Analysis, modeling and design of utility line current conditioner

by Kamalesh Chatterjee

A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in Electrical Engineering
Montana State University

Abstract:
Data processing devices such as a computer typically feature a diode bridge rectifier at the front end of the power circuit. The diode bridge rectifier, in conjunction with its capacitive filter is a nonlinear load. The device draws current with a high crest factor and rich in harmonics. These harmonic currents cause power quality problems. Such problems have prompted the development of unity power factor rectifiers, which use active current shaping techniques to draw sinusoidal current from the supply. However, such unity power factor rectifiers have not become popular in commercial data processing devices. Incorporating unity power factor rectifier in every device would lead to additional cost. Power quality problems become noticeable only in places where the loading by the data processing devices is substantial part of the total load. There is not enough incentive for the manufacturers to incorporate unity power factor rectifier with every device. Moreover, consumers usually place higher premium in processor speed, memory size, etc.

This thesis presents an alternative approach to solve power quality problems in such scenarios, only when the problems become severe and cause persistent malfunction. The proposed Utility Line Current Conditioner is based on a boost type ac to ac converter topology. The converter would act as an interface between the supply line and the non-linear load. The boost ac-ac converter is adapted to perform line current control in a single-phase line, loaded by a rectifier load. An inner average current control loop and an outer voltage control loop are used to perform the active wave shaping function.

This thesis presents detailed analysis of the basic converter topology, principle of operation, defining equations and design techniques. The dynamic models incorporate high frequency small signal model for the current control loop and a low frequency model for the voltage control loop. The modeling technique is versatile and could be directly applied to ac to dc unity power factor rectifiers as well. Dynamic performance characteristics of the overall system are discussed. Experimental results for a prototype 750 W converter are presented.

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APPROVAL

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Kamalesh Chatterjee

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

Giri Venkataramanan ________________ 14 APR 2000
Date

Approved for the Department of Electrical Engineering

John Hanton ________________ 4-14-00
Date

Approved for the College of Graduate Studies

Bruce McLeod ________________ 4-24-00
Date

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ABSTRACT

Data processing devices such as a computer typically feature a diode bridge rectifier at the front end of the power circuit. The diode bridge rectifier, in conjunction with its capacitive filter is a nonlinear load. The device draws current with a high crest factor and rich in harmonics. These harmonic currents cause power quality problems. Such problems have prompted the development of unity power factor rectifiers, which use active current shaping techniques to draw sinusoidal current from the supply. However, such unity power factor rectifiers have not become popular in commercial data processing devices. Incorporating unity power factor rectifier in every device would lead to additional cost. Power quality problems become noticeable only in places where the loading by the data processing devices is substantial part of the total load. There is not enough incentive for the manufacturers to incorporate unity power factor rectifier with every device. Moreover, consumers usually place higher premium in processor speed, memory size, etc.

This thesis presents an alternative approach to solve power quality problems in such scenarios, only when the problems become severe and cause persistent malfunction. The proposed Utility Line Current Conditioner is based on a boost type ac to ac converter topology. The converter would act as an interface between the supply line and the non-linear load. The boost ac-ac converter is adapted to perform line current control in a single-phase line, loaded by a rectifier load. An inner average current control loop and an outer voltage control loop are used to perform the active wave shaping function.

This thesis presents detailed analysis of the basic converter topology, principle of operation, defining equations and design techniques. The dynamic models incorporate high frequency small signal model for the current control loop and a low frequency model for the voltage control loop. The modeling technique is versatile and could be directly applied to ac to dc unity power factor rectifiers as well. Dynamic performance characteristics of the overall system are discussed. Experimental results for a prototype 750 W converter are presented.

CHAPTER – 1

INTRODUCTION

Electrical power distribution systems almost universally operate as sinusoidal ac voltage sources. The properties of the load determine the amplitude and the waveform of the current drawn from the voltage source. Most lighting loads, heating loads and motor loads are linear loads. When supplied by a sinusoidal voltage source, the current drawn is also sinusoidal. Most data processing devices require dc power source. The dc power is derived from the ac supply by using a rectifier, terminated by a filter. The rectifier-filter is a non linear load. Current drawn from the supply by such loads is not sinusoidal and is rich in harmonics.

Harmonic currents generate electromagnetic interference and affect other devices connected to the same supply line. They also result in degradation of the supply voltage waveform quality. Harmonic currents also result in an increase of rms value of the line current without contributing to the power transfer, resulting in under-utilization of utility installations and increased transmission loss. These degrading effects of harmonic currents become noticeable only when the non-linear loads are a large part of the total load connected to the utility line. With the widespread use of computers and other data processing devices, the contribution of non-linear loads is steadily increasing.

In order to mitigate such problems caused by poor quality of input currents, technology of ac to dc harmonic free rectifiers has become widely available during the last decade. They are often called unity power factor rectifiers or power factor controllers. However, such unity power factor rectifiers have not become popular in commercial data processing devices. Incorporating unity power factor rectifier in every device would lead to additional cost. The power quality problems become noticeable only in places where the loading by the data processing devices is substantial part of the total load. There is not enough incentive for the manufacturers to incorporate unity power factor rectifier with every device. Moreover, consumers usually place higher premium in processor speed, memory size, etc. and not on the supply current waveform quality.

This thesis presents an alternative approach to solve power quality problems in such scenarios. The solution needs to be applied only when the problem becomes severe and causes persistent malfunction of equipment or other equipment connected to the same line. The proposed solution being named as ac to ac Utility Line Current Conditioner (ULCC), is an interface between the utility line and a data processing device such as a computer. The device is used as an add on device only in places where power quality problems demand the additional investment.

ULCC draws sinusoidal current from the supply and regulates the voltage being supplied to the load. It is based on pulse width modulated power converters. They have been shown to be versatile to perform ac-ac power flow control in various applications [1,2]. The boost ac-ac converter is adapted to perform line current control in a single-phase line, loaded by a rectifier load. An inner average current control loop and an outer voltage control loop are used to perform the active wave shaping function.

Chapter 2 presents a detailed study of the rectifier type of load. Non linear loads such as rectifier loads are studied in detail and measures of harmonic distortion are reviewed. Typical measures of Total Harmonic Distortion (THD) of input current, harmonic currents and current crest factor are provided. Existing solutions to remove harmonic currents are discussed. The concept of the proposed ULCC is introduced.

Chapter 3 presents the power circuit topology of the ULCC. Equivalent circuits and defining equations for different switching intervals are presented. Simplified steady state analytical waveforms are given. During polarity reversal of input line voltage, the zero crossing spike of the input current has been identified as a bottleneck in control and a solution is proposed.

Chapter 4 presents design oriented analysis of the proposed ULCC. From a given set of converter specifications, it presents the equations to select the boost inductor and other circuit elements. Rms and average currents in different branches of the circuit are determined.

Classical circuit averaged model of the boost converter and the control transfer function presented in literature are used to model the average current control loop in Chapter 5. Loop stability and component selection is discussed using Bode plots. A simplified low frequency model of the current loop is introduced.

Chapter 6 presents the dynamic modeling and analysis of the complete system of utility line current conditioner supplying rectifier type of load. The voltage control scheme is discussed in detail. Models of different subsystems are shown separately. Voltage control loop stability is discussed using Bode plots. Closed loop output impedance and input susceptibility are discussed.

A 750 W prototype circuit built to verify the proposed concepts is presented in Chapter 7. Experimental waveforms of input current and other quantities are presented for different type of loads. THD of input current under different load conditions, individual harmonic percentages, line regulation, load regulation and efficiency of the converter are included.

CHAPTER – 2

POWER QUALITY PROBLEMS CAUSED BY RECTIFIER LOADS

Power factor for linear loads is reviewed. Operation of a rectifier type of load is studied in detail. Experimental results of input current waveform are presented. It is shown that input current waveform is rich in harmonics. Crest factor and Total Harmonic Distortion (THD) are defined as a measure of harmonic distortion. Input current harmonics are plotted.

Conventional solutions to improve power quality are discussed. These are: (a) passive filter at the input, (b) ferroresonant transformer, and (c) active power factor correction integrated to the input stage of the rectifier. As a solution to the power quality problems only where it is necessary, the utility line current conditioner is proposed.

2.1 Linear Loads and Power Factor

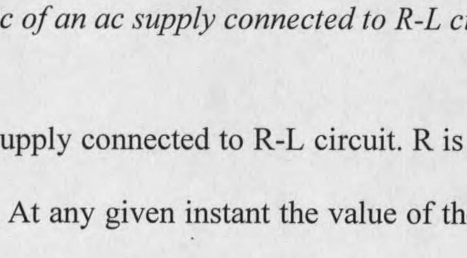

Fig. 2.1: Schematic of an ac supply connected to R-L circuit.

Fig. 2.1 presents an ac supply connected to R-L circuit. R is the resistance of the circuit and L is the inductance. At any given instant the value of the supply voltage is v(t) and the current drawn by the load is i(t). The defining equation of the above circuit is

$$L\frac{di(t)}{dt} + Ri(t) = v(t) \tag{2.1}$$

Eq. 2.1 represents a linear differential equation. So, the circuit is called a linear circuit and the R-L load is said to be a linear load. If the supply voltage is a sine wave of some given frequency the input current would also be a sine wave of the same frequency. Since the circuit is inductive the current drawn by the load i(t) would lag the input voltage by an angle (say) θ. Typical voltage and current waveforms are presented in Fig. 2.2. This may also be illustrated in the form of a phasor diagram as shown in Fig. 2.3.

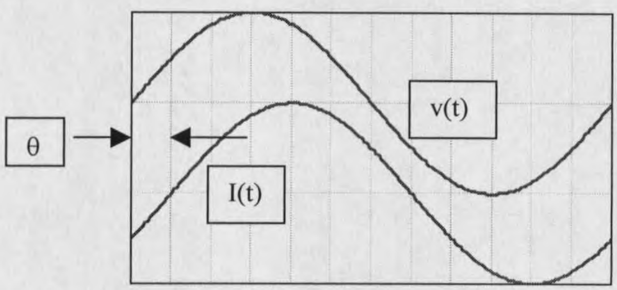

Fig. 2.2: Voltage and current waveforms of the R-L circuit.

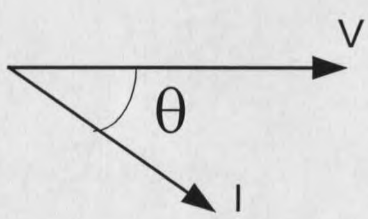

Fig. 2.3: Voltage and current phasor of the R-L circuit.

The average power P drawn by the load per cycle is given by

$$P = \frac{1}{2\pi} \int_0^{2\pi} v(t)\ i(t)\ d(\omega t) \tag{2.2}$$

Under such sinusoidal excitation and response conditions as with linear loads, it can be shown that the power P is related to the rms voltage, V_{rms} and the rms current, I_{rms}

$$P = V_{rms}\ I_{rms}\ \cos(\theta) \tag{2.3}$$

Power factor of the load may be defined as

$$\text{Power factor} = \frac{P}{V_{rms}\ I_{rms}} \tag{2.4}$$

Power factor becomes equal to $\cos(\theta)$ for such linear loads. However, when the load is such that it can not be expressed in terms of linear differential equations, then the load is called non linear. In such cases the current waveform will not be a pure sinusoidal waveform. Since the supply voltage is periodic the current would continue to be periodic and we can define the rms quantities of voltage and current. The definition of power factor as in Eq. 2.4 would be valid. But the power factor would not have a simple interpretation as in the case of linear loads. Rectifier loads are examples of such nonlinear loads and the following section presents a study of rectifier loads.

2.2 Rectifier Loads

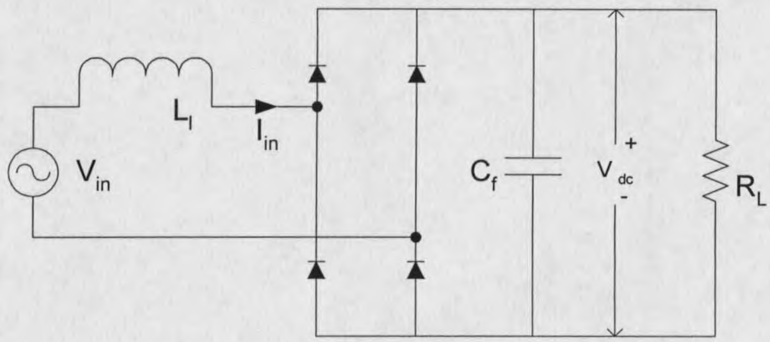

Fig. 2.4: Schematic of a rectifier load connected to ac supply

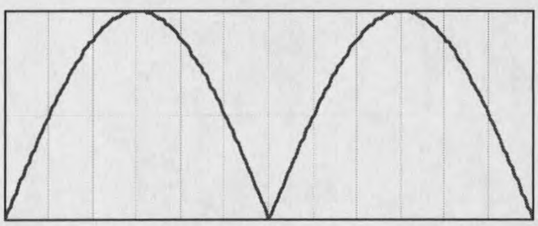

Fig. 2.5: Output voltage waveform of a bridge rectifier in absence of any other circuit at the output.

Fig. 2.4 shows an ac supply connected to a rectifier load. The four diodes connected in the above configuration form a full bridge rectifier. In absence of any other circuit at the output of the rectifier, the output voltage would look like a rectified sine wave as depicted in Fig. 2.5. This waveform, if decomposed into Fourier series, would have a dc component and higher harmonics. A filter is used to remove the harmonics. In Fig. 2.4,