Power Factor Improvement of Nonlinear Load Using Boost Converter with Average Current Control

SONARGAON UNIVERSITY (SU)

A Thesis

Submitted of the Faculty of Science and Engineering in Partial Fulfilment of the requirement for Degree of.B.Sc. In Electrical and Electronics Engineering.

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Declaration

It is declared hereby that this thesis paper or any part of it has not been submitted anywhere else for the award of any degree.

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Certification

This is to certify that this project entitled **"Power Factor Improvement of Nonlinear Load Using Boost Converter with Average Current Control"** is done by the following students under my direct supervision. This project work has been carried out by them in the laboratories of the Department of Electrical and Electronic Engineering under the Faculty of Engineering, Sonargaon University (SU) in partial fulfilment of the requirements for the degree of Bachelor of Science in Electrical and Electronic Engineering.

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Abstract

Now a days, development of industrial application is increases and electrical energy is always in great demand. To meet the demand, we have to improve the quality of power i.e. to improve the power factor of electrical load. Generally, nonlinear load is reason of poor power factor and that effects on conductor losses, voltage regulation, cost and rating of machine. Nonlinear loads are the main source of harmonics which increases Total Harmonic Distortion (THD) in distribution system and results in poor power factor. Conventionally, in full-bridge diode rectifier, large value capacitors are used to get purer DC output. But the use of large value Capacitor introduces current harmonics in supply side. In this type of nonlinear loads, boost converter with average current control strategy is useful. In this paper, simulation results of boost converter with average current control strategy, to reduce harmonics in non-linear load, are presented. The full bridge rectifier with large value capacitor is considered as non-linear load. Results shows that use of boost converter with average current control strategy improves supply side power factor considerably. Also, supply side harmonics are reduced.

Table of Contents

Chapter 1

Introduction

1.1 Introduction

Due to the growth of nonlinear loads, such as Power Electronics converters, SMPS (Switching Mode Power Supplies), Computer, serious power pollution is produced & reflected in to the distribution & Transmission networks. The low power factor and high pulsating current from the AC mains are the main disadvantages of the diode rectifier and phase-controlled rectifier. These circuits generate serious power pollution in the transmission or distribution system. The power pollutants such as reactive power and current harmonics results in line voltage distortion, heating of core of the transformer and electrical machines, and increasing losses in the transmission

and distribution line. A passive filter is often used to improve the power quality because of its simple circuit configuration. Bulk passive elements, fixed compensation characteristics, and series and parallel resonances are the main drawbacks of this scheme. Two approaches for current harmonics elimination and power factor improvement are power factor correctors, as shown in Fig. 1(a), and active power filters, as shown in Fig. 1(b). The former is used to produce a sinusoidal current on their AC side. The latter can compensate for current harmonics generated by nonlinear loads in the power system. Several circuit topologies and control strategies of power factor correctors [1–4] and active power filters [5–8] have been proposed to perform current or voltage harmonics reduction and increase the power factor. In order to meet the requirements in the proposed standards such as IEC 61000-3-2 and IEEE Std 519 on the quality of the input current that can be drawn by low-power equipment, a PFC circuit is typically added as a front end-stage. The boost PFC circuit operating in continuous conduction mode (CCM) is the propulsor are choice for medium and high power (400 W to a few kilowatts) applications. This is because the continuous nature of the boost converter's input current results in low conducted electromagnetic interference (EMI) compared to other active PFC topologies such as buck-boost and buck converters. The conventional power quality compensation approach is given in Fig. 1(c). The active rectifier of the AC/DC/AC converter is used to regulate the DC bus voltage for motor drive. The nonlinear load produces a pulsating current with large current harmonics. An active power filter is employed to compensate the reactive power and current harmonics drawn from the nonlinear load and the AC/DC/AC converter. This strategy needs an additional inverter and measurement of both the nonlinear load currents and the compensated currents.

In electrical engineering, the power factor (PF) of an AC electrical power system is defined as the ratio of working power (measured in kilowatts, kW) absorbed by the load to the apparent power (measured in kilovolt amperes, kVA) flowing through the circuit. Power factor is a dimensionless number in the closed interval of −1 to 1. The "ideal" power factor is one (also referred to as "unity"). This is when there is no reactive power through the circuit, and hence apparent power (kVA) is equal to real power (kW). A load with a power factor of 1 is the most efficient loading of the supply.

That said this is not realistic, and the power factor will in practice be less than 1. Various power factor correction techniques are used to help increase the power factor to this ideal state. To help explain this better, let’s take a step back and talk about what power is. Power is the capacity to do work. In the electrical domain, electrical power is the amount of electrical energy that can be transferred to some other form (heat, light, etc) per unit of time.

Mathematically power factor is the product of voltage drop across the element and current flowing through it. Considering first the DC circuits, having only DC voltage sources, the inductors and capacitors behave like short circuits and open circuits respectively in steady-state. Hence the entire circuit behaves like a resistive circuit and the entire electrical power is dissipated in the form of heat. Here the voltage and current are in the same phase and the total electrical power is given by:

Electrical power = Voltage across the element × Current through the element.

Its unit is Watt = Joule/sec.

Now coming to the AC circuit, here both inductor another d capacitor over a certain amount of impedance given by:

$$X_L = 2\pi \text{ L and } X_C$$

The inductor stores electrical energy in the form of magnetic energy and the capacitor stores electrical energy in the form of electrostatic energy. Neither of them dissipates it. Further, there is a phase shift between voltage and current. Hence when we consider the entire circuit consisting of a resistor, inductor, and capacitor, there exists some phase difference between the source voltage and current. The cosine of this phase difference is called the electrical power factor. This factor ($-1 < \cos\varphi < 1$) represents the fraction of the total power that is used to do the useful work. The other fraction of electrical power is stored in the form of magnetic energy or electrostatic energy in the inductor and capacitor respectively.

The total power, in this case, is: This is called apparent power and its unit is VA (Volt-Amp) and denoted by ‘S’. A fraction of this total electrical power that does our useful work is called active power. We denote it as ‘P’. P = Active power = Total electrical power. cosφ and its unit is watt. The other fraction of power is called reactive power. Reactive power does no useful work, but it is required for the active work to be done. We denote it with ‘Q’ and mathematically is given by: Q = Reactive power = Total electrical power. sinφ and its unit is VAR (Volt-Amp Reactive). This reactive power oscillates between source and load. To help understand this better all this power is represented in the form of a triangle.

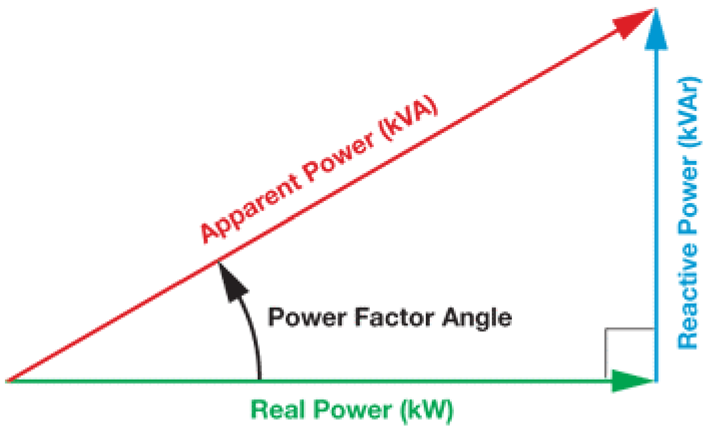

Fig.1.1: Power factor correction

Mathematically, S2 = P2 + Q2, and the electrical power factor is active power / apparent power. Power Factor Improvement The term power factor comes into the picture in AC circuits only. Mathematically it is the cosine of the phase difference between the source voltage and current. It refers to the fraction of total power (apparent power) which utilised to do he useful work called active power.

$$\text{Cos } \boldsymbol{\phi} = \frac{\text{Active power}}{\text{Apparent power}}$$

Need for Power Factor Improvement Real power is given by P = VIcosφ. The electrical current is inversely proportional to cosφ for transferring a given amount of power at a certain voltage. Hence higher the pf lower will be the current flowing. A small current flow requires a less cross-sectional area of conductors, and thus it saves conductors and money. From the above relation, we see having a poor power factor increases the current flowing in a conductor, and thus copper loss increases. A large voltage drop occurs in the alternator, electrical transformer, transmission, and distribution lines – which gives very poor voltage regulation. The KVA rating of machines is also reduced by having a higher power factor, as per the formula:

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$$KVA = \frac{\text{KW}}{\text{Cos } \phi}$$

Hence, the size and cost of the machine are also reduced. This is why the electrical power factor should be maintained close to unity – it is significantly cheaper. Methods of Power Factor Improvement There are three main ways to improve power factor: Capacitor Banks Synchronous Condensers Phase Advancers Capacitor Banks Improving power factor means reducing the phase difference between voltage and current. Since the majority of loads are of inductive nature, they require some amount of reactive power for them to function. A capacitor or bank of capacitors installed parallel to the load provides this reactive power. They act as a source of local reactive power, and thus less reactive power flows through the line. Capacitor banks reduce the phase difference between the voltage and current. Synchronous Condensers Synchronous condensers are 3 phase synchronous motors with no load attached to their shaft. The synchronous motor has the characteristics of operating under any power factor leading, lagging, or unity depending upon the excitation. For inductive loads, a synchronous condenser is connected towards the load side and is overexcited. Synchronous condensers make it behave like a capacitor. It draws the lagging current from the supply or supplies the reactive power. Phase Advancers This is an AC exciter mainly used to improve the PF of an induction motor. They are mounted on the shaft of the motor and are connected to the rotor circuit of the motor. It improves the power factor by providing the exciting ampere turns to produce the required flux at the given slip frequency. Further, if ampere-turns increase, it can be made to operate at the leading power factor. Power Factor Calculation In power factor calculation, we measure the source voltage and current drawn using a voltmeter and ammeter respectively. A wattmeter is used to get the active power. Now, we know P = VIcosφ watt.

$$\textit{From this } \cos\boldsymbol{\phi} = \frac{P}{VI} \text{ or } \frac{Wattmeter\ reading}{Voltmeter\ reading \times Ammeter\ reading}$$

Hence, we can get the electrical power factor. Now we can calculate the reactive power Q = VI sinφ VAR This reactive power can now be supplied from the capacitor installed in parallel with the load in local. The reactive power of a capacitor can be calculated using the following formula:

$$Q = \frac{V^2}{X_C} \Rightarrow \text{C} = \frac{\text{Q}}{2\pi V^2 f\, V^2}\ farnd$$

1.2 Motivation

The advent of power electronics motivated by the evolution of the power semiconductor technology plays a key role in distinct applications that are essential to modern society. In this context, the intensive use of nonlinear loads in residential, commercial, and industrial facilities has contributed to the significant increase of harmonic pollution of the power grid. Therefore, minimizing the harmonic content associated to the existing voltage and current waveforms in accordance with international standards is essential to preserve power quality [1]. Passive solutions such as tuned low-pass filters (LPFs) are simple and robust choices for harmonic mitigation purposes, although performance can be compromised if the load scenario comes to vary. Besides, increased size, weight, and volume regarding the filter elements and resonance risk are significant drawbacks in this case [2]. On the other hand, active approaches associated with the use power electronic converters have proven to be quite effective in distinct practical solution, although cost and complexity must be carefully taken into account. With the introduction of the instantaneous power theory in [3], active power filters (APFs) became an interesting alternative to LPFs, as it is possible to perform harmonic compensation at both distribution and consumer levels, as well as to control the reactive power flow and ensure voltage stability in transmission levels. However, such equipment presents high cost due the use of high-power semiconductors. APFs can also be combined with LPFs in terms of hybrid filters, resulting in improved performance and cost-effective solutions [4]. With the widespread use of electronic loads, it is often necessary to obtain dc voltages from the ac utility grid employing power converters. Diode bridge rectifiers can be used for this purpose, although large output filter capacitors are employed to minimize the existing ac ripple at twice the grid frequency. Unfortunately, this practice leads to distorted currents drawn from the source, as the input power factor is poor as a consequence of low-frequency harmonics [5]. Power factor correction (PFC) is a topic that has been intensively explored over the last decades. Considering that the harmonic emissions of facilities and individual loads must be limited in order to avoid distorting the voltage at the point of common coupling (PCC), standards IEEE 519, IEC 61000-3-2, and IEC 61000-3-4 have been proposed in order to maintain power quality indices to acceptable levels [6-8]. Aiming to keep the input current nearly sinusoidal while emulating the behaviour of a resistive load, a dc-dc converter supplied by the ac grid and a diode bridge called front-end stage is typically employed in many practical applications. Thus, it is possible to impose a sinusoidal shape to the inductor current and obtain a regulated dc output voltage using a dedicated control system. The classical buck, boost, buck-boost, Ćuk, SEPIC (single-ended primary inductance converter), and Zeta topologies can be promptly adopted as front-end stages [9]. Specifically, in the case of the single-phase ac-dc buck converter, the input current becomes null when the instantaneous ac input voltage is lower than the output voltage, thus introducing some discontinuities in the resulting input current waveform, as poor performance results [10]. Step up/step down converters can also be employed in PFC, although some important aspects must be taken into account. Firstly, the maximum voltage stresses on the semiconductors Experimental Evaluation of Active Power Factor Correction Techniques in A Single-Phase AC-DC Boost Converter T are equal to the sum of the peak input voltage and the output voltage, as MOSFETs (metal oxide semiconductor field effect transistors) with high drain-to-source on resistance may be required, with consequent increase of conduction losses [11].

Secondly, the input current in the buck-boost and Zeta converters is pulsating even when operation occurs in continuous conduction mode (CCM), as input low-pass filters may be necessary [12]. Thirdly, the Cuk, SEPIC, and Zeta converters are fourth-order systems, as the control system design may not be a trivial task [9]. Considering the behaviour of the inductor current in the aforementioned topologies, three operating modes exist: - discontinuous conduction mode (DCM): in this case, the inductor current remains null during part of the switching period. The inductor size can be significantly reduced due to the high inductor current ripple. The control system is simplified due to the lack of a proper loop responsible for imposing a reference waveform to the input current, which naturally follows the shape of the sinusoidal input voltage. However, the current stresses on the semiconductors are drastically increased due to high current peaks, thus leading to increased conduction losses and reduced overall efficiency. Besides, high electromagnetic interference (EMI) levels will exist, thus demanding the use of additional input filters; - critical conduction mode (CRM): the inductor current becomes null only at the beginning and the end of the switching cycle. The inductor size is also reduced similarly to DCM. The control system employs a simple zero-crossing detection circuit so that the input current is maintained nearly sinusoidal. However, low efficiency will exist due to the high inductor current ripple, thus limiting this approach to low power levels. - CCM: the inductor current does not become null over the entire switching cycle. Since a large inductor is typically used to keep the inductor current ripple as low as possible according to proper design constraints, conduction losses and EMI levels are consequently minimized if compared with operation in DCM and CRM. The control system becomes more complex, as it must provide a reference signal to the input current so that it remains nearly sinusoidal and in phase with the input voltage. It is then reasonable to state that the boost converter is by far the most popular topology in general-purpose PFC applications, from which numerous single-phase and three-phase high power factor rectifiers have been derived so far [11]. The continuous nature of the input current ensures reduced EMI levels without the use of additional filters. Literature presents some works dedicated to summarize and determine the most relevant characteristics of power converters in PFC applications. An extensive review is developed in [13], where the so-called improved power quality converters (IPQCs) are described in terms of existing configurations, control strategies, design aspects, selection, and choice of components for a given application. The topologies are presented considering the power flow characteristic and classified as buck, boost, or buck-boost types. Apparently, this work is one of the most comprehensive studies involving PFC converters, although not all ac-dc boost PFC converters are addressed. Besides, neither simulation nor experimental results are presented. A similar but more specific study focused on boost-based converters operating in CCM can be found in [14], where overall key aspects such as component count, stresses on semiconductors, and particular characteristics regarding the main existing topologies are investigated, even though quantitative results are not provided as well. A study specifically focused on boost-type topologies is shown in [15], where the operation in CCM and DCM is considered in order to develop a modelling technique that allows designers to choose both the mode of operation and the type of converter. A technical report focused on the use of a specific integrated circuit (IC) is presented in [16], where the authors claim that boost converters operating at rated powers higher than 300 W should operate in CCM, while recommending operation in CRM for at power levels lower than 200 W. On the other hand, the choice of a given mode for the range between 200 W and 300 W depends on the designer. Some aspects on the design procedures of the classical, interleaved, and bridgeless boost converters are presented. The performances of such rectifiers using IC NPC1605 are also analysed experimentally in terms of the input current total harmonic distortion (THD), input power factor, and efficiency over a wide range of the line voltage. However, a comparison of distinct control techniques specifically considering the operation in CCM is not performed. In this context, distinct approaches have been proposed so far in the literature, which can be implemented with either analogy integrated circuits (ICs) or microprocessors. For instance, the use of sliding mode control (SMC) is proposed in [17] for PFC applications, with improved system stability and robustness when disturbances come to occur. Even though its implementation is simpler if compared with other nonlinear controllers, the use of digital circuits is mandatory in this case, being this solution is typically more complex than IC-based analogy ones. The use of an adaptive notch filter based on the second-order generalized integrator (SOGI) in the voltage control loop of PFC rectifiers is also suggested in [18] to improve the converter performance if compared with the conventional techniques, also leading to increased complexity. A unified model g approach for several control techniques based on the Fourier analysis of the input current is derived in [19], as it is possible to compare the transient response of three controllers. However, it is worth mentioning that the works devilled in [17-19] only present simulation results, as further investigation at the experimental level is well justified. Considering the lack of works specifically focused on the performance of PFC converters operating in CCM and employing distinct control techniques, this work is dedicated to the performance analysis of a single-phase boost converter. The harmonic content of the input current and the input power factor is verified in terms of two values of the RMS input voltage. Besides, the dynamic behaviour of the converter when submitted to load steps is analysed experimentally. For this purpose, three commercial analogy ICs are chosen for the implementation of a 250-W laboratory prototype. Even though the analysis is developed for a specific operating point, it is expected that the main conclusions regarding the obtained results can be extended to another converter

1.3 Aim and scope of the thesis

The History of Bangladesh's Power Sector is one of persistent hard work and success. We have been growing up technologically and also producing Power. The achievements have been driven by a single-minded dedication, Public-privet sector collaboration the in-power sector. In Bangladesh, Natural gas is the leading and the economical source of energy. It is an important source of energy that accounts for 75 percent of the commercial energy of the country which is likely to be depleted by the year 2020. In 1990-1991 the installed capacity stood at 2350MW.In 2016- 2017 the installed capacity has increased to over 13500MW. Today the installed capacity has increased to over 16193MW. In working to achieve its electrification goals, Bangladesh is adopting flexible power solutions alongside traditional grid connectivity with 10% of off-grid power. For this reason, the electrification rate has increased –In1990-The rate was 8.5%, In 2009-The rate was 47%, Today-The rate is around 90%-Privet-Public Partnership (Government contribution 56% & Privet contribution 46% of financial support) actually helped to raise the electrification rate.

In our country, the present Generation is around 10000MW though our capacity is still 13500MW. But day by day power demand is rapidly expanding for increasing urbanization and the massive amount of industrialization.

Table: 1.1. Present Installed Generation capacity on (MW as of 18 Aug 2021)

Installed Generation Capacity (MW)	
Public Sector	Installed Generation Capacity (MW)
BPDB	6013
APSCL	1444
EGCB	957
NWPGCL	1401
B-R POWER GEN	149
RPCL	182
Subtotal	10146(46%)
Private Sector	
IPPs	8042
SIPPs (BPDB)	99
SIPPs (REB)	251
15 YR. Rental	169
3/5 YR. Rental	920
Power Import	1160 (5%)
Subtotal	9491(43%)
Total	17,043 *

*Including Captive Power & Off Grid Renewable Energy Total Installed Capacity (22,031 + 2,800 + 404) = 25,235MW

Table: 1.2. Transmission Consumer of Bangladesh

MAXIMUM DEMAND SERVED FAR	**13,792 MW**	**27-04-2021**
TRANSMISSION LINES (400 kV)	861 Ckt. K.M	FY-2020
TRANSMISSION LINES (230 kV)	3658Ckt. K.M	FY-2020
TRANSMISSION LINES (132 kV)	7677Ckt. K.M	FY-2020
GRID SUB-STATION CAPACITY (400/230 kV)	3770 MVA	FY-2020
GRID SUB-STATION CAPACITY (400/132 kV)	1300 MVA	FY- 2020
GRID SUB-STATION CAPACITY (230/132 kV)	13,075 MVA	FY- 2020
GRID SUB-STATION CAPACITY (132/33 kV)	25,624 MVA	FY- 2020
DISTRIBUTION LINES (33 KV & BELOW) (only BPDB)	33,640 K.M	FY-2020
CONSUMER NUMBER (BPDB)	32,36,802	FY-2020

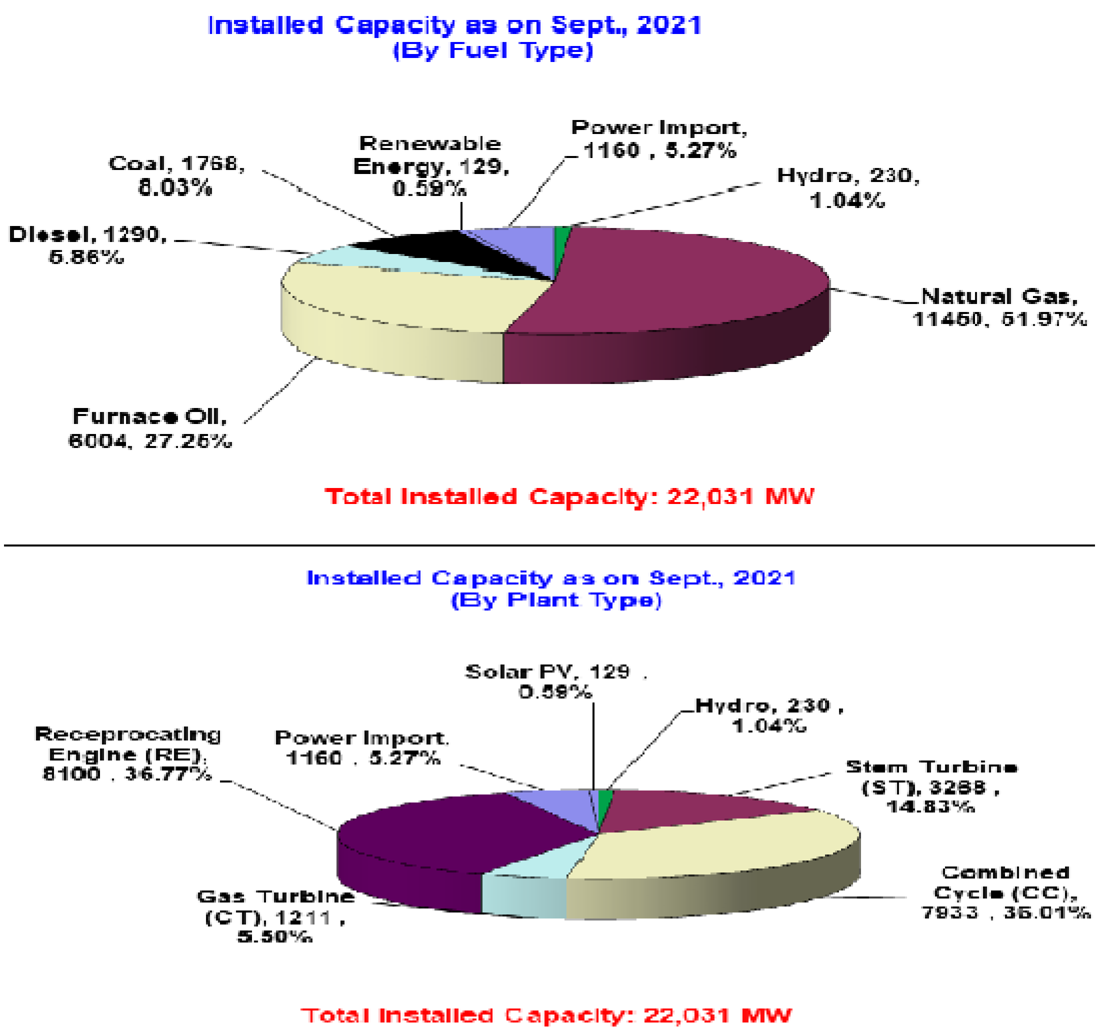


Fig.1.2. Primary Grid System of Bangladesh

It is the second division of the power system. From generating station to distribution, the whole system is known as a transmission system. The generating station is normally situated far away from the locality. The transmission system helps to transmit this energy to the consumers. This system can be AC or DC form. The alternating current (AC) form is used now for its popularity and conveniences, especially HVDC (High voltage direct current) graining its possibility day by day. An important part of this system is transformers, which are helping to increase voltage levels to make long-distance transmission easier. Nowadays, 3-phase, 3-wire AC system is universally accepted and economically beneficial for generation and transmission.

Advantages of high transmission voltage

- Reduces volume of conductor material: Volume of the conductor material= $3P\rho l$ 2 $WV2cos2\phi$

- Increases transmission efficiency: Transmission efficiency= $[1 - \sqrt{3}\ J\rho l\ Vcos\phi]$ approx.

- Decreases percentage line drop: %age line drop= $J\rho l\ V \times 100$

Performance of Power System In old days, small power stations were built to supply electricity for lighting and heating purpose because of there was a little demand of electricity. By dint of modern civilization, use of electrical energy is increased comprehensively. Performance of power system is achieved by increasing the power generation and uninterrupted power supply while minimizing the losses and economically beneficial. So, while studying the performance of power system, it is desirable to determine its voltage regulation and efficiency. 1.8.1 Voltage Regulation In electrical engineering, particularly in electrical engineering, voltage regulation describes the ability of a system to provide near-constant voltage over a wide range of load conditions. The voltage regulation is the difference between the secondary no load voltage of the transformer and the full load voltage with respect to its full load voltage. Basically, every transformer has a voltage drop due to its impedance (resistive, inductive properties). Therefore, at different voltages and load conditions, this internal voltage drop across the transformer windings will vary and affect the final secondary output voltage. Suppose, an electrical power transformer is open-circuited, means load is not connected with secondary terminals. In this situation, the secondary terminal voltage of the transformer will be

its secondary induced e.m.f $E2$. When the full load is connected to the secondary terminals of the transformer, the rated current $I2$ flows through the secondary circuit and a voltage drop occurs. In this situation, the primary winding will also draw the equivalent full load current from the source. The voltage drop in the secondary is $I2\ Z2$ where, $Z2$ is the secondary impedance of the transformer. Now if at thinning condition, any one measures the voltage between secondary terminals, he or she will get voltage $V2$ across load terminals which is obviously less than no load secondary voltage $E2$ and this is because of $I2\ Z2$ voltage drop in the transformer.

Expression of Voltage Regulation of Transformer, represented in percentage,

is $Voltage\ regulation$ (%) = $E2 - V2\ V2 \times 100\%$ 1.8.2

In general term, efficiency means the ration between output energy and input energy and expressed as percentage. It is a very important term of any system because we can get the overall overview of any system by calculating its efficiency. In the power system, various types of loses count from generating station to the consumers. Our main focus is to decrease the losses and increase the efficiency. The power obtained at the receiving end of a transmission system is generally lower than the final sending power due to losses. That's why saving energy is more efficient than generating energy. The relationship between the final reception power and the final sending power of receiving's system is known as the energy efficiency of the system.

$$\%\text{age efficiency}, \eta = \frac{\text{sending end power}}{\text{recieving end power}} \times 100$$

$$= \frac{V_R I_R cos\theta_R}{V_S I_S cos\theta_S} \times 100$$

Where,

VR = $Recieving\ end\ voltage$

Vs = $Sending\ end\ voltage$

IR = $Recieving\ end\ current$

Is = $Sending\ end\ current$

$cos\theta R$ = $Recieving\ end\ power\ factor$

$cos\theta s$ = $Sending\ end\ power\ facto$

Chapter 2

Background Study

Nowadays, the use of electronic appliances is incrincreasingich requires a DC power supply. So that interfacing between AC supply and DC load is an essential part of circuits. The uncontrolled rectifier is a basic converter used to convert AC to DC supply. This converter is an inexpensive and effective as well. To obtain pure DC output from converter, capacitor is connected at the end of diode bridge as a filter. It reduces ripples in rectified output, however the rectifier creates one problem that it draws pulsating current from AC supply at peak time of line voltage [1]. Because of such nonlinear load, power factor decreases and harmonic distortion arises in input current. Supply-side current harmonics effects on line voltage, core heating of transformer and electrical machines. Also, it increases losses in distribution and transmission network [2]. To achieve improved power factor and reduce harmonics in current, there are several topologies and control strategies. Power factor correction shapes the input current of the power supply to be in synchronization with the mains voltage, in order to maximize the active power drawn from the mains.

merit to understand the quality of load with respect to the source. According to the definition of power factor, input-side power factor of rectifier is the ratio of active power to apparent power of input side of the rectifier.

2.1. Power Factor Improvement

Most of the electric energy used in world is generated, distributed and utilised in sinusoidal form. Sources of

this type is frequently called alternating current (ac) source. The figure-1 shows the typical voltage and

current vectors in an ac circuit. The angle θ between voltage and current is called power factor angle and the

cosine of this angle is called the power factor. The cosine θ depicts that component of current which is in phase with the voltage.

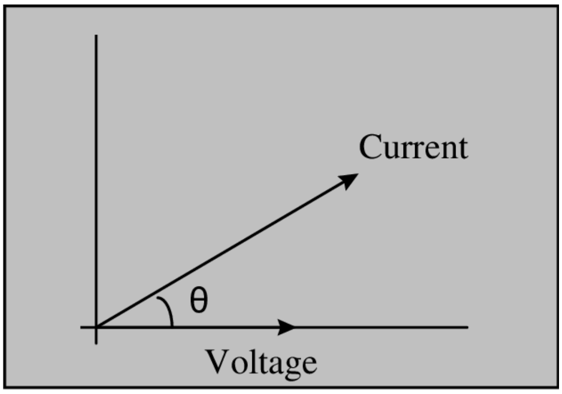


Fig. 2.1-Vector-diagram-for-ac-voltage-current

The resistive loads in an electric circuit have a power factor of unity, whereas for a purely inductive load the power factor is zero. However, in practice, the actual loads in an electro behaviort are partly resistive and partly

inductive. This combination of inductive and resistive loads makes the power factor of the plant to a value

between zero and one. Lower the power factor, more are the losses, or in other words for an efficient operation of the plant, the power factor should be close to unity.

To improve the power factor, shunt capacitors are used. The value of capacitance required is a function of the type of electrical load in the plant. In view of the capital cost involved for the installation of capacitors, a reasonably high-power factor of the order of 0.8 to 0.9 is considered while designing the capacitors for power factor control.

2.2. Working Principle

Reactive power can be described as a by-product of an electrical energy system. It circulates through the generators, transmission lines, and transformers, but it is not delivered anywhere. It must be recognized and accounted for, however, since it plays an important role in the stability, cost of power, and voltage control of the system. Reactive power is measured much like active power, that is, through a vector product of current and voltage. Reactive power does not dissipate any energy other than the losses it creates through current circulation in the equipment and the transmission lines. Every kind of load except a perfect heating load generates reactive power. Reactive power can be leading (current vector leading the voltage vector) or it can be lagging (current vector lagging the voltage vector). Since reactive power can be leading or lagging, the total balance must be zero. The leading power is because of capacitance in the power circuit. Similarly, the lagging power is because of inductance in the power circuit. Motors, transformers in the industries are large sources of lagging (inductive) power. In order to control excessive lagging (inductive) power, capacitors may have to be connected to the power circuit. Since capacitors are the source of leading power, they compensate for the lagging power created by common equipment in the industries like motors and transformers. Capacitors should be located as near to the load as possible. However, this is not practically possible because of the cost, availability of space, and other environmental conditions. Capacitors can be located as in:

i. Individual Compensation

In such installation's capacitors are installed parallel to the equipment and are controlled by a common switch. This is generally suited for high output induction motors, furnaces, transformers.

ii. Group compensation

This method resorts to compensation of the group of loads fed from the same bus bar. This is particularly useful when small loads are connected to a common bus bar.

iii. Central Compensation

This can apply to HT and/or LT capacitors. The output of capacitors has to be divided in a number of steps with auto / manual control depending upon the initial power factor of the load and its variation.

2.3. Installation Guidelines

capacitors for overhead distribution systems can be pole-mounted in banks of 300 to 3600 KVAR at nearly any primary voltage up to 34.5 kV phase to phase. Pad-mounted capacitors are used for underground distribution systems in the same range of sizes and voltage ratings.

Common Capacitors Connections

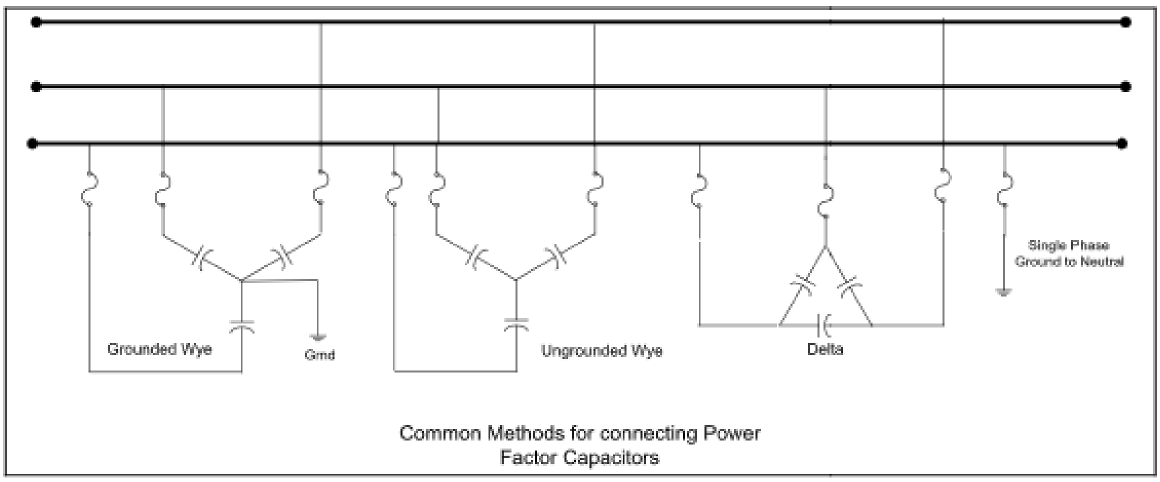


Fig. 2.2. common Methods for connection Power Factor Capacitors

The above figure-04 shows four of the most common capacitors connections: 3-phase grounded wye, 3-phase ungrounded wye, 3-phase delta, and single phase. Grounded and ungrounded wye connections are usually made on primary circuits whereas delta and single-phase connections are usually made on low voltage circuits. The majority of the power capacitor requirement installed on primary distribution feeders has been connected to grounded wye. There are a number of advantages froths type of connection. With the grounded wye connection, switch tanks and frames are at ground potential. This provides increased personnel safety. Grounded wye connections provide faster operation of the series fuse in case of capacitor failure. Grounded capacitors can bypass some line surge to the ground and therefore exhibit a certain degree of self-protection from transient voltages and lightning surges. The grounded wye connections also provide a low-impedance path for harmonics. If the capacitors are electrically connected ungrounded wye, the maximum full current would be limited to three times the line current. If too much fault current is available, generally above 5000 A, the use of current-limiting fuses must be considered.

2.4. Estimation of KVAR required to improve power factor:

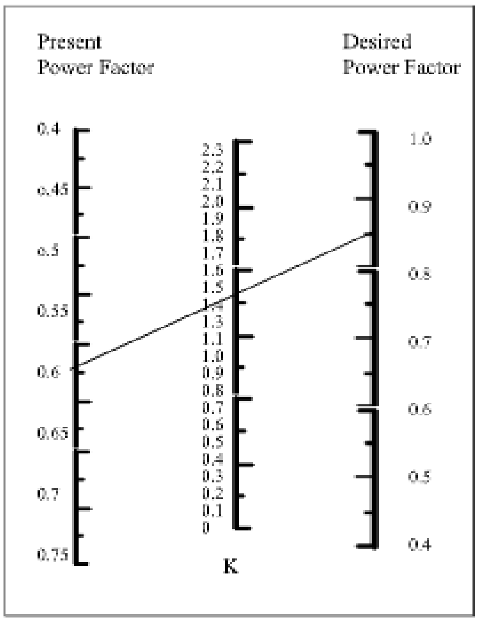
A quick estimate of capacitive KVAR required for improvement of power factor at a given load can be made from the Nomogram shown in the figure. However, in most cases, the capacitor bank rating has to be carefully selected after due consideration of the rated voltage of the system, system over voltages harmonics in the system, rating of the series reactor, etc. A Nomogram (fig-3) is used for calculating the necessary capacitor rating QC

(KVAR) required to improve the power factor of a load P (KW):

$$QC = K \times P$$

For example: for a load P of 1500 KW, to improve the power factor from 0.6 to 0.85, the factor K from Nomogram is 1.4.

$$QC = 1.4 \times 1500 = 2100 \text{ KVAR}$$



Nomogram

Fig.2.3 Nomogram

Case Study:

Here in this case study, we are considering an industrial installation where there is one HT switchgear with two incomers and four LT switchgear with two incomers. We have calculated the resistance of power cables and busbars which is required to calculate power loss in the existing power factor. We have taken desired power factor as 0.95 and again calculated the losses at the new power factor. The difference between the two is 4.5 kilowatt per hour. In one year, this gain will be 39420 kwhr. If we take Energy cost as Rs 6.5per kwhr, there will be saving of gain will be Rs 2.56 lakhs. In addition, there will be a considerable reduction in heating in this switchgear which will improve the reliability of the switchgear and the power system. The total active power required to improve the power factor to 0.95 is 967 KVAR.

	Parameters with Existing Power Factor						
	P.F.	kW	kVAR	kVA	I(LV)	I(HV)(line)	I(HV)(phase)
PMCC2							
IC1	0.784	342	270	437	607.975	38.22871	22.07200196
IC2	0.765	345	342	445	619.105	38.92855	22.47606607
PMCC3							
IC1	0.762	365	307	475	660.842	41.55294	23.99130648
IC2	0.852	367	223	432	601.018	37.79131	21.81946189
PMCC4							
IC1	0.909	98	45	109	151.646	9.535307	5.505373487
IC2	0.86	88	52	101	140.516	8.835468	5.101309378
PMCC5							
5E	0.874	930	518	1065	1481.68	93.16607	53.79103453
PMCC8							
IC1	0.8	40	30	49	68.1711	4.286514	2.474892668
IC2	0.67	37	39	55	76.5185	4.811393	2.77794075
Main IC1	0.686	1385	1476	2020	176.709	35.34187	20.40523751
Main IC2	0.85	4785	2975	5620	491.637	98.32738	56.77100733

Parameters with Desired Power Factor								
	P.F.	kW	kVAR	kVA	I(LV)	I(HV)	I(HV)(phase)	Required Reactive Power
PMCC2								
IC1	0.95	342	112.409964	360	500.8487	31.49276	18.1828849	157.590036
IC2	0.95	345	113.3960163	363.1578947	505.2421	31.76901	18.3423839	228.6039837
PMCC3								
IC1	0.95	365	119.9696984	384.2105263	534.5315	33.61069	19.4057105	187.0303016
IC2	0.95	367	120.6270666	386.3157895	537.4604	33.79486	19.5120432	102.3729334
PMCC4								
IC1	0.95	98	32.21104231	103.1578947	143.518	9.02424	5.21030035	12.78895769
IC2	0.95	88	28.92420126	92.63157895	128.8733	8.103399	4.67863705	23.07579874
PMCC5								
5E	0.95	930	305.6762178	978.9473684	1361.957	85.6382	49.444687	212.3237822
PMCC8								
IC1	0.95	40	13.14736421	42.10526316	58.57879	3.683363	2.12665321	16.85263579
IC2	0.95	37	12.16131189	38.94736842	54.18538	3.407111	1.96715422	26.83868811

	Calculation for resistance										
	CABLE HV(185sq mm Al.)			BUSBAR LV(Al. ρ=.03816(Ω sq.mm)/m at 20degC				TRANSFORMER RESISTANCE		NET RESISTANCE	
	R(ohm/km)at 70degC	CABLE LENGTH(meter)	RESISTANCE (ohm)	THICKNESS(mm)	WIDTH(mm)	LENGTH(meter)	RESISTANCE(ohm)	HV(ohm)	LV(ohm)	HV(ohm)	LV(ohm)
PMCC2											
IC1	0.198	70	0.01386	10	150	7	0.00017808	0.257	0.000365	0.27086	0.00054308
IC2	0.198	75	0.01485	10	150	7	0.00017808	0.257	0.000365	0.27185	0.00054308
PMCC3											
IC1	0.198	65	0.01287	10	150	8	0.00020352	0.257	0.000365	0.26987	0.00056852
IC2	0.198	70	0.01386	10	150	8	0.00020352	0.257	0.000365	0.27086	0.00056852
PMCC4											
IC1	0.198	65	0.01287	10	150	7	0.00017808	0.257	0.000365	0.26987	0.00054308
IC2	0.198	60	0.01188	10	150	7	0.00017808	0.257	0.000365	0.26888	0.00054308
PMCC5											
5E	0.198	70	0.01386	10	150	7	0.00017808	0.257	0.000365	0.27086	0.00054308
PMCC8											
IC1	0.198	280	0.05544	10	150	6	0.00015264	0.257	0.000365	0.31244	0.00051764
IC2	0.198	275	0.05445	10	150	6	0.00015264	0.257	0.000365	0.31145	0.00051764
	CABLE HV(630sq mm Al.)										
HT											
IC1	0.0582	1500	0.0873	10	160	7	0.00016695	0.318	0.003505	0.4053	0.00367195
IC2	0.0582	1500	0.0873	10	160	7	0.00016695	0.318	0.003505	0.4053	0.00367195

Chart-3: Calculation of resistance

				Loss Calculation before pf correction					
	NET RESISTANCE			CURRENT(before)			LOSSES(before)		Total Losses(before)
	HVt/f(ohm)	HVline(ohm)	LV(ohm)	HVline(amp)	HVphase(amp)	LV(amp)	HV(watts)	LV(watts)	(watts)
PMCC2									
IC1	0.257	0.01386	0.00054	38.2287074	22.07200196	607.97462	436.377	602.2211	1038.598122
IC2	0.257	0.01485	0.00054	38.92854643	22.47606607	619.10459	457.0013	624.4722	1081.473499
PMCC3								0	
IC1	0.257	0.01287	0.00057	41.55294282	23.99130648	660.84198	510.4402	744.8387	1255.278904
IC2	0.257	0.01386	0.00057	37.791308	21.81946189	601.01839	426.4484	616.0877	1042.536087
PMCC4								0	
IC1	0.257	0.01287	0.00054	9.535306879	5.505373487	151.64584	26.87885	37.46676	64.34560213
IC2	0.257	0.01188	0.00054	8.835467842	5.101309378	140.51587	22.84626	32.16887	55.01513542
PMCC5								0	
5E	0.257	0.01386	0.00054	93.1660718	53.79103453	1481.6773	2591.78	3576.781	6168.561154
PMCC8								0	
IC1	0.257	0.05544	0.00052	4.286514102	2.474892668	68.171068	7.778445	7.216877	14.99532124
IC2	0.257	0.05445	0.00052	4.81139338	2.77794075	76.518545	9.731244	9.092483	18.82372692
HT								0	
IC1	0.318	0.0873	0.00367	35.34187137	20.40523751	176.70936	724.3462	343.9831	1068.329265
IC2	0.318	0.0873	0.00367	98.3273847	56.77100733	491.63692	5606.813	2662.607	8269.419376
						Total Losses =			**20077.37619**

Chart-4: Loss calculation at existing power factor

			Loss Calculation after pf correction						
	NET RESISTANCE			CURRENT(after)			LOSSES(after)		Total Losses(after)
	HVt/f(ohm)	HVline(ohm)	LV(ohm)	HVline(amp)	HVphase(amp)	LV(amp)	HV(watts)	LV(watts)	(watts)
PMCC2									
IC1	0.257	0.01386	0.000543	31.4927567	18.18288491	500.8487	296.1447	408.6938	704.8385687
IC2	0.257	0.01485	0.000543	31.7690089	18.3423839	505.2421	304.3606	415.8954	720.2559244
PMCC3								0	
IC1	0.257	0.01287	0.000569	33.6106906	19.4057105	534.5315	333.9613	487.3192	821.2805341
IC2	0.257	0.01386	0.000569	33.7948588	19.51204316	537.4604	341.0232	492.6743	833.6975418
PMCC4								0	
IC1	0.257	0.01287	0.000543	9.02424021	5.210300355	143.518	24.07479	33.55815	57.63294526
IC2	0.257	0.01188	0.000543	8.10339938	4.678637053	128.8733	19.21722	27.05897	46.27618754
PMCC5								0	
5E	0.257	0.01386	0.000543	85.638198	49.44468704	1361.957	2189.867	3022.121	5211.987262
PMCC8								0	
IC1	0.257	0.05544	0.000518	3.68336335	2.126653206	58.57879	5.743457	5.328806	11.07226282
IC2	0.257	0.05445	0.000518	3.4071111	1.967154216	54.18538	4.879769	4.559459	9.439227911
HT								0	
IC1	0.318	0.0873	0.003672	25.5072912	14.72707345	127.5365	377.3078	179.1788	556.4866145
IC2	0.318	0.0873	0.003672	88.1244682	50.88017795	440.6223	4503.603	2138.706	6642.308767
						Total Losses			**15615.27584**

Chart-5: Loss calculation after improved power factor.

It is evident from the above charts that power factor of PMCC-8, I/C-2 and main I/C-2 are very low in comparison to other switchgears. Immediate steps are to be taken to improve the power factor of both the switchgears. KVAR required to design the capacitor bank can be taken from chart-2 or using Nomogram as discussed in the chapter-4 of this paper.

Now a days, development of industrial application is increases and electrical energy is always in great demand. To meet the demand, we have to improve the quality of power i.e. to improve the power factor of electrical load. Generally, nonlinear load is reason of poor power factor and that effects on conductor losses, voltage regulation, cost and rating of machine. Nonlinear loads are the main source of harmonics which increases Total Harmonic Distortion (THD) in distribution system and results in poor power factor. Conventionally, in full bridge diode rectifier, large value capacitors are used to get purer DC output. But the use of large value Capacitor introduces current harmonics in supply side. In this type of nonlinear loads, boost converter with average current control strategy is useful. In this paper, simulation results of boost converter with average current control strategy, to reduce harmonics in non-linear load, are presented. The full bridge rectifier with large value capacitor is considered as non-linear load. Results shows that use of boost converter wit average current control strategy improves supply side power factor considerably. Also, harmonics supply side harmonics are reduced.

Power Factor and why its important Power factor is a measure of how effectively you are using electricity. Various types of power are at work to provide us with electrical energy. Here is what each one is doing. Working Power – the “true” or “real” power used in all electrical appliances to perform the work of heating, lighting, motion, etc. We express this as kW or kilowatts. Common types of resistive loads are electric heating and lighting. An inductive load, like a motor, compressor or ballast, also requires Reactive Power to generate and sustain a magnetic field in order to operate. We call this non-working power kVAR’s, or kilovolt-amperes-reactive. Every home and business have both resistive and inductive loads. The ratio between these two types of loads becomes important as you add more inductive equipment. Working power and reactive power make up Apparent Power, which is called kVA, kilovolt-amperes. We determine apparent power using the formula, kVA2 = kV*A. Going one step further, Power Factor (PF) is the ratio of working power to apparent power, or the formula PF = kW / kVA. A high PF benefits both the customer and utility, while a low PF indicates poor utilization of electrical power. Here is an example. A steel stamping operation runs at 100 kW (Working Power) and the Apparent Power meter records 125 kVA. To find the PF, divide 100 kW by 125 kVA to yield a PF of 80%. This means that only 80% of the incoming current does useful work and 20% is wasted through heating up the conductors. Because Edisto Electric must supply both the kW and kVA needs of all customers, the higher the PF is, the more efficient our distribution system becomes. Improving the PF can maximize current-carrying capacity, improve voltage to equipment, reduce power losses, and lower electric bills. The simplest way to improve power factor is to add PF correction capacitors to the electrical system. PF correction capacitors act as reactive current generators. They help offset the non-working power used by inductive loads, thereby improving the power factor. The interaction between PF capacitors and specialized equipment, such as variable speed drives, requires a well-designed system.PF correction capacitors can switch on every day when the inductive equipment starts. Switching a capacitor on can produce a very brief “over-voltage” condition. If a customer has problems with variable speed drives turning themselves off due to “over-voltage” at roughly the same time every day, investigate the switching control sequence. If a customer complains about fuses blowing on some but not all, of their capacitors, check for harmonic,

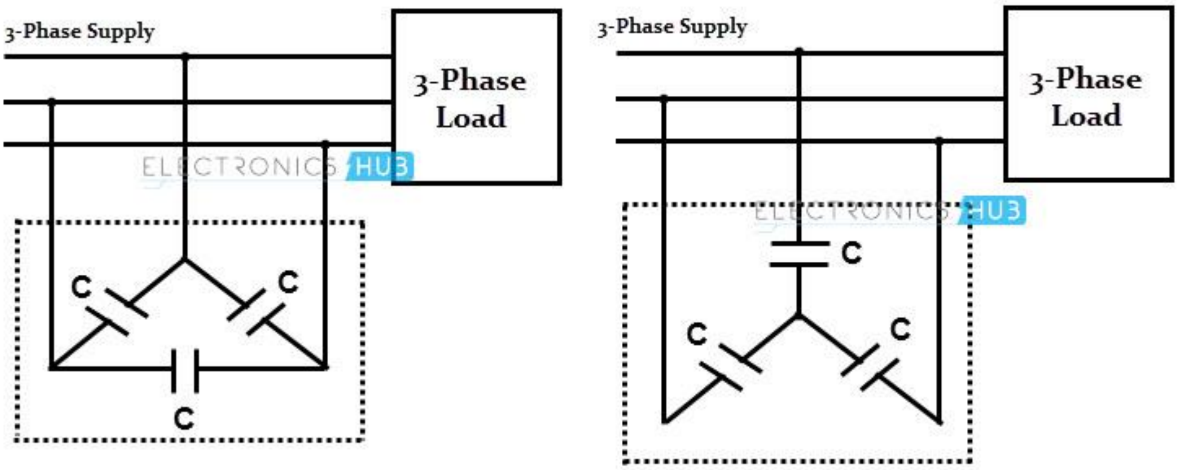


Fig. 2.4. Capacitor bank installed in parallel with 3- phase load delta and star connected

- Power Factor
- Active, Reactive, Apparent and Complex Power. Simple explanation with formulas.
- Causes of low Power Factor
- Disadvantages of Low Power Factor
- Advantages of Power factor improvement and Correction
- How to Calculate the Suitable Capacitor Size in Farads & KVAR for Power factor Improvement (Easiest way ever)

- How to Convert Capacitor Farads into KVAR and Vice Versa (For Power factor improvement)

Methods for Power Factor Improvement

The following devices and equipment are used for Power Factor Improvement.

1. Static Capacitor
2. Synchronous Condenser
3. Phase Advancer

2.5. Static Capacitor

We know that most of the industries and power system loads are inductive that take lagging current which decreases the system power factor (See Disadvantages of Low Power factor) . For Power factor improvement purposes, Static capacitors are connected in parallel with those devices which work on low power factors.

These static capacitors provide a leading current that neutralizes (totally or approximately) the lagging inductive component of load current (i.e. leading component neutralizes or eliminates the lagging component of load current) thus power factor of the load circuit is improved. These capacitors are installed in Vicinity of large inductive load e.g Induction motors and transformers etc, an improve the load circuit power factor to improve the system or devises efficiency. Suppose, here is a single-assaultive load which is taking a lagging current (I), and the load power factor is Cosθ as shown in fig-1. In fig-2, a Capacitor (C) has been connected in parallel with the load. Now a current (Ic) is flowing through Capacitor which leads 90° from the supply voltage (Note that Capacitor provides leading Current i.e., In a pure purely active circuit, the Current leading 90° from the supply Voltage, in other words, Voltage are 90° lagging from Current). The load current is (I). The Vectors combination of (I) and (Ic) is (I') which is lagging from voltage at θ2 as shown in fig 06

Fig.2.5. Static Capacitor

It can be seen from fig 3 that the angle of θ2 < θ1 i.e. angle of θ2 is less than from angle of θ2. Therefore, Cosθ2 is less than from Cosθ1 (Cosθ2> Cosθ1). Hence the load power factor is improved by a capacitor. Also note that after the power factor improvement, the circuit current would be less than from low power factor circuit current. Also, before and after the power factor improvement, the active component of current would be the same in that circuit because the capacitor eliminates only the reactive component of current. Also, the Active power (in Watts) would be the same after and before power factor improvement.

Advantages:

- Capacitor bank offers several advantages over other methods of power factor improvement.
- Losses are low in static capacitors
- There is no moving part, therefore need low maintenance
- It can work in normal conditions (i.e. ordinary atmospheric conditions)
- Do not require a foundation for installation
- They are lightweight so it is can be easy to installed

Disadvantages:

- The age of static capacitor bank is less (8 – 10 years)
- With changing load, we have to ON or OFF the capacitor bank, which causes switching surges on the system
- If the rated voltage increases, then it causes damage it
- Once the capacitors spoiled, then repairing is costly

2. Synchronous Condenser

When a Synchronous motor operates at No-Load and over-excited then it's called asynchronous Condenser. Whenever a Synchronous motor is over-excited when it provides a leading current and works like a capacitor. When a synchronous condenser is connected across supply voltage (in parallel) then it draws leading current and partially eliminates the re-active component and this way, power factor is improved. Generally, a synchronous condenser is used to improve the power factor in large industries.

Advantages:

- Long life (almost 25 years)
- High Reliability
- Step-less adjustment of power factor.
- No generation of harmonics of maintenance
- The faults can be removed easily
- It's not affected by harmonics.
- Require Low maintenance (only periodic bearing greasing is necessary)

Disadvantages:

- It is expensive (maintenance cost is also high) and therefore mostly used by large power users.
- An auxiliary device has to be used for this operation because synchronous motor has no self-starting torque
- It produces noise

3. Phase Advancer

Phase advancer is a simple AC exciter which is connected on the main shaft of the motor and operates with the motor's rotor circuit for power factor improvement. Phase advancer is used to improve the power factor of induction motor in industries. As the stator windings of induction motor takes lagging current 90° out of phase with Voltage, therefore the power factor of the induction motor is low. If the exciting ampere-turns are excited by external AC source, then there would be no effect of exciting current on stator windings. Therefore, the power factor of the induction motor will be improved. This process is done by Phase advancer.

Advantages:

- Lagging KVAR (Reactive component of Power or reactive power) drawn by the motor is sufficiently reduced because the exciting ampere-turns are supplied at slip frequency (fs).
- The phase advancer can be easily used where the use of synchronous motors is Unacceptable

Disadvantage:

- Using Phase advancer is not economical for motors below 200 H.P. (about 150kW)

Power Factor Improvement in single-phase and three-phase star & delta connections

Power factor improvement in the three-phase system by connecting a capacitor bank in

(1). Delta connection

(2). Star Connection) Mathematically,

$$I \propto V \quad \text{or} \quad V/I = \text{Constant} = R$$

Where "R" is a Constant of proportionality and is called Resistance of the Conductor.

Current = Potential Difference / Resistance

$$I = V / R$$

Good to know

For calculation and simplifying of electric circuits (measuring of Current, Voltage and Resistance), we can use Ohm's Law in the following three forms

$I = V/R$

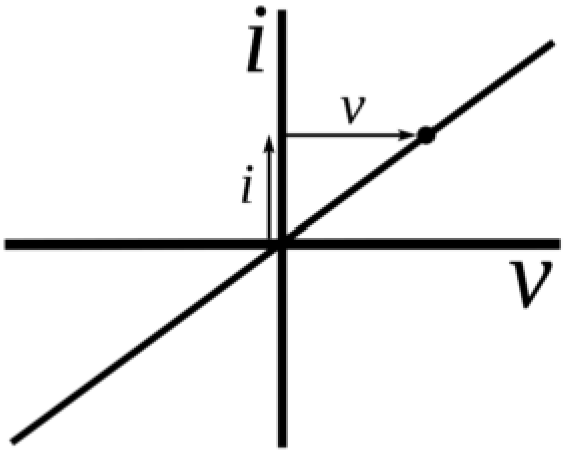


Fig.2.6. Ohm's Law

R= V/I or
V = IR
Better explanation of Ohm's Law

2.6. Nonlinear Load Using

Passive Filters

Passive filters connected between the non-linear load and the series active power filter play an important role in the compensation of the load current harmonics. With the connection of the passive filters, the series active power filter operates as a harmonic isolator. The harmonic isolation feature reduces the need for precise tuning of the passive filters allows their design to be insensitive to the system impedance and eliminates the possibility of filter overloading due to supply voltage harmonics. The passive filter can be tuned to the dominant load harmonics and can be designed to correct the load-displacement power factor. However, for industrial loads connected to the stiff supply, it is difficult to design passive filters that can absorb a significant part of the load harmonic current, and therefore its effectiveness deteriorates. Especially compensation of diode rectifier type of loads, where a small kVA passive filter is required, it is difficult to achieve the required tuning to absorb a significant percentage of the load harmonic currents. For this type of application, the passive filter cannot be tuned exactly to the harmonic frequencies because they can be overloaded due to the system voltage distortion and/or system current harmonics. The single-phase equivalent circuit of a passive LC filter connected in parallel to a non-linear current source and to the power distribution system is shown in Fig. 39.38. From this figure, the design procedure of this filter can be derived. The harmonic current component flowing through the passive filter and the current component flowing through the source is are given by the following expressions.

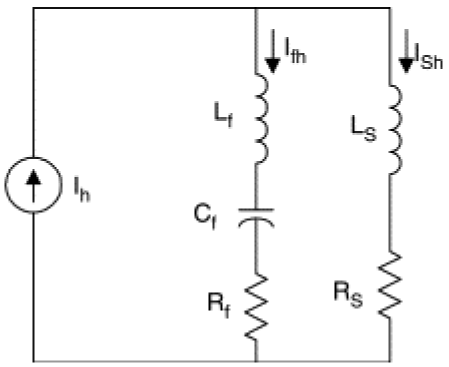


Fig:2.7. filter current

Principles of Operation

Series active power filters compensate current system distortion caused by non-linear loads by imposing a high impedance path to the current harmonics, which forces the high-frequency currents to flow through the LC passive filter connected in parallel to the load (Fig. 41.30). The high impedance imposed by the series active power filter is created by generating a voltage of the same frequency that the current harmonic component needs to be eliminated. Voltage regulation or voltage unbalance can be corrected by compensating the fundamental frequency positive, negative, and zero sequence voltage components of the power distribution system (Fig. 41.29) In this case, the series active power filter injects a voltage component in series with the supply voltage and therefore can be regarded as a controlled voltage source, compensating voltage regulation on the load side (sags or swells), and voltage unbalance. Voltage injection of arbitrary phase with respect to the load current implies active power transfer capabilities which increase the rating of the series active power filter, and in most cases require an energy storage element connected in the dc bus. Voltage and current waveforms shown in Figs. 41.32, 41.33, and 41.34 illustrate the compensation characteristics of a series active power filter operating with a shunt passive filter**.**

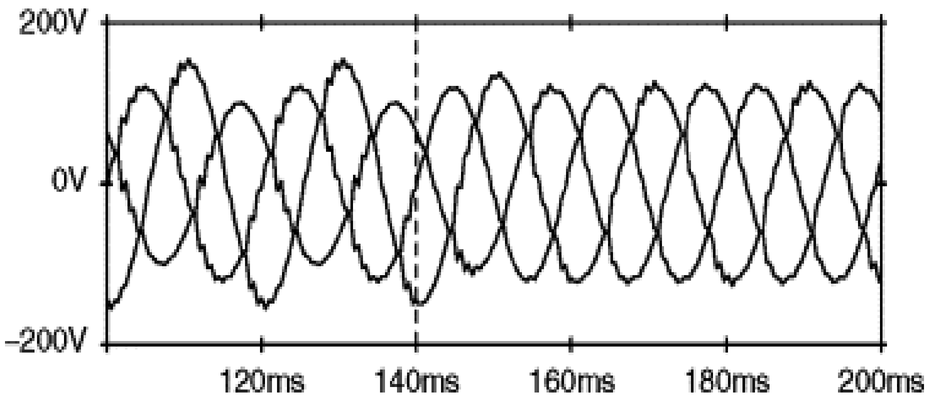


Fig.2.8. Shunt passive filter.

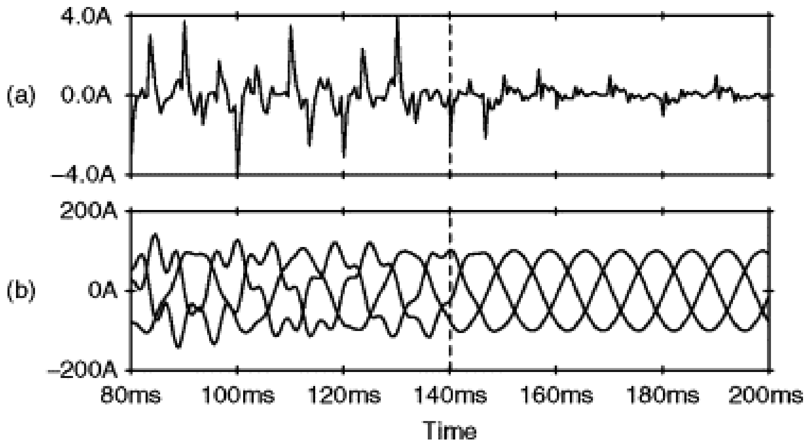


Fig. 2.9. Shunt passive filter

2.7. Boost Converter with Average Current Control

Single phase diode rectifiers are the most commonly used circuits for application where the input is the ac supply (e.g.: computers, telecommunications, air conditioning etc). These classical converters operate by rectifying the input ac line voltage and filtering it with large capacitor. The filter capacitor reduces the ripple present in the output voltage but introduces distortion in the input current which reduces the power factor. So, PFC techniques are used. Various power factor correction (PFC) techniques are employed to overcome these power quality problems out of which the boost converter topology has been extensively used in various ac/dc and dc/dc applications. In fact, the front end of today's ac/dc power supplies with power factor correction (PFC) is almost exclusively implemented with boost topology [2-4]. The low power factor and high pulsating current from the AC mains are the main disadvantages of the diode rectifier and phase-controlled rectifier.

These circuits generate serious power pollution in the transmission or distribution system. The power pollutants such as reactive power and current harmonics results in line voltage distortion, heating of core of transformer and electrical machines and increasing losses in the transmission and distribution line the boost PFC circuit operating in continuous conduction mode (CCM) is the popular choice for medium and high power (400 W to a few kilowatts) application. This is because the continuous nature of the boost converter's input current results in low conducted electromagnetic interference (EMI) compared to other active PFC topologies such as buck-boost and buck converters. The active rectifier of the AC/DC/AC converter is used to regulate the DC bus voltage for motor drive. The nonlinear load produces a pulsating current with large current harmonics [5-6]. An active power filter is employed to compensate for the reactive power and current harmonics drawn from the nonlinear load and the AC/DC/AC converter. This strategy needs an additional inverter and measurement of both the nonlinear load currents and the compensated currents. The cost of implementation of this strategy is very high [7-9].

To combine the capabilities of power factor correction, active power filter and AC/DC converter, a new power factor correction technique using PFC Boost converter is proposed to work simultaneously as an active power filter to supply compensated currents that are equal to the harmonic currents \ (excitation leading to saturation). A hysteresis current control is adopted to track the required line current command. In this arrangement PFC boost converter can be used to eliminate the harmonic current generated by the diode rectifier. The PFC boost converter supplies the required harmonic current produced by the non-linear load, hence the total arrangement draws a nearly sinusoidal current with improved power factor [10-12]. In a conventional switching power supply using a buck derived technique, an inductor is used in the output stage. Current control mode is actually output current control, resulting in many performance advantages [11-13].

In contrast, in a high-power factor pre-regulator using the boost technique, the inductor is used in the input stage. Current control mode then controls input current, allowing it to be easily followed to the desired sinusoidal wave shape. In high power factor boost pre-regulators the peak/average error is very serious because it causes distortion of the input current waveform. While the peak current follows the desired sine wave current, the average current does not. The peak/average error becomes much worse at lower current levels, especially when the inductor current becomes discontinuous as the sine wave approaches zero in every half cycle. To achieve low distortion, the peak/average error must be small. This requires use of a large inductor to make the ripple current small. The resulting shallow inductor current ramp makes the already poor noise immunity much worse.

The average current mode method can be used to sense and control the current in any circuit branch. Hence it can control input current accurately with buck and fly back techniques and can control output current with boost and fly back techniques [13,14]. This paper initially involves simulation of basic power electronic conventional rectifier circuits and the analysis of the current and voltage waveforms. It starts with simple circuits and switches to advanced circuits by implementing advanced techniques such as active PFC and their subsequent effect on the current and voltage waveforms expecting better results, mainly focusing on the objective of improving the input current waveform i.e. making it sinusoidal by tuning the circuits. Here for average current mode control, PI controllers are used. All the simulation is done by PSIM.

2.8. Power Factor with Different Loads

Power factor is defined as the cosine of the angle between voltage and current in an ac circuit. If the circuit is inductive, the current lags behind the voltage and the power factor are referred to as lagging. However, in a capacitive circuit, current leads to the voltage, and the power factor are said to be leading. 2.1 Linear System It is AC electrical loads where the voltage and current waveforms are sinusoidal. The current at any time is proportional to voltage. Power factor is determined only by the phase difference between voltage and current. 2.2 Non-Linear System Applies to those ac loads where the current is not proportional to voltage. The nature of the nonlinear current is to generate harmonics in the current waveform. This distortion of the current waveform leads to distortion of the voltage waveform. Under this condition, the voltage waveform is no longer proportional to the current. For sinusoidal voltage and non-sinusoidal current PF can be expressed as:

$$PF = \frac{V_{rms} \times I_{1rms}}{V_{rms} \times I_{rms}} \times \cos\theta \qquad (1)$$

$$PF = \frac{I_{1rms}}{I_{rms}} \times \cos\theta = K_d \times K_p \qquad (2)$$

Where, cosθ is the displacement factor of the voltage and current. Kp is the purity factor or the distortion factor. Another important parameter that measures the percentage of distortion is known as the Total Harmonic Distortion (THD).

Effects of Harmonics on Power Quality

The contaminative harmonics can decline power quality and affect system performance in several ways. As presence of harmonics declaims the transmission efficiency and also creates thermal problems, both conductor and iron loss are increased. In 3-Φ system, neutral conductor becomes unprotected due to odd harmonics. Triggering is misconducted as the peak harmonics create currents which interrupts the protection system of an automatic relay. Huge current flows through the ground conductor of system with four wire 3-Φ when odd number of n- current is present in harmonics. Finally, harmonics could cause other problems such as electromagnetic interference to interrupt communication,

degrading reliability of electrical equipment, increasing product defective ratio, insulation failure, audible noise, etc.

2.9. Types of Power Factor Correction

1. Passive PFC

Harmonic current can be controlled in the simplest way by using a filter that passes current only at line frequency (50 or 60 Hz). Harmonic currents are suppressed and the nonlinear device looks like a linear load. Power factor can be improved by using capacitors and inductors. Power factor can be improved by using capacitors and inductors. But the disadvantage is they require large value high current inductors which are expensive and bulky.

2. Active PFC

An active approach is the most effective way to correct power factor of electronic supplies. Here, we place boost converter between the bridge rectifier and the load. The converter tries to maintain a constant DC output bus voltage and draws a current that is in phase with and at the same frequency as the line voltage.

2.10. Boost Converter

To prevent the problem of pulsating input current PFC techniques are used. Best result can be obtained by using active PFC techniques based on switch mode power converters. The boost topology is by far more popular than other PFC techniques. The circuit diagram of a boost converter is shown in Figure-08.

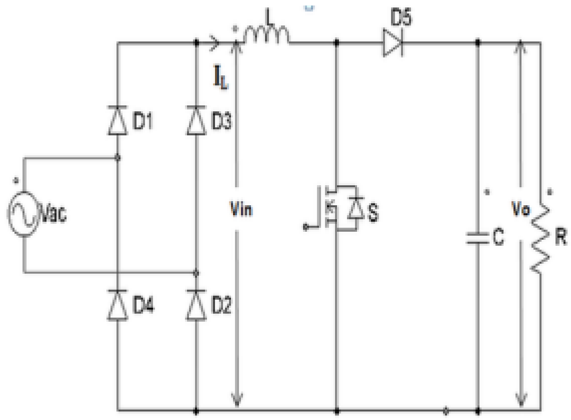


Fig: 2.10. Boost Converter

When the switch S is on the current IL rises and flows through inductor L. When switch S is off the current IL decreases and flows through L, diode D5, C, and R. The current IL falls until switch S is turned on again.

So, when switch S is on:

$$\frac{\Delta i_L}{\Delta t} = \frac{V_{in}}{L} \qquad (3)$$

Again, when the switch is off:

$$V_{in} - V_o = L\frac{di_L}{dt} \qquad (4)$$

Here Vin is the rectified input voltage and Vo is the output voltage. So, the boost converter draws continuous input current. This input current can be controlled to follow a sinusoidal reference using average current mode control technique.

2.11. Average Current Mode Control

System specifications

Average current control Boost Converter for the improvement of power factor and total harmonic distortion has been used in this work. The boost converter is a highly efficient step-up DC/DC switching converter. The converter uses a transistor switch, typically a MOSFET, to pulse width modulate the voltage into an inductor. Rectangular pulses of voltage into an inductor result in a triangular current waveform. For this work it is also assumed that the converter is used in the continuous mode, which implies that the inductor's current never goes to zero. Boost converter has two conduction states, continuous conduction mode and discontinuous conduction mode. The block diagram of boost converter is shown in Figure.09 The average current mode control method is feedback control for current. It contains two PI controllers to stabilize the system. After using this average current control method, the results are good.

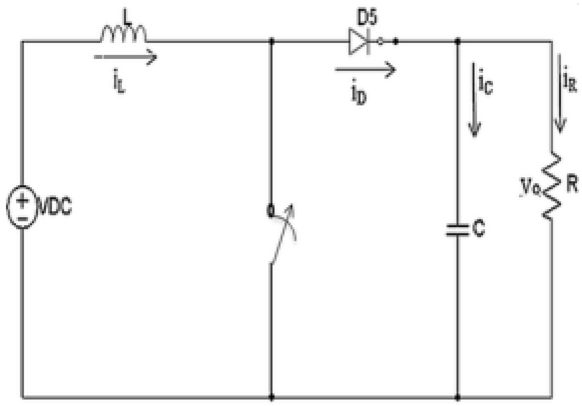


Fig: 2.11. Basic Diagram of Boost Converter

The average current mode controls the control circuit consists of two parts. They are:

• Feed forward/current control loop

• Feedback /voltage control loop

2.11.1. Current Control Loop

The purpose of the current control loop is to force the current waveform to follow the shape of the voltage waveform. In order for the current to follow the voltage, the internal current amplifier has to be designed to capture enough of the harmonics of the output voltage using external capacitors and resistors. Once designing this it uses information from the gain modulator to adjust the PWM control that controls whether the power MOSFET is switched on or off. The heart of the PFC controller is the gain modulator. The gain modulator has two inputs and one output. The left input to the gain modulator block is called the inductor current (IL). The reference current is the input current that is proportional to the input full-wave rectified voltage. The other input, located at the bottom of the gain modulator, is from the voltage error amplifier. The error amplifier takes in the output voltage (using a voltage divider) after the boost diode and compares it to a reference voltage. The error amplifier will have a small bandwidth so as not to let any abrupt changes in the output or ripple erratically affect the output of the error amplifier. The gain modulator multiplies or is the product of the reference current and the error voltage from the error amplifier (defined by the output voltage).

2.11.2. Voltage Control Loop

The gain modulator and the voltage control loop work together to sample the input current and output voltage, respectively.

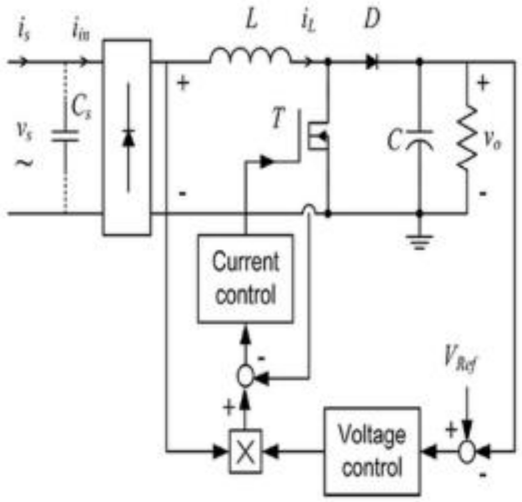


Fig: 2.12. Average current mode control

These two measurements are taken and then compared against each other to determine if a gain should be applied to the input of the current control. This decision is than compared against a sample of the output current to determine the duty cycle of the PWM. Once designing this it uses information from the gain modulator to adjust the PWM control that controls whether the power MOSFET is switched on or off. The heart of the PFC controller is the gain modulator. The gain modulator has two inputs and one output. The left input to the gain modulator block is called the inductor current (IL). The reference current is the input current that is proportional to the input full-wave-rectified voltage. The other input, located at the bottom of the gain modulator, is from the voltage error amplifier. The error amplifier takes in the output voltage (using a voltage divider) after the boost diode and compares it to a reference voltage. The error amplifier will have a small bandwidth so as not to let any abrupt changes in the output or ripple erratically affect the output of the error amplifier. The gain modulator multiplies or is the product of the reference current and the error voltage from the error amplifier (defined by the output voltage).

2.12. Summary

THD and PF correction of Boost Converter using Average current control method is presented in this thesis. PSIM software has been used for circuit design, measurement of THD and PF. Initially, results of the open-loop uncontrolled rectifier are shown, followed by a description of the average current control method. The average current control method resulted in enhancement of the performance and improvement of the results (THD and PF). In the results of the uncontrolled rectifiers, it can be seen that harmonics are very high. Closed loop-controlled rectification is then used for harmonics reduction and PI controllers were tuned to get satisfactory results. The comparison of Inductor current and the reference current is also presented which is essential for the comparison of rectified scaled voltage and the output DC voltage. Furthermore, the transient and steady-state analysis of the average current control method is also given, which shows satisfactory results. In the end, an improved THD value of 4.45% is achieved using simulation.

Chapter 3

Real Time Power Factor Correction in Industrial Plants with Non-Linear Loads

Large industrial plants like paper and metal industries have in their electric power system a large number of non-linear loads. These loads generate current harmonics in the electric power lines and contribute to reduce the power factor in the bus bars they are connected to as well as in the whole system. The installation of shunt capacitors is a traditional method of correcting the power factor. However, using this method in plants with non-linear loads can bring forth the phenomenon of parallel resonance. Typically, some previous analysis is carried out to verify if resonance can occur. This analysis is made based on the topology of the circuit and on the harmonic content in various points of the electric power system. This study is known as harmonic load flow analysis and it determines the order, magnitude and phase of the harmonics that produce the resonance. Then, blocking inductors are installed in series with the capacitor banks, creating filters that eliminate the current harmonics responsible for resonance. This is the usual method. This work describes a research activity that is being carried out at INATEL. This research aims at developing a system for power factor correction using exclusively capacitors, without the need for filters. This will be made through the correct choice of the capacitors to be switched on or off for simultaneously correcting the power factor and avoiding parallel resonance. This choice is made based on an analysis of the topology of the electric power system and on measurements of its harmonic content, both in real-time.

3.1. THE SOFTWARE OF THE SYSTEM

Fig.3.1 shows a simple electric power system diagram containing one main station, two secondary stations, and linear and non-linear loads powered by these secondary stations.

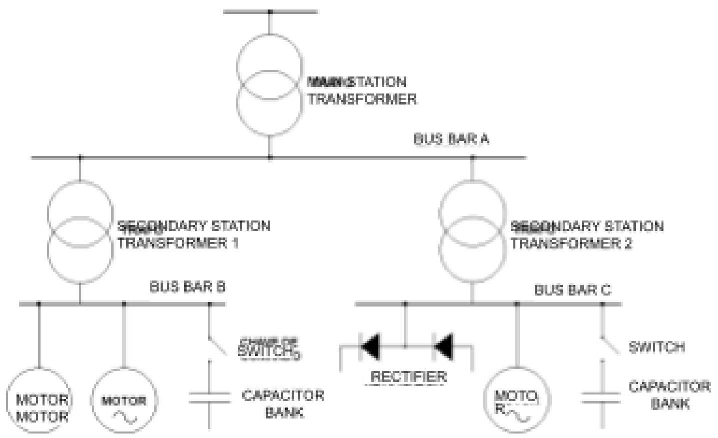


Fig. 3.1. Electric power system example.

3.2. CHARACTERIZATION OF NONLINEAR LOADS IN POWER DISTRIBUTION GRID

With the advent of modern diversified sources of electrical energy, the issue of power quality becomes both more ambiguous and more complicated. We will address here first the new aspects that are coming in for thanks to the new ways of producing electrical energy, which are becoming more and more popular, and thanks to the emergence of a new paradigm known as smart-grid which involves mutual interaction of power electrical systems and electronic systems for its proper functionality [1]. Nowadays we are witnessing changes in the demand and energy use which in fact means “new” load characteristics, and trends changing the nature of the aggregate utility consumption. All of that is mostly due to the electronic devices that became ubiquitous. It is presumed that the overall household consumption for electronic appliances will rise with a rate of 6% per year so reaching 29% of the total household consumption in the year 2030. In the same, time, household consumption is expected to reach 40% of the overall electricity demand. The immense rise of the office consumption due to the enormous number of computers in use is also to be added. That stands for educational, administrative, health, transport, and other public services, too.

One may get the picture if one multiplies the average consumption of a desk-top (about 120 W) with the average number of hours per day when the computers is on (about 7), and the number of computers (billion(s)?). Electronic loads are strongly related to the power quality thanks to the implementation of AC/DC converters that in general draw current from the grid in bursts. The current voltage relationship of these loads, looking from the grid side, is nonlinear, hence nonlinear loads. In fact, while keeping the voltage waveform almost sinusoidal, they impregnate pulses into the current so chopping it into seemingly arbitrary waveform and, consequently, producing harmonic distortions. Having all this in mind the means for characterization of the load from the nonlinearity point of view becomes one of the inevitable tools of quality evaluation of smart grid. The problem is further complicated when different power generation technologies and resources are combined leading. New subsystem in the power production, transport, and consumption emerge named micro-grids and the overall system is supposed to become a smart-grid. For example, due to the rise of the number of different kinds of electricity sources even the frequency of the grid voltage may be considered as “unknown” asking for algorithms and software to be implemented in real time to extract the frequency value [2] and, based on that, to compute the amplitudes of the harmonics [3, 4, 5]. Due to the nonlinearities, measurement of power factor and distortion, however, usually requires dedicated equipment. For example, use of a classical ammeter will return incorrect results when attempting to measure the AC current drawn by a non-linear load and then calculate the power factor. A true RMS multi-meter must be used to measure the actual RMS currents and voltages and apparent power.

To measure the real power or reactive power, a wattmeter designed to properly work with non-sinusoidal currents must be also used. Contemporary methods and algorithms for spectrum analysis are presented in this paper. The basic definitions of parameters describing nonlinear loads are introduced. Alternative definitions for reactive power and their calculation methods are elaborated, also. In our previous research we were first developing a tool for efficient measurements that would allow for proper and complete characterization of the nonlinear loads [6, 7]. Namely we found that the tools for characterization of modern loads available on the market, most frequently, lack at least one of the following properties: low price, abelite ty of implementation of complex data processing algorithms (versatility), ability to store and statistically analyse the measured data, and ability to communicate with its environment no matter how distant it is. All these were achieved by the system reported in [6, 7] and the measurement results demonstrated here were obtained by these tools. Next, we implemented these tools for the characterization of small loads.

The results obtained, as reported in [8] and [9] for example, were, in some cases, surprisingly different from what was expected. That stands for the power components which are not the active power and for the abundance of harmonics. In [10] and [11] we demonstrated that based on the main's current, b they proper data processing, despite the complex signal transformation between the mains and the components of a computer via the power supply chain, one may deduce the activities within the computer. Even more, one may recognize software running within the computer. Such information is distributed via the grid. Here we will for the first time summarize the theoretical background of all computations necessary to be performed for complete characterization of small loads.

Then, we will demonstrate our new results in the implementation of the theory and the measurement tools on a set of nonlinear loads. The definitions used in the modern characterization of the main's current, voltage, and power which are implemented by our system will be listed in the second section so enabling the main attention to be devoted to the set of measured results and their analysis, which will be given next. The paper will be organized as follows. First, a short description of the measurement experiment will be given. To preserve conciseness, for this purpose, we will mainly refer to our previous work.

3.3. PARAMETER DEFINTIONS

Although power quality is a relatively ambiguous concept, limited mostly to conversations among utility engineers and physicists, as electronic appliances take over the home, it may become a residential issue as well.

3.4. MEASUREMENT SYSTEM

In order to establish a comprehensive picture about the properties of a given load one needs to perform complete analysis of the current and voltage waveforms at its terminals. In that way the basic and the higher harmonics of both the current and the voltage may be found. More frequently, however, indicators related to the power are sought in order to quantitatively characterize the load. Namely, a linear resistive load will have voltage and current in-phase and will consume only real power. Any other load will deviate from this characterization and one wants to know the extent of deviation expressed by as much indicators as necessary to get a complete picture. All these were implemented in our measuring system which will be shortly described in the next. The solution, as described in full details in [6, 7], is based on a real time system for nonlinear load analysis. The system is based on virtual instrumentation paradigm, keeping the main advantage of legacy instruments – determinism in measurement. The system consists of three subsystems: acquisition subsystem, real-time application for parameter calculations, and virtual instrument for additional analysis and data manipulation (Fig. 2).

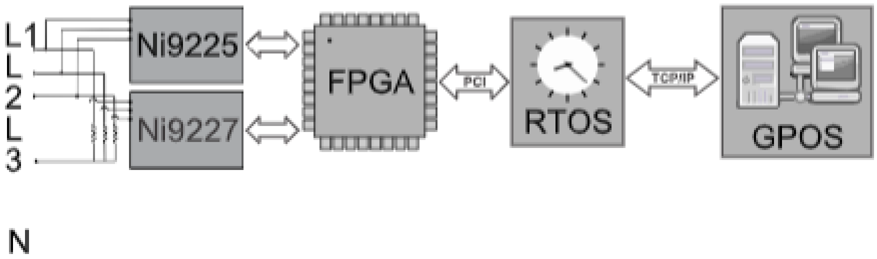


Fig. 3.2. The system architecture

The acquisition subsystem, Fig. 3, is implemented using field programming gate array (PXI chassis equipped with PXI-7813R FPGA card with Vertex II FPGA) in control of data acquisition [26]. Acquisition is performed using NI 9225[27] and NI 9227 [28] c- series acquisition modules connected to PXI-7813R FPGA card [26]. A/D resolution is

24- bit, with 50 kSa/s sampling rate and dynamic range ±300 V for voltages and ±5 A for currents. The FPGA provides timing, triggering control, and channel synchronization maintaining high-speed, hardware reliability, and strict determinism. The FPGA code is implemented in a LabVIEW development environment. The function of the FPGA circuit is acquisition control.

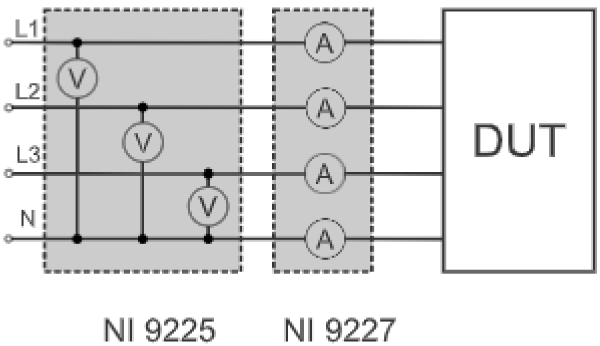


Fig. 3- Connection diagram of acquisition subsystem

The software component is implemented in two stages, executing on real-time operating system (Phar Lap RTOS, [29, 30]) and general-purpose operating system (GPOS). Described system enables calculation of a number of parameters in real-time that characterize nonlinear loads, which is impossible using classical instruments. The measured quantities are calculated from the current and voltage waveforms according to IEEE 1459-2000 and IEEE 1459-2010 standards [12, 13]. Real time application (Fig. 3) calculates power and power quality parameters deterministically and saves calculated values on local storage. The application is executed on real time operating system.

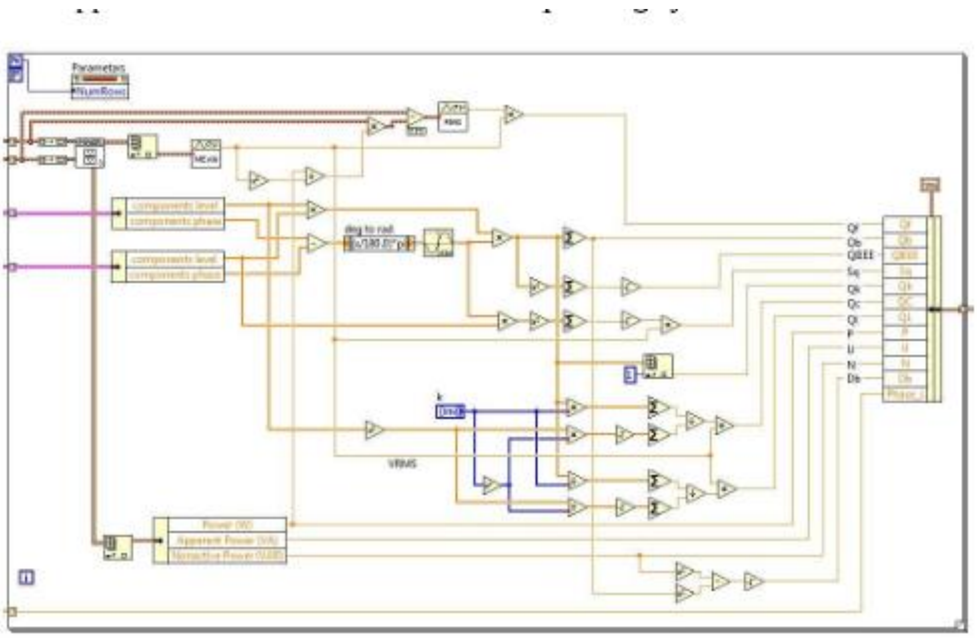


Fig. 4- Part of real-time application in G code, alternative reactive power calculations

Virtual instrument, implemented in National Instruments LabVIEW [30, 31] environment, is used for additional analysis and data manipulation represents user interface of described system. It runs on general purpose operating system, physically apart from the rest of the system. Communication is achieved by TCP/IP. Parameters and values obtained by means of acquisition and calculations are presented numerically and graphically (Fig. 5).

Fig. 5- Virtual instrument provides measurements of various parameters

3.5. MEASUREMENT RESULTS

We have performed measurements on various small loads. The parameters obtained may be used for decision making of various kinds, such as verification of compliance to some standards or categorization within quality frames. As small loads here, we consider various devices: CFL and LED lamps, power supply devices and battery chargers in case of personal communication and computing devices. These devices are ubiquitous and in everyday use, thus their cumulative effect on power distribution grid is not negligible [32], [33]. Various parameters that characterize nonlinearity, efficiency and quality are measured and calculated. Table 1 shows measured results obtained on small loads such as various compact fluorescent lamps (CFL, 7 W – 20W), incandescent lamps (100W and 60W), two low-power 1 W indoor LED (light emitting diode) lamps, prototype of street 34 W LED lamp and CRT computer monitor for reference. Compact fluorescent lamp is good example of nonlinear load [34]. It brings reduction in total energy consumption (about 20%, comparing to incandescent lamp of equivalent luminosity), but with harmonic currents and increased harmonic loss on distribution transformer. Measurements show that CFL lamps have good correction of displacement power factor, but significant distortion leading to low total power factor (Table 1). CFLs are equipped by power supply units which conduct current only during a very small part of fundamental period, so the current drawn from the grid has the shape of a short impulse.

No.	Type	Power	P (W)	U(VA)	N (VAR)	QB(VAR)	DB(VAR)	Qf (VAR)	QIEEE (VAR)	Sq (VAR)	Qk (VAR)	QC (VAR)	QL (VAR)
1	CFL Rod		11.56	17.84	13.58	-6.16	12.10	13.58	6.16	10.24	-6.16	-4.43	-6.11
2	CFL bulb E27	20	17.14	27.72	21.78	-8.43	20.08	21.78	8.43	14.48	-8.43	-6.46	-8.37
3	CFL tube E27	20	16.77	28.46	23.00	-8.44	21.39	23.00	8.45	14.55	-8.45	-6.07	-8.39
4	CFL bulb E27	15	11.59	18.91	14.94	-5.31	13.97	14.94	5.32	9.22	-5.32	-4.00	-5.28
5	Inc E27	100	86.77	86.78	0.80	-0.50	0.63	0.80	0.50	0.56	-0.50	-0.36	-0.49
6	CFL spot E14	7	5.87	9.32	7.25	-2.83	6.67	7.25	2.81	4.23	-2.81	-2.17	-2.80
7	CFL bulb E27	7	6.16	9.86	7.71	-2.64	7.24	7.71	2.65	4.83	-2.65	-2.03	-2.63
8	CFL bulb E14	9	6.46	10.78	8.63	-2.72	8.19	8.63	2.72	5.45	-2.72	-2.08	-2.70
9	CFL tube E14	11	9.89	16.11	12.72	-4.71	11.82	12.72	4.69	7.89	-4.69	-3.61	-4.66
10	CFL tube E27	18	17.10	28.86	23.24	-8.73	21.54	23.24	8.75	13.27	-8.75	-6.64	-8.68
11	CFL tube E27	11	10.63	17.67	14.12	-5.83	12.85	14.12	5.83	8.85	-5.83	-4.41	-5.79
12	CFL helix E27	11	9.58	16.27	13.16	-4.93	12.20	13.16	4.95	8.75	-4.95	-3.68	-4.90

13 Inc E14	60	55.06	55.06	0.61	-0.37	0.49	0.61	0.37	0.37	-0.37	-0.27	-0.37
14 CFL helix E27	18	17.21	28.87	23.18	-8.82	21.43	23.18	8.83	15.55	-8.82	-6.77	-8.76
15 CFL helix E27	20	18.41	30.68	24.54	-9.95	22.43	24.54	9.93	16.14	-9.93	-7.56	-9.86
16 CFL tube E27	15	12.66	21.97	17.95	-6.32	16.80	17.95	6.33	11.63	-6.33	-4.80	-6.28
17 Spot E27	15	16.92	34.24	29.77	-3.88	29.52	29.77	4.14	20.01	-4.13	-1.98	-4.06
18 Spot E27	10	13.23	26.33	22.76	-2.97	22.56	22.76	3.17	15.45	-3.17	-1.51	-3.12
19 Bulb W E27	8	10.00	19.53	16.77	-2.81	16.54	16.77	2.94	11.52	-2.93	-1.74	-2.89
20 Bulb W E27	6	8.51	9.45	4.11	0.08	4.11	4.11	0.07	3.29	0.07	0.08	0.07
21 Bulb E27	6	8.69	9.58	4.04	0.09	4.04	4.04	0.08	3.28	0.08	0.08	0.08
22 Bulb E27	3	4.07	7.70	6.54	-0.84	6.48	6.54	0.90	4.35	-0.90	-0.45	-0.88
23 RGB E27	3	1.92	3.17	2.52	0.01	2.52	2.52	0.01	1.39	0.00	0.05	0.00
24 Spot E14	3	4.00	8.05	6.99	-0.98	6.92	6.99	1.04	4.86	-1.04	-0.52	-1.02

Further, personal devices such as tablet computer, mobile phone, laptop computer and cordless telephone containing rechargeable batteries are analysed regarding operating conditions. Measured results are presented in Table 3. Working conditions are standby (device turned off and battery not charging), working and charging (device turned on and battery charging) and charging only (device turned off and battery charging). A standalone battery charger is also tested. Following values are measured and shown in the table: voltage RMS (V), current RMS (I), frequency (f), cosine of 1st harmonic phase difference (cosφ 1), TPF – total power factor (%), DPF – distortion power factor (%), THD V – voltage total harmonic distortion (%),THD I – current total harmonic distortion (%), active power (P), Bureau’s reactive power (Q B), apparent power (U), distortion power (D), non-active power (N), phasor power (S), first harmonic active power (P 1) and higher harmonics active power (P H).

first have a glimpse at the distortions of the current (THD I). As can be seen even in the best cases the THD I is larger than 20%. There is a case, a mobile phone battery charger while charging, where the THD I is 154.51% which means the harmonics exceed by a large margin the fundamental. Note that this is not an isolated case. One may observe several THD I s of similar value. To summarize, THD I is exposing the nonlinear character of all small loads, some of which are extremely nonlinear producing harmonics larger than the fundamental one.

Table 3 Personal devices in different working conditions

No.	Device description	V (V)	I (mA)	f (Hz)
1	Charger 230V 1.7A - 2XAAA NiCd battery charging. 850mAh	236.06	9.89	50.02
2	Tablet computer turned on. Li-Polimer 8220 mAh battery charging	235.70	80.92	49.98
3	Tablet computer turned off. Li-Polimer 8220 mAh battery charging	236.59	61.65	49.99
4	Tablet computer turned off. charger 230V/2A connected. not charging	236.51	1.70	50.00
5	Mobile phone charger connected. not charging 230V/0.2A	236.62	1.33	9.99
6	Mobile phone turned on. Li-Ion 1230 mAh battery charging	235.65	53.72	49.98
7	Mobile phone turned off. Li-Ion 1230 mAh battery charging	236.09	48.05	50.01
8	Laptop comp. (type 1) turned on. charger 230V. 1.7A connected, not charging	233.49	22.99	50.01
9	Laptop comp. (type 1) turned on. Li-ION 2200mAh battery charging	232.81	231.39	50.00
10	Laptop comp. (type 1) turned off. Li-ION 2200mAh battery charging	233.52	106.52	49.99
11	Laptop comp. (type 2) turned on. Charger 230V 1.5A connected, not charging	233.07	15.71	49.99
12	Laptop computer (type 2) turned on. Li-ION 4400mAh battery charging	232.05	436.60	49.97
13	Cordless telephone base charger 230V/40mA disconnected	232.77	21.05	49.97
14	Cordless telephone base. 2XAAA. NiCd. 550mAh battery not charging	233.68	21.71	50.00
15	Cordless telephone base. 2XAAA. NiCd. 550mAh battery charging	233.55	25.60	49.99

No.	TPF (%)	DPF (%)	THDV (%)	THDI (%)	P (W)	QB (VAR)	U (VA)	D (VAR)	N (VAR)	S (VAR)	P1 (W)	PH(W)
1	32.93	70.81	1.70	94.47	0.77	1.77	2.33	1.62	2.20	1.68	0.78	-0.02
2	57.36	58.15	1.73	137.76	10.94	-1.74	19.07	15.53	15.62	11.08	11.08	-0.14
3	55.12	55.54	1.70	146.23	8.04	-0.93	14.59	12.13	12.17	8.09	8.17	-0.12

4	21.43	79.20	1.67	114.80	0.09	0.18	0.40	0.35	0.39	0.20	0.05	0.00
5	12.64	101.35	1.69	59.01	0.04	0.17	0.31	0.26	0.31	0.18	0.02	0.00
6	52.73	53.66	1.71	154.51	6.67	-1.18	12.66	10.69	10.76	6.78	6.73	-0.05
7	51.18	51.98	1.77	161.72	5.81	-0.96	11.34	9.70	9.75	5.88	5.87	-0.06
8	7.00	95.18	1.78	29.07	0.38	1.38	5.37	1.61	5.36	5.12	0.38	-0.01
9	53.67	54.76	2.00	147.11	28.91	-6.10	53.87	45.04	45.45	29.55	29.65	-0.71
10	47.51	50.62	1.92	164.35	11.82	-4.64	24.87	21.39	21.89	12.70	12.18	-0.28
11	12.69	99.22	1.94	40.82	0.46	1.46	3.66	1.42	3.63	3.37	0.43	0.00
12	96.74	97.30	1.83	20.90	98.01	-10.67	101.31	23.32	25.65	98.59	97.86	0.02
13	23.50	90.76	1.80	43.70	1.15	4.33	4.90	1.97	4.76	4.48	1.16	-0.01
14	47.31	92.64	1.78	36.64	2.40	4.09	5.07	1.81	4.47	4.74	2.43	-0.01
15	70.29	92.99	1.82	37.24	4.20	3.66	5.98	2.16	4.25	5.57	4.23	-0.02

early days it was known as cos of the load while only linear loads were considered supposedly having reactive component introducing phase shift between the voltage and the current. The total power factor (TPF) encompasses the whole event including the distortions of both the voltage and the current and their mutual phase shift. As can be seen from Table 1, there is only one case where the TPF is approaching unity which is supposed to be its ideal value. In many of the cases the value of TPF is smaller than 50% meaning that the active power is smaller than a half of the total power drawn from the main which, as we could see from the previous paragraph, is mainly due to the distortions. In general, since most of the chargers are considered of small power (look to the column P1 in Table 3), no power factor correction is built in so that significant losses are allowed. That, to repeat once more, would not be a problem if the number of such devices, being attached to the mains all the time, is not in the range of billion(s). The next column, the distortion power factor (DPF), represents the percentage of power taken by the harmonics. As we can see, except for a small number of cases where the harmonics are approximately on the level of half of the total power, in most cases they are taking as large power as the fundamental. Note, the harmonics are unwanted not only because of efficiency problems. In fact, in the long term, the presence of harmonics on the grid can cause:

- Increased electrical consumption
- Added wear and tear on motors and other equipment
- Greater maintenance costs
- Upstream and downstream power-quality problems,
- Utility penalties for causing problems on the power grid

Overheating in transformers, and similar. Similar conclusion may be drawn in by comparison of the Distortion (D) and the power of the first (fundamental) harmonic (P 1). There are only three cases where the second is larger than the former. To summarize the data from Table 3 one may say that an electronic load to the grid which in fact represents a power supply of a telecommunication or IT device, represents a small but highly nonlinear load. In many cases the TPF of such a load is in favour of everything but not the active power to be delivered to the device.

3.6. SUMMARY

Due to the changes in the nature of the electrical loads to the grid new aspects of the characterization of the loads to the electrical grid are emerging. These are related mainly to the nonlinearities of modern electronic loads and to the subsystems used for conversion from DC to AC and vice versa which is becoming unavoidable in modern production and distribution systems. To qualify and quantify the properties of the modern power electrical systems new tools are to be developed to be able to cope with the new properties of the signals arising at the grid-to-load and grid to power- producing-facility interface. That stands for both theoretical algorithms for computation and for the very measurement equipment. In these proceedings, we represent our results in the development and implementation of a measurement system for small loads that are becoming ubiquitous and consequently of big concern for the quality of the delivered electrical energy. We also present the measurement prejudice that these loads are small and unimportant. Our hardware and software solutions may be characterized as advanced, accurate, and versatile while at the same time of low price making them very attractive for practical use being it in the laboratory or in field conditions.

Chapter-4

Boost Converter with Average Current Control

4.1 General Perspective

Current mode control is a two-loop system as shown in the simple example of Fig. 1. The switching power supply inductor is “hidden” within the inner current control loop. This simplifies the design of the outer voltage control loop and improves power supply performance in many ways, including better dynamics. The objective of this inner loop is to control the state-space averaged inductor current, but in practice, the instantaneous peak inductor current is the basis for control. (Switch current -equal to inductor current during the “on” time--is often sensed.) If the inductor ripple current is small, peak inductor current control

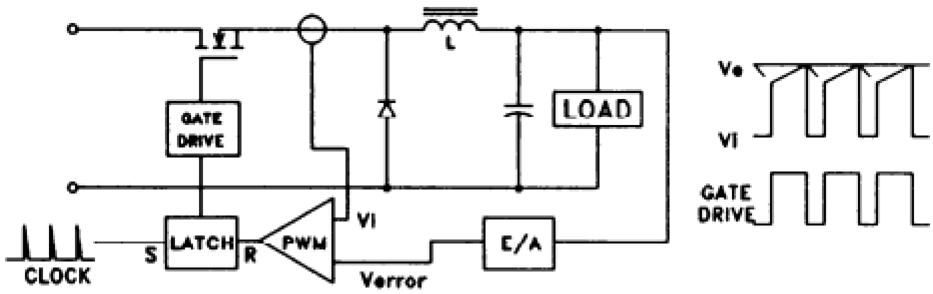


Fig. 4.1. Peak Current Mode Control Circuit and Waveforms

is nearly equivalent to average inductor current control. In a conventional switching power supply employing a buck-derived topology, the inductor is in the output. Current mode control then actually outputs current control, resulting in many performance advantages. On the other hand, in a high-power factor preregular using the boost topology, the inductor is in the input. Current mode control then controls input current, allowing it to be easily conformed to the desired sinusoidal waveshape.

4.2 Peak Current Mode Control Problems

Poor noise immunity

The peak method of inductor current control functions by comparing the upslope of inductor current (or switch current) to a current program level set by the outer loop-see Fig. 1. The comparator turns the power switch off when the instantaneous current reaches the desired level. The current ramp is usually quite small compared to the programming level, especially when V, is low. As a result, this method is extremely susceptible to noise. A noise spike is generated each time the switch turns on. A fraction of a volt coupled into the control circuit can cause it to turn off immediately, resulting in a subpar monic operating mode with a much greater ripple. Circuit layout and bypassing are critically important to a successful operation. Slop e compensation is required. The peak current mode control method is inherently unstable at duty ratios exceeding 0.5.

4.3 APPLICATION NOTE-01

resulting in sub-harmonic oscillation. A compensating ramp (with as lope equal to the inductor current downslope) is usually applied to the comparator input to eliminate this instability. In a buck regulator, the inductor current downslope equals VLJ. With V. constant, as it usually is, the compensating ramp is fixed and easy to calculate-but it does complicate the design. With a boost regulator in a high-power factor application, the downslope of inductor current equals (V, &$J/L and thus varies considerably as the input voltage follows the rectified sine waveform. A fixed ramp providing adequate compensation will overcompensate much of the time, with resulting performance degradation and increased distortion.

Peak to average current error.

The peak to average current error inherent in the peak method of inductor current control is usually not a serious problem in conventional buck derived power supplies. This is because the inductor ripple current is usually much smaller than the average full load inductor current, and because the outer voltage control loop soon eliminates this error. In high power factor boost PR regulators the peak/avg error is very serious because it causes distortion of the input current waveform. While the peak current follows the desired sine wave current program, the average current does not. The peak/avg error becomes much worse at lower current levels, especially when the inductor current becomes discontinuous as the sine wave approaches zero every half cycle. To achieve low distortion, the peak/avg error must be small. This requires a large inductor to make the ripple current small. The resulting shallow inductor current ramp makes the already poor noise immunity much worse.

Topology problems.

Conventional peak current mode control actually controls inductor current. As normally used for output current control, it is most effective when applied to a buck regulator where the inductor is in the output. But for fly back or boost topologies the inductor is not in the output, the wrong current is controlled, and much of the advantage of current mode control is lost. Likewise, the boost topology with its inductor at the input is well suited for input current control in a high-power factor preregular, but buck and fly back topologies are not well suited because the inductor is not in the input and the wrong current is controlled.

Average Current Mode Control

Peak current mode control operates by directly comparing the actual inductor current waveform to the current program level (set by the outer loop) at the two inputs of the PWM comparator. This current loop has low gain and so cannot correct for the deficiencies noted above. Referring to Fig. 2, the technique of average current mode control overcomes these problems by introducing a high gain integrating current error amplifier (CA) into the current loop. A voltage across R, (set by the outer loop) represents the desired current program level. The voltage across current sense resistor R, represents actual inductor current. The difference, or current error, is amplified and compared to a large amplitude sawtooth (oscillator ramp) at the PWM comparator inputs. The gain-bandwidth characteristic of the current loop can be tailored for optimum performance by the compensation network around the CA. Compared with peak current mode control, the current loop gain crossover

frequency, fc, can be made approximately the same, but the gain will be much greater at lower frequencies. The result is:
1) Average current tracks the current program with a high degree of accuracy. This is especially important in high power factor regulators, enabling less than 3% harmonic distortion to be achieved with a relatively small inductor. In fact, average current mode control functions well even when the mode boundary is crossed into the discontinuous mode at low current levels. The outer voltage control loop is oblivious to this mode change. 2) Slope compensation is not required, but there is a limit to loop gain at the switching frequency in order to achieve stability. 3) Noise immunity is excellent. When the clock pulse turns the power switch on, the oscillator ramp immediately dives to its lowest level, volts away from the corresponding current error level at the input of the PWM comparator. 4) The average current mode method can be used to sense and control the current in any circuit branch. Thus, it can control input current accurately with buck and fly back topologies and can control output current with boost and fly back topologies.

Designing the Optimum Control Loop Gain Limitation at fs: Switching power supply control circuits all exhibit subharmonic oscillation problems if the slopes of the waveforms applied to the two inputs of the PWM comparator are inappropriately related. With peak current mode control, slope compensation prevents this instability. Average current mode control has a very similar problem, but a better solution. The oscillator ramp effectively provides a great amount of slope compensation. One criterion applies in a single pole system: The amplified inductor current downslope at one input of the PWM comparator must not exceed the oscillator ramp s Lope at the other comparator input. This criterion puts an upper limit on the current amplifier gain at the switching frequency, indirectly establishing the maximum current loop gain crossover frequency, fc. It is the first thing that needs to be considered in optimizing the average current mode control loop.

In the following examples, we assume that the power circuit design has been completed, and only the CA compensation n remains to be worked out.

Example 1: Buck Regulator Output Current

The simple buck regulator shown in Fig. 2 has the following operating parameters:

Switching Frequency, f' = 100 kHz
Input Voltage, V, N = 15 - 30V
Output Voltage, V0 = 12V
Output Current, I, = 5A (6A O.L.)
Inductance, L = 60 PH
max. MO @ 30V (100 kHz) = 1.2A
Sense Resistance, R, = 0.10

C_{FP} is temporarily omitted. Zero **R_F, C_{FZ}** is well below the switching frequency. Near fs, the amplifier gain is flat. The overall current loop has only one active pole (from the inductor). The inductor current is sensed through **R_S,** (How this is accomplished will be discussed later.) The inductor current waveform with its sawtooth ripple component is amplified and inverted through the CA and applied to the comparator. The inductor current downslope (while the switch is off) becomes an upslope, as shown in Fig. 2. To avoid subharmonic oscillation, this off-time CA output slope must not exceed the oscillator ramp slope. In Fig. 2, the off-time

CA output slope is much less than the oscillator ramp slope, indicating that the CA gain is less than optimum. Calculating the slopes: Inductor Current Downslope = Vo/L Oscillator Ramp Slope = Vs/Ts = $V_S f_S$ Where Vs is the oscillator ramp p-p voltage, Ts and fs are the switching period and frequency

Calculating the slopes:

Inductor Current Downslope = Vo/L
Oscillator Ramp Slope = Vs/Ts = Vsfs

Where Vs is the oscillator ramp p-p voltage, Ts and fs are the switching period and frequency.

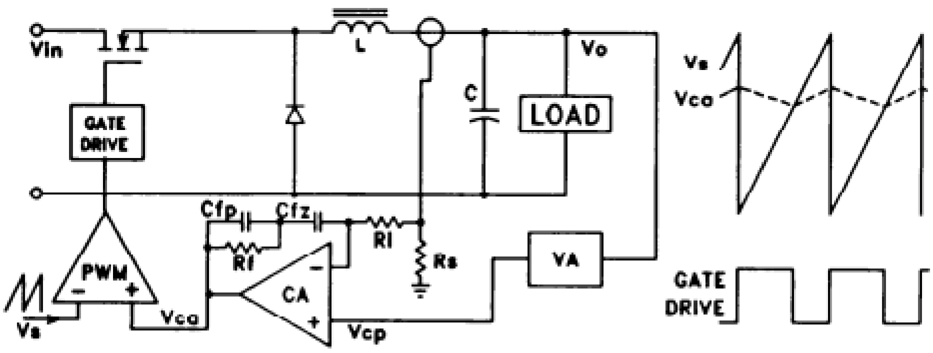


Fig.4. 2. Average Current Mode Control Circuit and Waveforms

4.4 APPLICATION NOTE-02

The inductor current downslope is translated into a voltage across current sense resistor **Rs** and multiplied by the **CA** gain, **GU** This is set equal to the oscillator ramp slope to determine the **CA** gain allowed at **fs:**

$$(V_O/L)R_S G_{CA} = V_S f_S$$

$$\therefore \quad \max \quad G_{CA} = \frac{\hat{v}_{CA}}{\hat{v}_{RS}} = \frac{V_S f_S L}{V_O R_S} \qquad \textbf{(1)}$$

Applying the values given in the example, and with **Vs** of **5Vpp,** the maximum **GCA** at the switching frequency is 25 (28dB). The current error amplifier gain at fs is set to this optimum value by making the ratio RJR, = 25. The small-signal control-to-output gain of the buck regulator current loop power section (from **V_{CA}** at the **CA** output to **V_{RS},** the voltage across **R_S**) is:

$$\frac{\hat{v}_{RS}}{\hat{v}_{CA}} = \frac{R_S}{V_S}\frac{V_{IN}}{sL} = \frac{1590}{f} \quad (@30V) \qquad \textbf{(2)}$$

The overall open-loop gain of the current loop is found by multiplying (1) and (2). The result is set equal to 1 to solve for the loop gain crossover frequency, **fc**:

$$\frac{R_S}{V_S}\frac{V_{IN}}{2\pi f_C L}\frac{V_S f_S L}{V_O R_S} = 1$$

$$f_C = \frac{f_S V_{IN}}{2\pi V_O} = \frac{f_S}{2\pi D} \qquad (3)$$

Setting the **CA** gain at the limit found in (1), the crossover frequency will never be less than one sixth of the switching frequency. (This is exactly the same result reported by Middlebrook [1] for peak current mode control with recommended slope compensation.) In this example, **fc** is 20 kHz with $\mathbf{V_{IN}}$, at 15V (D= .8), and 40 kHz when $\mathbf{V_{IN}}$, at 30V (D= .4). Fig. 3 - Buck Waveforms, Optimized Gain If the error amplifier had a flat gain characteristic, the phase margin at crossover would be 90° -much more than required-and the gain at lower frequencies wouldn't be much better than with peak current mode control. But zero $\mathbf{R_F, C_{FZ}}$ placed at 10 kHz, below the minimum crossover frequency, reduces the phase margin to 63°, and boosts the low frequency gain dramatically, with an integrator gain of 250K/f. It is this characteristic which causes the current loop to rapidly and accurately home in on the average current called for by the outer loop. Even though the comparator actually turns off the power switch when a peak inductor current is reached, this peak current level is adjusted by the current amplifier so that the average current is correct. Fig. 3 shows the start-up waveforms of the voltages at the PWM comparator inputs and the inductor current with $\mathbf{V_{IN}}$ at 30V and full load. Note how the amplified and inverted inductor current downslope virtually coincides with the oscillator ramp, because the **CA** gain was set at the optimum level according to Equation (1). Note also that if the **CA** gain is increased further, not only will the off-time slope exceed the oscillator ramp slope, but the positive excursion may reach the **CA** compliance limit, clipping or clamping the waveform.

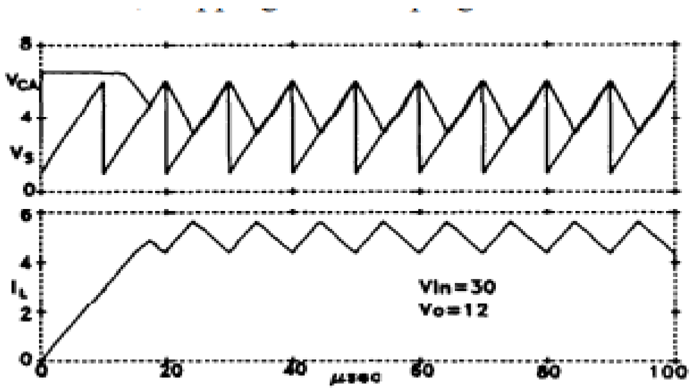


Fig. 4.3. Buck Waveforms, Optimized Gain

Pole $\mathbf{R_F, C_{FP}\, C_{FZ}/(C_{FP}+ C_{FZ})}$ is set at switching frequency fs (100 kHz). This pole has one purpose-to eliminate noise spikes riding on the current waveform, the nemesis of peak current mode control. The sawtooth **CA** output waveform is also diminished, especially the higher-order harmonics, and shifted in phase as shown in Fig. 4. The pole-zero pair (at 100 kHz and 10 kHz) reduces the phase margin at the crossover to a very acceptable 45° -see Fig. 5. The reduced amplitude and slopes of the **CA** waveform resulting from the 100 kHz pole might suggest that the **CA** gain could be in

4.5. APPLICATION NOTE-03

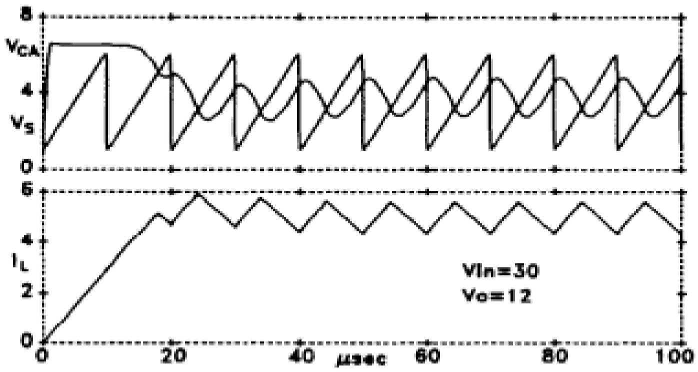


Fig. 4 - Buck with Additional Pole at f_S

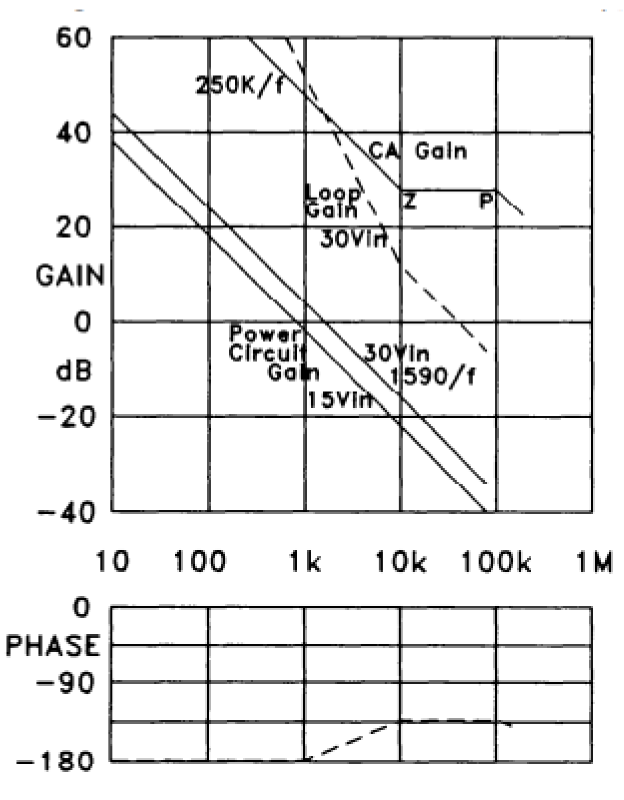


Fig. 4.4. Buck Regulator Bode Plot

creased beyond the maximum value from Equation (1), but beware-Eq. (1) is valid only for a system with a single pole response at fs, but with $\mathbf{C_{FP}}$ added there are now two active poles at $\mathbf{f_s}$. Experimentally, increasing $\mathbf{G_{CA}}$, may incur subharmonic oscillation.

Discontinuous Operation. When the load current I, becomes small, the inductor current becomes discontinuous. The current level at the continuous/discontinuous mode boundary is:

$$I_O = I_L = \frac{V_O(V_{IN}-V_O)}{V_{IN}2f_SL} \qquad \textbf{(4)}$$

Worst case is at max $\mathbf{V_{IN}}$, when ripple current is greatest. In this example, the mode boundary occurs at $\mathbf{I_o}$**,** (=$\mathbf{I_J}$ of 0.2A when $\mathbf{V_{IN}}$ is 15V, and at 0.6A when VIN is 30V. In the discontinuous mode, below the mode boundary, changes in $\mathbf{I_o}$**,** require large duty cycle changes. In other words, the power circuit gain suddenly becomes very low. Also, the single pole characteristic of continuous mode operation with its 90° phase lag disappears, so the power circuit gain is flat-independent of frequency. The current loop becomes more stable, but much less responsive. With peak current mode control in the discontinuous mode, peak/avg current error becomes unacceptably huge. But with average current mode control, the high gain of the current error amplifier easily provides the large duty cycle changes necessary to accommodate changes in load current, thereby maintaining good average current regulation. Referring to Fig. 2, when the current loop is closed, the voltage across current sense resistor $\mathbf{V_{RS}}$ & equals the current programming voltage $\mathbf{V_{CP}}$& (from the voltage error amplifier) at frequencies below $\mathbf{f_s}$. The transconductance of the closed current loop is a part of the outer voltage control loop:

$$g = \frac{\hat{i}_L}{\hat{v}_{CP}} = \frac{\hat{v}_{RS}/R_S}{\hat{v}_{CP}} = \frac{1}{R_S} \qquad \textbf{(5)}$$

The closed loop transconductance rolls off and assumes a single pole characteristic at the open loop crossover frequency, $\mathbf{f_s}$.

4.6 APPLICATION NOTE-04

Example 2: Boost Regulator Input Current.

A 1 kW off-line preregular (Fig 6) operates with the following parameters:

Switching Frequency, $\mathbf{f_s}$ = 100 **kHz**

Input Volts, V_{IN} = 90 - 270V rms

output Volts, & = 380Vdc

Max. O.L. IIN (@90V) = 12A rms, 17A pk

L = 0.25mH

$\mathbf{A_{IL}}$, $\mathbf{\Delta I_{IN}}$ @90V = 3.4A

The max. overload line current at min. $\mathbf{V_{IN}}$ corresponds to 1080W input. The max. peak overload 60Hz line current (17A) should-by design-correspond to a limit on the current programming signal, I, the max peak 100kHz current through the switch and rectifier is 17A plus one-half $\Delta\mathbf{I_L}$: 17 + 3.4/2 = 18.7A

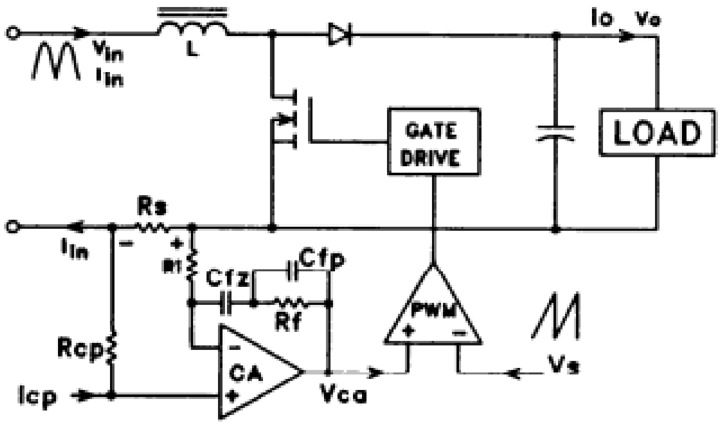


Fig. 4.5. Boost Preregular Circuit

The current downslope occurs when the power switch is off:

Inductor Current Downslope = (**V_o -V_{IN}**)/**L**

Worst case when **V_{IN}** = $V_{o/L}$

Oscillator Ramp Slope = Vs/Ts = Vs **f_s**

Multiply the downslope by Rs and CA gain and set equal to the oscillator ramp slope, then solve for maximum CA gain:

$$(V_O/L)R_S G_{CA} = V_S f_S$$

$$\therefore \quad \max \quad G_{CA} = \frac{\hat{v}_{CA}}{\hat{v}_{RS}} = \frac{V_S f_S L}{V_O R_S} \qquad (6)$$

Note the form of Equation (6) is identical to the buck regulator in (1). Using the values for

this application, the maximum **G_{CA}**, is 6.58, accomplished by making **R_F/R_I** = 6.58. The small-signal control-to-input gain of the current loop power section (from **V_{CA}** at the CA output, to **V_{RS}**, the voltage across **R_S**,) is:

$$\frac{\hat{v}_{RS}}{\hat{v}_{CA}} = \frac{R_S}{V_S}\frac{V_O}{sL} = \frac{2420}{f} \qquad (7)$$

Note that (7) is nearly identical to (2) for the buck regulator, except the gain depends on **V_o**. (which is constant), rather than **V_{IN}** . The overall current loop gain is found by multiplying (6) and (7). The result is set equal to 1 to solve for the crossover frequency, **f_C**:

$$\frac{R_S}{V_S}\frac{V_O}{2\pi f_C L}\frac{V_S f_S L}{V_O R_S} = 1$$

$$f_C = \frac{f_S}{2\pi} \qquad \textbf{(8)}$$

With the ***CA*** gain at the limit found in (6), the current loop **f**C is fixed at **f**S/6 (16.7 kHz). As with the earlier example, with a flat gain error amplifier the phase margin at crossover is 90° — larger than necessary. So, zero R_f, C_{FZ} is set at 1/2 of the minimum crossover frequency (**f**C/2 = f_s/28.33 kHz), providing a low = frequency boost with an integrator gain of 55K/f. Pole R_F, C_{FP} C_{FZ}/ (C_{FP}+ C_{FZ}) is set at 6 times the zero frequency (50 kHz) to eliminate noise spikes. Together, the zero at 8.33 kHz and the pole at 50 kHz leave a phase margin at crossover of 40°. Start-up waveforms are shown in Fig. 7, and the Bode plot in Fig. 8.

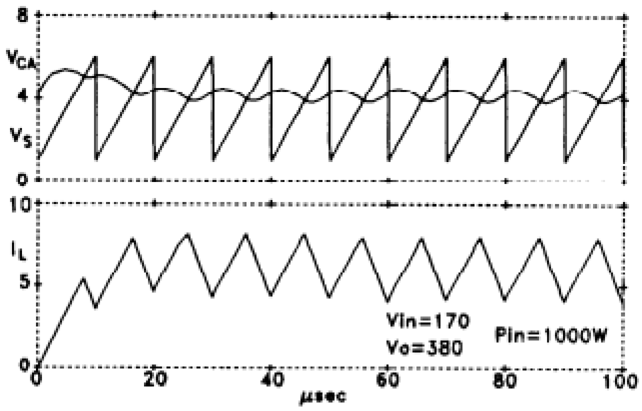


Fig. 4.6. Boost Regulator Waveforms

4.6. APPLICATION NOTE-05

Referring back to Fig. 6 — when the current loop is closed, the voltage across current sense resistor V_{RS} & equals the voltage across current programming resistor V_{RCP}. In this case, programmed with a current source I_{CP}, the current gain of the closed current loop is:

$$G = \frac{i_L}{i_{CP}} = \frac{v_{RS}/R_S}{v_{RCP}/R_{CP}} = \frac{R_{CP}}{R_S} \qquad (9)$$

The closed loop current gain rolls off and assumes a single pole characteristic at the open loop crossover frequency, f_s.

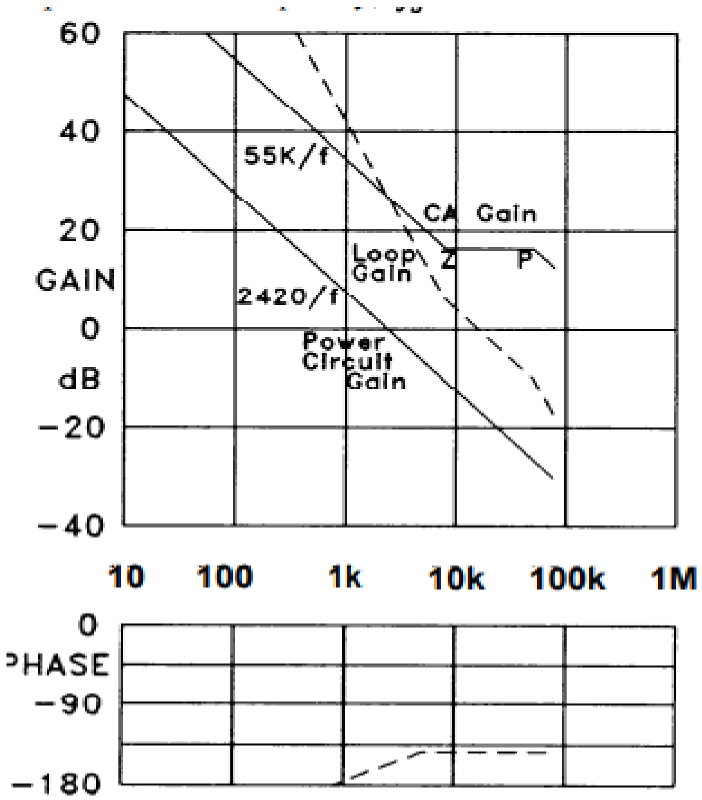


Fig. 4.7. Boost Regulator Bode Plot

In a high-power factor preregular application, the current is programmed to follow the rectified line voltage. As the rectified sine wave voltage and current approaches, the cusp at zero, the inductor current becomes discontinuous. Discontinuous operation can occur over a substantial portion of the line cycle, especially when line current is low at high line voltage and/or low power input. With peak current mode control, discontinuous operation results in a large peak/average current error. A large inductance is required to make ripple current small and put the mode boundary at a low current level. However, average current mode control eliminates the peak/average error. A small inductance can and should be used to reduce cost, size and weight and improve current loop bandwidth. Figure 9 shows a boost preregular programmed to follow a 60 Hz (rectified) sine wave input. The lower waveforms show the programmed and actual line current waveforms. (The programmed waveform has been increased by 5% to make the two waveforms visible. The actual waveform leads the programmed waveform by a small amount and has less than 0.5% 3rd harmonic distortion! The upper waveforms show the duty cycles of the switch and diode throughout the line cycle. The inductor current is continuous when the current is high, and the switch and diode duty cycles add up to 1. But as the current approaches zero crossing, operation becomes discontinuous as shown by the appearance of "dead" time (when neither the switch, the diode, or the inductor are conducting).

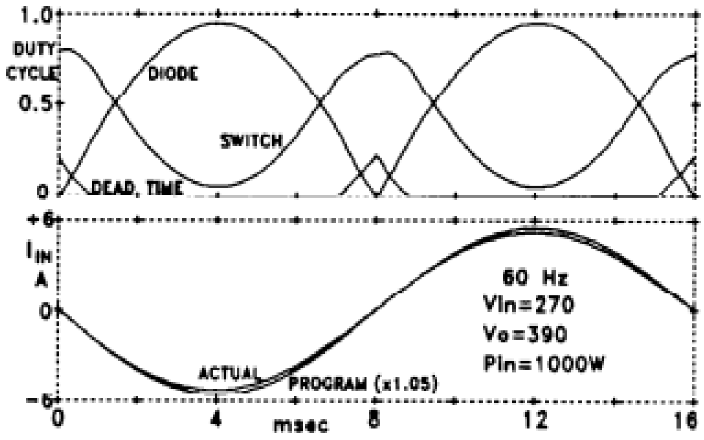


Fig. 4.8. Boost 60Hz Sine Wave Input Current

Note that the switch duty cycle does not change as much when operation becomes discontinuous. With the boost (and fly back) topology in the discontinuous mode, average input current tends to follow input voltage at a constant duty cycle. Even though plenty of CA gain is available to change the duty cycle, little change is required for perfect tracking. Figure 10 shows how the actual input current sine wave tracks the programming signal at 400 Hz. The distortion is worse -- 4.5% 3rd harmonic. This is for two reasons:

4.7. APPLICATION NOTE- 06

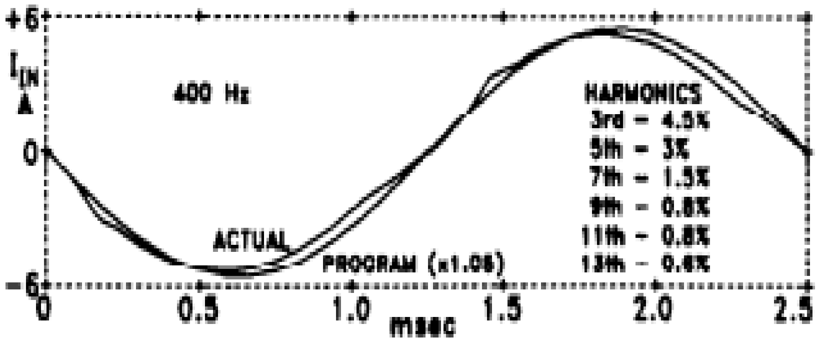


Fig.4.9. Boost 400Hz Sine Wave Input Current

The harmonic components of the rectified 400 Hz waveform are at higher frequencies and closer to the current loop crossover frequency where the loop gain is less, compared with the 50 or 60 Hz harmonics. The inductor current has difficulty rising off zero because the input voltage is so very low at that point. So, the inductor current lags coming off zero, then catches up and overshoots the programmed level. (This effect is much worse with peak current mode control because of the large inductor required.)

Controlling Average Switch Current In the previous examples, average current mode control was applied to controlling inductor current (buck output current and boost input current). This is relatively easy because the inductor current is mostly DC with only a small amount of ripple to deal with. But if it is desired to use a buck or fly back topology to control input current in a high-power factor application, then the chopped current waveform through the power switch must be averaged, a more difficult task.

Example 3: Fly back Regulator Input Current: A 1000 W off-line preregular uses a fly back circuit in order to achieve a standard 300V output bus even though the input voltage ranges above and below 300V (Figs. 11,12). The fly back converter could be designed to operate in the discontinuous inductor current mode in this application. The discontinuous fly back converter is not difficult to control (crudely) by fixing the duty cycle during each line half-cycle, but the peak currents through the power switch and rectifier are nearly twice as high as with continuous mode operation.

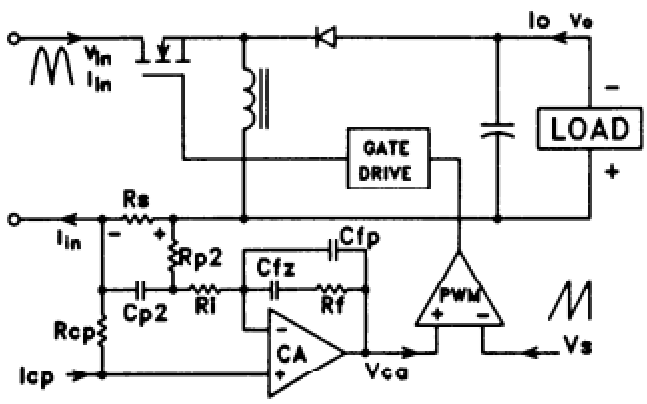


Fig. 4.10. Fly back Preregular Circuit

The high peak current lowers efficiency and requires devices with higher current ratings. Continuous mode operation suffers the problem that the boundary is crossed into the discontinuous mode at light loads and high input voltage, unless a large filter inductor is used, which hurts the frequency response and the power factor as well as the pocketbook. This dilemma disappears with average current mode control because it functions well in the discontinuous as well as the continuous mode, enabling the use of a small inductance value. In this example, the fly back converter operates in the continuous mode when it is important do so at high current levels, to keep the maximum peak current to half that of a strictly discontinuous fly back converter. The operating parameters are:

Switching Frequency, f_s = 100 kHz

Input Volts, V_{IN} = 90 - 270V rms

Output Volts, V_0 = 300V dc

Max. O.L. I_{IN} (@90V) = 12A rms, 17A pk

L = 0.25mH

Δ_{IL} @9OV = 3.6A

$\mathbf{R_S}$= 0.025n

The max. overload rms line current at min. V_{IN} equates to 1080W input (2160Wpk 60Hz). The max. overload peak 60 Hz line current (17A) should be made to correspond to a limit on the current programming input, I_{CP}. Unlike the boost converter, the fly back input current is chopped, so the peak 100kHz current through.

4.8. APPLICATION NOTE- 07

The switch, the inductor, and the rectifier are much greater than the 60 Hz peak current-see Fig. 12. The worst case, at low line and max. overload input current is:

$$I_{PK(100kHz)} = \frac{I_{PK(60Hz)}}{D} = \frac{17}{.702} = 24.2A$$

Add to this one-half Δ_{IL} to obtain the absolute max. peak current through the switch, inductor, and rectifier: 24.2 + 3.6/2 = 26A. Compared to the boost converter, the fly back topology requires higher current and higher voltage devices and generates a lot more input noise because of the chopped waveform. In its favour, the fly back converter can operate with any input/output voltage ratio, can provide current limiting, and input/output isolation. As discussed in the previous example, the boost converter amplifier gain at f_S was limited only by the criteria that the inductor current downslope must not exceed the oscillator ramp slope. The power circuit control-to-input current gain had a simple -1 slope from zero to f_S, making it very easy to compensate. But with the flyback converter, the chopped switch current waveform will be averaged. This results in a lower crossover frequency, f_c, and lower gain-bandwidth for two reasons: 1. The large amplitude chopped current waveform must be integrated by the CA. The upslope of the resulting triangular waveform at the CA output must not exceed the oscillator ramp slope. (The inductor current downslope is not relevant.)

2. There is a zero (conventional left half-plane) in the control-to-input current gain characteristic. These zero moves with the output current level. Loop gain crossover cannot be much higher than the lowest zero frequency. The small-signal control-to-input gain of the flyback current loop power circuit (from V_{CA} at the CA output, to V_{RS}, the voltage across R_S,) is:

$$\frac{\hat{v}_{RS}}{\hat{v}_{CA}} = \frac{R_S}{V_S}\left(I_L + \frac{V_O}{sL}\right) \qquad \textbf{(10)}$$

This is the characteristic of a “normal” zero-a -1 slope with 90° phase lag below fi and flat gain with no phase shift above fi. The zero frequency may be calculated:

$$f_Z = \frac{V_O}{2\pi L I_L} \qquad (11)$$

Note that the zero moves inversely with inductor current and inductance value. This zero has a big effect on loop compensation. To obtain the best loop response, it is important that f_{zim} be as high as possible, by making the inductance small. Fortunately, with average current mode control, there is no need to worry about crossing into discontinuous operation. The limit on making the inductance too small is when the inductor ripple current becomes too large, increasing peak switch and rectifier currents an undesirable amount. Using the specific values of this example, the power circuit gain is:

$$\frac{\hat{v}_{RS}}{\hat{v}_{CA}} = \frac{I_L}{200} - j\,\frac{960}{f}$$

The minimum zero frequency is 8 kHz, which occurs at 24.2A, the max. overload inductor current at 90V low line. The gain above f_Z is 0.12 (-18.4dB). The power circuit gain is shown in the Bode plot of Fig. 13. Turning now to the current error amplifier (Fig. 11), the chopped input (switch) current waveform is shown in Fig. 12 flows through R_S. The average value of this waveform, chopped at 100 kHz, is compared to the current program level across R_{CP}, and amplified. Assume for the moment that C_{P2}, is zero and C_{PZ}, is shorted. The CA gain in the vicinity of 100 kHz is determined by the integrator $(R_I,+R_{P2})C_{FP}$. Averaging is accomplished because the DC gain is high, but the 100 kHz rectangular waveform with its harmonics is amplified relatively little. The rectangular waveform is converted into a triangular wave as shown in Fig. 12.

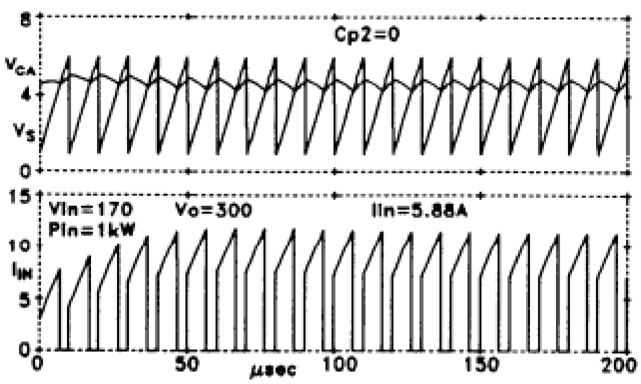


Fig. 4.11. Fly back Regulator Waveforms

The optimum CA integrator gain at 100 kHz is the gain at which the maximum CA output upslope equals the oscillator ramp slope. This is the same principle used in the previous two examples, but in those cases the inductor (whose current was being controlled) did most of the averaging. The inductor did the integration to provide the triangular ripple current waveform and the CA gain was flat in the vicinity of is. But in this fly back preregular example, the chopped switch current is being controlled so the averaging and the triangular waveshape are achieved by an integrating amplifier. The upslope of the CA output occurs when the switch is off and the 100 kHz current waveform is at zero. The CA inputs are both at program voltage V_{CP} & V_{CPmax} - equates to the max. overload peak 60Hz input current (17A) through R_S. Therefore, during the switch "off" time, the maximum current through **R** = (R_I+R_{P2}) & is:

$$I_{RImax} = \frac{V_{CPmax}}{R} = \frac{I_{INpk} R_S}{R}$$

The upslope of the CA output is determined by the current through R_I, charging C_{FP}:

$$\max CA\ Upslope = \frac{I_{RImax}}{C_{FP}} = \frac{I_{INpk} R_S}{C_{FP} R_I}$$

$$Oscillator\ Ramp\ Slope = V_s/T_s = V_s f_S$$

Equating the slopes and solving for C_{FP}:

$$\frac{I_{INpk} R_S}{C_{FP} R} = V_S f_S$$

$$C_{FP} = \frac{I_{INpk} R_S}{V_S f_S R} \qquad (12)$$

Using the values from this example, and assuming R = 10K (R_I=9K, R_{P2}=1K):

$$C_{FP} = \frac{17 \times .025}{5 \times 0.1 \times 10^6 \times 10K} = 85\,pF$$

The CA integrator gain may now be calculated and entered in the Bode plot:

$$G_{CA} = \frac{1}{2\pi f R C_{FP}} = \frac{187{,}000}{f} \qquad (13)$$

The compensation circuit as designed so far (with C_{P2}, zero and C_{FZ} open) has high loop gain and is very stable only when the inductor current is high, maintaining the power circuit zero near the position shown in Fig. 13, so that its gain is flat at f_C. At lower current levels, the power circuit zero slides down to the right and

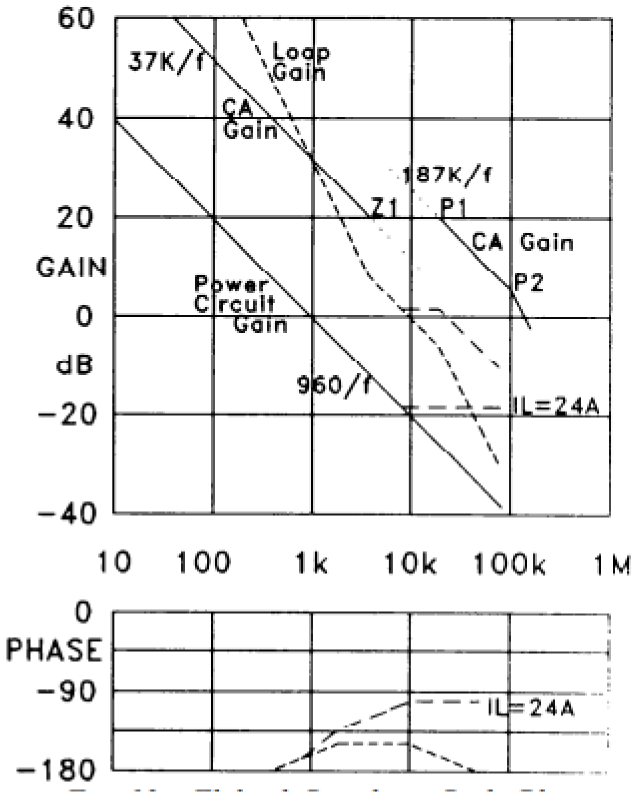


Fig. 4.12. Fly back Regulator Bode Plot

4.9. APPLICATION NOTE- 08

Equation shows, droop is minimized by maximizing secondary inductance-use the largest you can get. Don't use a large R_S, value to obtain a large secondary voltage-it's not necessary and makes reset more difficult. Make the turns ratio as low as possible by using two or three primary turns if space allows. Don't reduce the turns ratio by reducing the secondary turns-this is counter-productive because the inductance goes down with the turns squared. For example, consider the fly back input current preregular of Fig. 11, using a current transformer in series with switch instead of the **0.0250Ω** sense resistor shown. Using the Pulse Engineering #51688 current sense inductor with one turn primary, the turns ratio is 1:200. Secondary inductance is 80 mH. The **24A** max. overload pulse current becomes a **0.12A** current pulse on the secondary side. A **1OΩ** sense resistor will have a max. the voltage of **l.3V** sent to the CA, and the max. secondary voltage including diode forward drop is **2.0V**. The maximum pulse width is **7.02µsec.** Applying these values to Eq. 17:

$$\Delta I_{PRI(droop)} = \frac{200}{1}\frac{2.0}{80\times10^{-3}}\,7\times10^{-6} = .035A$$

Only 35mA droop out of 24A isn't bad! When two C.T.s are used-one on either side of isolation boundary-their turns ratios must be proportioned the same as the power transformer pre/sec turns ratio so that currents through R_s will be equalized. All of the equations containing R_s, given earlier in this paper assume the sense resistor is measuring current directly. When using a current sense transformer, reflect the actual $\boldsymbol{R_S}$, on the C.T. secondary side into the primary by substituting $\boldsymbol{R_S N_P / N_S}$.

4.10. SUMMARY

Current mode control as usually implemented in switching power supplies actually senses and controls peak inductor current. This gives rise to many serious problems, including poor noise immunity, a need for slope compensation, and peak-to-average current errors which the inherently low current loop gain cannot correct. Average current mode control eliminates these problems and may be used effectively to control currents other than inductor current, allowing a much broader range of topological application.

Chapter 5
Model design & Simulation

The widespread use of battery-operated portable devices such as cell phones and laptops has created the need for DC to DC conversion power supplies such as switched mode power supplies. The prominence of distributed energy sources such as solar photovoltaic systems, which produce DC power has created a demand for DC to DC converters. DC converters are widely used for traction motor control in electric automobiles, trolley cars, marine hoists, forklifts trucks, and mine haulers. They provide high efficiency, good acceleration control and fast dynamic response. They can be used in regenerative braking of DC motors to return energy back into the supply.

This attribute results in energy savings for transportation systems with frequent steps. DC converters are used in DC voltage regulators; and also are used, with an inductor in conjunction, to generate a DC current source, specifically for the current source inverter.[1] In this paper, some mathematical derivations are given first, and second, simulated and experimental results are provided to verify the effectiveness of the proposed voltage-boosting converter topology.

5.1. Model Design

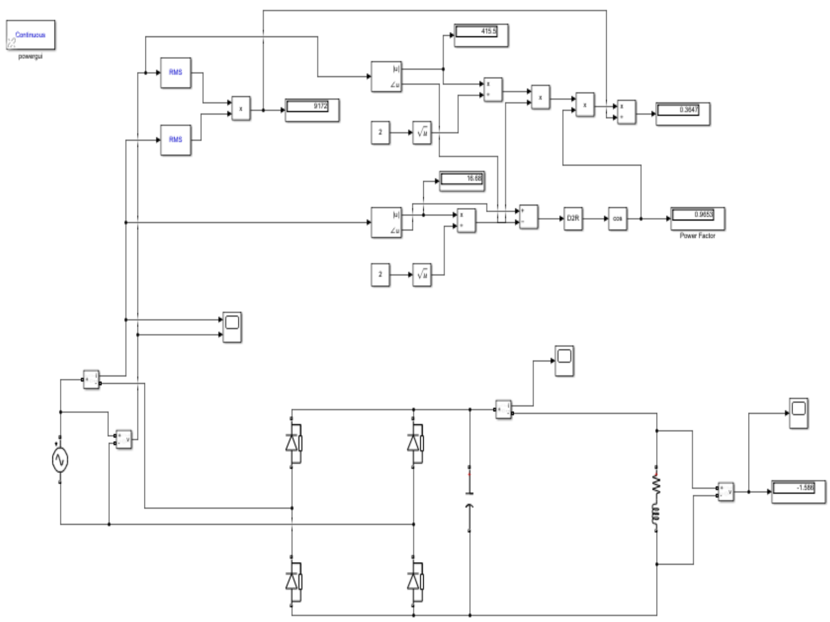


Fig: 1. A simulation model of non-linear load without power factor improvement.

Here in this design, we can divide the calculation in two parts.

- Here in one part we rectified the AC signal by using A bridge rectifier.
- In another part we calculated the power factor of the circuit.

5.2. PI controller

In this circuit, we add PI controller two implement the average current control method where the output voltage is taken as feedback, to compared with a reference voltage. after adding this power factor calculate again.

A simple closed loop PI controller system shown in.

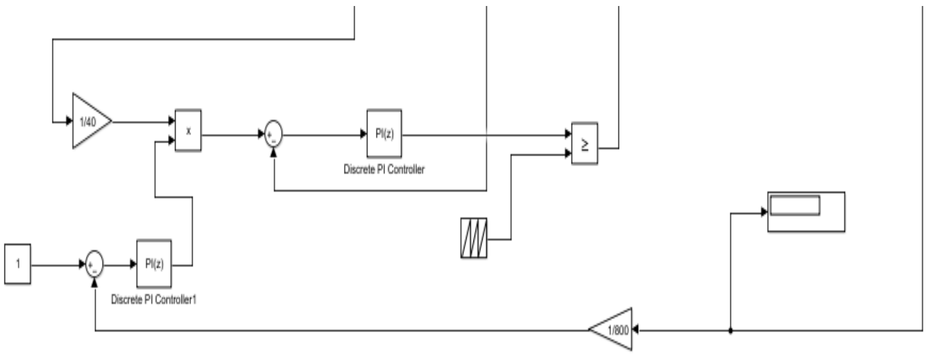
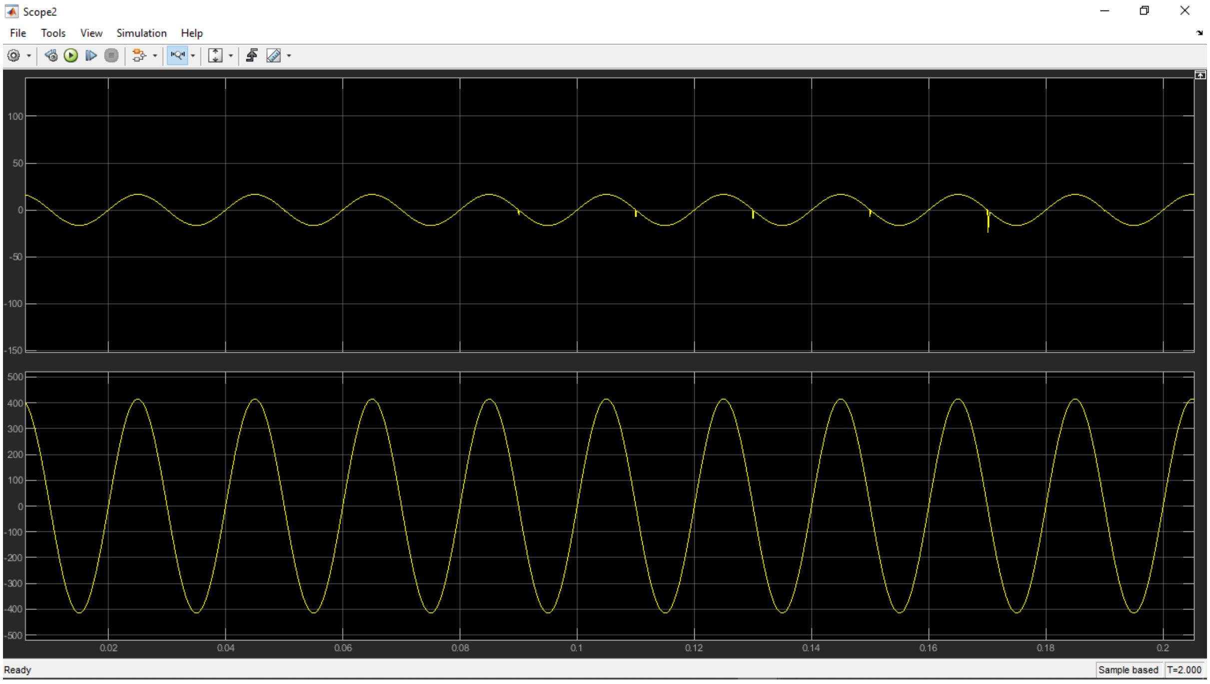


Fig:2. Average current mode control using PI controller

5.3. SIMULATION RESULTS

5.3.1. Input Current & Input voltage

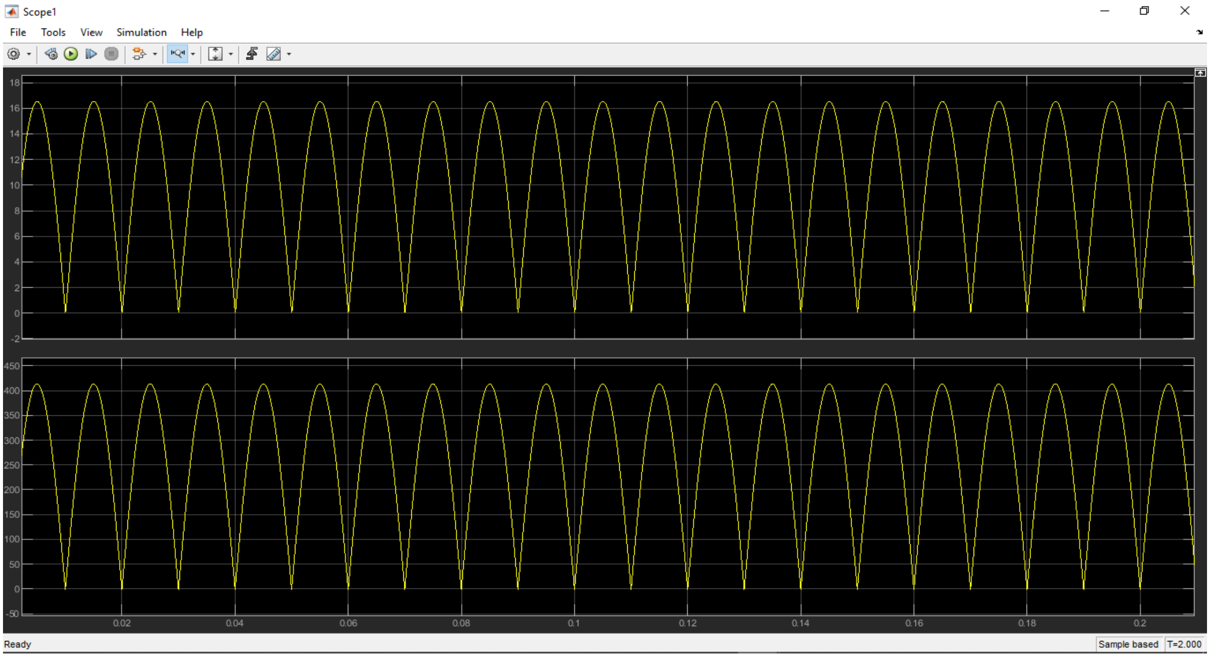
Here we show that input & output voltage waveshape without power factor improvement in this graph we calculated the waveshape are distorted becomes of harmonics.



SIMULATION RESULTS(CONTINUED)

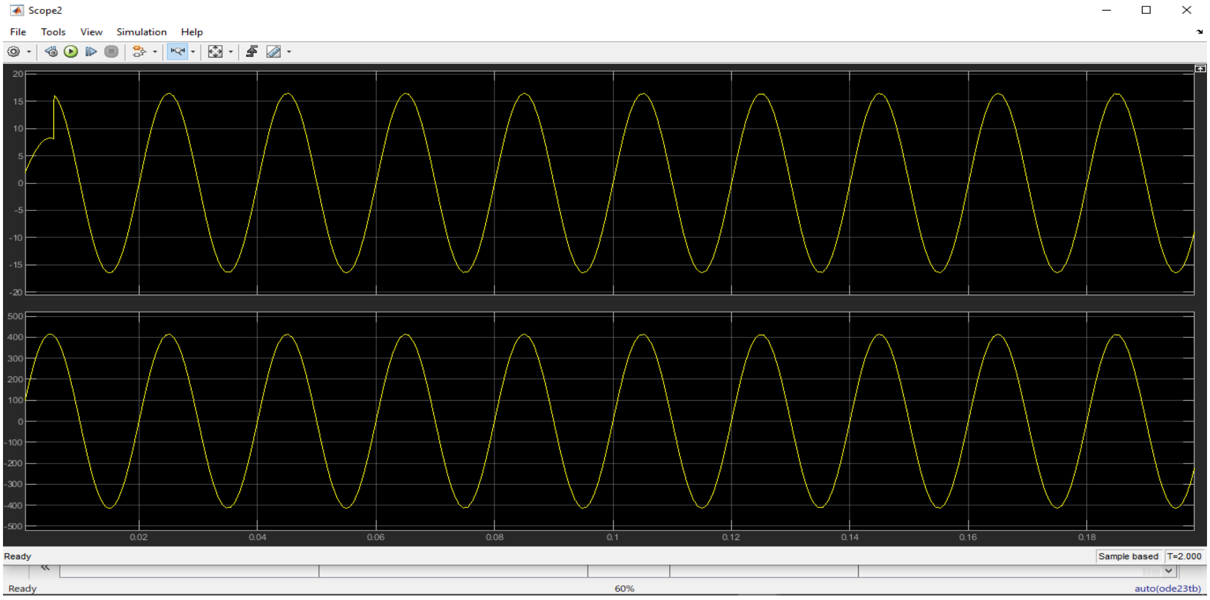
5.3.2. Output current & Output voltage (Without power factor improvement)

In this circuit the output current & output voltage before adding the power factor improvement method this two figure the waveshape are pulsating om nature.



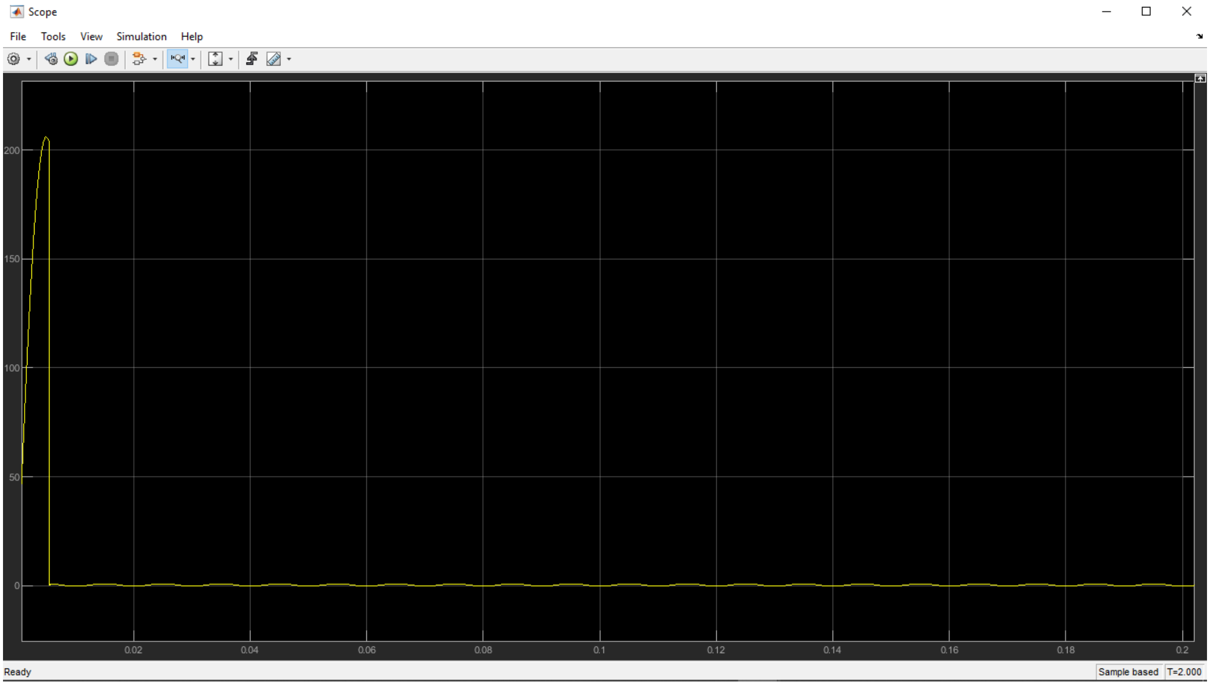
5.3.3. Input Current & Input Voltage with power factor improvement

After adding the power factor improvement method, the input current & input voltage are nearly pure sinusoidal the calculate of harmonic arc reduce.



5.3.4. Output Current with power factor improvement

Add this is the output current waveshape which we collect from the rectifier output previously the waveshape was not DC but after adding the average current control method the waveshape become nearly DC.



5.5. SUMMARY

This paper presents use of boost converter to improve supply side power factor when nonlinear load is connected to AC supply. Here, AC to DC full wave rectifier is considered as a nonlinear load and boost converter is connected between rectifier and load. The source power factor with rectifier as a nonlinear load is very poor also, THD is considerably high. When controlled boost converter is connected between rectifier and load source side power factor can be improved up to desired level as well as THD in AC source is improved up to considerably. Simulation result shows that with the use of current controlled boost converter source side power.

Chapter 6
RESULTS AND DISCUSSIONS

Here is the table of comparison.

Here we two parameter two compared the result in fast parameter the power factor we calculated before adding the power factor improvement method was 0.3647 which is very poor after correction the value of power factor increase up to 0.921 and the current waveshape as we see from the graph before adding power factor improvement method is pulsating in nature and after we adding the correction method. The waveshape become nearly DC.

6.1. Table of comparison:

SL. No.	Parameter	Before correction	After correction
1	Power factor	0.3647	0.921
2	Current waveshape	pulsating	nearly DC

- Here, without the power factor improvement, the overall power factor is very poor(pf=0.3647).
- After adding a boost converter with a controlling mechanism, the power factor is improved up to the desired level as well as THD also decreases.
- The waveshapes show that the rectifier output has also changed and becomes a nearly pure sinusoidal signal. The proposed feedback controlling mechanism is the reason behind it.

6.2. Conclusion

- The power factor correction using boost converter can be used to attain a decent power factor along with some advantages such as higher output voltage, less bulky as compared to capacitor banks used for PFC.
- The effects of harmonics are also reduced by feedback control.
- It has overcome the drawbacks which are available in other techniques.

6.3. References

- Sudhakar Babu, Dr. G. V. Shiva Krishana Rao, "Simulation of Active Power Factor Correction Using Boost Type Converter", International Journal of Science, Engineering and Technology Research (IJSETR), Volume 3, Issue 10, October 2014.

- Dhivya A, Murali D, "Average Current Mode Control Technique Applied to Boost Converter for Power Factor Improvement and THD Reduction", International Journal of Innovative Research in Science, Engineering and Technology(IJIRSET), Volume 3, Issue 2, May 2016.

- Santhosh Kumar R, Shreeshayana R, "Design and Simulation Analysis of Power Factor Correction Using Boost Converter with IC UC3854", International Journal of Innovative Research in Science, Engineering and Technology(IJIRSET), Volume 6, Issue 5, May 2017.

- Sujata Powniker and Sachin Shelar, "Devolopment of Active Power Factor Correction Controller Using Boost Converter", 2016 IEEE International WIE Conference on Electrical and Computer Engineering (WIECON-ECE) 19-21 December 2016, AISSMS, Pune, India.

- Mohammad H Rashid, power electronics Handbook (Academic press, 2001)