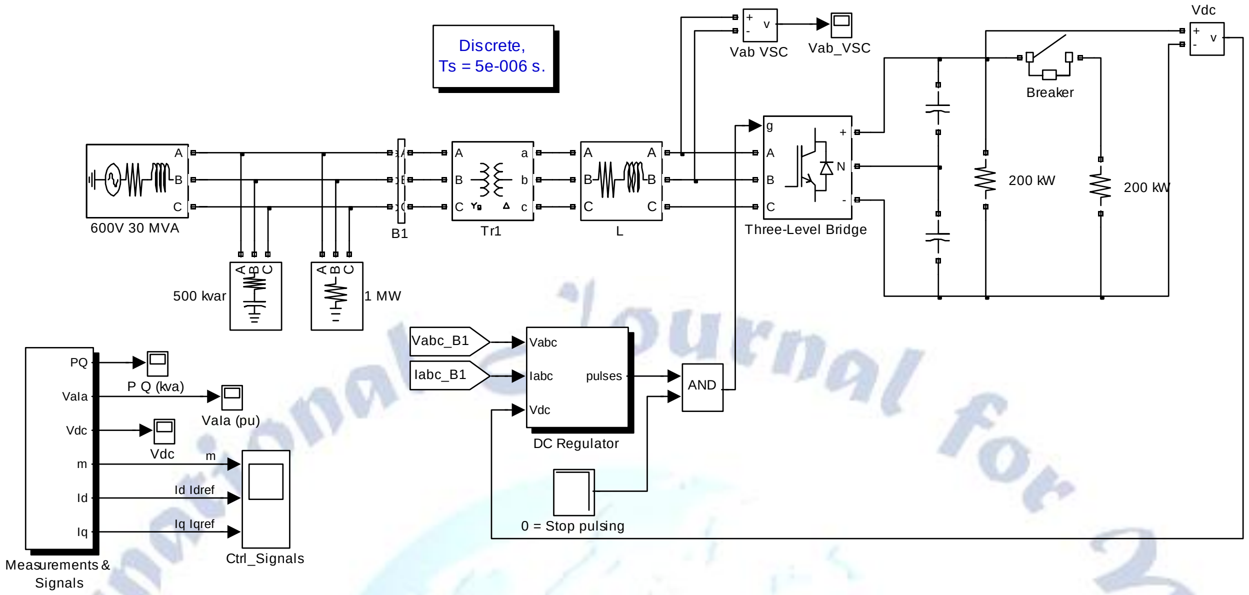
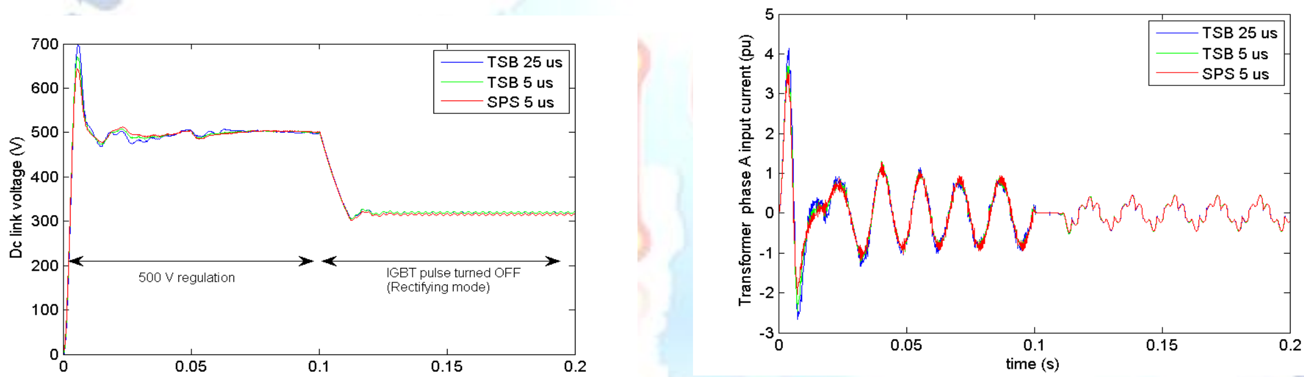


Fig. 4: 3-level NPC AC-DC converter



(a)

(b)

Fig 5: DC-link voltage (a) and Transformer input current (b): comparison between SPS and proposed inverter model (TSB)

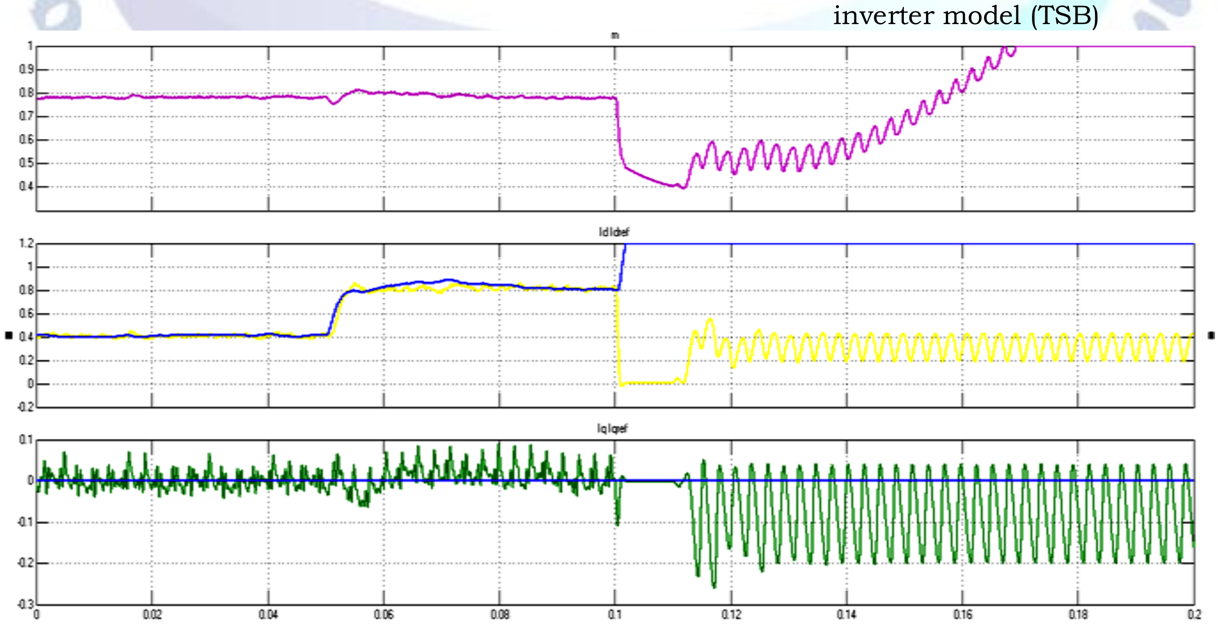


Fig:6 (a) Modulation Index, (b) Id Reference current (c) Iq reference current

CONCLUSION

The unity power factor controller (UPC) is presented to control NPC AFE 3-level converter for improved power quality at input and load side. The performance of three-phase NPC AFE 3-level converter has been evaluated with unity power factor controller. Simulation results are presented to study the performance of the system during transients as well as in steady state. It is observed that 3-level converter is operating at almost unity power factor with supply current THD within the limits imposed by IEEE519 standard. Simulated results also show that NPP regulator in conjunction with UPC is able to balance the capacitor voltages under balanced and unbalanced load with the addition of dc off-set in supply line current. The simulation results with an auxiliary circuit to balance the dc link capacitor voltages show effective balancing of dc link capacitor voltages without any adverse effects in terms of power quality. The features of UPC with NPP regulator and auxiliary circuit, observed in simulation study are also validated through experimentation performed on the low power prototype developed in laboratory using dSPACE DS 1103. Further, it can be concluded that the UPC with NPP regulator is suitable for drives application where depth of unbalance is not much whereas an auxiliary circuit is effective for active power filter where depth of unbalance is high.

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