Different power factor correction engineering essay

Different power-factor correction methods are reviewed, as well as the back ground to the power-factor. Problem is arising in modern electrical distribution systems due to the connection of rapidly increasing numbers of non-linear electronic loads. The basic principles of harmonic generation and limitation in power systems are first discussed. The main part presents a critical review of commonly used power-factor correction techniques that have been identified in a literature review, and highlights the advantages and disadvantages of these techniques. After the analysis of methods and their working principles, the development of the most promising systems such as the boost-type PFC converters is considered. Finally, a project plan is proposed for the next phase of the dissertation work. This will involve investigating the operation, dynamic control and performance of the most promising systems by conducting a theoretical study and setting up and running a number of simulation models using the MATLAB/SIMULINK software tools.

Key-words: Power factor correction, harmonic mitigation, PFC converters

Contents

List of Abbreviations and Principle Symbols

Abbreviations:

AC Alternating Current

APF Active Power Filter

CCM Continuous Conduction Mode

DC Direct Current

DCM	Discontinuous Conduction Mode
DF	Distortion Factor
FFT	Fast-Fourier analysis
IGBT	Insulated Gate Bipolar Transistor
PF	Power Factor
PFC	Power Factor Correction
PWM	Pulse Width Modulation
RMS	Root Mean Square
THD	Total Harmonic Distortion
TDD	Total Demand Distortion

Principle Symbols:

Power Factor

Distortion Factor

Displacement Factor

h Harmonic contents

RMS value of the line-current fundamental component

RMS value of the line-current harmonic components

Total RMS value of the line-current

1. Introduction

It is now clearly visible from power systems journals and general literatures that power-factor correction is now an important research topic in the power systems area. As non-linear power electronic systems are increasingly being connected to power systems in greater quantities as well as capacities for such applications as power quality control, adjustable speed drives, uninterruptible power supplies, renewable energy-source interfacing, and so on [1] [2]. The power quality regulators of those systems are highly concerned now, because some of their drawbacks, such as harmonics generation and reduced power factor can spoil their advantages [3]. Power electronic systems are effective because their high efficiency and rapidly adjustable output. However, when processing and controlling the input electric energy suitable for users [4], power electronic systems often operate at a low power-factor, and that may cause serious problems to power system operators by reducing distribution component RMS current capacity and to other users on the same network by distorting the sinusoidal supply voltage seen by other user connected at the same point of common coupling as a heavy electronic or power electronic load.. Of all power line disturbances, harmonics are probably the most serious one for power users because they exist under steady state conditions.

This literature review considers harmonic generation prediction of power electronic systems and examines the effectiveness of harmonic mitigation methods. The boost-type power factor correction converters will be taken as the core power factor correction method for future research. The existing publications arising from research in this area and their conclusions have set a good foundation for this report. Results in this report will be based on a theoretical study and simulation studies using software MATLAB/SIMULINK power-factor correction system models which be developed.

2. Background

This section provides discussion on the fundamental principles of power-factor correction, including definitions of power-factor terms and a consideration of the common standards which affect how harmonics controlled in power system. Also, the harmonic generation prediction of ideal power electronic systems is discussed at the end of this section

2. 1 Important definitions and objective of power-factor correction

The power factor (PF) is the ratio of the real power to the apparent power [5] and gives a measure of AC supply utilization on how efficient that the energy is supplied and can be converted into effective work output. The definition of power factor is as shown below:

(2. 1)

In the definition, the value of the power factor is always between 0 and 1, and can be either inductive or capacitive. That means average power is always lower than apparent power. The reason is harmonic components and phase-displacement angle,.

Hence, the power factor equivalent can be described as below:

(2. 2)

is termed the (current) distortion factor (DF) and represent the harmonic components in the current and relative to wave shape [6]. DF is defined as the ratio of the fundamental current component to the RMS current value [4].

is termed the displacement factor and defined as the current and voltage waveform phase angle [6]. Displacement factor has unity value for in-phase current and voltage. The increase of displacement angle will cause larger reactive current in the power system [4].

Hence, the objective of power-factor correction is to decrease the current distortion or harmonic content and increase the displacement factor or bring the current in phase with the voltage. The closer power factor is to the unity value, the higher efficiency and lower energy loss. And the power system will operate at a lower supply voltage.

Another commonly used index for measuring the harmonic content of a waveform applied for current distortion level is total harmonic distortion, THD. THD is the distortion current as a percentage of the fundamental current. The equation of THD is given by:

or (2. 3)

In AC supply utilizations, power factor,, can be expressed in terms of THD and the displacement factor:

(2. 4)

With these equations, it is easy to see that high THD leads to low power factor and even damaging of the power network. THD and power factor will be used together in the following work as important index in measuring performance of the harmonic mitigation techniques.

2. 2 Effects and limitation of harmonic distortion on power system

In any power conversion process, to get high efficiency and low power loss are important for two reasons: the cost of the wasted energy and the difficulty in removing the heat generated due to dissipated energy [4]. The performance of power output efficient is defined by several factors. The power factor and harmonic distortion are the most important ones.

References [8] [9] show the main issues of harmonics within the power system include the possibility of them exciting series and parallel resonances which cause a further increase of harmonic levels, low efficiency caused in generation, transmission, and utilization of electric energy, increasing thermal losses in the electrical components and shortening their useful life and causing malfunction of motors and other components in the power system.

Those effects can be divided into three general categories: “ Thermal stress, Insulation stress and Load disruption” [10]. Those represent effects on increasing equipment losses and thermal losses, increased value of current drawn from the power system and insulation stress and failure to action and malfunction of some electrical devices and systems.

The IEEE Standard 519-1992 recommended harmonic current limits with an additional factor, TDD. This is very same as THD except the distortion factor is expressed by load current instead of fundamental current magnitude [11]. Hence, the equation of TDD is given by:

(2. 5)

Therefore, IEEE Standard 519-1992 limitation for harmonic current in power system expressed with TDD is shown below:

Maximum harmonic current distortion in percent of

Individual harmonic order (Odd harmonics)

TDD

<20

4. 0

2. 0

1. 5

0. 6

0. 3

5. 0

20 <50

7. 0

3. 5

2. 5

1. 0

0. 5

8. 0

50 <100

10. 0

4. 5

4. 0

1. 5

0. 7

12. 0

100 <1000

12. 0

5. 5

5. 0

2. 0

1. 0

15. 0

> 1000

15. 0

7. 0

6. 0

2. 5

1. 4

20. 0

Even harmonics are limited to 25% of the odd harmonics limits above.

Table 2. 1 IEEE 519-1992 Standard for harmonic current limits [12].

Also, there are limitations for power system harmonic voltage and power factor regulation, like IEC 61000-3-2 standard. The methods for power factor correction should not cause disturbances for other aspects of performance.

2. 3 Harmonics generation in power electronic systems

Power electronic systems may naturally operate at low power-factor due to large harmonic generation and phase shifting in controlled devices like controlled rectifiers. Understanding characteristics of the harmonic current is essential for harmonic mitigation research. Based on the form on the two sides, converters can be divided into four categories [4] including:

1. AC to DC (rectifier)

2. DC to AC (inverter)

3. DC to DC

4. AC to AC

Power electronic systems always draw high quality of low frequency harmonic current from the utility and hence cause problems for other users. Take an ideal single-phase diode bridge rectifier as example, the total harmonic distortion can be up to 48. 43% [4] and the 3rd harmonic current can be as large as one third of the fundamental current. If a non-linear load is considered, the displacement factor will fall down from unity value and cause a decrease of power factor. This is surely over the harmonic standards limitation and needs to be corrected.

Theoretically, Rectifiers and choppers output DC and draw a fundamental AC source current and large low frequency harmonic content. On the other hand, inverters output low frequency AC and supply fundamental current and harmonic content usually at higher frequency. Harmonic contents can be reduced by harmonic mitigation techniques and hence increase power factor.

Take Fourier analysis result diagram of single-phase diode bridge rectifier and PWM control Buck converter as example.

(a) (b)

Figure 2. 1 Fourier analysis diagram for input current of (a) single-phase diode bridge rectifier and (b) PWM control Buck converter.

2. 4 Software tools for harmonic mitigation evaluation

To filtering harmonic current in the power system, the frequency of harmonic contents is essential. However, in practice, the harmonic frequency is not absolutely equal to the theoretical value and that makes analysis of harmonic frequencies very difficult. The reason is stray inductance and capacitance in the system and reverse recovery time and forward voltage drop of non-ideal devices [1]. To analyze harmonic contents, appropriate software can be helpful. In this project, the software chosen to help analyzing harmonic current drawn by power electronic systems is MATLAB/SIMULINK.

Taking the three-phase diode bridge rectifier as an example, a simulation model can be established as shown below. In the model, a three-phase 50Hz AC power supply is used for a resistive load and most devices are not ‘ ideal’. The model is followed by the diagram of input current waveform and frequency spectrum of AC input current. Values of each order harmonic content and total THD are given by Fast-Fourier (FFT) analysis in powergui analysis tools. With the help of Fourier analysis, the performance of harmonic mitigation techniques can be evaluated and compared quickly.

Figure 2. 2 Simulation model for three-phase diode bridge rectifier.

Figure 2. 3 Waveform of rectifier input current (phase A).

Figure 2. 4 Frequency spectra of AC input current of three-phase rectifier.

3. Power Factor Correction Techniques

After tens of years developing and improving, various types of power factor correction techniques or harmonic mitigation techniques can be chosen to solve power factor problem. Those techniques can be divided into five categories [11] [13] as shown below:

1. Passive filters

Passive filters can improve power factor with low cost and reduce high frequency harmonics effectively. However, they are always in large size and cannot vary flexibly with system changes [4] [14]. If tuning reactors are not used, parallel resonance may occur in operation [15].

2. Active filters

Active filters improve power factor and provide stable output even under varying supply condition, and reduce harmonics in the output current effectively and efficiently [4] [16]. These, however, always requires much higher costs and the harmonic currents they injected may flow into other system components [13] [14].

3. Hybrid systems

Hybrid active filters combine active and passive filters together in various forms [17]. Hence they can reduce initial and running costs and improve performance of the filter [11] [13]. Smaller filter inductor, smaller dimension, light weight and better filter performance hybrid system take advantages of both passive and active filters [18]. However, the complexity of operation is the main drawback of hybrid systems.

4. Phase multiplication

Increasing the pulse number of power converters can raise the lowest harmonic order generated by the converter [2]. Typically, 6-pulse converter has the lowest harmonic order of 5 [1]. When rising pulse number to 12, the lowest harmonic order can increase to 11. As value of harmonic current are ideally proportional to fundamental current value [4], the amount distortion of the power system can de reduce to a low level. On the other hand, the effectiveness of this technique is based on balanced load [13] which rarely happens in practice.

5. PWM

PWM converters have much better performance compared to traditional converters like diode rectifiers and square-wave control inverters [4]. As a control strategy improvement, PWM harmonic mitigation technique can even used with some devices for traditional converters and hence get broad application prospect [11]. However, the topology complexity and difficult on designing controllers [19] makes the use of PWM is limited.

The objective of these techniques is to make the input current nearly a pure sinusoidal waveform and hence to improve the power factor in electrical supply system. All these five techniques are discussed separately in the following work.

3. 1 Passive filters

Passive filters have widely been used to absorb harmonics generated by the power electronic systems, primarily due to their simplicity, low cost and high efficiency [20]. Passive filters are always consists inductors, capacitors and damping resistors [21]. The objective of the passive filter is to stop the flow of the harmonic current from disturbing power system, either by preventing them with the usage of series filters or diverting them to a shunt path [9] [11]. That is the different between series filter and shunt filter, too.

Series filters can be tuned LC system or only a single inductor in the system. Parallel inductance and capacitance are tuned to provide low impedance for fundamental frequency current and high impedance for a selected frequency current, always high level harmonic current. The series tuned filters are simple and reliable to use. The circuit configuration can be shown as below.

Figure 3. 1 Series LC tuned filter.

The series tuned filters are always used as input filter for power electronic systems. However, a big drawback limits the using. If the series tuned filter is used in a VSI system as the input filter for the inverter, several order harmonic current need to be filtered, 5th, 7th, and so on. Each order harmonic current required an individual filter, and hence the size of the system can be intolerable.

On the other hand, shunt filter have much more types including shunt-tuned filter, double-band pass filter and 1st, 2nd and 3rd -order damped filters. Also, broadband filters are good solution for filtering wide range of harmonics

[22]. The circuit configurations of these widely used passive filters are like shown below.

(a) (b) (c) (d)

Figure 3. 2 Typical harmonic filters: (a) Single-tuned filter (b) Double tuned filter

(c) High-pass parallel filter (d) C-type high-pass filter [5] [27].

A few single tuned filters cope with large level harmonic contents and a high-pass (2nd order) filter filtering high frequency harmonics is the typical model for shunt passive filters and can get better characteristic than series filters [24]. Take the single tuned filter as example, single-tuned filter also called the band-pass filter as only a selected frequency of current can pass in low impedance. The tuning frequency of the single-tuned filter could be:

(3. 1)

And at this frequency, the impedance of the filter is:

(3. 2)

where s is the Laplace operator, L represents value of inductance and C represents the capacitance value.

However, mostly passive filters can only filtering 30% of harmonic current in the power system [23] and can not match IEEE 519-1992 standard well. Even the broadband filter, which can filter a range of harmonic contents and reduce system THD to approximately 10%, the resonance caused by the filter and the big size of inductor and capacitor still limit the usage of the filter.

So we can get the list of advantages and disadvantages for passive filters shown in table 3. 1.

Advantages

Disadvantages

Effectively for filtering high frequency harmonics

Low availability for low frequency harmonic filtering

Very low cost and reliable

Bulky devices and inflexible devices parameters

Simple structure

Individual branch is necessary for each dominant harmonics in the system

High probability resonance

Table 3. 1 List of passive filter performances [4] [14] [25] [29].

3. 2 Active power filters (APF)

The basic idea of an active filter is to compensate current or voltage disturbance so as to reduce the reactive power electronic systems drawn from the power system [23]. The active filters using in power system are not the same as what we use in electronic circuits. The active filters conventional means combined operational amplifiers and passive components like inductors and capacitors, and always been used in electronic circuits operating under low voltage. That is the beginning of the active compensation applications and came out earlier than active filters using in power systems. The active filters which are used in power system for active power compensation and harmonic compensation are always called Active Power Filter (APF) [30]. The ‘ active’ in APF means the filters are act as power sources or generators and provide compensation currents which have opposite phase angle with the harmonic currents in power system [30]. Similarity between electronic circuit active filters and power system active filters are the requirement of external power supply. The active filters which are talked in the following parts are all means APF.

With the active power filters, the compensation for reactive power and for harmonic current can de done at the same time, hence efficiency on harmonic compensation and also dynamic response are all be improved [23]. The trend of active power filters began in 1970s and was introduced by Mr. Akagi. The incentive for active filters is the inductor is not appropriate to use under high frequency, so the trend is to replace the inductor with active components. As the harmonic contents in the power system various frequently, fast response of active filters required a good control strategy to make active filters ‘ smarter’ and faster. But more complex devices and sophisticated control strategy are required, that all makes active filters more expensive and hard to use [26].

Active filters can also be classified by converter type as shunt-type active filters and series-type active filters. The diagrams of two basic types of active filters are shown below. The other way to classify active filters is the phase number of filters which will be discussed later.

(a) (b)

Figure 3. 3 Diagrams of (a) Shunt-type active filter and (b) Series-type active filter [11] [28].

Series active filters are good at compensate voltage harmonics and capacitive, voltage-source loads. When applied to an inductive or current-source load, a low impedance parallel branch is necessary. Similarly, shunt active filters are always used with inductive, current-source loads and high current distortion conditions. Sometimes over current condition occurs with the use of shunt-type active filters [31].

Typical working principle of the active power filter is:

1. Detection.

The sensor detects the waveform of the instantaneous load current and feedback to the controller, which is typically a digital processing block.

2. Analysis.

Load current is always high distortion current including fundamental current and many orders of harmonic current. The processor must distinguish the fundamental current with the harmonic currents and give out the information including frequency, value, and phase angle of harmonic contents, so as to control the power source inverter providing opposite phase current of harmonic current.

3. Compensation.

The power source inverter draws current from individual DC voltage supply and converting to required current to cancel harmonic currents. Like the diagram shown below.

Figure 3. 4 Diagram of compensation characteristics [31].

Hence, we can draw a conclusion of advantages and disadvantages of active power filters shown in the table below.

Advantages

Disadvantages

High compensation efficiency and high ability on harmonic compensation

Low reliability with sophisticated control system and devices

Small size components

Difficult to construct a large rated current source with a rapid current

Fast action on harmonic current variation makes good dynamic response

High initial costs and running costs

No resonance causing

Complex control strategy and controllers are necessary

Suitable for widely supply and load conditions, like unbalanced power supply

Table 3. 2 List of active power filter performances [13] [22] [30] [31].

3. 3 Hybrid systems

Hybrid filters comes from the idea to combine the advantages of both passive filters and active filters together hence to get brilliant performance on harmonic mitigation [17]. Combine passive filters and active filters can significantly reduce costs and improve the compensation characteristics in the power system. Also, various types of hybrid systems of passive and active filters can get better performance than only passive or active filters.

Like the reference [18] and [20], small rating active power filter and passive filter connected in serial or shunt type. Smaller filter inductor, smaller dimension, light weight and better filter performance hybrid system take advantages of both passive and active filters [18]. However, as the basement of the hybrid power filters are always active power filters, the initial costs and control complexity is still big disadvantages of hybrid systems.

3. 4 Phase multiplication

The purpose of phase multiplication is to increase the pulse number of the converter and hence to increase the harmonic order and frequency [4]. The low frequency harmonics can be mitigated effectively and phase multiplication technique does not cause serious resonance and other bad effects on power system performances [13]. The practical application of phase multiplication technique, the multipulse converters, have the ability to draw low distortion current from power source and generate DC current with low level ripple [32].

Typically, 6-pulse converter has the lowest harmonic order of 5 [1]. When rising pulse number to 12, the lowest harmonic order can increase to 11. As value of harmonic current are ideally proportional to fundamental current value [4], the amount distortion of the power system can de reduce to a low level. Also, the multipulse thyristor converters can output various value current by controlling the thyristor fairing angle () [32].

The drawbacks of phase multiplication technique are mostly the contradiction between the cost and output characteristic. If controlled output is required, the multipulse converter should contain at least 12 switching devices and that can be a big amount of costs. On the other hand, multipulse converter only use diodes may operate on low efficiency [11].

3. 5 PWM

PWM (Pulse Width Modulation) is a modern control technique for power electronic systems. PWM converters have much better performance compared to traditional converters like diode rectifiers and square-wave control inverters [4]. Like the phase multiplication technique, PWM control can raise the frequency of harmonic contents of current so as to reduce the effect caused by harmonics. Also, converters using PWM control can have high efficiency and small size. With all these advantages, PWM control absorbed great concern in modern power conversion systems.

However, the topology complexity and difficult on designing controllers [19] makes the use of PWM is limited.

3. 6 Power factor correction converter

Power factor correction (PFC) converter is a typical active power factor correction method. As a mature technique for power factor correction, PFC converters have been widely used in power electronic systems to achieve high power factor (PF) and low harmonic distortion [33]. PFC convener forces the input current follow the input voltage, which makes the input current drawn from power supply nearly in a unity power factor [34]. The Boost-type PFC converters are the most used topology which have many advantages, such as low level ripple in the input current, high power factor, small size and simple circuit structure [35]. A typical circuit diagram of Boost-type PFC converter is as shown below from reference [36].

Figure 3. 5 Typical circuit diagram of Boost-type PFC converter [36].

As we seen in the diagram before, conventional PFC converter consists two main stages [33] – [37]:

Power factor correction stage.

This stage is combined with a diode rectifier and a DC/DC converter and used to correct power factor of the input current drawn from the power system. The most used type of chopper is Boost chopper. Also, the new Buck and Cuk type PFC converters are increasingly being used now. The switching working principle can be divided into two types, DCM and CCM.

2. DC/DC converter

The chopper here is used to convert the power output voltage and current match the user’s demand. Since choppers only drawn low distortion power from supply, the typical filter on the utilization end is always a passive filter.

This is the working principle for conventional PFC converters, the two-stage DCM/CCM Boost-type PFC converter. However, this type of PFC converter has some disadvantages and need to be improved [33]-[39]:

1. Stage number

Individual control system and switching devices are required for each stage of PFC converter, hence increasing the costs of the whole system and cause some other problems, such as power density, transmission efficiency and control response [38]. Also, the design of control system can be a challenge.

A new one-stage PFC converter topology has been introduced to power factor correction research area. The circuit diagram is as shown in figure 3. 6 [36]. The combination of the power factor correction converter and the forward converter may bring many advantages point as below [36]:

1. High power factor correction performance

2. Reduced value of ripple in the DC output

3. Low initial cost and running cost

4. High efficiency and easy control system

And so on.

Figure 3. 6 Circuit diagram of single stage PFC converter [36].

2. Converter type

Like shown in figure 3. 6, Buck converter is increasingly being used in PFC converters. Also, Cuk converter and other type of choppers are becoming good choice for PFC converters [36]-[39]. The Buck type PFC converter was rarely used since its high input current distortion. However, with the characteristic improving of the Buck type PFC converter, it can reach good performance with specific dual mode duty cycle control scheme [36]. The main advantage of Buck type PFC converter is easy to reduce the stage number to one stage.

3. Devices and control strategy

One of the most important aims in the design of power electronic systems is the reduction of the size of the passive devices, since it allows increase on the power density and the reduction in the initial and running cost. As inductor and capacitor are still using in the PFC converter, the reduction of them can be very important [33] [37].

However, the improvement of devices must base on the developing of the control strategy [37]. With a good detect and control system, the size of the inductor and capacitor can be reduced while the harmonic content can still meet the requirement [33].

The further analysis and improvement of PFC converter based on this literature review will be an important work in the last stage of project.

4. Conclusion

This literature review provides a critical study on power factor issues and power factor correction techniques. A theoretical review of power factor definitions and harmonic generation by power electronic systems are presented at the beginning of the paper. The performance of five basic types of harmonic mitigation techniques has been discussed with the support of many previous research publication and their results. The PFC converter is chosen as the promising system for power factor correction after the analysis and comparison. The simulation model establishment and simulation comparison of power factor correction techniques will be important works for the next period of the project. Also, design rules and guidance of PFC converters will be designed in the next period, too.