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POWER FACTOR CORRECTION USING SINGLE STAGE DISCONTINUOUS CONDUCTION MODE BOOSTER RECTIFIER

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By

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POWER FACTOR CORRECTION USING SINGLE STAGE DISCONTINUOUS CONDUCTION MODE BOOSTER RECTIFIER

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Chairman: **Sinan Mahmoud Abdullah, Ph.D.**

Faculty **:** **Engineering**

A single stage three-phase power factor correction circuit using a boost input current shaper has been described in both simulation and experimental work. To reduce the cost and avoid complexity the boost dc-to-dc converter is operated in discontinuous conduction mode using only one active switch. A low cost harmonic injection method for single switch three-phase DCM boost rectifiers has been simulated and tested. In this method, a periodic voltage which is proportional to the inverted ac component of the rectified three-phase line-to-line input voltage is injected in the control circuit to vary the duty cycle of the rectifier switch within a line cycle, so that the fifth-order harmonics of the input current is reduced to meet THD<10% requirement.

The analysis of the injected signal and modified harmonic currents of the rectifier has been presented and verified on a laboratory prototype. Based on the equivalent multi-model an average small signal model of the boost power stage is developed and verified by simulation. The variations of the small signal model against load are demonstrated, and the compensator designed for constant switching frequency PWM is discussed. The simulated results show that at light load, the dominant pole of the control-to-output transfer function approaches the origin and causes more phase delay, complicating the control design circuit. To avoid the no load case and simplify the control design, a dummy is added.

The single stage three-phase boost power factor correction with improved input current distortion has been simulated using OrCad release 9.1 software. The results show there is an agreement between the simulation and experimental work.

Abstrak tesis yang dikemukakan kepada Senat Unjiversiti Putra Malaysia sebagai memenuhi keperluan unuk ijazah Master Sains.

PEMBETULAN FAKTOR KUASA MENGGUNAKAN PENERUS TOLAKAN PEMBALIKAN TAHAP TUNGGAL

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Litar pembetulan faktor kuasa tiga fasa tahap tunggal menggunakan pembentuk arus masukan tolakan telah dihasilkan dalam tesis ini. Bagi mengurangkan kos dan mengelakkan kerumitan, penukar dc ke dc tolakan dijalankan dalam mod pengaliran tidak berterusan dengan menggunakan hanya satu suis aktif. Kaedah suntikan harmonik berkos rendah bagi penerus tolakan suis tunggal 3 fasa DCM telah diterangkan. Dalam kaedah yang dicadangkan, suatu voltan berkala yang berkadaran kepada komponen ac songsangan bagi voltan-voltan talian ke talian 3 fasa terterus telah disuntik ke dalam litar kawalan untuk mengubah kitar tugas suis penerus dalam satu kitar talian, supaya harmonik tertib kelima bagi arus masukan dapat dikurangkan untuk memenuhi keperluanTHD<10%.

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Analisis isyarat suntikan dan arus harmonik terubahsuai bagi penerus telah dipersembahkan dan dibuktikan pada prototaip makmal. Model isyarat kecil purata berasaskan berbilang model setara dibangunkan dan dibuktikan melalui penyelakuan. Perubahan model isyarat kecil terhadap beban ditunjukkan, dan rekabentuk pemampas dibincangkan. Keputusan-keputusan menunjukkan pada beban ringan, kutub perusa bagi fungsi pemindah kawalan kepada keluaran mencapai asalan dan menyebabkan lebih lengah fasa, yang merumitkan litar rekabentuk kawalan.

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ABBREVIATIONS

Symbols

A	Ampere
AC	Alternating Current (A)
C	Capacitor (farad)
CCM	Continuous Conduction Mode
C_f	Capacitor Filter (farad)
D	Duty Cycle
D_o	Output diode
DC	Direct Current (A)
DCM	Discontinuous Conduction Mode
DPS	Distribution Power System
EMI	Electromagnetic Interference
F	Frequency (Hz)
f_s	Switching Frequency (Hz)
FSF	Frequency Scaling Factor
I	Current (A)
IEC	International Electrotechnical Commision
I_f	Fundamental Current (A)
IGBT	Insulated Gate Bipolar Transistor
KHz	kilo Hertz
L	Inductor (H)
L_f	Inductor Filter (H)
L_e	Equivalent Inductor (H)
M	Voltage Conversion Ratio
m	Modulation index
MOSFET	Metal Oxide Silicon Field Effect Transistor
PFC	Power Factor Correction
PWM	Pulse Width Modulation
P_o	Output Power (kW)
R	Resistance (ohm)
RMS	Root Mean Square
THD	Total Harmonic Distortion (%)
T_r	Line Period (second)
T_s	Switching Period (second)
UPS	uninterruptible Power Supply
V	Voltage (V)
V_o	Output Voltage (V)
V_m	Maximum Phase Voltage (V)
V_{in}	Input Voltage (V)
V_{ip}	Line-To-Line Peak Voltage (V)
V_{ref}	Reference Voltage (V)
Z	Impedance (ohm)
ZCS	Zero Current Switching
ZCT	Zero Current Transition
ZVT	Zero Voltage Transition

CHAPTER I

INTRODUCTION

With the development of advanced power semiconductor devices, more and more power electronic equipment such as the switched mode power supplies, uninterruptible power supplies (UPS), AC and DC motor drives, and AC-to-DC power converters are used as interface with the utility voltage source. Due to nonlinear behavior of power switched circuits, distorted currents are normally drawn from the line, resulting in low power factor and high total harmonics distortion (THD), which degrade power quality and is considered the main source of many system malfunctions. The non-sinusoidal shape of the input current drawn by the power switched circuit causes a number of problems in the sensitive electronic equipment and in the power distribution network. The distorted input current flowing through the system produces distorted voltages at the input of the common coupling. Thus, the increased harmonic currents result in increasing the volt-ampere ratings of the utility equipment, such as generators, transmission lines, and transformers.

Basically, there are two types of harmonic sources. The first being the well-known harmonic current source and thyristor converters are common sources of harmonic currents. The distortion of current waveform, i.e. the generation of harmonics, results from the switching operation. Because the harmonic current contents and characteristics are less dependent on the ac side, this type of harmonic source behaves like a current source. Therefore, they are called harmonic current source. The second type will be the harmonic voltage source, which is that of diode rectifiers

with smoothing DC capacitors at the output. Although the current is highly distorted, its harmonic amplitude is greatly affected by the impedance of the ac side, whereas the rectifier voltage is less dependent upon the AC impedance. Therefore, a diode rectifier behaves like a voltage source rather than a current source. Accordingly, the harmonic current originate from the rectifier voltage, and its contents are determined and dependent, upon the rectifier voltage and the ac impedance.

Harmonics problems are increasing concerns in the recent past and several technical guidelines regarding suppressions of system harmonic contents have been enacted. Conventional way of suppressing harmonic currents generated by the nonlinear loads is realized by installing a bank of passive tuned and one or two high pass power filters beside these loads. The effects of passive filters are very sensitive to temperature and parameter changes so this approach is only cost effective in high power applications. In low and medium power applications, active power factor correction (PFC) converters have been analyzed in recent years [1-4]. The power factor correction circuits are designed to achieve two distinct objectives: to convert the AC power drawn from the input line to a stable DC output power, and to shape the line currents to follow the waveform of the line voltage so that the system power quality can be maintained. The first objective is associated with balancing power between input and output. Incorporating one or more large storage elements into the circuit can solve the problem. The second objective is handled by using high frequency switching techniques to chop the input current and to move the harmonic components to high frequency range. The input current now is a sinusoidal waveform with the line frequency modulated by many high frequency components, which are easily to be filtered out.

To obtain a three-phase converter, we can use three single-phase converters with their outputs connected in parallel and with the input of each converter connected to one phase of the three-phase source (as shown in Figure 2.7). This approach, though possible, is not as desirable as the approach, which involves the use of a single converter to provide the desired three-phase AC-to-DC power conversion. Recent interest in the developments of three-phase converters capable of operation with unity power factor has led to a number of converters. Amongst three phase AC-to-DC PWM rectifiers, boost-type topologies are frequently used because of continuous input currents and high output voltages. Basically, two topologies are most popular: a six-switches full-bridge boost rectifier and a single switch boost rectifier. The first one uses six switches to achieve sinusoidal input current control and to share the output power as shown in Figure 2.3 (a), resulting in features, which include continuous input current, excellent power factor, and low switch current rating [5, 23, 24]. However, this circuit is very complicated in power stage and control, making it too expensive for medium power level (5kW-10kW) applications. The second one uses six diodes and one switch to control input currents and output power as depicted in Figure 2.8 [6-14]. It is simple in power stage and control; hence, inexpensive. However, it has the disadvantage substantially high peak current of the switching devices due to the DCM operation. For medium power applications such as telecommunication and battery chargers this topology is a very attractive solution.

Shaping input phase currents into discontinuous waveforms can lead to a power factor correction, in a single-switch rectifier. The average values of these waveforms in one switching cycle are proportional to the instantaneous values of their

corresponding phase voltages. As a result, the phase input currents are forced to track the input voltages, and almost unity power factor is obtained.

However, if the rectifier is implemented with the conventional low bandwidth output voltage feedback control at constant switching frequency, which keeps the duty cycle of the switch constant during a rectified line period, the rectifier input current exhibits a relatively large fifth-order harmonics, limiting the applications of the rectifier. Therefore, the single switch three-phase rectifier cannot be pushed to higher power levels because its input current harmonics cannot meet the THD requirements or IEC1000-3-2 (A) standards. Based on harmonic analysis, it is found that the current distortions are related to the rectifier voltage gain M [11], which is defined as:

$$M = V_o / V_{ip}$$

Where V_o is the rectifier output voltage and V_{ip} is the input line-to-line peak voltage. The higher the voltage conversion ratio (M) is, the lower the harmonics become, whereas a larger M derives a high output voltage. This is not a desirable solution because it will increase the voltage stress across the power devices of the rectifier itself, as well as across the devices of the converter that will be connected across the output of the discontinuous conduction mode (DCM) rectifier.

To alleviate this problem to some extent, different modulation techniques have been proposed to reduce the harmonic distortion of the input currents without increasing the bus voltage beyond practical levels. The first approach proposed to improve the harmonic distortion of the input currents involves operating the single-switch boost rectifier in the critical mode [10], [11]. To do this, the power switch must be turned

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on at the instant at which the boost diode current reaches zero. As a result, the switching frequency becomes variable, and the effective duty cycle modulation over the line cycle results in reduced THD of the input currents. The drawback of operating the DCM boost rectifier in the critical mode is the wide switching frequency variation that depends upon both load and input voltage limits.

Another approach to improve the THD of the input current involves controlling to a constant level the average current in the boost diode [16]. In order to keep the average current constant through the boost diode, the duty cycle must be modulated over the line cycle, resulting in an improved input current waveform. The drawback of this method is the extra current sensor required to control the average boost diode current.

A simple technique that can be used to reduce the harmonic distortion of the input current is the so-called harmonic injection method [17-21]. This method is illustrated in Figure 1.1, and the principles for achieving optimal harmonic injection are described by Sun [17] and Zhang [18]. This method utilizes voltage ripples of the rectifier output voltage and employs phase detecting and phase-locking loop circuits to properly synchronize the injected signal with the rectifier input currents. Figure 1.1 shows that a modulating signal is added to the control signal in order to modulate the duty cycle over the line period. By controlling the modulation index, it is possible to improve the THD of the input currents. When the DCM boost rectifier operates for example at 8kW of output power and with a constant duty cycle over the line period, the fifth-order harmonic is well above the limit specified by the IEC 1000-3-2 Class A standard. However, under the same operating conditions, the harmonic injection

method is able to lower the amplitude of the fifth-order harmonic to slightly below the limit, while still maintaining the same bus voltage. Therefore, the harmonic injection technique helps the boost rectifier to comply with the THD requirement, or the IEC standard at higher power levels. For example, for 800V bus voltage and constant duty cycle control, the maximum power that can be extracted from the DCM boost rectifier is 6kW at 220V line-to-neutral input voltage. At the same bus voltage and the same input phase voltages, the harmonic injection technique increases the power limit to more than 8kW, while still complying with the IEC standard or the THD requirement [21]. Therefore, the harmonic injection helps to increase the power level that can be extracted from the DCM boost rectifier without exceeding the limits of harmonic emissions established by the IEC 1000-3-2 Class A standard and improve the THD, while avoiding increased bus voltage beyond practical levels.

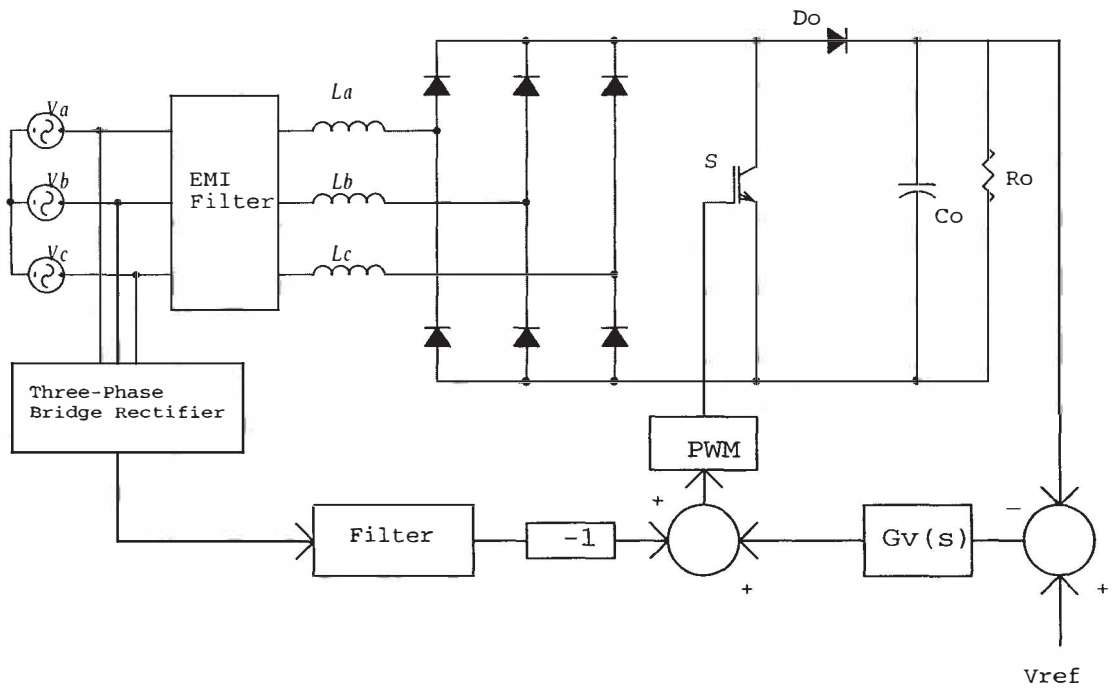

Figure 1.1 Three-phase DCM Boost Rectifier With Harmonic Injection Method.

1.1 Scope and Objectives of The Thesis

The scope of the research is to design and construct a low cost topology of a distribution power system front-end converter for high power applications. A single switch three-phase discontinuous conduction mode (DCM) boost rectifier, which has the advantages of simplicity and low cost, is used to achieve high power factor and low input current total harmonic distortion (THD). A harmonic injection method is proposed to meet the THD<10%.

The objectives of the project are as follows:

- Design, and construct of the single stage power factor correction boost rectifier.
- Implementation of a low cost harmonic injection method.
- Achieve low input current THD, high efficiency.
- Achieve an optimum modulation index value for the injected signal.

1.2 Thesis Structure

Chapter II reviews recent progress in topology, control, and design aspects in three-phase power factor correction (PFC) techniques. Different switching rectifier topologies are presented for various applications. Analysis and operation of a single switch three-phase DCM boost rectifier are presented.

In chapter III, a six-order harmonic-injected PWM concept is first implemented. Based on harmonic analysis, it is found that the dominant harmonic in the single

switch three-phase boost rectifier with constant switching frequency PWM is the fifth-order harmonic. Modulating the duty cycle with a sixth-order harmonic can reduce this harmonic. Even though a seventh-order harmonic is created at the same time, the total harmonic distortion can be improved. By properly injecting the sixth-order harmonic, the input current harmonics can be optimized to meet the THD requirement.

Secondly, a harmonic injection technique is developed. Based on the voltage compensator designed for constant switching frequency PWM, a synchronized harmonic generator is used to provide a sixth-order sinusoidal signal. A multiplier is used to modify the signal with modulation index. An adder is used to inject the signal into the voltage feedback loop.

Thirdly, the design of a single switch three-phase boost rectifier is considered. Based on the steady state analysis, the boost inductor design is addressed. An average small-signal model is developed and verified with simulation, and the variation of the model against load is investigated. Then, the small-signal model is used to design the voltage compensator for the single switch three-phase boost rectifier.

Chapter IV presents the results and discussion of the simulation model, and the experimental prototype. Chapter V presents the conclusions and future developments, recommended by the author.

CHAPTER II

LITERATURE REVIEW

2.1. Power Converter.

In general sense, a power converter can be defined as a device, which converts one form of energy into another on a continuous basis. An AC-to-DC power converter is widely used for obtaining an adjustable DC voltage from the utility three-phase main supply. The DC output may be used for DC power supply, DC motor drive, battery charger, or for generating the DC link of an inverter. A power converter circuit provides an interface between subsystem, which imposes relationship between the voltage and current waveforms and those of one port and those on the other. Power conversion circuit is commonly classified into different topologies such as AC-to-DC converters, DC-to-AC converters, or DC-to-DC converters.

The basic power converter of the same topology, which can convert AC-to-DC in which energy flows from the AC network to the DC network is known as a rectifier, whereas DC-to-AC converter whereby energy flows in the opposite direction, from a DC-to-AC network is known as an inverter.