Three phase six-switch PWM buck rectifier with power factor improvement

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Abstract. Conventional Phase Controlled Rectifier injects low order current harmonics into the AC mains. Large size filtering components are required to attenuate these harmonics. In this paper, three phase six-switch PWM buck rectifier is presented which operates at nearly unity power factor and provides variable output voltage. Small size energy storing components are required depending upon switching frequency. MATLAB simulation is performed and modified Sinusoidal Pulse Width Modulation (SPWM) switching technique is used in 3kW prototype converter to demonstrate low input current THD, nearly unity displacement factor, well regulated output voltage and reduced switching losses compared to conventional SPWM.

1. Introduction

In most of the power electronic applications, AC/DC converter is widely used as a first stage rectifier. DC obtained from this rectifier is further converted into desired amplitude and frequency. Most common topology of rectifier is three phase controlled rectifier (PCR). PCR is capable of delivering controlled DC voltage but it has a very low input power factor at low conduction angle and introduces unwanted distortion in AC mains. It does not comply with IEEE-519 standard of low input current harmonics. Large size low frequency input filters are required in PCR to improve its power factor. This results in both increased cost and large size of the PCR. PWM rectifiers have replaced the conventional PCR due to their high efficiency, good voltage regulation, nearly unity power factor and small input/output filter size depending upon switching frequency. PWM rectifiers are normally operated at high switching frequency where low frequency harmonics are easily suppressed. PWM rectifiers are increasingly becoming popular due to the availability of fast switching, high voltage and high current IGBT's[1].

Three phase PWM regenerative boost rectifier [2] is shown in figure 1. Output voltage is greater than the peak of the line to line RMS voltage in this rectifier. This is a four quadrant rectifier capable of bidirectional power flow. Operation of this rectifier is similar to boost SMPS. When SWR₁ is turned on, voltage is applied across the inductor and it gets energized. When SWR₂ is turned off, inductor de-energizes through the diode of SWR₁ charging the capacitor. Unity power factor is achieved by controlling the current in the inductor.
Three phase PWM regenerative boost rectifier is shown in figure 1. Output voltage of this rectifier is less than 1.26 times line to line RMS voltage [3]. It is a unidirectional converter and power flow is controlled by controlling the depth of modulation and delay angle. Modulation index and delay angle provide a flexible control over output voltage as well as input displacement factor [3]. Change in delay angle produces lagging power factor which compensates the leading power factor of input capacitor resulting in unity displacement factor [3]. However unity displacement factor is not achieved if capacitor current is greater than rectifier current for low loads. Some applications of this rectifier are UPS battery chargers, DC motor speed control, front end converter in wind farms and front end converter in variable speed ac drives.

Three phase six-switch PWM buck rectifier is shown in figure 2. Output voltage of this rectifier is less than 1.26 times line to line RMS voltage [3]. It is a unidirectional converter and power flow is controlled by controlling the depth of modulation and delay angle. Modulation index and delay angle provide a flexible control over output voltage as well as input displacement factor [3]. Change in delay angle produces lagging power factor which compensates the leading power factor of input capacitor resulting in unity displacement factor [3]. However unity displacement factor is not achieved if capacitor current is greater than rectifier current for low loads. Some applications of this rectifier are UPS battery chargers, DC motor speed control, front end converter in wind farms and front end converter in variable speed ac drives.
The rest of this paper discusses the design, simulation and implementation of three phase six-switch PWM buck rectifier optimized to provide variable output voltage with low ripple contents and nearly unity power factor using small filters.

2. Design of three phase six-switch PWM buck rectifier

2.1 PWM technique

Assuming balanced set of three-phase input voltages, the objective of this rectifier is to draw sinusoidal input currents in phase with input voltages. Only active power flows through the bridge. The ripple content is very low in the output voltage and it is well regulated since the devices are being switched at high frequency. As the input voltages are balanced, a three phase modified Sinusoidal PWM (SPWM) is applied to the switches and switching waveforms are shown in figure 3. Switching instants of all the switches are clearly mentioned in figure 3. Each switch is continuously conducting for 60° in the center of switching pattern. There are no overlapping pulses in the switching waveforms instead freewheeling diode is used for overlapping instants resulting in the reduction of switching losses up-to 30%. Switching pattern of 2kHz SPWM is generated using analogue discrete IC’s and also both the modulation index and the delay angle is controlled.
Figure 3. Modified Sinusoidal Pulse Width Modulation.
2.2 Power topology
Power topology consists of power semiconductors devices, AC-side filter [4] and DC-side filter. IGBT's are used with series fast recovery diode to block the reverse voltages across the IGBT. The reverse blocking capability of IGBT is poor and series diode is required. AC-side filter is implemented using gapped core inductor of 3mH and paper capacitor of 10uF. It results in a small size filter with cut-off frequency of 920Hz. DC-side filter consists of an inductor and capacitor. Inductor is designed to maintain low ripple current and continuous flow of load current. Small capacitor is required to filter out high frequency ripple components from the load current.15mH inductor and 1000uF capacitor are used in the prototype and simulation. RC snubber of 10Ω and 0.1uF is used across each switch. Resistive load of 39Ω is used.

2.3 MATLAB Simulink simulation
Three phase six-switch PWM buck rectifier circuit has been simulated with Simulink using the values described in the last section. Input voltage is 400V_p-p_rms and output voltage is variable from 80V to 342V. Figure 4(a) shows the simulation results of R phase voltage and current. It can be seen that voltage and current are in phase, displacement factor is nearly unity and THD is also low resulting in nearly unity power factor. Figure 4(b) shows the simulation results of output voltage and current. Voltage across D_w is shown in figure 5.
Figure 4(a). $V_{R,rms}$ and $I_{R,rms}$. 
Figure 4(b). $V_{dc}$ and $I_{dc}$.

Figure 5. $V_{DW}$. 
2.4 Experimental verification

3kW prototype of three phase six-switch PWM buck rectifier has been implemented using components described in previous section. Input voltage is $400V_{p-p, \text{rms}}$ and output voltage is variable from 80V to 342V. Figure 6(a) shows the experimental results of R phase voltage and current. Experimental results clearly verify the simulation results. Nearly unity power factor is achieved. Figure 6(b) shows the experimental output voltage and current. It can be seen that ripple content is very low in output voltage and current. Figure 7 shows the SW$_{R1}$ pulses. It can be seen that there are no overlapping instants in the SW$_{R1}$ pulses resulting in low switching losses. Figure 8 shows the experimental voltages across D$_w$.

![Image of experimental results](image)

**Figure 6(a).** $V_{R,\text{rms}}$ in ch1 and $I_{R,\text{rms}}$ in ch2.

![Image of experimental results](image)

**Figure 6(b).** $V_{dc}$ in ch1 and $I_{dc}$ in ch2.
Figure 7. $SW_{R1}$ pulses.

Figure 8. $V_{DW}$. 
3. Conclusions
It has been shown that three phase six-switch PWM buck rectifier is capable of drawing input current with low THD and nearly unity displacement factor using the modified SPWM. Switching losses may be reduced up-to 30% using the suggested SPWM scheme. Output voltage is variable over a wide range. Energy storing components are small in size compared to PCR due to high switching frequency. It is highly suitable for replacing conventional PCR at medium power level.

References

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