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ORIGINAL CONTRIBUTION

Design and Simulation of a Pulse Width Modulated Rectifier

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ABSTRACT

The interest towards improving the quality of power supplied to the electronic equipments has been increasing to ensure the optimum utilization of power generated. A low power factor is responsible for reducing the active power available from the grid and causing a high harmonic distortion of the line current eventually resulting in electromagnetic interference problems and cross-interferences, through the line impedance, between different systems connected to the same supply. The standard rectifier employing a diode bridge followed by a filter capacitor for DC utilities gives unacceptable performances in terms of power quality according to the rising benchmark set by recent developments in the relevant field. One of the most popular topology for power factor correction is certainly the boost topology. The disadvantage of Power factor Corrected Boost Converter is power can only flow from AC side to DC side. Bidirectional power flow is possible if instead of PFC boost converter a Pulse width Modulated Rectifier is used. In this work a PWM rectifier has been designed and simulated in MATLAB and the proposed control strategy has been implemented.

KEYWORDS— Power factor, Harmonic Distortion, Rectifier, Diode bridge, Boost topology, Power factor correction, Bidirectional power flow, PWM rectifier, MATLAB.

1. INTRODUCTION

In most power electronic applications such as switch mode DC power supplies (SMPS), uninterruptible power supplies (UPS), AC and DC motor drives, AC to DC converters are used as the interface with the utility voltage source. In general, line frequency diode rectifiers are used to convert line frequency AC to DC. Rectifier output is a DC voltage whose average magnitude is uncontrolled. A large filter capacitor is used at the rectifier output to reduce the ripple in the DC voltage [1]. DC voltage and DC current are unipolar and unidirectional. Therefore, power flow is always from the utility AC input to the DC side.

A class of power electronic systems utilize line frequency thyristor controlled AC-to-DC converters as the utility interface. In these converters average DC output voltage is controllable in magnitude and polarity, but the DC current remains unidirectional. Because of the reversible polarity of the DC voltage power flow through these converters is reversible [2]. But the trend is to use these converters only at very high power levels such as in high voltage DC transmission systems. Because of the very high power levels, the technique to filter the current harmonics and to improve the power factor of operation are quite different in these converters. In general, where the DC voltage remains essentially constant are considered.

The power factor PF at which an equipment operates is the product of the current ratio I_1/I_s and the displacement power factor DPF. The displacement power factor equals the cosine of the angle φ_1 by which the fundamental frequency component in the current waveform is displaced with respect to the input voltage waveform. The current ratio I_1/I_s is the rato of the rms value of the fundamental frequency current component to the rms value of the supply current [3]. The

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*Corresponding author: sourav_bec@gmail.com power factor indicates how effectively the equipment draws power from the utility. At a low power factor of operation for a given voltage and power level, the current drawn by the e4quipment will be large, thus requiring increased volt-ampere ratings of the utility equipment such as transformers, transmission lines and generators. The importance of the high power factor has been recognized by residential and office equipment manufacturers for their own benefit to maximize the power available from a wall outlet. For example, from a 230V, 10A electrical circuit in a building, the maximum power available is 2.3kW, provided the power factor is unity. The maximum power that can be drawn without exceeding the 10A limit decreases with decreasing power factor. The ongoing arguments indicate the responsibility and desirability on the part of the equipment of operation. This requires that the displacement power factor should be high and the current harmonics should be low to yield a high current ratio $I_1/I_{s.}$

Conventional AC/DC power converters that are connected to the line through diode rectifier draw a non-sinusoidal input current. Because of the large harmonic content, typical diode rectifiers used for interfacing power electronic equipment with the utility system exceeds the limits on individual current harmonics and THD specified [4]. These harmonic currents flowing through the impedances in the electrical utility distribution system can cause several problems such as voltage distortion, heating, noises. These harmonics distort the local voltage waveform; potentially interfering with other electrical equipment connected to the same electrical service and reduces the capability of the line to provide energy. In addition to the effect on the power line quality, the poor waveform of the input current also affects the power electronic component itself in different ways [5]. This fact and the presence of standards or recommendations have forced to use power factor correction in power supplies.

Inductors and capacitors can be used in conjunction with diode bridge rectifier to improve the waveform of the current drawn from the utility grid. Obvious disadvantages of such an arrangement are cost, size, losses and the significant dependence of the average dc voltage on the power drawn by the load.

By using a power electronic converter for current shaping it is possible to shape the input line current drawn by bridge rectifier to be sinusoidal and in phase with the input voltage.

In certain applications, for example, in motor drives with regenerative braking, the power flow through the utility interface converter reverses during the regenerative braking while the kinetic energy associated with the inertias of the motor and load is recovered and fed back to the utility system. One approach used in the past is to employ two back-to-back connected converters. During the normal mode, converter 1 acts as a rectifier and the power flows from the ac input to the dc side. During regenerative braking, the gate pulses to the thyristors of converter 1 are blocked and converter 2 operates in an inverter mode where the polarity of dc bus voltage remains the same but the direction of current reverses. There are several drawbacks associated with this approach: (1) the input current has a distorted waveform and the power factor is low, (2) the dc voltage is limited in the inverter mode because of the minimum extinction angle requirement of converter 2 while it operates in an inverter mode, and (3) there is a possibility of commutation failure in the inverter mode due to ac line disturbances.

It is possible to overcome these limitations by using a switch-mode converter.

2. DESIGN

Basic Principle of Boost Converter

Figure 1 shows a boost converter. Its main application is in regulated DC power supplies and the regenerative braking of DC motors. As the name implies, the output voltage is always greater than the input voltage. When the switch is on, the diode isreverse biased, thus isolating the output stage. Theinput supplies energy to the inductor. When the switch is off, the output stage receives energy from the inductor as well as from the input. The output filter capacitor is assumed to be very large to ensure a constant output voltage at steady state.

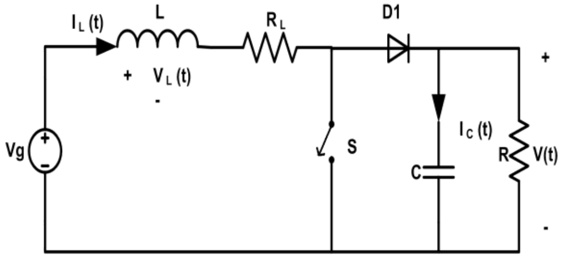

Figure 1: Boost converter operational circuit

The switch used in the boost converter configuration is typically a power BJT, power MOSFET, or IGBT. DC power is obtained by rectifying the power from an AC source using a diode bridge rectifier. The boost converter converts the rectified DC voltage to a higher output voltage.

The key principle that drives the boost converter is the tendency of an inductor to resist changes in current. The operation of the boost converter has two distinct states.

The switch is closed. The current I_L(t) flows through L, R_L and back to the voltage source. In this mode the inductor stores energy.

The switch is opened. The path for the inductor current to flow is through the freewheeling diode D1, capacitor C and load R. The stored energy in the inductor collapses and the polarity across the inductor is reversed. The energy is transferred from the inductor to the capacitor and the capacitor gets charged to a voltage higher than the source voltage.

At the end of On-state, the increase of I_L is

$$\Delta I_{LON} = \frac{1}{L}\int_0^{DT} V_i dt = \frac{DT}{L} V_i \qquad (1)$$

D is the duty cycle which represents the fraction of the total time period T that the switch is kept on. So, D varies from 0 to 1. During the off period the change in I_L is:

$$V_i - V_o = L\frac{dI_L}{dt} \qquad (2)$$

So, the variation of I_L during the off period is

$$\Delta I_{LOFF} = \int_{DT}^{T} \frac{(V_i - V_o)dt}{L} = \frac{(V_i - V_o)(1-D)T}{L}$$

………. (3)

The inductor current has to be the same at the start and end of the cycle at steady state. So,

$$\Delta I_{LON} + \Delta I_{LOFF} = 0 \qquad (4)$$

Substituting the values of ΔI_{LON} and ΔI_{LOFF} we get

$$\frac{V_o}{V_i} = \frac{1}{1-D} \qquad (5)$$

which can be rearranged to find $D = 1 - \frac{V_i}{V_o}$

So, from this expression we can see that the output voltage is always higher than the input voltage.

3. PROPOSED CONTROL STRATEGY

The rectifier being the dominant mode of operation, $i_s$is defined with a direction, as shown in fig. an inductance L_s (which augments the internal inductance of the utility source) is included to reduce the ripple in i_s at a finite switching frequency. In the circuit of fig. V_d is established by charging the capacitor C_d through the switch mode converter. The value of V_d should be of a sufficiently large magnitude so that v_{conv1} at the ac side of the converter is produced by a PWM that corresponds to a PWM in a linear region. This is necessary to limit ripple in the input current i_s. Therefore, V_d must be greater than the peak of the input ac voltage, that is,

$$V_d > \sqrt{2}V_s$$

The control circuit to regulate V_d at its reference value V_d^* and to achieve a unity power factor of operation is shown in Fig 3. The amplified error between V_d and V_d^* is multiplied with the signal proportional to the input voltage v_s waveform to produce the reference current signal i_s^*. A current-mode control such as a tolerance band control or a fixed frequency control can be used to deliver i_{s1} equal to i_s^* and in phase with the line voltage v_s. the magnitude and direction of power flow are automatically controlled by regulating V_d at its desired value.

The control strategy proposed in this work is hysteresis control. In hysteresis current control the current is made to vary within a specific band, as shown in figure 2. Current–mode control can be achieved by sensing the current of the switching power devices or energy storage element and integrating it into main voltage control loop [6].Whenever the actual current reaches the upper limit of the band the positive switch pair of the converter must be off and whenever the current falls to the lower limit of the band, that switch pair must be ON. In this control scheme the switching frequency is not constant.

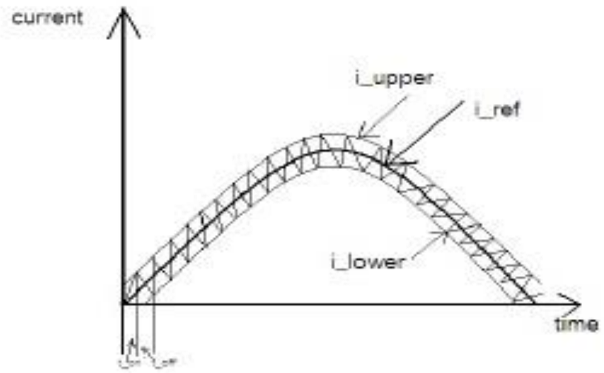

Figure 2: Input current waveform of PFC boost converter with hysteresis control

Implementation of PI controller

Output voltage from the boost converter is compared with reference voltage level before feeding in the controller circuit. Proper choice of the PI controller parameters are decided by the transfer function obtained from the dc to dc converter model.

From Figure1, when the switch is at position 1,

$$V_L(t) = V_g - i_L(t)R_L \tag{6}$$

Using small ripple approximation, i_L(t) replaced by its dc component I_L, hence

The block diagram of the implemented control strategy is shown in figure 3.

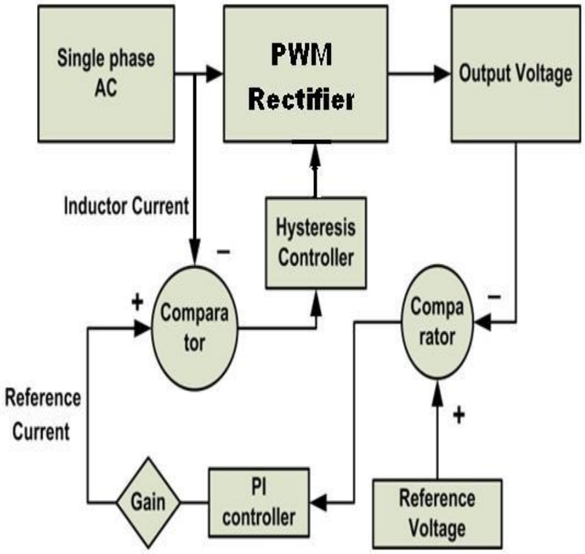

Figure 3: Block diagram of the proposed control strategy

$$V_L(t) = V_g - I_L R_L \tag{7}$$

Similarly,

$$i_c(t) = -\frac{V}{R} \tag{8}$$

During the first subinterval,the switches are in position 1 for time dTs and during the second subinterval, of length of switching duration is (1 – d)Ts.The duty cycle $d(t)$may now be a time-varying quantity.Using small signal approximation, the state equations of the circuit can be developed considering that natural frequency of the converter network is much smaller than the switching frequency.

Small signal control (d(s)) to output transfer function is described by [**7**],

$$G_d(s) = G_{d0}\frac{1-\frac{s}{\omega_z}}{1+\frac{s}{Q\omega_0}+(\frac{s}{\omega_0})^2}$$

(9)

With the condition Vg(s) =0

Line to output transfer function can be obtained with d(s) =0 as,

$$G_g(s) = G_{g0}\frac{1}{1+\frac{s}{Q\omega_0}+(\frac{s}{\omega_0})^2} \qquad (10)$$

Where,

$$G_{g0} = \frac{1}{1-D}, \omega_0 = \frac{1-D}{\sqrt{LC}}$$

$$G_{d0} = \frac{V}{1-D}, \qquad \omega_z = \frac{(1-D)^2 R}{L}, \qquad Q = (1-D)R\sqrt{LC}$$

Design of PI controller requires transient analysis and without detail analysis of each mode of switching cycle combined state equation model is formed for both ON and OFF state in the form of a set of two linear time-variant state equations ignoring ripple components. Linearization technique to optimize proportional and integral constant values using Ziegler-Nichols tuning method is applied.

4. SIMULATION

The simulation of both the normal boost converter and the pulse width modulated rectifier has been done in MATLAB and the results have been compared.

In figure 5 AC supply voltage is fed to the diode bridge rectifier. Diode bridge rectifier output is unregulated. So, for a desired DC voltage level rectifier output is fed to boost converter. Though, boost converter output is a regulated DC that meets the user requirement due to the switching operation of the boost converter the input current drawn from the AC utility becomes non-sinusoidal [8].

In figure 7 instead of the diode bridge rectifier, AC supply voltage is fed to the IGBT based bridge converter which is operated as a pulse width modulated rectifier. Rectifier output is at a boosted level which is greater than the peak amplitude of the supply voltage to maintain the operation of the converter always in under modulation zone. The DC output voltage is compared with a reference DC voltage and the comparator output is fed to the PI controller and PI controller output is multiplied with a gain to generate the current reference for hysteresis current controller. Inductor current is sensed and fed to the current controller. This current controller controls the states of the two diagonal switch pairs. Whenever the inductor current reaches the upper limit of the band a particular switch pair of the converter must be off and whenever the current falls to the lower limit of the band, that switch pair must be ON to maintain the proper direction of power flow. In this case input current drawn from the supply follow the AC supply voltage to emulate a resistive load.

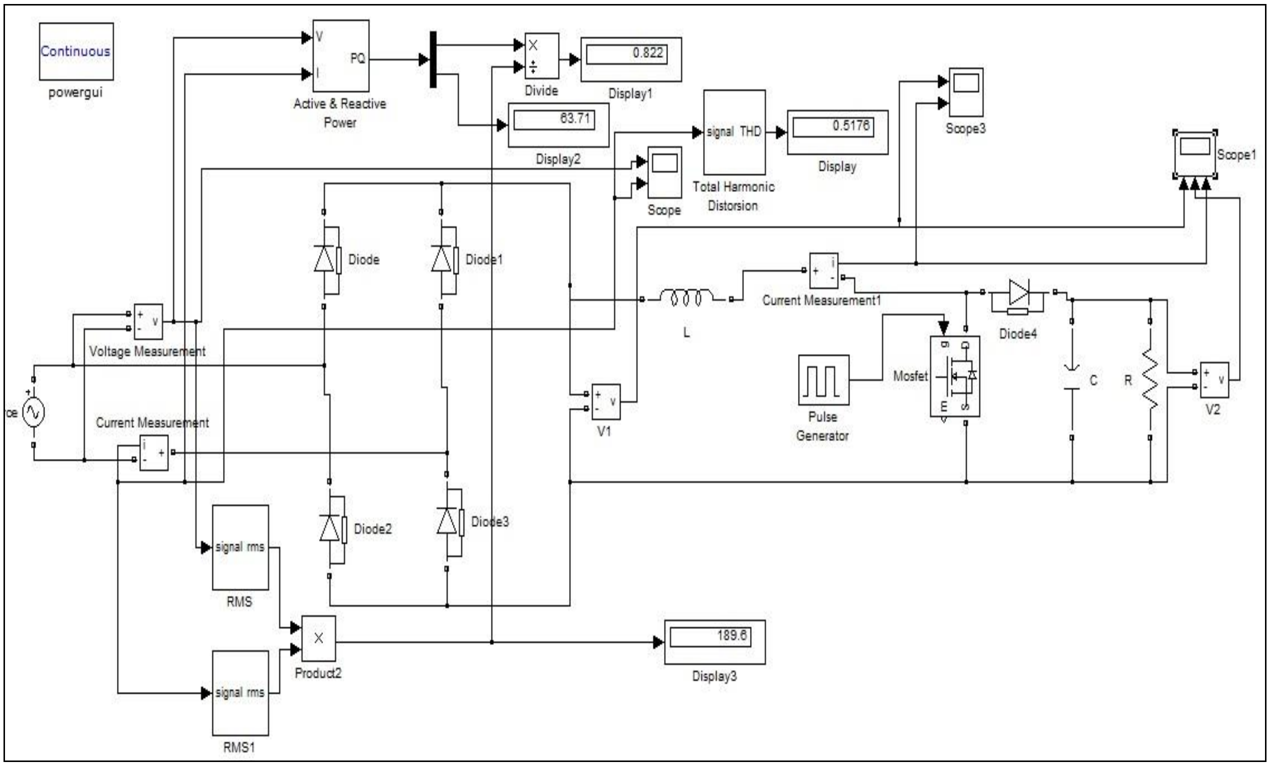

Figure 5: Circuit Diagram for the rectifier fed boost converter without power factor correction

Figure 5 shows the simulation diagram of the boost converter without power factor correction. The input AC voltage and current waveforms for a boost converter without power factor correction are shown in figure 6. It can clearly be seen that the current waveform is not following the voltage waveform and the power factor obtained from the simulation is 0.822 and the THD for input current is 51.76%. The current waveform is observed to be far from sinusoidal.

Figure 6: Input Voltage and input current waveforms of the rectifier fed boost converter without power factor correction

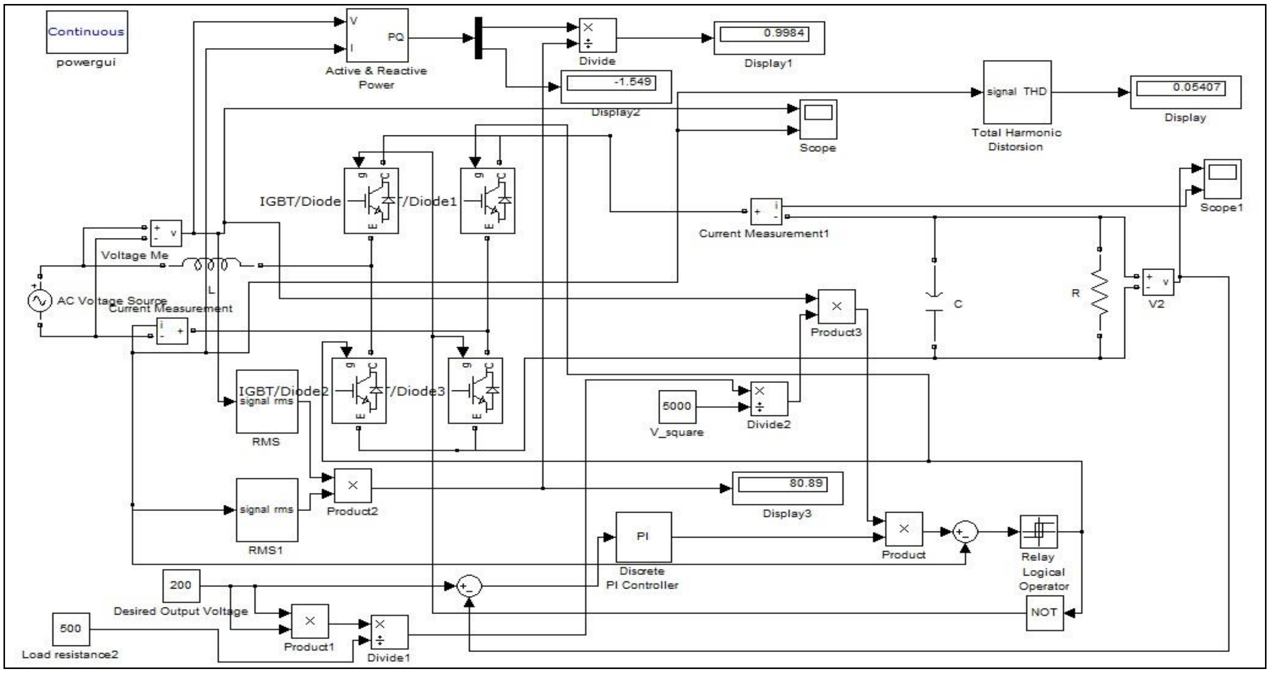

Figure 7: Circuit diagram for Pulse Width Modulated Rectifier operation

The Input AC voltage and current waveforms of the Pulse width Modulated Rectifier are shown in figure 8. The inductor current is following the input AC supply voltage. Hence, current drawn from supply is in same phase with the voltage waveform. Consequently, the power factor obtained is 0.999 and the THD is 3.19%. Both of these values show improved operation compared to a boost converter without power factor correction.

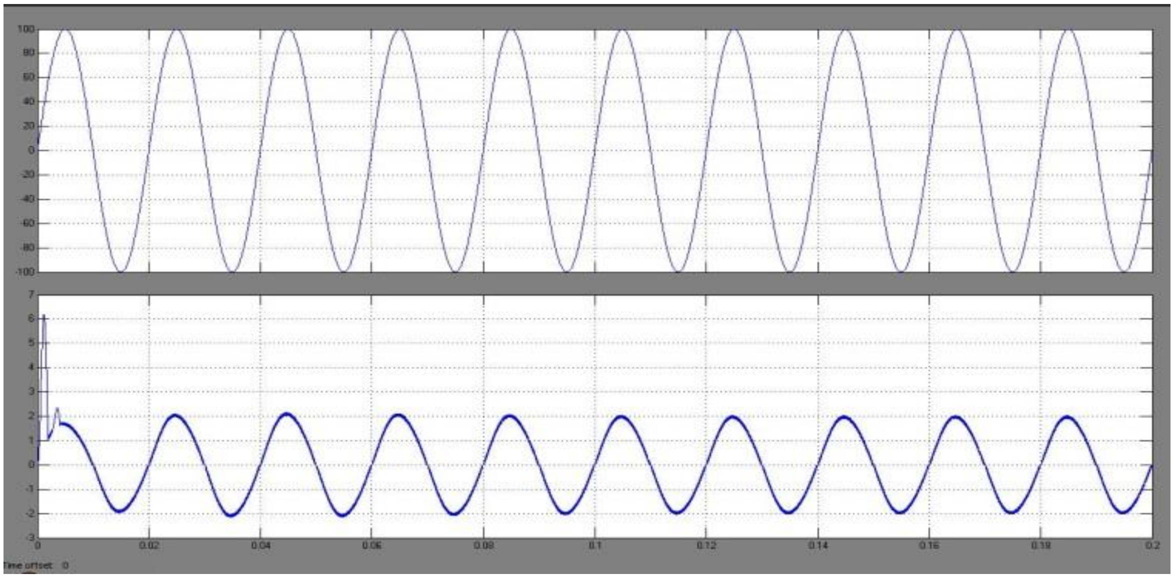

Figure 8: Supply voltage and input current waveforms of the Pulse width Modulated Rectifier

5. CONCLUSION

In this paper the principle of operation, design, off-line simulation without power factor correction and implementation of control strategy for a pulse width modulated rectifier has been discussed. Calculation of Power Factor has been done based on active and reactive power measurement with the inbuilt MATLAB-Simulink block. Total harmonic distortion has also been calculated using the inbuilt MATLAB-Simulink block.

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