Power Quality Improvement in Single Phase AC-DC Three Level Boost Converter Using PI and SMC

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Abstract: This paper proposes the single phase ac-dc three-level boost converter with controller circuit such as sliding mode controller, proportional integral controller and employs three-level pulse width modulation technique. Solid state switched mode three-level boost converter along with the control methods achieve unity power factor, high efficiency, precisely regulated dc output in boost converter, reduced output voltage ripple and less than 5% of total harmonic distortion with unidirectional power flow. The outstanding feature of proposed control scheme is line current is driven to follow sinusoidal reference current command which is in phase with sinusoidal input voltage and guaranteeing dc-link capacitor voltage balance in every switching cycle. Comparative analysis of PI controller and sliding mode controller is carried out. The performances of converter under load variation, unbalanced load condition and sudden change in load condition for various control strategies were verified.

Introduction

Multilevel converter is emerging for new breed of medium to high voltage applications such as large electric drives, dynamic voltage restorers, reactive power compensations, FACTS devices [1], grid connected applications [2] and fuel cell applications [3]. In this converter the number of switches can be reduced as two with unidirectional power flow [4]. Various pulse width modulation techniques used are Voltage-oriented PI control of three-phase grid connected PWM [5], H-bridge transistorized converter intended for front-end power conversion at high power-factor [6], Phase shifting of pulse width modulated technique [7]. The capacitor voltage unbalance problem is inherent in the above mentioned PWM techniques. In this paper three-level PWM technique is used. Switching pulses for power devices can be generated from three control signals b₁, b₂ and b₃ [8]. Various current control techniques are implemented to meet IEEE norms for power quality. The PFC, which exploits a principle of generating and tracking the desired current profile in a single phase ac-dc boost converter [9]. A nonlinear system can be asymptotically stabilized with a linear proportional-integral (PI) controller [10]. A tri-state boost converter with an additional boost inductor was designed by PI control technique to eliminate the right-half-plane (RHP) zero [11]. The concept of voltage control for AC-DC converter using sliding mode control attributes converting a non-linear system into equivalent linear system [12]. Sliding mode controller provides robustness and good dynamic response [13]. In order to estimate fixed switching frequency the indirect SM controllers are needed which becomes complicated circuit implementation. Variable band hysteresis modulation (HM) based sliding mode control is suggested for single switch double-buck converter, in which both the duty cycle and switching frequency are utilized as control parameters [14]. Analog phase-locked loop implementation of the sliding-mode control for dc-ac converter is also implemented but preserve transient performances [15]. One type of SM controllers extends the properties of hysteresis control to enforce the state trajectory along the sliding surface leads to simple design procedure with variable switching frequency [16].
In this paper PI controller is used which integrates the linear control techniques. Variable structure system based HM-SM controller is also implemented. Reference inductor current is derived from voltage regulator, capacitor voltage balance compensator and from power estimator.

**Problems formulation**

The focus of the project is to design a single phase ac-dc dual output three-level boost converter to get desired output voltage, reduced output voltage ripple with the configuration should satisfies IEEE 1159 standard for power quality, IEEE 519 standard for harmonics. Main problems arising and affecting the performance of three-level converter is represented in figure 1.

![Fig. 1 Control methods](image1)

![Fig. 2 Circuit diagram](image2)

Figure 2 shows the circuit diagram of single phase ac-dc three level converter. An inductance $L_b$ is used to reduce the current ripple. The single phase three level rectifier is controlled to reduce harmonic content in the line current, to increase efficiency and to give unity power factor. The advantage behind this converter is voltage rating of the power semiconductors are reduced to half of dc bus voltage; the inductor boost volume is one quarter of the conventional boost converter.

**Proposed control techniques**

![Fig. 3 Block diagram of controller](image3)

Figure 3 shows the control block diagram of three-level ac-dc converter with three control signals. PI controller works as voltage regulator which reduces the voltage error. The inductor current error is given as the input to the current controller. Here the current controllers used are sliding mode controller and PI controller. The reference inductor current is expressed as,
\[ i_{\text{err}}^* = \frac{2(V_1 + V_2)}{V_{\text{peak}}} + K_p V_{\text{err}} + K \sum V_{\text{in}} \sin \omega t \]  

where, \( K_p \)–Proportional gain, \( K_i \)-Integral gain  

\[ V_{\text{err}} = V_{\text{dc}}^* - V_{\text{dc}} \]  

In order to achieve three level PWM technique, the dc voltage is controlled in the range of \( V_m < V_o < 2V_m \). The adopted single phase rectifier can be operated in three-level modulation techniques based on the proposed control schemes with three control signals. Single phase three-level ac-dc rectifier is operated in two regions such as \( |v_s| < v_o / 2 \) and \( v_o / 2 < |v_s| < v_o \).

Region selector (\( b_1 \)) is used to find whether the rectified output voltage is in region 1 or 2. Compensated capacitor selector compensates two capacitor’s voltage \( (v_1, v_2) \) under unbalance condition of load by providing one of the control signals (\( b_2 \)). Switching function can be given in equation (6).

\[
\begin{align*}
  b_1 &= \begin{cases} 
    1, & |v_s| > \min(v_1, v_2) \\
    0, & |v_s| < \min(v_1, v_2)
  \end{cases} \\
  b_2 &= \begin{cases} 
    1, & v_1 > v_2 \\
    0, & v_1 < v_2
  \end{cases} \\
  b_3 &= \begin{cases} 
    1, & i_{L}^* - i_L > h \\
    0, & i_{L}^* - i_L < -h
  \end{cases}
\end{align*}
\]

\[ Q_1 = \overline{b_1} b_2 + \overline{b_1} b_3 + b_2 b_3 \]

\[ Q_2 = \overline{b_1} b_2 + \overline{b_1} b_3 + \overline{b_1} b_3 \]  

**Sliding mode control.** Sliding mode control is a nonlinear control method that alters the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to slide along the cross section of the system’s normal behavior. In this control structure phase trajectories move along the boundaries of the control structures and changes their state from one continuous structure to another based on the current position in the state space and control law is not a continues function of time. Hence, sliding mode control is a variable structure control (VSC) method.

\[ \Psi = x_1 + \tau x_2 \]  

\[ \dot{x}_1 = x_2 \]  

\[ \dot{x}_2 = \frac{di_{L}(t)}{dt} \]  

\[ \frac{di_{L}(t)}{dt} = \frac{V_o(t) + V_s(t) + V_s(t)u(t)}{L_b} \]  

\[ \frac{dv_o(t)}{dt} = \frac{i_{L}(t)}{C} - \frac{V_o(t) - i_L(t)u(t)}{RC} \]  

Switching function \( s(x) = i_{L}(t) - i_{L\text{ref}} \) induces sliding motions in the system and its control law is given as,

\[ u_{eq} = 1 - \frac{v_s}{v_o(t)} \]
Fig. 4 Sliding motion

\[ \text{if } \Psi > + \beta \rightarrow u(t) = 0 \]
\[ \text{if } \Psi < -\beta \rightarrow u(t) = 1 \]  \hspace{1cm} (13)

where \( \beta \) defines suitable hysteresis band. When the region is \( \Psi < -\beta \), the switch is close and the motion occurs along a phase trajectory corresponding to \( u(t) = 1 \). When the system status crosses the line \( \Psi = +\beta \) the switch is turned off. Observing that the phase trajectories are directed toward the line itself in proximity of the sliding line, the resulting motion is made by continuous commutations around the sliding line, because of that the system status is driven to the final equilibrium point.

**PI control.** The PI controller takes into account the desired output of the converter to produce control signal which is necessary to reduce the error signal approximately to zero. A proportional controller gain (\( K_p \)) will have the effect of reducing the rise time and will not eliminate the steady state error. An integral control gain (\( K_i \)) will have the effect of eliminating the steady state error but makes transient response worse. From the transfer function of three-level boost converter proportional gain and integral gain values are obtained as \( k_p = 0.163 \) and \( k_i = 0.9 \).

**Simulation Results and Discussion**

In order to investigate the proposed three-level modulation technique, MATLAB simulation is carried out at 100 W output power and 10 kHz switching frequency. The mains voltage is 28 V (rms) with 50 Hz frequency. The boost inductance is 3mH. The capacitance of two capacitors is 2000 µF.
In open loop control input current waveform is not sinusoidal and having THD of 42 % (figure 8). In figure 9 sinusoidal input current is obtained by sliding mode control. Power factor is close to unity and THD will be 3.2 % which satisfies the IEEE 519 Std for THD. Voltage across two capacitors is balanced by new PWM technique as shown in figure 7. Efficiency is 90.2 % for rated power. Figure 10 shows that even though load has been suddenly changed at 0.2s,0.4s etc output voltage in maintained as constant.

**Conclusion**

The AC-DC three-level converter with sliding mode controller and PI controller under various load, unbalanced load and sudden change in load condition is proposed using MATLAB simulation. The capacitor voltage unbalance problem is improved by three-level PWM control scheme. Sliding mode and PI controller provides unity power factor, voltage regulation, less harmonic distortion, high efficiency, and good steady state performance. Sliding mode controller controls inductor current within limited band and provides good dynamic response enough for fast
recovery of the dc-link voltage due to load change. Sliding mode controller provides better power factor, lesser THD and good transient response than the results obtained in PI controller.

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