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POWER QUALITY IMPROVEMENT USING MULTILEVEL INVERTERS – A REVIEW

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ABSTRACT

A conventional two-level voltage source converter has so far been the most widely used converter in active power filters, however it creates several harmonic components and has a high switching stress, leading to additional power quality and loss issues. In recent years, a new breed of voltage source converters capable of producing a desired voltage from several levels of dc voltage as inputs, commonly referred to as multilevel inverters, has made active filtering a mature technology for improvement of power quality. In comparison with a two-level converter, a multi-level converter has less harmonic distortion and less switching stress. The selection of switching technique to control the inverter plays an effective role on harmonic elimination while generating the ideal output voltage. Intensive studies have been performed on the selection of topology and control techniques, and the best control scheme is suggested by various authors, according to various application areas.

Keywords: Active power filter (APF); Harmonics; Multilevel Inverters; Power Quality; Pulse Width Modulation (PWM); Voltage source Inverters.

INTRODUCTION

Electrical power is one of the factors that most influences the economic development in our society. Since the beginning of the use of electricity the continuous improvement of generation, distribution and use of electricity tries to satisfy the ever increasing quality and performance needs of most sectors of human activity.

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Even then the need for effective control and efficient use of electric power has resulted in massive proliferation of power semiconductor processors / converters in almost all areas of electric power such as in utility, industry, and commercial applications. This has resulted in serious power quality problems, as these non-linear converters contribute to harmonic injection into the power system, poor power factor, voltage unbalance, reactive power burden, etc. all leading to low system efficiency. Due to these problems, power quality improvement has been a challenge for researchers. Conventionally passive LC filters and capacitors for reducing harmonics and improving the power factor of the ac loads were employed, but they present some disadvantages [16]. The increased severity of power quality problems and other problems associated with the passive filters have required a focus on a power electronic solution, that is, active power filters (APF).

A conventional two-level voltage source converter has so far been the most widely used converter in active power filters; however it creates several harmonic components beside the fundamental frequency component and has a high switching stress, both leading to additional power quality and loss issues. Significant improvements in the output voltage quality and converter losses can be obtained by increasing the voltage levels generated at the converter output. A multi-level converter is a power electronic circuit capable of producing a desired voltage from several levels of dc voltage as inputs. In comparison with a two-level converter, a multi-level converter has less harmonic distortion and less switching stress. By increasing the number of levels, the output waveform of a multi-level converter becomes smoother and closer to a sine wave; however cost and complexity increase. The use of proper modulation technique for switching of inverter can help to produce an approximate sine wave by using less number of switches. So, the selection of switching technique to control the inverter plays an effective role on harmonic elimination while generating the ideal output voltage.

This paper aims to present a comprehensive review on the role of multilevel inverters in power quality improvement. More than 60 publications are reviewed and classified in five categories. The first category [1-17] focuses on growing concern for Power quality: problems, and its solutions. The second category [18-32] discusses the role of Active Power Filter in improvement of power quality. The third category [33-41] deals with the emergence of the Multilevel Inverters and their use in improvement of power quality. The fourth category [42-60] suggests various modulation strategies for multilevel inverters. The fifth and final category [61-63] focuses on the dc capacitor voltage balancing methods in multilevel inverters. However, some publications belong to more than one category and have been classified based on their dominant contribution.

The Literature Review is presented in six parts. Starting with an introduction, the paper discusses the reasons for the growing concern for power quality, and various methods for power quality improvement. The subsequent sections cover state of the art of the Active Power Filter and Multilevel Inverters as power quality improvement technology, their different configurations used, their control methodologies, and the problem of dc capacitor voltage balancing. Finally, the paper ends with the concluding remarks.

GROWING CONCERN FOR POWER QUALITY AND IMPROVEMENT METHODS

Power Quality has no fully accepted definition, but surely the response involves the waveforms of current and voltage in an ac system, the presence of harmonic signals in bus voltages and load currents, the presence of spikes and momentary low voltages, and other issues of distortion. Perhaps the best definition of power quality [5] is, “the provision of voltages and system design so that the user of electric power can utilize electric energy from the distribution system successfully, without interference or interruption”. A broad definition of power quality borders on system reliability, outages, voltage unbalance in three-phase systems, power electronics and their interface with the electric power supply and many other areas. Power Quality concern has increased, with the growing use of sensitive and susceptive electronic and computing equipment (e.g. personal computers, computerized workstations, uninterruptible power supplies, etc) and other nonlinear loads (e.g. fluorescent lighting, adjustable speed drives, heating and lighting control, industrial rectifiers, arc welders, etc). The reasons behind the growing concern about power quality are:

Change in characteristics of the electric loads, and harmonics causing equipment to fail prematurely.

Deregulation of the electricity market.

In interconnected rlectric power systems, any disturbance can have an extended serious economic impact for large industrial type consumers due to process shutdown.

In [1] N.G.Foster, presents various case histories of investigations that Power Quality Servers have been involved with covering EM field disturbances, flicker disturbance, a disturbing load, and sensitive load equipment. Foster concludes that resolving PQ problems requires technical knowledge of the electrical principles, and practical experience in identifying and solving power quality problems. The findings by John Stones and Alan Collinson [3], outlines the increasing relevance of a range of power quality issues, their sources, and measurement methods. The widespread use of electronic equipment, such as information technology equipment, power electronics controllers, energy-efficient lighting, led to a complete change of electric loads nature. These loads are simultaneously the major causes and the major victims of power quality problems. In [4], Almeida has presented various causes and consequences of Power Quality problems. The economic impacts associated with power quality are also characterized and finally some solutions to mitigate the power quality problems are presented. Various types of power quality variations and monitoring equipment; and different tools for analyzing and presenting the power quality measurement results are discussed in [5].

Among various power quality problems, the harmonics presence in the power lines results in serious problems, like: greater power losses in distribution; EMI problem in communication systems; and operation failures of protection devices, electronic equipments and, industrial processes. These problems result in high costs for industry and commercial activities. The major issues associated with the supply of harmonics to nonlinear loads are severe overheating and insulation damage, which can permanently damage the device and result in loss of generation causing widespread blackouts. Due to these problems, power quality improvement [6-17] has become being obligatory to solve the problem of the harmonics. Conventionally passive LC filters and capacitors for reducing harmonics and improving the power factor were employed, but they present some disadvantages [10]: they only filter the frequencies they were previously tuned for; its operation cannot be limited to a certain load or group of loads; resonance can occur due to the interaction between the passive filters and others loads, with unexpected results.

A new approach different from conventional filters is proposed in [6, 14, 16], that is the use pulse width modulation (PWM) as it offers some advantages [14]: low switching losses, good utilization of DC power, good linearity in voltage and or current control, and low harmonics contents in the output voltage and or currents, especially in the low-frequency region. However, they have some disadvantages also [14]: attenuation of the wanted fundamental component of the

PWM waveform; drastically increased switching, means greater stresses on associated switching devices and therefore derating of those devices, and generation of high-frequency harmonic components. Various traditional methods dealing with harmonic currents and their shortcomings identified in [7]. Unlike conventional and K-Rated transformers, power quality improvement HarMitigators create an attractive payback by reducing power system losses and improving power factor.

B.Singh, B.N.Singh, A.Chandra, K.A.Haddad, A.Pandey, and D.P.Kothari [11] presents an exhaustive review of three-phase improved power quality ac–dc converters, control strategies, selection of components, comparative factors, recent trends, their suitability, and selection for specific applications. IPQCs may be considered to be better alternatives for power quality improvement because of reduced size, higher efficiency, lower cost, and enhanced reliability. These converters provide improved power quality not only at input ac mains but also at dc output for better design of the overall equipment. Paper [15], aims to identify the prominent concerns in the area and thereby to recommend DSTATCOM and DVR that can be applied at the utility level without much design changes, and can enhance the quality of the power.

A Review Paper [12], explains the various harmonic mitigation techniques including Line reactors, Isolation transformers, K-Factor transformers, Tuned harmonic filters, Low pass harmonic filters, Phase shifting transformers, and Active harmonic filters, etc that have emerged as the means of power quality improvement in three phase power systems. Reviewing the advantages and disadvantages of each method, it In interconnected rlectric power systems, any disturbance can have an extended serious economic impact for large industrial type consumers due to process shutdown suitable for harmonic compensation. Their advantages are discussed and a comprehensive comparison among all is made in terms of required ratings, costs, performance, and controls. The increased severity of power quality problems and problems associated with the above mentioned techniques have required a focus on a power electronic solution, that is, active power filters.

ROLE OF ACTIVE POWER FILTERS IN POWER QUALITY IMPROVEMENT

Among the various options available to improve power quality, the use of active power filters [18-32] is widely accepted and implemented as a more flexible and dynamic means of power conditioning. Akagi, presents "New Trends in Active Filters for Power Conditioning" [18], and discusses the harmonic solutions provide by the Active Harmonic Filters. Unlike traditional passive harmonic filters, modern active harmonic filters have the following multiple functions as stated by Akagi in [22] : harmonic filtering, damping, isolation and termination, reactive-power control for power factor correction and voltage regulation, load balancing, voltage-flicker reduction, and/or their combinations. M.El-Habrouk, M.K.Darwish and P.Mehta, presents the classification of Active Filters [21] based on power rating; power-circuit connections; system parameters to be compensated; control techniques employed; reference current and voltage estimation technique in a review on Active Filters. B.Singh, Kamal Al-Haddad, and A.Chandra, presents a review [19] of active filter configurations, control strategies, selection of components, other related economic and technical considerations, and their selection for specific applications.

The active power filter generates the appropriate compensating signals that cancel the harmonic and reactive power components from the mains. The reference compensation signals are generated by making use of a control algorithm. Many control techniques have been designed, developed, and realized for active filters in recent years. All control methods are divided into two main groups [28]. The first group is reference parameter detection method. This can be done in either the time domain or frequency domain [24]. The second group is derivation methods of the switching functions for active filters. A brief literature based comparison of different current control techniques applied to Voltage source Inverter Based three-phase shunt active Power Filter was presented in [25]. Arun Jayendran, V.Sreeram, and S.V.Sivadas, in [31] presented a comparative study of various schemes used for generating the reference current. PQ theory, DQ theory, and Synchronous detection gave best results in case of error in estimated fundamental frequency component and minimizing THD. Correlation technique gave smallest reaction time and showed least THD in estimated fundamental harmonic component. The LPF feedback technique gave a long reaction time of 3 cycles but it has advantage of being independent of fundamental frequency. There have been several published papers on large number of control strategies, like P-Q Theory [20, 23, 25]; Sag/Swell Mitigation [27]; Improved P-Q Theory [29]; Dual Instantaneous Reactive Power Theory [30]; etc, as applied to active filters.

The time-varying nature of an active filter makes it suitable to be controlled by a variable structure approach such as the sliding mode control, [32]. SMC can be used to compensate reactive power, current harmonics, power factor and balancing of supply currents with unbalanced nonlinear loads. Furthermore, robustness and simplicity of implementation make the sliding mode control particularly more attractive. The application of the positive sequence voltage detector (PSVD) from within the active filter controller can compensate for load current harmonics even when the input voltage is highly distorted and unbalanced. It has been observed that the combination is capable for reducing the current harmonics to a larger extent even for a high voltage distortion and unbalanced conditions in the mains supply voltage input.

ROLE OF MULTILEVEL INVERTERS IN POWER QUALITY IMPROVEMENT

These shunt active power filters and series active power filters are basically pulse width modulated (PWM) current source inverters (CSI) and voltage source inverters (VSI), respectively. The power electronics device which converts DC power to AC power at required output voltage and frequency level is known as inverter. Inverters can be broadly classified into single level inverter and multilevel inverter. The concept of multilevel converters has been introduced since 1975 [34]. The term multilevel began with the three-level converter. Subsequently, several multilevel converter topologies have been developed. However, the elementary concept of a multilevel converter [33-41] to achieve higher power is to use a series of power semiconductor switches with several lower voltage dc sources to perform the power conversion by synthesizing a staircase voltage waveform.

A multilevel converter has several advantages over a conventional two-level converter that uses high switching frequency pulse width modulation (PWM). The attractive features of a multilevel converter can be briefly summarized as staircase waveform quality, common-mode voltage, input current, switching frequency, minimum harmonic distortion, reduced EMI/RFI generation, etc. Therefore, they are suitable for high voltage, high power applications despite DC voltage balancing problems and complex modulation, compared to two-level converters. A multilevel converter not only achieves high power ratings, but also enables the use of capacitors, batteries, and even renewable energy voltage sources as the multiple dc voltage sources.

J.S.Lai and F.Z.Peng [33], presents three recently developed multilevel-voltage source converters: Diode Clamped, Flying Capacitor, and Cascaded H-Bridge with separate dc sources; their operating principle, features, constraints, and potential applications. Using Multilevel Converter not only solves harmonics and EM1 problems, but also avoids possible high frequency switching dv/dt induced motor failures. With a balanced voltage stress in devices and utility compatible features, MLC are emerging as a new breed of power converters for high-voltage high-power applications.

A Multilevel Inverter is created [34] by cascading two three-phase three-level inverters using the load connection, with only one dc voltage source, that can operate as a seven-level inverter and naturally splits the power conversion into a higher-voltage lower-frequency inverter and a lower-voltage higher-frequency inverter. Two types of control: controlling the two three-level inverters jointly and separately, are developed that included capacitor voltage balancing so that a dc source was needed for only one three-level inverter. A survey [37] presents different topologies, control strategies and modulation techniques used by multilevel inverters. Regenerative and advanced topologies are also discussed. Finally, applications and future developments are addressed. Cascaded multilevel inverter have evolved from a theoretical concept to real applications due to high degree of modularity, possibility of connecting directly to medium voltage, high power quality, high availability, and the control of power flow in the regenerative version.

Various publications [35, 38-41], presents the operation of cascaded multilevel converter based on Active Power Filter for harmonic mitigation and reactive power compensation in power distribution systems. Power quality improvement with proposed filter has been verified by the simulation results with MATLAB/SIMULINK. The performance of the APF in [38] has been analyzed with dynamic load variation and unbalanced main voltage scenario. Multilevel inverter based shunt APF is found to inject the compensating current, hereby reduces the magnitude of the significant harmonics in the line current and hence the Total Harmonic Distortion. Paper [41] proposes the design of a shunt active power filter under the condition of voltage sag, unbalanced loads, and distorted source voltages, applicable to compensate the harmonics, reactive and negative sequence currents. Closed loop control of shunt active filter is designed for better performance.

CONTROL TECHNIQUES AND DC CAPACITOR VOLTAGE BALANCING

Traditional PWM methods employ high switching frequencies of the order of several kHz. Undesirable harmonics occur at much higher frequencies. Thus, filtering is much easier and less expensive. Also, the generated harmonics might be above the bandwidth of some actual systems, which means there is no power dissipation due to these harmonics. Traditional PWM schemes also have the inherent problems of producing Electromagnetic Interference, which can damage electrical motors. Furthermore, high switching frequencies can make this problem worse due to the increased number of times these common-mode voltages are applied to the motor during each fundamental cycle. The multilevel fundamental switching scheme [42] employs switching frequencies of the order of 50Hz, which leads to conduction losses comparable to typical PWM schemes. As switching losses increase with increase in switching frequency, so this scheme will lead to lower switching losses. Therefore, using the multilevel fundamental switching scheme will result in increased efficiency. Multilevel converters inherently tend to have a smaller dv/dt due to the fact that switching involves several smaller voltages. Furthermore, switching at the fundamental frequency will also result in decreasing the number of times these voltage changes occur per fundamental cycle. So, using traditional PWM switching schemes will result in an increased "oversizing" of devices to prevent voltage and current surges from destroying components. Furthermore, they might require more snubber circuits and EMI filters.

The selected switching technique to control the inverter will also have an effective role on harmonic elimination while generating the ideal output voltage. Intensive studies have been performed on carrier-based, sinusoidal, space vector and sigma delta PWM methods in open loop control of inverters. To achieve better performance, hybrid modulation techniques are used. The most common multilevel inverter topologies, control schemes and their advantages have been reviewed in [47, 50]. The harmonic elimination ability of SHE-PWM is better than that of CPS-SPWM, while its calculation work becomes tremendous and difficult with the level number increasing. CPS-SPWM is easy to realize and its calculation speed is fast even under a very high level.

Improvement in switching techniques is one of the effective methods for increasing the voltage quality in MLI. In [42, 60], a novel switching technique involving frequency modulated PWM applied to multilevel inverter and its analysis considerably reduces total harmonic distortion. In [43], it has been proposed that by the simple addition of a (1/2) carrier magnitude dc offset for specific modulation depth regions, harmonic distortion is reduced up to 40% than common phase disposition PWM. A unique space vector analysis [44] of hybrid converter modulation is introduced to successfully maintain the conditioning inverter capacitor voltage so that only one dc source is needed for the cascaded multilevel inverter. The scheme proposed in [46] allows use of a single dc power source with the remaining $n-1$ dc sources being capacitors, which is referred to as hybrid cascaded H-bridge multilevel inverter. A different approach, based on equal area criteria and harmonic injection that requires four simple equations is presented in [52], which remain same for different numbers of switching angles and no increase of calculation time is expected with number of switching angles. The proposed method can be used to achieve excellent harmonic elimination in multilevel inverter for the modulation index range at least from 0.2 to 0.9.

In [49], the single phase MLIs (various topologies) have been simulated in MATLAB/SIMULINK and harmonic reduction at different stages is compared. 7-level inverter is found to have least value of THD. The proposed MLI with reduced switches is found to further reduce the THD. Paper [53] presents a comparative study of nine-level DC MLI for constant switching frequency of sinusoidal PWM and sinusoidal Natural PWM with switching frequency Optimal Modulation. The distortion of the output voltage decreases as the number of level increases and it is further improved by applying PWM techniques. The work [55] attempts to reduce the harmonic content in the output voltage by incorporating a single phase 9 level cascaded MLI and PWM techniques. Also comparative analysis is made for various values of switching angles and an equal input dc supply. An alternative method [56] of using lower voltage cells with floating dc links to compensate only for the voltage distortion of a NPC converter is considered. The analogy between the floating HBs and the series active filters is used to develop a strategy for the harmonic compensation of the NPC output voltage and the control of the floating dc-link voltages. Comparison among various multicarrier control techniques the total harmonic distortion analysis has been done in [57], and Alternative phase opposite disposition (APOD) is observed as best technique as compared with other multicarrier control techniques. Comparison among various carrier based disposition modulation techniques PDPWM, PODPWM and APODPWM have been tabulated in [58]. The PDPWM method has given the better results for all modulation indexes.

Various artificial intelligent techniques, like genetic algorithm [51], fuzzy [54], neural network [59], etc can also be used with available modulation techniques to get better performance. There are other switching schemes also that can be implemented on a multilevel inverter but do not produce a staircase waveform. Some examples include Bipolar Programmed PWM, Unipolar Programmed PWM [48], and Virtual Stage PWM. One pitfall of using multilevel inverters is to approximate sinusoidal waveforms that concerns harmonics. However, by altering the times at which these sharp transitions occur, one can reduce and/or eliminate some of the unwanted harmonics. For proper operation, multi-level converters need to receive equal dc voltages on their dc side. If dc sources, i.e. batteries, are used, it is relatively straightforward to ensure that the dc side voltages remain equal during the operation of the converter. This luxurious case, however, does not normally exist in reality. DC side voltage is often provided with passive capacitors. Therefore these dc capacitors need to have equal shares of the dc voltage. One of the main drawbacks of the multi-level diode-clamped converters is that they experience unequal and drifting voltages on their dc sides, which leads to malfunction of the converter and distortion of the ac-side voltage waveform. The current solutions to the problem can be categorized into circuit-based solutions and control and switching modifications. A number of approaches have been proposed for voltage drift phenomena, including the following:

Use of isolated dc sources for each capacitor to maintain the capacitor voltages at their desire value, is proposed in [33]. The switching pattern for this approach is not very complicated; however, using isolated dc sources adds to the cost and complexity of the system.

Use of auxiliary converters to inject current to the dc side intermediate branch In order to balance the dc capacitor voltages, is proposed in [61, 62].

Modifications in the switching pattern to balance and maintain the dc capacitor voltage are proposed in [63].

For the first two approaches, additional power hardware is needed, which makes the converter circuitry expensive and more complex. In comparison with these two approaches, the third approach provides an economically reasonable method to solve the voltage balancing problem; however it requires a more complicated switching strategy.

CONCLUSION AND FUTURE SCOPE

The concept of multilevel inverters has emerged as a one of the best technique of power quality improvement, due to several remarkable features like a high degree of modularity, the possibility of connecting directly to medium voltage, high power quality, both input and output, high availability, and the control of power flow in the regenerative version. As multilevel inverters donot require passive filters at output, thus economical. Also the compensation current produced is well within the acceptable limits. By implementing the various multilevel control techniques the total harmonic distortion analysis has been done, and improvement in power quality is observed.

Multi-level converters need to receive equal dc voltages on their dc side, thus dc capacitor voltage balancing is taken care of so as to ensure proper operation. Intensive studies prove that to achieve better performance, hybrid modulation techniques should be used. This paper has reviewed the recent developments and applications of multilevel inverters as power quality improvement, including new modulation techniques, and control strategies.

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