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Improved Active Power Filter Performance for Renewable Power Generation Systems

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ABSTRACT:An active power filter implemented with a four-leg voltage-source inverter using a predictive control scheme is presented. Traditionally, active power filters have been controlled using pretuned controllers, such as PI-type or adaptive, for the current as well as for the dc-voltage loops. PI controllers must be designed based on the equivalent linear model, while predictive controllers use the nonlinear model, which is closer to real operating conditions. An accurate model obtained using predictive controllers improves the performance of the active power filter, especially during transient operating conditions, because it can quickly follow the current-reference signal while maintaining a constant dc-voltage. Although active power filters implemented with three-phase four-leg voltage-source inverters are presented in this paper. The use of a four-leg voltage-source inverter allows the compensation of current harmonic components, as well as unbalanced current generated by single-phase nonlinear loads.This paper presents the mathematical model of the 4L-VSI and the principles of operation of the proposed predictive control scheme, including the design procedure. The mathematical model of the active power filter, including the effect of the equivalent power system impedance, is derived and used to design the predictive control algorithm. Predictive control represents a very intuitive control scheme that handles multivariable characteristics, simplifies the treatment of dead-time compensations, and permits pulse-width modulator replacement. The use of a predictive control algorithm for the converter current loop proved to be an effective solution for active power filter applications, improving current tracking capability, and transient response.The compensation performance of the proposed active power filter and the associated control scheme under steady state and transient operating conditions is demonstrated through simulations results. The results are verified by MATLAB/SIMULINK

Key-words: Active Power filter, pulse width modulator, four-leg-voltage-source inverter,PI-controllers

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I. INTRODUCTION

Renewable Generation affects power quality due to its nonlinearity, since solar generation plants and wind power generators must be connected to the grid through high-power static PWM converters [1]. The non uniform nature of power generation directly affects voltage regulation and creates voltage distortion in power systems. This new scenario in power distribution systems will require more sophisticated compensation techniques.

Although active power filters implemented with three-phase four-leg voltage-source inverters (4L-VSI) have already been presented in the technical literature [2]–[6], the primary contribution of this paper is a predictive control algorithm designed and implemented specifically for this application. Traditionally, active power filters have been controlled using pretuned controllers, such as PI-type or adaptive, for the current as well as for the dc-voltage loops [7], [8]. PI controllers must be designed based on the equivalent linear model, while predictive controllers use the nonlinear model, which is closer to real operating conditions. An accurate model obtained using predictive controllers improves the performance of the active power filter, especially during transient operating conditions, because it can quickly follow the current-reference signal while maintaining a constant dc-voltage.

So far, implementations of predictive control in power converters have been used mainly in induction motor drives [9]–[16]. In the case of motor drive applications, predictive control represents a very intuitive control scheme that handles multivariable characteristics, simplifies the treatment of dead-time compensations, and permits pulse-width modulator replacement. However, these kinds of applications present disadvantages related to oscillations and instability created from unknown load parameters [15]. One advantage of the proposed algorithm is that it fits well in active power filter applications, since the power converter output parameters are well known [17]. These output parameters are obtained from the converter output ripple filter and the power system equivalent impedance. The converter output ripple filter is part of the active power filter design and the power system impedance is obtained from well-known standard procedures [18], [19]. In the case of unknown system impedance parameters, an estimation method can be used to derive an accurate R–L equivalent impedance model of the system [20].

This paper presents the mathematical model of the 4L-VSI and the principles of operation of the proposed predictive control scheme, including the design procedure. The complete description of the selected current reference generator implemented in the active power filter is also presented. Finally, the proposed active power filter and the effectiveness of the associated control scheme compensation are demonstrated through simulation and validated with experimental results obtained in a 2 kVA laboratory prototype.

II. RENEWABLE ENERGY RESOURCE

A natural resource qualifiesas a renewable resource if its stock (quantity) can increase over time. Natural resources which qualify asrenewable resourcesare,for xample, oxygen, fresh water, solar energy, timber, and biomass. But they can become non-renewable resources if more of them is used than nature can reproduce in the same time at that place. For example ground water may be removed from an aquifer at a greater rate than that of new water flowing to that aquifer. Removal of water from the pore spaces may cause permanent compaction (subsidence) that cannot be reversed. Human consumption and use at sustainable levels primarily uses renewable resources versus non-renewable resources.

Difference between renewable and non-renewable resources:

Renewable energy:

Renewable energy is energy which is generated from natural sources i.e. sun, wind, rain, tides and can be generated again and again as and when required. They are available in plenty and by far most the cleanest sources of energy available on this planet. For e.g: Energy that we receive from the sun can be used to generate electricity. Similarly, energy from wind, geothermal, biomass from plants, tides can be used this form of energy to another form.

Here are some of the renewable sources of energy:-

Pros:

- The sun, wind, geothermal, ocean energy are available in the abundant quantity and free to use.
- The non-renewable sources of energy that we are using are limited and are bound to expire one day.
- Renewable sources have low carbon emissions, therefore they are considered as green and environment friendly.
- Renewable helps in stimulating the economy and creating job opportunities. The money that is used to build these plants can provide jobs to thousands to lakhs of people.
- You don't have to rely on any third country for the supply of renewable sources as in case of non-renewable sources.
- Renewable sources can cost less than consuming the local electrical supply. In the long run, the prices of electricity are expected to soar since they are based on the prices of crude oil, so renewable sources can cut your electricity bills.
- Various tax incentives in the form of tax waivers, credit deductions are available for individuals and businesses who want to go green.

Cons:

- It is not easy to set up a plant as the initial costs are quite steep.
- Solar energy can be used during the day time and not during night or rainy season.
- Geothermal energy which can be used to generate electricity has side effects too. It can bring toxic chemicals beneath the earth surface onto the top and can create environmental changes.
- Hydroelectric provide pure form of energy but building dams across the river which is quite expensive can affect natural flow and affect wildlife.
- To use wind energy, you have to rely on strong winds therefore you have to choose suitable site to operate them. Also, they can affect bird population as they are quite high.

India has done a significant progress in the power generation in the country. The installed generation capacity was 1300 megawatt (MW) at the time of Independence i.e. about 60 year’s back. The total generating capacity anticipated at the end of the Tenth Plan on 31-03-2007, is 1, 44,520 MW which includes the generation through various sectors like Hydro, Thermal and Nuclear. Emphasis is given to the renewable energy programme towards gradual commercialization. This programme is looked after by the Ministry of Non-

Conventional Sources of energy. Since the availability of fossil fuel is on the decline therefore, in this backdrop the norms for conventional or renewable sources of energy (RSE) is given importance not only in India but has attracted the global attention.

The main items under RSE are as follows:

i) Hydro Power
ii) Solar Power
iii) Wind Power
iv) Bio-mass Power
v) Energy from waste
vi) Ocean energy
vii) Alternative fuel for surface transportation

Evolution of power transformer technology in the country during the past five decades is quite impressive. There are manufacturers in the country with full access to the latest technology at the global level. Some of the manufacturers have impressive R&D set up to support the technology.

Renewable energy is very much promoted by the Chinese Government. At the same time as the law was passed, the Chinese Government set a target for renewable energy to contribute 10% of the country's gross energy consumption by 2020, a huge increase from the current 1%.

It has been felt that there is rising demand for energy, food and raw materials by a population of 2.5 billion Chinese and Indians. Both these countries have large coal dominated energy systems in the world and the use of fossil fuels such as coal and oil releases carbon dioxide (Co_2) into the air which adds to the greenhouse gases which lead to global warming.

Renewable Energy Development in India

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There are about 80,000 villages yet to be electrified for which provision has been made to electrify 62,000 villages from grid supply in the Tenth Plan. It is planned that participation of decentralized power producers shall be ensured, particularly for electrification of remote villages in which village level organizations shall play a crucial role for the rural electrification programme.

Emphasis is given to the renewable energy programme towards gradual commercialization. This programme is looked after by the Ministry of Non-Conventional Sources of energy. Simultaneously private sector investments in renewable energy sources are also increased to promote power generation. So far an excessive reliance was preferred on the use of fossil fuel resources like coal, oil and natural gas to meet the power requirement of the country which was not suitable in the long run due to limited availability of the fossil fuel as well as the adverse impact on the environment and ecology.

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Hydro Power:-

India is endowed with a large potential of hydro power, of which only 17% has been harnessed so far. The hydro electricity is a clean and renewable source of energy. It has been felt that there is a long gestation period in hydro projects due to delays in forest and environment clearance, rehabilitation of the project effected people besides inter-state disputes and construction holdups due to several reasons. Under RSE only small hydro projects are considered since they do not require large pondage and have the capacity to provide power to remote and hilly terrain where extension of the grid system is either un-economic or not possible. It has been estimated that the potential available in the country under small hydropower schemes is of the order of 15000 MW in which the plans that are considered are up to 25 MW capacity individually which are classified as small hydro projects under the Ministry of Non-Conventional Sources of energy. The small hydro power stations are mostly located in hilly areas and are given priority for local benefits to the residents which provide them gainful employment through the energy potential.

Solar Power:-

The climatic condition in India provides abundant potential of solar power due to large scale radiation available during a wider part of the year due to tropical condition in the country. The solar power can be developed for long term use through the application of solar photo- voltaic (SPV) Technology which provides a potential of 20MW per sq. Km. The other method for Utilization of solar energy is through the adoption of solar thermal Technology. The programmes are under way to utilize SPV by connecting to grid power systems.

It has come to notice from a report of Xinhva news agency that Shanghai, the business capital of China, is launching a 100000 rooftop solar photo voltaic (SPV) system which would generate 430 million KWH of electricity which would be enough to supply power to the entire city for two days.

The other popular use is by stand- alone applications which include solar powered street lights, domestic lights, water pumps etc. The cost of the photo SPV modules is quite expensive which is in the range of $ 3-4 per watt, in spite of best efforts, the price could not come down in India, China and other countries. The effort is to bring the price down to $ 1 per watt when it may be more popular for use. The efforts to use amorphous silicon technology were cheaper but its long terms use is not practicable. The SPV technology if cheep, would be useful for people living in far - flung areas as extending grid would involve high cost.

The solar thermal devices are widely used in the country for various purposes such as solar water heaters, solar cookers, solar dryers etc. There is wide scope for development of solar thermal application for which the research is in progress. The energy obtained through Solar Thermal route is 35 MW per sq. km.

Wind Power

The wind power development in the country is largely of recent period which has been found to be quite impressive. As per available data, it is 5340 MW by March 31, 2006, through wind power. Earlier it was estimated that the potential for wind power in the country was 20,000 MW which has been revised to 45000MW after collecting the data on the potential available in the coastal and other areas of the country.

At present India is fifth in the world after Germany, USA, Denmark and Spain in terms of wind power. It has been observed that the private sector is showing interest in setting of wind power projects. The unit size of wind turbine generators which were earlier in the range of 55-100 kw are now preferred in the range of 750-1000 kw. It has been observed that the productivity of the larger machine is higher as compared to the smaller machine. In respect of cost consideration, it has been noticed that the cost of such a project is about Rs.40 million to Rs.50 million per MW which includes all local civil, electrical works and erection also. The life of a wind power project is estimated to be about 20 years.

China has guaranteed all certified renewable energy producers in its service area that the grid will purchase their power and the price will be spread out to all the users across the grid. According to sources, such commitments can only spur further development in the renewable energy sector.

Bio-mass Power

There is quite a high energy potential available in the country in resources such as firewood, agroresidues and animal wastes. These resources are mainly utilized by the rural population of the country. It has been estimated that there is a potential to install 19500 MW capacity through biomass conservation technologies like combustion, gasification, incineration and also bagasse – based co-generation in sugar mills. So far only around 380 MW of this potential has been tapped and there is wide scope for expanding the size of their use for the benefit of the majority of the rural population to meet their energy needs.

Energy from Waste

It has been estimated that there is about 30 million tones by solid waste and 4400 million cubic meters of liquid waste generated every year in urban areas through domestic as well as commercial establishment. The manufacturing sector also contributes high quantity of waste. It has been estimated that through garbage there is a potential to generate 1700 MW of electricity. However all these activities are still to be given a practical shape.

Ocean Energy

The Ocean on the earth covers about 71% of the total surface which collects and store solar energy. If this energy is quantified in terms of Oil, it can be said that an amount of solar radiation equivalent in heat content to about 245 billion barrels of oil is absorbed by the sea. The energy available in the Ocean is clean, continuous and renewable. In future it would be possible to tap energy from the sea.

Alternative fuel for surface transportation:
Hydrocarbons used as fuels for transportation are to be replaced by other eco-friendly fuels for surface transport vehicles. Many options such as compressed natural gas (CNG), battery – powered vehicles and fuel cells are currently available.
The use of diesel in transportation in Delhi was causing pollution in the air. The Government has adopted CNG use for all vehicles using diesel fuel, which has improved the environment significantly

Policy followed in China.

Renewable energy is very much promoted by the Chinese Government. Earlier the emphasis was quite low but of late it has been observed that a high priority is given to renewable sources of energy. The new law stipulates the responsibilities of government and society in developing and applying renewable energy. At the same time as the law was passed, the Chinese Government set a target for renewable energy to contribute 10% of the country's gross energy consumption by 2020, a huge increase from the current 1% Seeing this as a future stimulus of renewable energy development, many Chinese and international observers are very excited, expecting a tremendous growth in the renewable energy market in the next 15 years as the result of the implementation of this law.

The policy adopted also provides subsidies and tax credits. However, wind power development in China has lagged far behind the world leaders in the past 10 years The total installed capacity only hit 769 MW recently, whereas, in India, the second largest developing country, the total capacity is 5340 MW. Between 1999 and 2002, only 211 MW was installed in China, while globally, 18,000 MW was added during the same period.

Transformer Technology

Transformers were first used in India in 1897 to light Darjeeling Municipal area. The commercial production of transformers commenced. in 1936 at Government Electrical factory, Bangalore. Later on new companies have started production and improvement in the Transformer Technology. When transformer factories were set up in 1960s there were no vendors in the country to supply processed raw materials and accessories.
Evolution of power transformer technology in the country during the past five decades is quite impressive. There are manufacturers in the country with full access to the latest technology at the global level. Some of the manufacturers have impressive R&D set up to support the technology.

Amorphous Metal Distribution Transformer
Huge amount of energy has been lost due to no-load loss of transformer core. Energy efficient transformer such as AMDT can effectively lower such energy wastage and at the same time reduce green house gases emission.
Reliability in distribution system can be brought about by incorporating following steps.

- Use transformers, which have minimum maintenance problems.
- Improve power factor of the system.
- Ensure proper protection to the system.
- Neutral grounding system should be effective.
- Introduce maintenance free equipment like Vacuum Circuit Breakers for all 11 KV feeders with auto re-closers.
- Undertake preventive maintenance and avoid emergencies.

Global warming and climate change

It has been felt that there is rising demand for energy, food and raw materials by a population of 2.5 billion Chinese and Indians. Both these countries have large coal dominated energy systems in the world and the use of fossil fuels such as coal and oil releases carbon dioxide (Co_2) into the air which adds to the greenhouse gases which lead to global warming. At present US is the largest contributor of Co_2 emissions but the development in India and China is going to increase their share in emission of such a gas. According to Kyoto Protocol this has to be controlled. Climate change shall be a cause of extinction of many bird varieties and other animals on the earth.
Renewable source of energy is the best solution for such a problem in the world. Both India and China are trying to develop their technology in this regard. India has the world's fourth largest wind power industry, while China is the global leader in harnessing solar energy for hot water.

Wind Power could generate almost 29 percent of the world's electricity by 2030 and was growing faster than any other clean energy source, a wind business group and environmental lobby Greenpeace said. 'At good locations wind can compete with the cost of both coal and gas-fired Power' the Global Wind Energy Council (GWEC) and Greenpeace said in a study, 'Global Wind Energy Outlook 2006'.The two said that wind, which now accounts for 0.8 percent of the world's electricity supply, was expanding faster than other renewable energies such as solar, geothermal or tidal power in a shift from fossil fuels.

There have been cases of farmers committing suicides due to poverty and failure of crop in some parts of India. A World Bank study released has found a correlation between climate change and farmer suicides. It says poor farmers who are unable to adapt to changing climates fall into debt and later, death traps. It can be surmised that energy development should be preferable by adopting measures which does not give rise to greenhouse gasses as it would effect change in climate leading to overall difficulties to the people who are accustomed to the climate as prevailing on the earth.

III. ACTIVE POWER FILTERS

Active Filters are commonly used for providing harmonic compensation to a system by controlling current harmonics in supply networks at the low to medium voltage distribution level or for reactive power or voltage control at high voltage distribution level. These functions may be combined in a single circuit to achieve the various functions mentioned above or in separate active filters which can attack each aspect individually. The block diagram presented in section shows the basic sequence of operation for the active filter. This diagram shows various sections of the filter each responding to its own classification.

Classification of active filters

The block diagram shown in figure represents the key components of a typical active power filter along with their interconnections. The reference signal estimator monitors the harmonic current from the nonlinear load along with information about other system variables. The reference signal from the current estimator, as well as other signals, drives the overall system controller. This in turn provides the control for the PWM switching pattern generator. The output of the PWM pattern generator controls the power circuit through a suitable interface. The power circuit in the generalized block diagram can be connected in parallel, series or parallel/series configurations, depending on the transformer used.

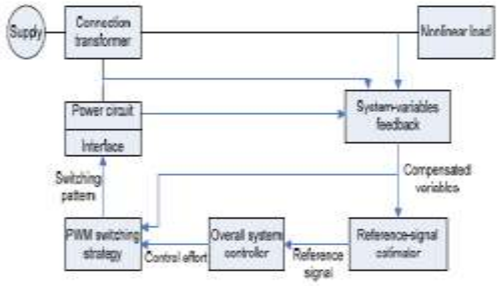

Figure 3.1 Generalized block diagram for active power filters [2]

Active power filters according to can be classified based on the following criteria:
1. Power rating and speed of response required in compensated systems;
2. Power-circuit configuration and connections;
3. System parameters to be compensated;
4. Control techniques employed; and
5. Technique used for estimating the reference current/voltage.

Classification according to power rating and speed of response in compensated system

The block diagram shown in figure shows the classification based on this criterion. The size of nonlinear loads play a major role in deciding the way different control methods are implemented. The filter required for compensation must be practical for the load and this decision affects the speed of response. In general a reciprocal relationship exists between the cost of a particular system to the required speed of response.

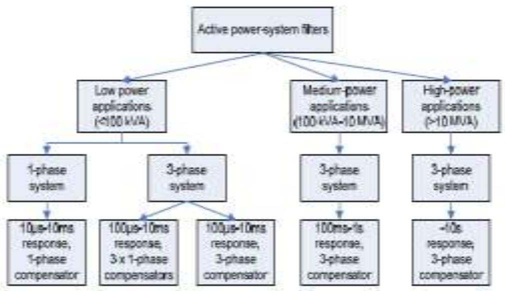

Figure 3.2 Subdivisions of active filters according to speed response and power rating [2]

Low power applications

Low power applications govern applications with a power rating below 100kVA. Applications of these sizes are generally associated with residential areas, commercial buildings, hospitals and for a wide range of medium sized factory loads and motor drive systems. Active filters chosen for this power range employ sophisticated techniques catering with high pulse number PWM voltage or current source inverters. The response time for smaller applications is relatively much faster than other sizes ranging from ten microseconds to ten milliseconds. This type comprises the following two categories.

Single-phase systems

Low power rating loads generally require single phase active filters. They are generally most employed in commercial buildings with a large number of computers. This application means that current harmonics can be treated at the point of common coupling (PCC). It is often economical and practical to install single phase active filters on distribution based sites of reduced size capacity than a larger rated filter installed upstream. This is due to the large number of the single-phase loads within one building and the harmful consequences associated with the presence of large amounts of harmonic in the neutral line. This allows for more selective compensation as the operating conditions vary. Due to the load capacity drawn from residential loads, it is rare for a high concentration of harmonics, and thus the impacts on the neutral lines are not significant. Residential customers tend not invest in purchasing active filters because there are no compulsory harmonic regulations however, the main advantage of such an installation are that operating frequencies can be increased moving to improved performance since only low ratings are employed.

Three-phase systems

The installation of three-phase filters is used for three-phase applications. Different filter configurations can be tested and installed based upon whether the loads are balanced or unbalanced. At levels below 100kVA, a three phase filter can be reconfigured to compensate for three individual single phases in one unit or for a single three-phase supply. When nonlinear loads are balanced, meaning all three phased impedances are equal, a single three-phase-inverter configuration is employed. This choice of inverter is used when the objective is to eliminate as many current harmonics as possible, assuming that the magnitudes and respective phase angles in each phase are the same. In the situation when nonlinear loads are unbalanced, or supply voltages are unsymmetrical, three single phase inverter circuits are used.

Medium power applications

Power systems ranging between 100kVA to 10MVA fit the class of a medium power application. Due to the fact that phase unbalances are reduced on this sized system, the major objective is to eliminate current harmonics. In general, capacitive andInductive static compensators, line-commutated thyristor converters, synchronous condensers and cascaded multilevel-inverter VAR compensators, are often more economic as reactive power compensation using active filters often is not viable. This is due to the high voltage as well as problems with isolation and series/parallel connection of switches. The speed of response expected in this range is of the order of tens of milliseconds.

High power applications

At high power ratings, the use of active filters becomes very uneconomical. This is because of the lack of high switching frequency power devices that can control the current flow. Thus, this is a major disadvantage for such systems. In addition, even the latest advances in semiconductor technology still fall short as extra high voltages of a few hundred kilovolts cannot be tolerated. The series-parallel combination is possible however; implementation is difficult and also cost-ineffective. Harmonic pollution upstream affecting high power ranges above 10MVA is not such a problem compared against low power systems. The implementation of single and three phase filters downstream at the low voltage system provides suitable compensation such that significant harmonic pollution upstream is minimal. The static-VAR compensation is then the major concern and is usually compensated for by using traditional static power conditioners/filters as well as several sets of synchronous condensers connected in parallel and cascaded multilevel-inverter VAR compensators. The required response time for such cases is in the range of tens of seconds, which is sufficient for contactors and circuit breakers to operate after taking the optimal-switching decision. Power fluctuations in the range of a few seconds are, on the other hand, treated by the generating stations' ancillary devices.

Classification according to power circuit, configurations and connections

The choice of power circuit chosen for the active filter greatly influences its efficiency and accuracy in providing true compensation. It is therefore important that the correct circuit configuration is chosen. Figure 3.3 classes' three major types of filter structures along with the relevant power circuit.

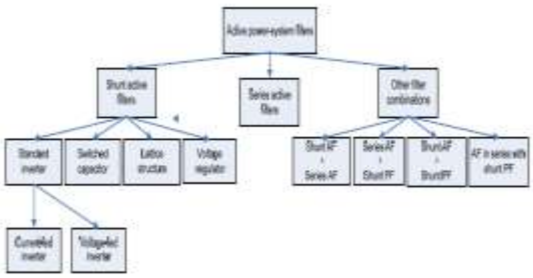

Figure 3.3 Subdivision of power system filters according to power circuit configurations and connections [1]

Shunt active filters

Shunt active filters are by far the most widely accept and dominant filter of choice in most industrial processes. Figures show the system configuration of the shunt design. The active filter is connected in parallel at the PCC and is fed from the main power circuit. The objective of the shunt active filter is to supply opposing harmonic current to the nonlinear load effectively resulting in a net harmonic current.

This means that the supply signals remain purely fundamental. Shunt filters also have the additional benefit of contributing to reactive power compensation and balancing of three-phase currents. Since the active filter is connected in parallel to the PCC, only the compensation current plus a small amount of active fundamental current is carried in the unit. For an increased range of power ratings, several shunt active filters can be combined together to withstand higher currents. This configuration consists of four distinct categories of circuit, namely inverter configurations, switched-capacitor circuits, lattice-structured filters and voltage-regulator-type

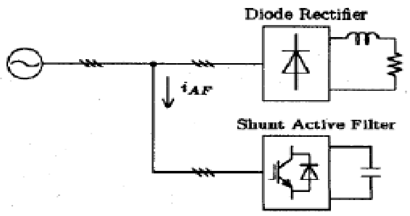

Figure 3.4 Shunt active filter used alone [4]

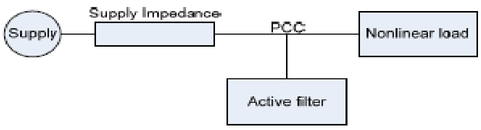

Figure 3.5 Shunt active filter network configuration [2]

Series active filters

The objective of the series active filter is to maintain a pure sinusoidal voltage waveform across the load. This is achieved by producing a PWM voltage waveform which is added or subtracted against the supply voltage waveform. The choice of power circuit used in most cases is the voltage-fed PWM inverter without a current minor loop. The active filter acts as a voltage source and thus it is often a preferred solution of harmonic producing loads such as large capacity diode rectifiers with capacitive loads. In general, series active filters are less commonly used against the shunt design. Unlike the shunt filter which carries mainly compensation current, the series circuit has to handle high load currents. This causes an increased rating of the filter suitable to carry the increased current. Series filters offer the main advantage over the shunt configuration of achieving ac voltage regulation by eliminating voltage-waveform harmonics. This means the load contains a pure sinusoidal waveform.

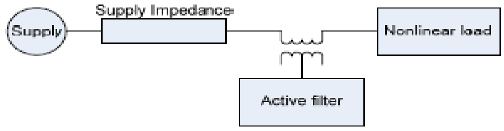

Figure 3.6 Series active filter configuration [2]

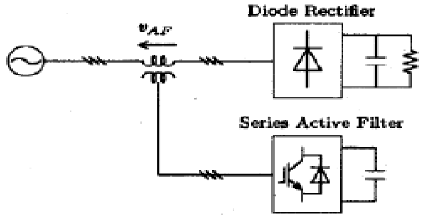

Figure 3.7 Series active filter used alone [4]

Other combinations

In some cases, the combinations of shunt and series active filters provide a greater effectiveness in eliminating harmonic pollution from the system.

Combination of both shunt and series active filters

The diagram shown in figure shows the combination of both parallel and series active filters. This system combines both the benefits of the shunt and series and is often used to achieve the demanding power system requirements. The control of active filters can be complex. A combination of the two provides an even greater complexity. The higher cost involved in a more complex design has shown a reduced demand for the combined structure. As a result of the increased cost and complexity, this combination has received less attention than other configurations. Flexible AC transmission systems, commonly abbreviated as FACTS regularly make use of the arrangement.

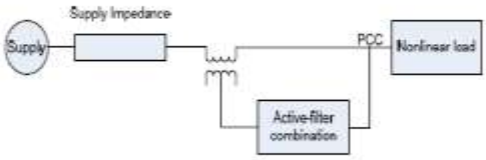

Figure 3.8 Combination of shunt and series active filters [2]

Combination of series active and shunt passive filters

The combination of the active parallel and active series filters in 3.4.3.1 was seen to be very complex in control yielding a high cost. One method of reducing these problems was to replace the parallel active filter with a passive structure. The series active filter, which constitutes high impedance for high-frequency harmonics, is accompanied by a parallel passive filter to provide a path for the harmonic currents of the load. This combination, represented by figure, permits an improvement over the characteristics of plain series active filters and the extension of their capabilities to include current- harmonic reduction and voltage-harmonic elimination. Passive filters are often easier and simple to implement and do not require any control circuit. This, this deserves to be most beneficial.

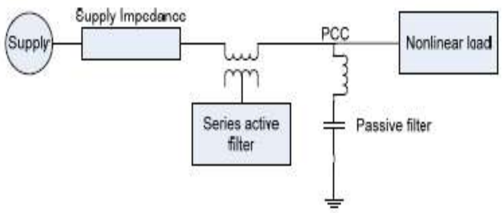

Figure 3.9 Series active and shunt filter combination [2]

Combination of shunt active and passive filters

Shunt active filters are best suitable to compensate for lower order harmonics thus only requiring low power rating which serves most economical. This configuration makes use of a passive filter which serves to compensate for the high order load current harmonics. This combination, represented by figure presents this important configuration. Combinations such as this can be designed to compensate for higher powers without excessive costs for high-power switching. The major disadvantage of this configuration is the fact that passive filters can only be tuned for a specific predefined harmonic and thus cannot be easily changed for loads which have varying harmonics.

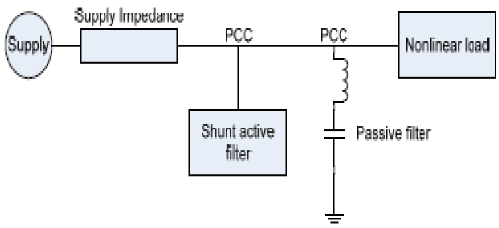

Figure 3.10 Shunt active and shunt passive filter combination [2]

Active filter in series with shunt passive filters

The combination of an active filter in series with a shunt passive filter is considered a significant design configuration for medium and high voltage applications. The passive filter is designed to reduce the voltage stress applied to the switches in the active filter. This design is in its infancy of development however, further research is still needed to assess the effectiveness of the configuration.

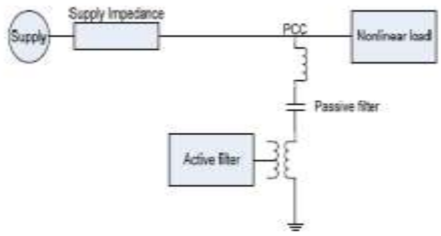

Figure 3.11 Active filter in series with shunt passive filter combination [2]

Classification according to compensated variable

Active filters are designed to provide suitable compensation for a particular variable or a multiple of sorts in cases of combination structures. Figure shows the variety of compensated variable that active filters can provide for.

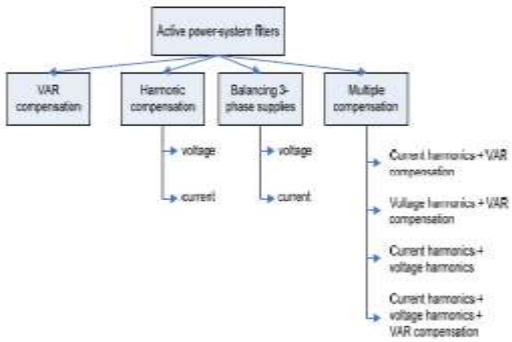

Figure 3.12 Subdivision according to compensated variables [2]

Reactive power compensation

The shunt active filter does provide reactive power compensation however; they rarely treat the problem of power-factor correction on its own owing to the fact that other quasidynamic, cheaper and slower-in-response reactive-power compensators are available in the market. When this technique is applied, lower power applications are more suited since the currents needed for reactive-power compensation are of the same order of magnitude as the rated current of the load. It would be a waste of sophisticated equipment to tackle them without the use of other power factor-correction devices, such as thyristor-controlled reactors and capacitors; especially in single-phase systems, where in certain specific applications the requirement is for accurate compensation without harmonics generation.

Harmonic compensation

Within the system, active filters can be used to provide suitable harmonic compensation for voltage harmonics and current harmonics. These harmonic are the most important variable requiring compensation.

Compensation of voltage harmonics

In general, the concern for compensating voltage harmonics is not high due to the fact that power supplies usually have low impedance. Generally, at the point of common coupling, ridged standards are implemented to ensure a correct level of total harmonic distortion (THD) and voltage regulation is maintained. The problem of compensating for voltage harmonics is to ensure the supply to be purely sinusoidal.

This is important for harmonic voltage sensitive devices such as power system protection devices and superconducting magnetic energy storage. Voltage harmonics are related to current harmonics by the impedance of the line. Although compensation of voltage harmonics helps to provide a reduction in current harmonics, this however, does not negate the necessity to current harmonic compensation.

Compensation of current harmonics

Current harmonic compensation strategies are exceptionally important. Current harmonics are greatly reduced by the compensation of voltage harmonics at the consumer's point of common coupling. The reduction in current harmonics is not only important for reasons such as device heating and reduction in life of devices but also in design of power system equipment. One of the major design criteria covers the magnitude of the current and its waveform. This is to reduce cable and feeder losses. Since the root mean square (RMS) of the load current incorporates the sum of squares of individual harmonics, true current harmonic compensation will aid system designers for better approached power rating equipment.

Balancing of three phase systems

In most low and medium voltage distribution systems, it is frequent to find situations where the currents and voltages in the three phases are not balanced and are not evenly distributed by 120 degrees.

Balancing of mains voltage in three phase systems

Voltage imbalance is a situation where each phase voltage is unequal in magnitude and is not displaced by 120 degrees. This is a direct result of current imbalances and the severity of the system imbalances is governed by the magnitude of the supply impedance. The solution to this problem is to add or subtract the corresponding amount of instantaneous voltage to force it to follow the reference sinusoidal waveform. On high voltage systems, the supply impedance does not impact severely on system performance and thus the problem of mains voltage unbalances are primarily related to low rating systems.

Balancing of mains current in three phase systems

In low power applications such as compensating for residential loads, the magnitude of currents supplied to the grid depends entirely upon the level of imbalance in the system. In most cases, the compensator would be forced to supply rated current. This places a limitation on the power handling capability.

Multiple compensation

To target a variety of variables requiring compensation, often it is usual to combine different combinations to improve the effectiveness of the filter. The following are the most frequently used combinations.

Harmonic current with reactive power compensation

One very common filter design makes use of combining aspects of reactive power compensation together with harmonic current elimination. This ensures the supply current remains purely fundamental free from distributing harmonics whilst making certain the current is in phase with the supply voltage. This approach is very cost effective because only one device is used for all aspects rather than including multiple circuits for each individual objective. The active filter used here however, suffers from poor power switching limits and thus can only serve as a compensator for low powered applications.

Harmonic voltages with reactive power compensation

This combination, however rare, takes place in certain configurations for controlling the voltage harmonics, which would normally affect indirectly (using suitable feedback) the reactive-power compensation. This compensation system is only suitable for low-power applications.

Harmonic current and voltages

To compensate for both current and voltage system harmonics, a shunt and series active filter configuration must be used respectively. Integrating this filter serves to eliminate load harmonics whilst ensuring the supply remains fundamental. This type of design contains very complex control algorithms and is normally used only for very sensitive devices such as power-system-protection equipment and superconducting magnetic-energy storage systems.

Harmonic current and voltages with reactive power compensation

This filter design incorporates all three compensating variables into one unit. It controls all harmonics and reactive power within the system. This is achieved by implementing of a parallel/series active filter combination. The control for this design is very complex and difficult to maintain and thus is not often employed.
Classification based upon control technique
Figure presents the basic control structure for active power system filters. The two main techniques are open look control and closed loop control.

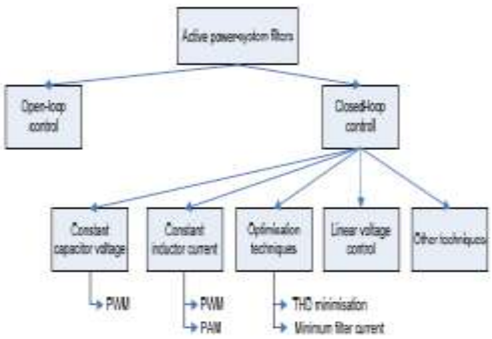

Figure 3.13 Classification of active power filters according to control techniques [2]

Open loop systems

Open-loop systems sense the load current and the harmonics it contains. They inject a fixed amount of power in the form of current (mainly reactive) into the system, which may compensate for most of the harmonics and/or reactive power available. Since there is no feedback loop on this system, there is no reference to check the performance and accuracy of the filter. This is a traditional technique and in present day is not often used.

Closed loop systems

Closed loop control systems incorporate a feedback loop providing greater accuracy of current injection for harmonic compensation as well as reactive power reduction well over the open loop design. This feature enables true sensing of the required variables under consideration. Almost all new techniques in use are of this type.

Constant capacitor voltage technique

In this technique, the DC link contains a capacitor and once charged, this capacitor voltage is the voltage source which controls the current waveform by PWM techniques. The voltage across the terminals of the capacitor often fluctuates due to the fact that energy is either supplied or expelled. To regulate and maintain terminal voltage levels, a reference voltage is chosen.

The difference between the actual capacitor voltage and the predefined reference voltage determines the active component of power required to compensate for losses in the filter. This error difference is added to the current-controller error signal to determine the overall system error to be processed by the current controller. This technique is widely accepted and is very popular.

Constant inductor current technique

The control replaces the use of the capacitor in the DC link with an inductor. The system operates much the same as mentioned in 3.6.2.1 however; the capacitor voltage is replaced with the inductor current. This is achieved in two ways: (i) current pulse-width modulation where like in the PWM provides the required pulses to represent the average current signal and (ii) current pulse amplitude modulation which is a new control method provides the active filter with a basis for amplitude modulation rather than solely the width.

Optimization technique

The optimization procedure for switched-capacitor and lattice-filter circuits is the same. The rate of rise of the current and the amplitude depend mainly on the size of the capacitors and the initial voltages on them. These factors are functions of the switching patterns, and they provide considerable flexibility in shaping the waveform of the current drawn by the filter. The key to controlling these filter configurations is to determine the appropriate switching function for the switches.

The main task of the system controller is to minimize a predetermined number of individual load-current harmonics, in addition minimizing either the THD or the fundamental component of the filter current. However, this is not performed instantaneously. A time delay exists between the detection of a change in the harmonic current and the application of the new set of switching angles obtained from the optimization procedure. This system is mainly suitable for constant or slowly varying loads.

Linear voltage control technique

Series active filters incorporating the additional benefit of voltage regulation can be controlled using the linear voltage control technique. Through regularly charging and discharging the capacitor through linear control, the capacitor voltage can be regulated. The reference capacitor voltage can be determined based upon the harmonic reference.

The charge in the supply loop of the circuit and thus switching frequency can be controlled by the regular variations of the capacitor voltage in contrast to the abrupt changes in inverter voltage waveforms. This technique ensures that the supply side receives no abrupt variation of voltage and this reduces the amount of high-frequency harmonics injected into the supply due to the presence of the PWM inverter.

Other techniques

Other control techniques exist that simply provide small changes to the aforementioned techniques, providing simply newer or better performance over their predecessors. These techniques may include the use of state of the art adaptive, predictive and sliding-mode controllers, which are normally difficult to implement without the use of Digital Signal Processing (DSP). These techniques can be implemented in either the time domain or the frequency domain.

Active filters harmonic detection and extraction

A shunt active filter acts as a controllable harmonic current source. In principle, harmonic compensation is achieved when the current source is commanded to inject harmonic currents of the same magnitude but opposite phase to the load harmonic currents. Before the inverter can subtly inject opposing harmonic currents into the power system, appropriate harmonic detection strategies must be implemented to efficiently sense and determine the harmonic current from the nonlinear load.

Types of harmonic detection strategies

There are 3 different types of harmonic detection strategies used to determine the current reference for the active filter. These are

1. Measuring the load harmonic current to be compensated and using this as a reference command;
2. Measuring source harmonic current and controlling the filter to minimize it; and
3. Measuring harmonic voltage at the active filter point of common coupling (PCC) and controlling the filter to minimize the voltage distortion.

Load current sensing

This method involves measurement of the load current and subsequent extraction of its harmonic content using a high pass filter scheme. The harmonic components, so extracted, are adjusted for polarity and used as reference commands for the current controller. This is explained with the help of equation 3.1 and figure 3.14. Denoting the harmonic components of the load current by, the describing equation for this strategy is lhi

$$i^*_c(t) = i_{lh}(t)$$

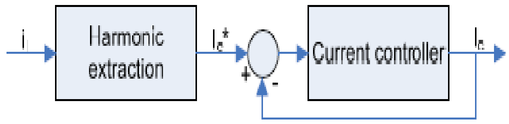

Figure 3.14 Load current sensing compensation schematic [7]

Source current sensing

In this strategy, the source current is measured and its harmonic component extracted. This is scaled by a suitable controller, generally of the proportional type. The output of the proportional controller is provided as a reference to the current controller. This is schematically represented in figure and analytically expressed by equation. Denoting the harmonic components of the source current byshi, the describing equation for this strategy is

$$i^*_c(t) = -K_{sh} \times i_{sh}(t)$$

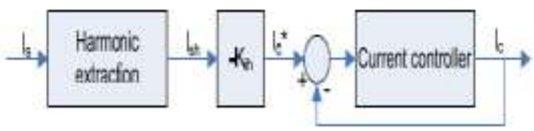

Figure 3.15 Source current sensing compensation schematic [7]

Point of Common Coupling (PCC) voltage sensing

This method requires measurement of the harmonic component of the Point of Common Coupling (PCC) voltage, e(t). The harmonic component is then used to generate the current reference, after passing it through a proportional controller. Schematically, it is represented in figure and analytically expressed by equation

Denoting the harmonic components of the PCC voltage by, the describing equation for this strategy is

$$i_c^*(t) = K_{vh} \times e_h(t) \quad (3.3)$$

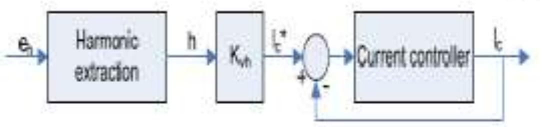

Figure 3.16 PCC voltage sensing compensation schematic [7]

Load current sensing and supply current sensing are suitable for shunt active filters installed in the vicinity of one or more harmonic producing loads by individual high-powered consumers. PCC voltage sensing is suitable for shunt active filters, which will be installed on distribution systems by utilities. Supply current detection is the most basic harmonic detection method for series active filters acting as a voltage source.

Classification based upon current/voltage reference estimation technique

There are numerous techniques each sub classified in figure which propose methods to calculate and determine the appropriate compensating reference current used for the active filter to pass to the PWM inverter.

Figure 3.17 Subdivision according to current/voltage estimation techniques [2]

Current/voltage reference synthesis (continuous time-domain)

In this method, an analogue signal filter is applied at the supply side to determine the current harmonics from the supply. This technique is very simple and easy to implement however introduces major amounts of magnitude and phase errors.

High pass filter method

This method uses a high pass filter to pass high ordered frequencies effectively removing low order components in the load current signal. The filtered frequencies constitute the reference portion. This technique however, is susceptible to noise as this is undesired.

Low pass filter method

This method is favored in terms of reference synthesis because unlike the high pass filter method, the effects of noise in the filtered portion are suppressed. The desired reference value is the harmonic component found in the load current. This is determined by subtracting the low order frequency component found from implementing a low pass filter from the total load current. This presents the harmonic portion from the load current waveform. This technique however, introduces large magnitude and phase errors.

Current/voltage reference calculation (discrete time or frequency domain)

The techniques mentioned have many disadvantages to their use namely, phase and magnitude errors as well as the effects of noise. The calculation of harmonics therefore provides the most appropriate alternative. Two major techniques are classified in either time domain or frequency domain.

Time domain approaches

The following seven subdivisions of time-domain approaches are mainly used for three-phase systems except for the fictitious-power-compensation technique which can be adopted for single- or three-phase systems. The time-domain methods are mainly used to gain more speed or fewer calculations compared to the frequency-domain methods.

Instantaneous reactive power algorithm

Instantaneous power theory determines the harmonic distortion from the instantaneous power calculation in a three-phase system, which is the multiplication of the instantaneous values of the currents and voltages .

$$\begin{pmatrix} p \\ q \end{pmatrix} = \begin{pmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{pmatrix} \cdot \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} \quad (3.4)$$

The values of the instantaneous power p and q, which are the real and respective imaginary powers, contain dc and ac components depending on the existing active, reactive and distorted powers in the system. The dc components of p and q represent the active and reactive powers and must be removed with high-pass filters to retain only the ac signals. The ac components converted by an inverse transformation matrix to the abc-frame represent the harmonic distortion, which is given as the reference for the current controller. These processes are depicted in figure.

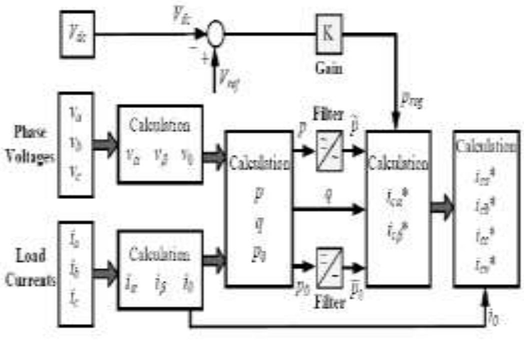

Figure 3.18 Calculations for the constant instantaneous supply power control strategy [8]

This operation takes place only under the assumption that the three-phase system is balanced and that the voltage waveforms are purely sinusoidal. If, on the other hand, this technique is applied to contaminated supplies, the resulting performance is proven to be poor.

Synchronous detection algorithm

This technique relies in the fact that the three phase currents are balanced. The average power is calculated and divided equally between the three phases. The signal is then synchronized relative to the mains voltage for each phase. This technique, however easy to implement, suffers from the fact that it depends to a great extent on the harmonics in the voltage signal.

Constant active power algorithm

The instantaneous and average powers of the load are calculated. The active power component of the system is controlled to keep the instantaneous real power constant, while maintaining the imaginary power to zero. This technique performs fairly well under ordinary conditions. However, the performance deteriorates when the supply is contaminated.

Constant power factor algorithm

This technique forces the instantaneous current signal to track the voltage-reference waveform. This implies that the power factor is fixed to unity and the system would only be suitable for the combined system of VAR and current-harmonic compensation.

Fictitious power compensation algorithm

The system controller is designed to minimize the undesired component of power. In this aspect, it is similar to the instantaneous-reactive-power algorithm but with a different definition of power. This approach is suitable for both single and three phase systems. However it involves a large amount of computation.

Synchronous frame based algorithm

This algorithm relies on Park transformations to transform the three phase system from a stationary reference frame into synchronously rotating direct, quadrature and zero-sequence components. These can easily be analysed since the fundamental- frequency component is transformed into DC quantities. The active and reactive components of the system are represented by the direct and quadrature components, respectively. The high-order harmonics still remain in the signal; however they are modulated at different frequencies. These are the undesired components to be eliminated from the system and they represent the reference harmonic current. The system is very stable since the controller deals mainly with DC quantities. The computation is instantaneous but incurs time delays in filtering the DC quantities. This method is applicable only to three-phase systems.

Synchronous flux detection algorithm

This technique applies Park transformations to transfer the system into synchronously rotating direct, quadrature and zero-sequence frames of reference. However, it applies the transformation on the flux linkage of the filter inductance, which is then controlled using the output voltages and currents in separate integral loops. The presence of these integral loops incorporates time delays, which depend on the frequency response of the special feed forward and feedback integrators.

Frequency domain approaches

The frequency-domain methods are mainly identified with Fourier analysis, rearranged in such a manner that this provides the result as fast as possible with a reduced number of calculations, to allow a real-time implementation in DSP's. Once the Fourier transform is taken, the APF converter-switching function is computed to produce the distortion canceling output. With this strategy the inverter switching frequency must be more than twice the highest compensating harmonic frequency. This strategy has a poorer dynamic response and it not as widely used.

Conventional Fourier and FFT algorithms

Using the Fast Fourier Transform (FFT), the harmonic current can be reconstructed by eliminating the fundamental component from the transformed current signal and then the inverse transform is applied to obtain a time-domain signal. The main disadvantage of this system is the accompanying time delay. This technique needs to take samples of one complete cycle (or an integral number of cycles) to generate the Fourier coefficients and it is therefore suitable for slowly varying load conditions.

Sine multiplication technique

This method relies on the process of multiplying the current signal by a sine wave of the fundamental frequency and integrating the result. This results in a loss of all the high-order harmonics using a simple low-pass filter. The performance is still slow (more than one complete mains cycle). This technique is similar to the Fourier techniques presented above; it is, however, differently implemented.

Modified Fourier series techniques

The principle behind this technique is that only the fundamental component of current is calculated and this is used to separate the total harmonic signal from the sampled load-current waveform. The practical implementation of this technique relies on modifying the main Fourier series equations to generate a recursive formula with a sliding window. This technique is adapted to use two different circular arrays to store the components of the sine and cosine coefficients computed every sampling sub cycle. The newly computed values of the desired coefficient are stored in place of the old ones and the overall sums of the sine and cosine coefficients are updated continuously. The computation time is much less than that of other techniques used for single-phase applications. This technique is equally suitable for single- or three-phase systems.

Other algorithms

There are numerous optimization and estimation techniques, and all the utilities and libraries for estimation can be used to perform this task. However some new methods arise, such as the neural network and adaptive-estimation techniques which are fairly accurate and have, of course, much better response. Unfortunately, presently available control hardware is not suitable for implementation of these techniques.

IV. VOLTAGE SOURCE INVERTER

SINGLE-PHASE VOLTAGE SOURCE INVERTERS

Single-phase voltage source inverters (VSIs) can be found as half-bridge and full-bridge topologies. Although the power range they cover is the low one, they are widely used in power supplies, single-phase UPSs, and currently to form elaborate high-power static power topologies, such as for instance, the multi cell configurations that are reviewed in Section 14.7. The main features of both approaches are reviewed and presented in the following.

HALF-BRIDGE VSI

Figure 14.2 shows the power topology of a half-bridge VSI, where two large capacitors are required to provide a neutral point N, such that each capacitor maintains a constant voltage vi=2. Because the current harmonics injected by the operation of the inverter are low-order harmonics, a set of large capacitors (C. and Cÿ) is required. It is clear that both switches S. and Sÿ cannot be on simultaneously because a short circuit across the dc link voltage source vi would be produced. There are two defined (states 1 and 2) and one undefined (state 3) switch state as shown in Table 14.1. In order to avoid the short circuit across the dc bus and the undefined ac output voltage condition, the modulating technique should always ensure that at any instant either the top or the bottom switch of the inverter leg is on.

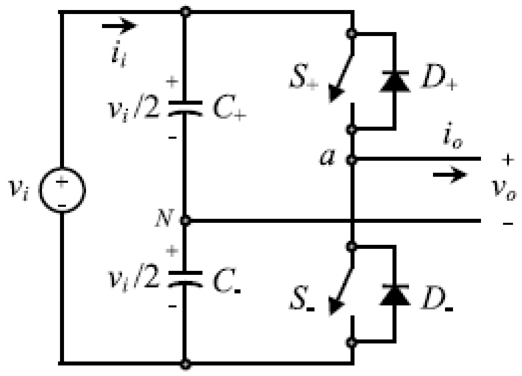

FIGURE 14.2 Single-phase half-bridge VSI.

TABLE 14.1 Switch states for a half-bridge single-phase VSI

State	State	ı	Components Conducting
+ is on and _ is off	1	ı/2	+ if >0 + if <0
_ is on and + is off	2	−ı/2	_ if >0 _ if <0
+ and _ are all off	3	−ı/2 ı/2	_ if >0 + if <0

Figure shows the ideal waveforms associated with the half-bridge inverter shown in Fig. 14.2. The states for the switches S. and Sÿ are defined by the modulating technique, which in this case is a carrier-based PWM.

The Carrier-Based Pulse width Modulation (PWM) Technique:

As mentioned earlier, it is desired that the ac output voltage. Va N follow a given waveform (e.g., sinusoidal) on a continuous basis by properly switching the power valves. The carrier-based PWM technique fulfils such a requirement as it defines the on and off states of the switches of one leg of a VSI by comparing a modulating signal vc (desired ac output voltage) and a triangular waveform vD (carrier signal). In practice, when vc > vD the switch S. is on and the switch is off; similarly, when vc < vD the switch S. is off and the switch Sÿ is on. A special case is when the modulating signal vc is a sinusoidal at frequency fc and amplitude ^vc , and the triangular signal vD is at frequency fD and amplitude ^vD. This is the sinusoidal PWM (SPWM) scheme. In this case, the modulation index ma (also known as the amplitude-modulation ratio) is defined as

$$m_a = \frac{\hat{v}_c}{\hat{v}_\Delta}$$ ……………. (14.1)

And the normalized carrier frequency mf (also known as the frequency-modulation ratio) is

$$m_f = \frac{f_\Delta}{f_c}$$ …………….. (14.2)

Figure 14.3(e) clearly shows that the ac output voltage $v_o = v_{aN}$ is basically a sinusoidal waveform plus harmonics, which features: (a) the amplitude of the fundamental component of the ac output voltage $\hat{v}_{o1}$ satisfying the following expression

$$\hat{v}_{o1} = \hat{v}_{aN1} = \frac{v_i}{2} m_a$$ ………………….. (14.3)

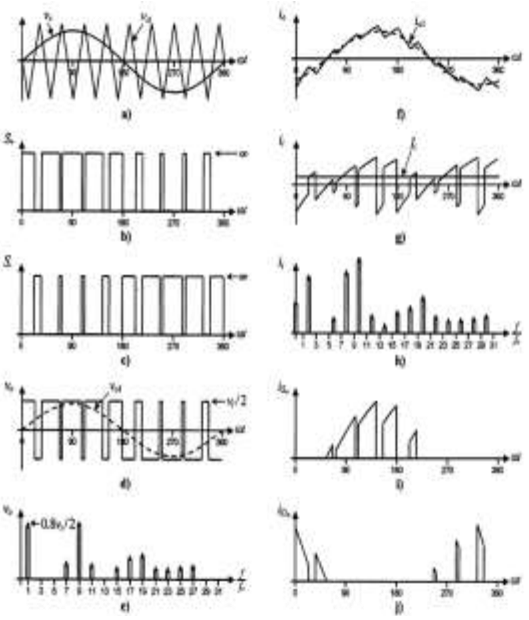

FIGURE 14.3 The half-bridge VSI. Ideal waveforms for the SPWM: (a) carrier and modulating signals; (b) switch S. state; (c) Switch Sÿ state; (d) ac output voltage; (e) ac output voltage spectrum; (f) ac output current; (g) dc current; (h) dc current spectrum; (i) switch S+ current; (j) diode + current.

will be discussed later); (b) for odd values of the normalized carrier frequency mf the harmonics in the ac output voltage appear at normalized frequencies fh centered around mf and its multiples, specifically,

$$h = l m_f \pm k \qquad l = 1, 2, 3, \ldots$$ …………… … (14.4)

Where k = 2; 4; 6; . . . for l = 1; 3; 5; . . . ; and k = 1; 3; 5; . . . for l = 2; 4; 6; . . . ; (c) the amplitude of the ac output voltage harmonics is a function of the modulation index ma and is independent of the normalized carrier frequency mf form f > 9; (d) the harmonics in the dc link current (due to the modulation) appear at normalized frequencies fp centered around the normalized carrier frequency mf and its multiples, specifically,

$$p = l m_f \pm k \pm 1 \qquad l = 1, 2, \ldots$$ ……….. …. (14.5)

where k = 2; 4; 6; . . . for l = 1; 3; 5; . . . ; and k = 1; 3; 5; . .for l= 2; 4; 6; . . . . Additional important issues are: (a) for small values of mf (mf < 21), the carrier signal vD and the modulating signal vc should be synchronized to each other(mf integer), which is required to hold the previous features; if this is not the case, sub harmonics will be present in the ac output voltage; (b) for large values of mf (mf > 21), the sub harmonics are negligible if an asynchronous PWM

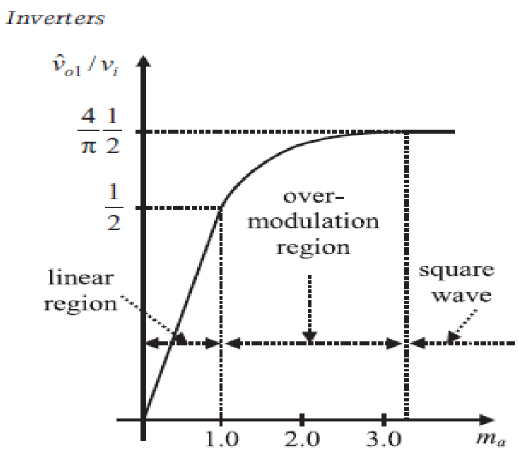

FIGURE 14.4 Fundamental ac component of the output voltage in a half-bridge VSI SPWM modulated.

Technique is used, however, due to potential very low-order sub harmonics, its use should be avoided; finally (c) in the Over modulation region (ma > 1) some intersections between the carrier and the modulating signal are missed, which leads to the generation of low-order harmonics but a higher fundamental ac output voltage is obtained; unfortunately, the linearity between ma and $\hat{v}_{o1}$ achieved in the linear region Eq. (14.3) does not hold in the over modulation region, moreover, a saturation effect can be observed (Fig. 14.4).

The PWM technique allows an ac output voltage to be generated that tracks a given modulating signal. A special case is the SPWM technique (the modulating signal is a sinusoidal) that provides in the linear region an ac output voltage that varies linearly as a function of the modulation index and the harmonics are at well-defined frequencies and amplitudes. These features simplify the design of filtering components. Unfortunately, the maximum amplitude of the fundamental ac voltage is vi=2 in this operating mode. Higher voltages are obtained by using the over modulation region (ma > 1); however, low-order harmonics appear in the ac output voltage. Very large values of the modulation index (ma > 3:24) lead to a totally square ac output voltage that is considered as the square-wave modulating technique that is discussed in the next section.

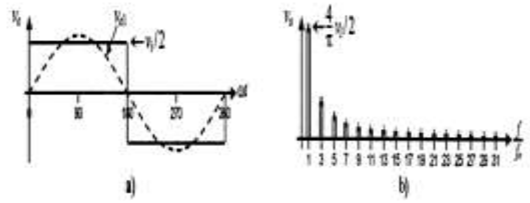

FIGURE 14.5 The half-bridge VSI. Ideal waveforms for the square-wave modulating technique: (a) ac output voltage; (b) ac output voltage spectrum.

Square-Wave Modulating Technique

Both switches S. and Sÿ are on for one-half cycle of the ac output period. This is equivalent to the SPWM technique with an infinite modulation index ma. Figure 14.5 shows the following: (a) the normalized ac output voltage harmonics are at frequencies h = 3; 5; 7; 9; . . . , and for a given dc link voltage; (b) the fundamental ac output voltage features amplitude given by

$$\hat{v}_{o1} = \hat{v}_{aN1} = \frac{4}{\pi}\frac{v_i}{2}, \quad \text{……………} (14.6)$$

And the harmonics feature an amplitude given by

$$\hat{v}_{oh} = \frac{\hat{v}_{o1}}{h} \quad \text{………….. } (14.7)$$

It can be seen that the ac output voltage cannot be changed by the inverter. However, it could be changed by controlling the dc link voltage vi . Other modulating techniques that are applicable to half-bridge configurations (e.g., selective harmonic elimination) are reviewed here as they can easily be extended to modulate other topologies.

Selective Harmonic Elimination:

The main objective is to obtain a sinusoidal ac output voltage waveform where the fundamental component can be adjusted arbitrarily within a range and the intrinsic harmonics selectively eliminated. This is achieved by mathematically generating the exact instant of the turn-on and turn-off of the power valves. The ac output voltage features odd half- and quarter wave symmetry; therefore, even harmonics are not present (voh = 0; h = 2; 4; 6; . . .). Moreover, the per-phase voltage waveform (vo = vaN in Fig. 14.2), should be chopped N times per half-cycle in order to adjust the fundamental and eliminate N -1 harmonics in the ac output voltage waveform. For instance, to eliminate the third and fifth harmonics and to perform fundamental magnitude control (N = 3), the equations to be solved are the following:

$$\cos(1\alpha_1) - \cos(1\alpha_2) + \cos(1\alpha_3) = (2 + \pi\hat{v}_{o1}/v_i)/4$$
$$\cos(3\alpha_1) - \cos(3\alpha_2) + \cos(3\alpha_3) = 1/2$$
$$\cos(5\alpha_1) - \cos(5\alpha_2) + \cos(5\alpha_3) = 1/2$$
……………… (14.8)

Where the angles α_1, α_2, and α_3 are defined as shown in Fig. 14.6a. The angles are found by means of iterative algorithms as no analytical solutions can be derived. The angles α_1, α_2, and α_3 are plotted for different values of $\hat{v}_{o1}$ =vi in Fig. 14.7a. The general expressions to eliminate an even N -1 (N -1 = 2; 4; 6; . . .) numbers of harmonics are

$$-\sum_{k=1}^{N}(-1)^k \cos(\alpha_k) = \frac{2 + \pi\hat{v}_{o1}/v_i}{4}$$
$$-\sum_{k=1}^{N}(-1)^k \cos(n\alpha_k) = \frac{1}{2} \qquad \text{for } n = 3, 5, \ldots, 2N-1$$
………….. (14.9)

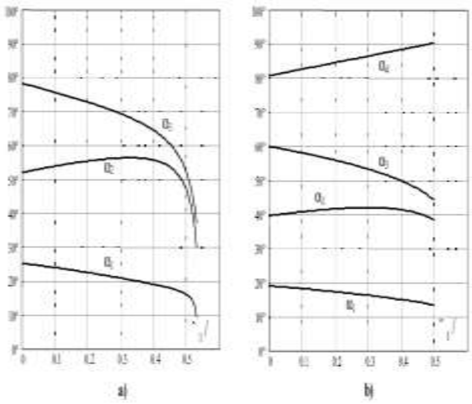

FIGURE 14.7 Chopping angles for SHE and fundamental voltage control in half-bridge VSIs: (a) third and fifth harmonic elimination; (b) third, fifth, and seventh harmonic elimination.

Where $\alpha_1, \alpha_2, \ldots, \alpha_N$ should satisfy $\alpha_1 < \alpha_2 < \cdots < \alpha_N < \pi/2.$ similarly, to eliminate an odd number of harmonics, for instance, the third, fifth and seventh, and to perform fundamental magnitude control (N-1 = 3), the equations to be solved are:

$$\cos(1\alpha_1) - \cos(1\alpha_2) + \cos(1\alpha_3) - \cos(1\alpha_4) = (2 - \pi\hat{v}_{o1}/v_i)/4$$
$$\cos(3\alpha_1) - \cos(3\alpha_2) + \cos(3\alpha_3) - \cos(3\alpha_4) = 1/2$$
$$\cos(5\alpha_1) - \cos(5\alpha_2) + \cos(5\alpha_3) - \cos(5\alpha_4) = 1/2$$
$$\cos(7\alpha_1) - \cos(7\alpha_2) + \cos(7\alpha_3) - \cos(7\alpha_4) = 1/2$$

…………… (14.10)

Where the angles $\alpha_1, \alpha_2, \alpha_3$, and α_4 are defined as shown in Fig. 14.6b. The angles $\alpha_1, \alpha_2, \alpha_3$ and α_4 are plotted for different values of $\hat{v}_{o1}/v_i$ in Fig. 14.7b. The general expressions to eliminate an odd N-1 (N-1 = 3; 5; 7; . . .) number of harmonics is given by

$$-\sum_{k=1}^{N}(-1)^k \cos(n\alpha_k) = \frac{2 - \pi\hat{v}_{o1}/v_i}{4}$$
$$-\sum_{k=1}^{N}(-1)^k \cos(n\alpha_k) = \frac{1}{2} \qquad \text{for } n = 3, 5, \ldots, 2N-1$$

……………. (14.11)

Where $\alpha_1, \alpha_2, \ldots, \alpha_N$ should satisfy $\alpha_1 < \alpha_2 < \cdots < \alpha_N < \pi/2.$

Full-Bridge VSI

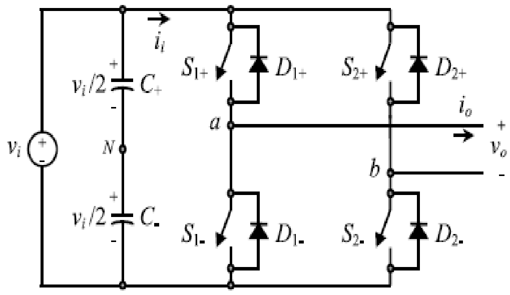

FIGURE 14.8 Single-phase full-bridge VSI.

Figure 14.8 shows the power topology of a full-bridge VSI. This inverter is similar to the half-bridge inverter; however, a second leg provides the neutral point to the load. As expected, both switches S_{1+} and S_{1-} (or S_{2+} and S_{2-}) cannot be on simultaneously because a short circuit across the dc link voltage source vi would be produced. There are four defined (states 1, 2, 3, and 4) and one undefined (state 5) switch states as shown in Table 14.2.

The undefined condition should be avoided so as to be always capable of defining the ac output voltage. In order to avoid the short circuit across the dc bus and the undefined ac output voltage condition, the modulating technique should ensure that either the top or the bottom switch of each leg is on at any instant. It can be observed that the ac output voltage can take values up to the dc link value vi , which is twice that obtained with half-bridge VSI topologies. Several modulating techniques have been developed that are applicable to full-bridge VSIs. Among them are the PWM (bipolar and unipolar) techniques.

TABLE 14.2 Switch states for a full-bridge single-phase VSI

State	State	v_{aN}	v_{bN}	v_o	Components Conducting	
S_{1+} and S_{2-} are on and S_{1-} and S_{2+} are off	1	$v_i/2$	$-v_i/2$	v_i	S_{1+} and S_{2-}	$i_o > 0$
					D_{1+} and D_{2-}	$i_o < 0$
S_{1-} and S_{2+} are on and S_{1+} and S_{2-} are off	2	$-v_i/2$	$v_i/2$	$-v_i$	D_{1-} and D_{2+}	$i_o > 0$
					S_{1-} and S_{2+}	$i_o < 0$
S_{1+} and S_{2+} are on and S_{1-} and S_{2-} are off	3	$v_i/2$	$v_i/2$	0	S_{1+} and D_{2+}	$i_o > 0$
					D_{1+} and S_{2+}	$i_o < 0$
S_{1-} and S_{2-} are on and S_{1+} and S_{2+} are off	4	$-v_i/2$	$-v_i/2$	0	D_{1-} and S_{2-}	$i_o > 0$
					S_{1-} and D_{2-}	$i_o < 0$
S_{1-}, S_{2-}, S_{1+} and S_{2+} are all off	5	$-v_i/2$	$v_i/2$	$-v_i$	D_{1-} and D_{2+}	$i_o > 0$
		$v_i/2$	$-v_i/2$	v_i	D_{1+} and D_{2-}	$i_o < 0$

Bipolar PWM Technique

States 1 and 2 (Table 14.2) are used to generate the ac output voltage in this approach. Thus, the ac output voltage waveform features only two values, which are vi and -vi. To generate the states, a carrier-based technique can be used as in half-bridge configurations (Fig. 14.3), where only one sinusoidal modulating signal has been used. It should be noted that the on state in switch S_+ in the half-bridge corresponds to both switches S_{1+} and S_{2-} being in the on state in the full-bridge configuration. Similarly, S_- in the on state in the half-bridge corresponds to both switches S_{1-} and S_{2+} being in the on state in the full-bridge configuration. This is called bipolar carrier-based SPWM. The ac output voltage waveform in a full-bridge VSI is basically a sinusoidal waveform that features a fundamental component of amplitude $\hat{v}_{o1}$ that satisfies the expression

$$\hat{v}_{o1} = \hat{v}_{ab1} = v_i m_a \quad \ldots\ldots\ldots\ldots\ldots (14.15)$$

In the linear region of the modulating technique (ma $\leq$ 1), which is twice that obtained in the half-bridge VSI. Identical conclusions can be drawn for the frequencies and amplitudes of the harmonics in the ac output voltage and dc link current, and for operations at smaller and larger values of odd mf (including the over modulation region (ma > 1)), than in half bridge VSIs, but considering that the maximum ac output voltage is the dc link voltage vi . Thus, in the over modulation region the fundamental component of amplitude $\hat{v}_{o1}$ satisfies the expression

$$v_i < \hat{v}_{o1} = \hat{v}_{ab1} < \frac{4}{\pi} v_i \quad \ldots\ldots\ldots\ldots (14.16)$$

In contrast to the bipolar approach, the unipolar PWM technique uses the states 1, 2, 3, and to generate the ac output voltage. Thus, the ac output voltage waveform can instantaneously take one of three values, namely $v_i, -v_i,$ the signal vc is used to generate van, and $-v_c$ is used to generate $v_{bN};$ $v_{bN1} = -v_{aN1}.$ On the other hand, $v_{o1} = v_{aN1} - v_{bN1} = 2 \cdot v_{aN1};$ thus $\hat{v}_{o1} = 2 \cdot \hat{v}_{aN1} = m_a \cdot v_i.$ This is called unipolar carrier-based PWM.

Identical conclusions can be drawn for the amplitude of the fundamental component and harmonics in the ac output voltage and dc link current, and for operations at smaller and larger values of mf, (including the over modulation region (ma > 1)), than in full-bridge VSIs modulated by the bipolar SPWM. However, because the phase voltages $(v_{aN} \text{ and } v_{bN})$ are identical but 180_ out of phase, the output voltage $(v_o = v_{ab} = v_{aN} - v_{bN})$ will not contain even harmonics. Thus, if mf is taken even, the harmonics in the ac output voltage appear at normalized odd frequencies fh centered around twice the normalized carrier frequency mf and its multiples. Specifically

$$h = lm_f \pm k \qquad l = 2, 4, \ldots \quad \ldots\ldots\ldots\ldots (14.17)$$

where k =1; 3; 5; . . . and the harmonics in the dc link current appear at normalized frequencies fp centered around twice the normalized carrier frequency mf and its multiples. Specifically,

$$p = lm_f \pm k \pm 1 \qquad l = 2, 4, \ldots \quad \ldots\ldots\ldots\ldots (14.18)$$

where k = 1; 3; 5; . . .. This feature is considered to be an advantage because it allows the use of smaller filtering components to obtain high-quality voltage and current waveforms while using the same switching frequency as in VSIs modulated by the bipolar approach.

Selective Harmonic Elimination:

In contrast to half-bridge VSIs, this approach is applied in a per-line fashion for full-bridge VSIs. The ac output voltage features odd half- and quarter-wave symmetry; therefore, even harmonics are not present $(\hat{v}_{oh} = 0,\ h = 2, 4, 6, \ldots).$ Moreover, the ac output voltage waveform $(v_o = v_{ab}$ in Fig. 14.8), should feature N pulses per half-cycle in order to adjust the fundamental component and eliminate N ÿ 1 harmonics. For instance, to eliminate the third, fifth and seventh harmonics and to perform fundamental magnitude control (N . 4), the equations to be solved are:

$$\cos(1\alpha_1) - \cos(1\alpha_2) + \cos(1\alpha_3) - \cos(1\alpha_4) = \pi\hat{v}_{o1}/(v_i 4)$$
$$\cos(3\alpha_1) - \cos(3\alpha_2) + \cos(3\alpha_3) - \cos(3\alpha_4) = 0$$
$$\cos(5\alpha_1) - \cos(5\alpha_2) + \cos(5\alpha_3) - \cos(5\alpha_4) = 0$$
$$\cos(7\alpha_1) - \cos(7\alpha_2) + \cos(7\alpha_3) - \cos(7\alpha_4) = 0$$

………… (17.19)

The general expressions to eliminate an arbitrary N $(N - 1 = 3, 5, 7, \ldots)$ number of harmonics are given by

$$-\sum_{k=1}^{N}(-1)^k \cos(n\alpha_k) = \frac{\pi}{4}\frac{\hat{v}_{o1}}{v_i}$$

$$-\sum_{k=1}^{N}(-1)^k \cos(n\alpha_k) = 0 \qquad \text{for } n = 3, 5, \ldots, 2N -$$

…………………. (17.20)

Where $\alpha_1, \alpha_2, \ldots, \alpha_N$ should satisfy $\alpha_1 < \alpha_2 < \cdots < \alpha_N < \pi/2.$

Shows a special case where only the fundamental ac output voltage is controlled. This is known as output control by voltage cancellation, which derives from the fact that its implementation is easily attainable by using two phase-shifted square-wave switching signals as shown in

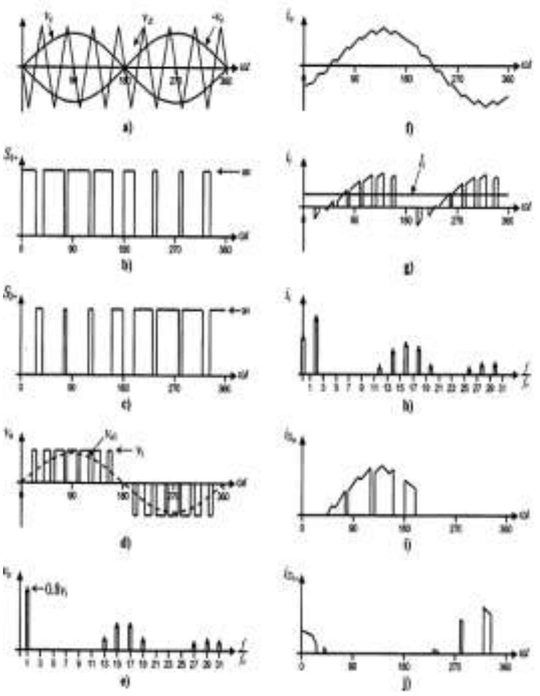

FIGURE 14.9 The full-bridge VSI. Ideal waveforms for the unipolar SPWM :(a) carrier and modulating signals; (b) switch 1+ state; (c) switch 2+ . state; (d) ac output voltage; (e) ac output voltage spectrum; (f) ac output current; (g) dc current; (h) dc current spectrum; (i) switch 1+ current; (j) diode 1+ current.

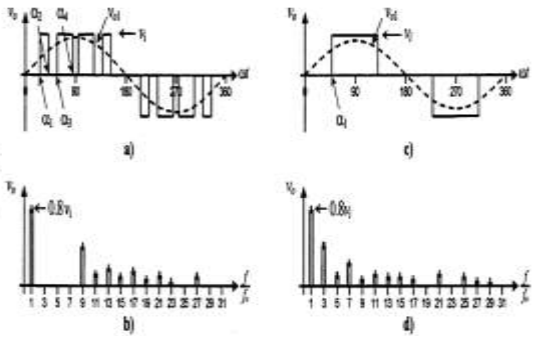

FIGURE 14.10 The half-bridge VSI. Ideal waveforms for the SHE technique: (a) ac output voltage for third, fifth, and seventh harmonic elimination; (b) spectrum of (a); (c) ac output voltage for fundamental control; (d) spectrum of (c).

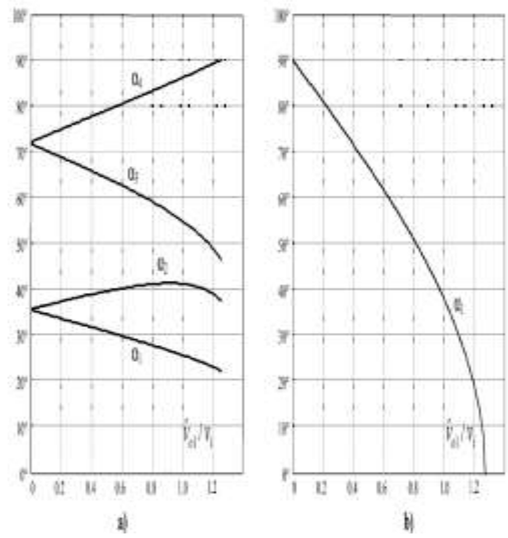

FIGURE 14.11 Chopping angles for SHE and fundamental voltage control in half-bridge VSIs: (a) fundamental control and third, fifth, and seventh harmonic elimination; (b) fundamental control.

Thus, the amplitude of the fundamental component and harmonics in the ac output voltage are given by

$$\hat{v}_{oh} = \frac{4}{\pi} v_i \frac{1}{h}\cos(h\alpha_1), \qquad h = 1, 3, 5, \ldots$$

……………… (14.21)

It can also be observed in Fig. 14.12c that for $\alpha_1 = 0$ square wave operation is achieved. In this case, the fundamental a output voltage is given by

$$\hat{v}_{o1} = \frac{4}{\pi} v_i$$

………… (14.22)

Where the fundamental load voltage can be controlled by the manipulation of the dc link voltage.

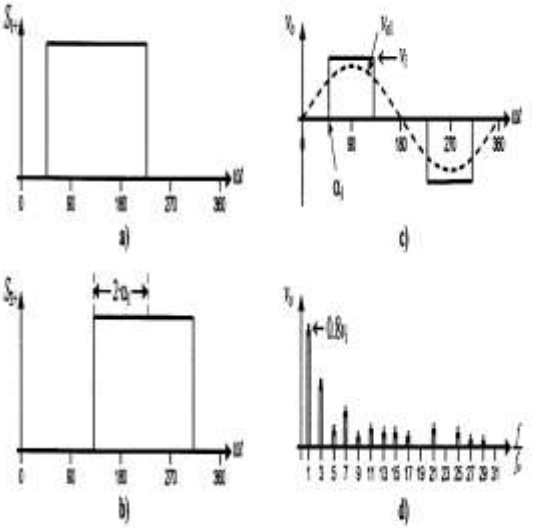

FIGURE 14.12 The full-bridge VSI. Ideal waveforms for the output control by voltage cancellation: (a) switch 1+ state; (b) switch 2+ state; (c) ac output voltage; (d) ac output voltage spectrum.

V. SRF THEORY

Rotating Transformation

The DQ transformation is a transformation of coordinates from the three-phase stationary coordinate system to the dq rotating coordinate system. This transformation is made in two steps: 1) a transformation from the three-phase stationary coordinate system to the two-phase, so-called ab, stationary coordinate system and
2) a transformation from the ab stationary coordinate system to the dq rotating coordinate system.

These steps are shown in Figure A.1. A representation of a vector in any n-dimensional space is accomplished through the product of a transpose n-dimensional vector (base) of coordinate units and a vector representation of the vector, whose elements are corresponding projections on each coordinate axis, normalized by their unit values. In three phase (three dimensional) space, it looks like this:

$$X_{abc} = \begin{bmatrix} a_u & b_u & c_u \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

Assuming a balanced three-phase system (xo= 0), a three-phase vector representation transforms to dq vector representation (zero-axis component is 0) through the transformation matrix T, defined as:

$$T = \frac{2}{3}\begin{bmatrix} cos(\omega t) & cos(\omega t - \frac{2}{3}\pi) & cos(\omega t + \frac{2}{3}\pi) \\ -sin(\omega t) & -sin(\omega t - \frac{2}{3}\pi) & -sin(\omega t + \frac{2}{3}\pi) \end{bmatrix}$$

In other words, the transformation from $X_{abc} = \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix}$ (three-phase coordinates) to $X_{dq} = \begin{bmatrix} X_d \\ X_q \end{bmatrix}$ (dq rotating coordinates), called Park's transformation, is obtained through the multiplication.

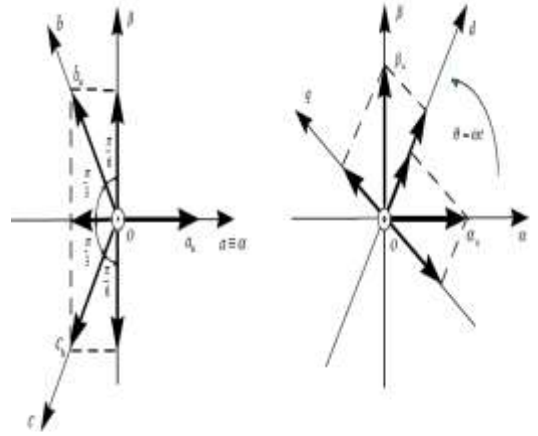

Figure A.1 Park's transformation from three-phase to rotating dq0 coordinate system

$$\begin{bmatrix} \alpha_u & \beta_u & o_u \end{bmatrix} = \begin{bmatrix} a_u & b_u & c_u \end{bmatrix} \frac{2}{3} \begin{bmatrix} 1 & 0 & \frac{1}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{2} \end{bmatrix} \qquad \begin{bmatrix} d_u & q_u & o_u \end{bmatrix} = \begin{bmatrix} \alpha_u & \beta_u & o_u \end{bmatrix} \begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} d_u & q_u & o_u \end{bmatrix} = \begin{bmatrix} a_u & b_u & c_u \end{bmatrix} \frac{2}{3} \begin{bmatrix} cos\theta & -sin\theta & \frac{1}{2} \\ cos(\theta - \frac{2\pi}{3}) & -sin(\theta - \frac{2\pi}{3}) & \frac{1}{2} \\ cos(\theta + \frac{2\pi}{3}) & -sin(\theta + \frac{2\pi}{3}) & \frac{1}{2} \end{bmatrix}$$

of the vector Xabc by the matrix T

$$X_{dq} = TX_{abc}$$

The inverse transformation matrix (from dq to abc) is defined as:

$$T' = \begin{bmatrix} cos(\omega t) & -sin(\omega t) \\ cos(\omega t - \frac{2}{3}\pi) & -sin(\omega t - \frac{2}{3}\pi) \\ cos(\omega t + \frac{2}{3}\pi) & -sin(\omega t + \frac{2}{3}\pi) \end{bmatrix}$$

The inverse transformation is calculated as:

$$X_{abc} = T' X_{dq}$$

VI. MODELING OF CASE STUDY

FOUR-LEG CONVERTER MODEL

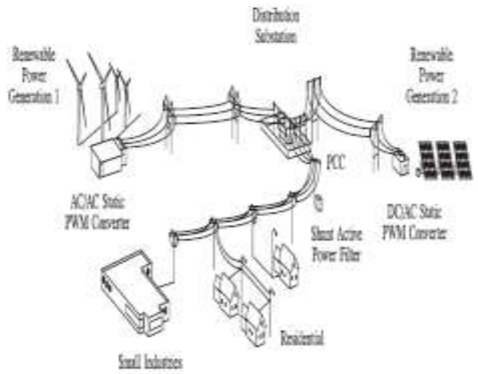

Fig. 1. Stand-alone hybrid power generation system with a shunt active power filter.

Fig. 1 shows the configuration of a typical power distribution system with renewable power generation. It consists of various types of power generation units and different types of loads. Renewable sources, such as wind and sunlight, are typically used to generate electricity for residential users and small industries. Both types of power generation use ac/ac and dc/ac static PWM converters for voltage conversion and battery banks for longterm energy storage. These converters perform maximum power point tracking to extract the maximum energy possible from wind and sun. The electrical energy consumption behavior is random and unpredictable, and therefore, it may be single- or three-phase, balanced or unbalanced, and linear or nonlinear. An active power filter is connected in parallel at the point of common coupling to compensate current harmonics, current unbalance, and reactive power. It is composed by an electrolytic capacitor, a four-leg PWM converter, and a first-order output ripple filter, as shown in Fig. 2. This circuit considers the power system equivalent impedance Zs , the converter output ripple filter impedance Zf , and the load impedance ZL .

The four-leg PWM converter topology is shown in Fig. 3. This converter topology is similar to the conventional three-phase converter with the fourth leg connected to the neutral bus of the system. The fourth leg increases switching states from 8 (23) to 16 (24), improving control flexibility and output voltage quality [21], and is suitable for current unbalanced compensation.

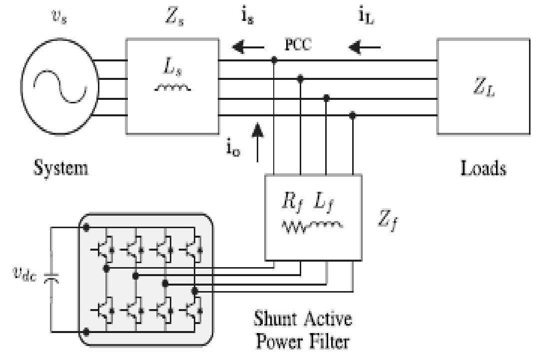

Fig. 2. Three-phase equivalent circuit of the proposed shunt active power filter.

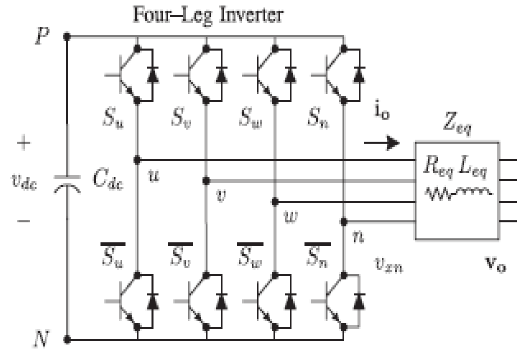

Fig. 3. Two-level four-leg PWM-VSI topology

The voltage in any leg x of the converter, measured from the neutral point (n), can be expressed in terms of switching states, as follows:

$$v_{xn} = S_x - S_n \, v_{dc}, \quad x = u,\ v,\ w,\ n. \tag{1}$$

The mathematical model of the filter derived from the equivalent circuit shown in Fig. 2 is

$$\mathbf{v_o} = v_{xn} - R_{eq}\,\mathbf{i_o} - L_{eq}\frac{d\,\mathbf{i_o}}{dt} \tag{2}$$

where Req and Leq are the 4L-VSI output parameters expressed as Thevenin impedances at the converter output terminals Zeq .Therefore, the Thevenin equivalent impedance is determined by a series connection of the ripple filter impedance Zf and a parallel arrangement between the system equivalent impedance Zs and the load impedance ZL

$$Z_{\text{eq}} = \frac{Z_s Z_L}{Z_s + Z_L} + Z_f \approx Z_s + Z_f \qquad (3)$$

For this model, it is assumed that ZL _ Zs , that the resistive part of the system's equivalent impedance is neglected, and that the series reactance is in the range of 3–7% p.u., which is an acceptable approximation of the real system. Finally, in (2) Req = Rf and Leq = Ls + Lf .

VII. DIGITAL PREDICTIVE CURRENT CONTROL

The block diagram of the proposed digital predictive current control scheme is shown in Fig. 4. This control scheme is basically an optimization algorithm and, therefore, it has to be implemented in a microprocessor. Consequently, the analysis has to be developed using discrete mathematics in order to consider additional restrictions such as time delays and approximations [10], [22]–[27]. The main characteristic of predictive control is the use of the system model to predict the future behavior of the variables to be controlled. The controller uses this informationto select the optimum switching state that will be applied to the power converter, according to predefined optimization criteria. The predictive control algorithm is easy to implement and to understand, and it can be implemented with three main blocks, as shown in Fig. 4.

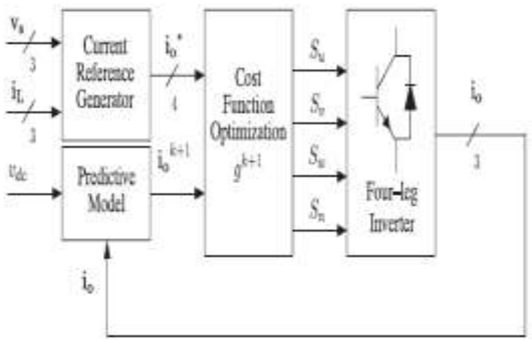

Fig. 4. Proposed predictive digital current control block diagram.

1) Current Reference Generator: This unit is designed to generate the required current reference that is used to compensate the undesirable load current components. In this case, the systemvoltages, the load currents, and the dc-voltage converter are measured, while the neutral output current and neutral load current are generated directly from these signals (IV).

2) Prediction Model: The converter model is used to predict the output converter current. Since the controller operates in discrete time, both the controller and the system model must be represented in a discrete time domain [22]. The discrete timemodel consists of a recursive matrix equation that represents this prediction system. This means that for a given sampling time Ts , knowing the converter switching states and control variables atinstant kTs , it is possible to predict the next states at any instant [k + 1]Ts .Due to the first-order nature of the state equations that describe the model in (1)–(2), a sufficiently accurate first-order approximation of the derivative is considered in this paper

$$\frac{dx}{dt} \approx \frac{x[k+1] - x[k]}{T_s}. \qquad (4)$$

The 16 possible output current predicted values can be obtained from (2) and (4) as

$$\mathbf{i_o}[k+1] = \frac{T_s}{L_{\text{eq}}}(v_{xn}[k] - \mathbf{v_o}[k]) + \left(1 - \frac{R_{\text{eq}} T_s}{L_{\text{eq}}}\right) \mathbf{i_o}[k]. \qquad (5)$$

As shown in (5), in order to predict the output current **io** at the instant (k + 1), the input voltage value **vo** and the converter output voltage vxN , are required. The algorithm calculates all 16 values associated with the possible combinations that the state variables can achieve.

3) Cost Function Optimization: In order to select the optimal switching state that must be applied to the power converter, the 16 predicted values obtained for **io**[k + 1] are compared with the reference using a cost function g, as follows:

$$\begin{aligned} g[k+1] = {} & (i^*_{ou}[k+1] - i_{ou}[k+1])^2 \\ & + (i^*_{ov}[k+1] - i_{ov}[k+1])^2 \\ & + (i^*_{ow}[k+1] - i_{ow}[k+1])^2 \\ & + (i^*_{on}[k+1] - i_{on}[k+1])^2 . \end{aligned} \qquad (6)$$

The output current (**io**) is equal to the reference (**i**∗ **o**) when g = 0. Therefore, the optimization goal of the cost function is to achieve a g value close to zero. The voltage vector **vxN** thatminimizes the cost function is chosen and then applied at the next sampling state. During each sampling state, the switching state that generates the minimum value of g is selected from the 16 possible function values. The algorithm selects the switching state that produces this minimal value and applies it to the converter during the k + 1 state.

VIII. CURRENT REFERENCE GENERATION

A dq-based current reference generator scheme is used to obtain the active power filter current reference signals. This scheme presents a fast and accurate signal tracking capability. This characteristic avoids voltage fluctuations that deteriorate the current reference signal affecting compensation performance [28]. The current reference signals are obtained from the corresponding load currents as shown in Fig. 5. This module calculates the reference signal currents required by the converter to compensate reactive power, current harmonic, and current imbalance. The displacement power factor (sin φ(L)) and the maximum total harmonic distortion of the load (THD(L)) defines the relationships between the apparent power required by the active power filter, with respect to the load, as shown

$$\frac{S_{\mathrm{APF}}}{S_L} = \frac{\sqrt{\sin\phi_{(L)} + \mathrm{THD}_{(L)}{}^2}}{\sqrt{1 + \mathrm{THD}_{(L)}{}^2}} \qquad \textbf{(7)}$$

where the value of THD(L) includes the maximum compensable harmonic current, defined as double the sampling frequency fs . The frequency of the maximum current harmonic component that can be compensated is equal to one half of the converter switching frequency.

The dq-based scheme operates in a rotating reference frame; therefore, the measured currents must be multiplied by the sin(wt) and cos(wt) signals. By using dq-transformation, the d current component is synchronized with the corresponding phase-to-neutral system voltage, and the q current component is phase-shifted by 90◦. The sin(wt) and cos(wt) synchronized reference signals are obtained from a synchronous reference frame (SRF) PLL [29]. The SRF-PLL generates a pure sinusoidal waveform even when the system voltage is severely distorted. Tracking errors are eliminated, since SRF-PLLs are designed to avoid phase voltage unbalancing, harmonics (i.e.,less than 5% and 3% in fifth and seventh, respectively), and offset caused by the nonlinear load conditions and measurement errors [30]. Equation (8) shows the relationship between the real currents iLx(t) (x = u, v,w) and the associated dq components (id and iq)

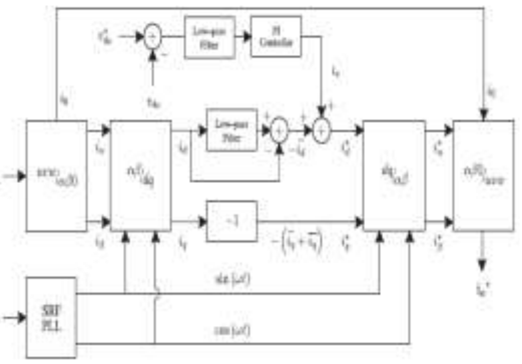

Fig. 5. dq-based current reference generator block diagram.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\omega t & \cos\omega t \\ -\cos\omega t & \sin\omega t \end{bmatrix} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Lu} \\ i_{Lv} \\ i_{Lw} \end{bmatrix}. \qquad (8)$$

A low-pass filter (LFP) extracts the dc component of the phase currents id to generate the harmonic reference components −_id . The reactive reference components of the phase-currents are obtained by phase-shifting the corresponding ac and dc components of iq by 180◦. In order to keep the dc-voltage constant, the amplitude of the converter reference current must be modified by adding an active power reference signal ie with the d-component, as will be explained in Section IV-A. The resulting signals i∗ d and i∗ q are transformed back to a three-phase system by applying the inverse Park and Clark transformation, as shown in (9). The cutoff frequency of the LPF used in this paper is 20 Hz

$$\begin{bmatrix} i^*_{ou} \\ i^*_{ov} \\ i^*_{ow} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 \\ 0 & \sin\omega t & -\cos\omega t \\ 0 & \cos\omega t & \sin\omega t \end{bmatrix} \begin{bmatrix} i_0 \\ i^*_d \\ i^*_q \end{bmatrix}. \qquad (9)$$

The current that flows through the neutral of the load is compensated by injecting the same instantaneous value obtained from the phase-currents, phase-shifted by 180◦, as shown next

$$i^*_{on} = -\left(i_{Lu} + i_{Lv} + i_{Lw}\right). \qquad (10)$$

One of the major advantages of the dq-based current reference generator scheme is that it allows the implementation of a linear controller in the dc-voltage control loop. However, one important disadvantage of the dq-based current reference frame algorithm used to generate the current reference is that a secondorder harmonic component is generated in id and iq under unbalanced operating conditions. The amplitude of this harmonic depends on the percent of unbalanced load current (expressed as the relationship between the negative sequence current iL,2 and the positive sequence current iL,1). The second-order harmonic cannot be removed from id and iq , and therefore generates a third harmonic in the reference current when it is converted back to abc frame [31]. Fig. 6 shows the percent of system current imbalance and the percent of third harmonic system current, in function of the percent of load current imbalance. Since the load current does not have a third harmonic, the one generated by the active power filter flows to the power system.

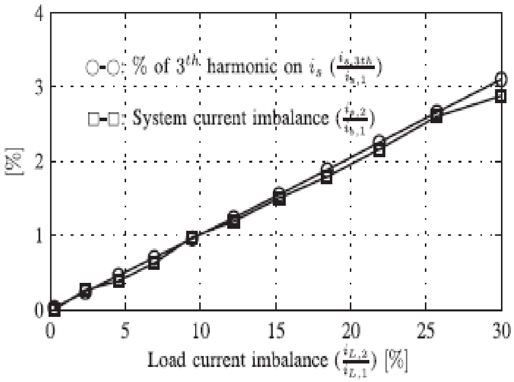

Fig. 6. Relationship between permissible unbalance load currents, the corresponding third-order harmonic content, and system current imbalance (with respect to positive sequence of the system current, is,1).

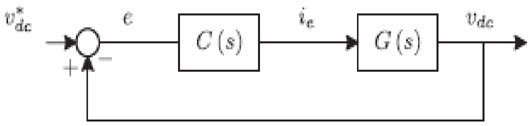

Fig. 7. DC-voltage control block diagram.

A. DC-Voltage Control

The dc-voltage converter is controlled with a traditional PI controller. This is an important issue in the evaluation, since the cost function (6) is designed using only current references, in order to avoid the use of weighting factors. Generally, these weighting factors are obtained experimentally, and they are not well defined when different operating conditions are required. Additionally, the slow dynamic response of the voltage across the electrolytic capacitor does not affect the current transient response. For this reason, the PI controller represents a simple and effective alternative for the dc-voltage control.

The dc-voltage remains constant (with a minimum value of 6 vs(rms)) until the active power absorbed by the converter decreases to a level where it is unable to compensate for its losses. The active power absorbed by the converter is controlled by adjusting the amplitude of the active power reference signal ie , which is in phase with each phase voltage. In the block diagram shown in Fig. 5, the dc-voltage vdc is measured and then compared with a constant reference value v∗ dc. The error (e) is processed by a PI controller, with two gains, Kp and Ti . Both gains are calculated according to the dynamic response requirement. Fig. 7 shows that the output of the PI controller is fed to the dc-voltage transfer function Gs , which is represented by a first-order system (11)

$$G(s) = \frac{v_{dc}}{i_e} = \frac{3}{2}\frac{K_p v_s \sqrt{2}}{C_{dc} v^*_{dc}}. \tag{11}$$

The equivalent closed-loop transfer function of the given system
with a PI controller (12) is shown in (13)

$$C(s) = K_p\left(1 + \frac{1}{T_i \cdot s}\right) \tag{12}$$

$$\frac{v_{dc}}{i_e} = \frac{\frac{\omega_n^2}{a}\cdot(s+a)}{s^2 + 2\zeta\omega_n \cdot s + \omega_n^2}. \tag{13}$$

Since the time response of the dc-voltage control loop does not need to be fast, a damping factor ζ = 1and a natural angular speed ωn = 2π · 100 rad/s are used to obtain a critically damped response with minimal voltage oscillation. The corresponding integral time Ti = 1/a (13) and proportional gain Kp can be calculated as

$$\zeta = \sqrt{\frac{3}{8}\frac{K_p v_s \sqrt{2} T_i}{C_{dc} v^*_{dc}}} \tag{14}$$

$$\omega_n = \sqrt{\frac{3}{2}\frac{K_p v_s \sqrt{2}}{C_{dc} v^*_{dc} T_i}}. \tag{15}$$

IX. SIMULATED RESULTS

A simulation model for the three-phase four-leg PWM converter with the parameters shown in Table I has been developed using MATLAB-Simulink. The objective is to verify the current harmonic compensation effectiveness of the proposed control scheme under different operating conditions. A six-pulse rectifier was used as a nonlinear load. The proposed predictive control algorithm was programmed using an S-function block that allows simulation of a discrete model that can be easily implemented in a real-time interface (RTI) on the dSPACE DS1103 R&D control board. Simulations were performed considering a 20 [μs] of sample time.

In the simulated results shown in Fig. 8, the active filter startsto compensate at t = t1 . At this time, the active power filter injects an output current iou to compensate current harmonic components, current unbalanced, and neutral current simultaneously. During compensation, the system currents **is** show sinusoidal waveform, with low total harmonic distortion (THD = 3.93%).At t = t2 , a three-phase balanced load step change is generated from 0.6 to 1.0 p.u. The compensated system currents remain sinusoidal despite the change in the load current magnitude. Finally, at t = t3 , a single-phase load step change is introduced in phase u from 1.0 to 1.3 p.u., which is equivalent to an 11% current imbalance. As expected on the load side, a neutral current flows through the neutral conductor (iLn), but on the source side,no neutral current is observed (isn). Simulated results show that the proposed control scheme effectively eliminates unbalanced currents. Additionally, Fig. 8 shows that the dc-voltage remains stable throughout the whole active power filter operation.

Table I
Specification Parameters

Variable	Description	Value [a]
$\mathbf{v_s}$	Source voltage	55 $[V]$
f	System frequency	50 $[Hz]$
v_{dc}	dc-voltage	162 $[V]$
C_{dc}	dc capacitor	2200 $[\mu F]$ (2.0 pu)
L_f	Filter inductor	5.0 $[mH]$ (0.5 pu)
R_f	Internal resistance within L_f	0.6 $[\Omega]$
T_s	Sampling time	20 $[\mu s]$
T_e	Execution time	16 $[\mu s]$

[a]Note: V_{base} = 55 V and S_{base} = 1 kVA.

X. CONCLUSION

Improved dynamic current harmonics and a reactive power compensation scheme for power distribution systems with generation from renewable sources has been proposed to improve the current quality of the distribution system. Advantages of the proposed scheme are related to its simplicity, modeling, and implementation. The use of a predictive control algorithm for the converter current loop proved to be an effective solution for active power filter applications, improving current tracking capability, and transient response.Simulated and experimental results have proved that the proposed predictive control algorithm is a good alternative to classical linear control methods. The predictive current control algorithm is a stable and robust solution. Simulated and experimental results have shown the compensation effectiveness of the proposed active power filter.

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