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Enhancing Power Quality of AC-AC Direct Converters using Hybrid Filters

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ABSTRACT

This study explores enhancing power quality in AC-AC direct converters using hybrid filters. AC-AC direct converters, crucial in motor drives and renewable energy systems, often face power quality issues like harmonic distortion and voltage fluctuations. Hybrid filters, which combine passive and active filtering techniques, offer an effective solution. The research examines the historical evolution of matrix converters, highlighting advancements that inform current AC-AC direct converter technology. Control strategies, specifically Space Vector Modulation (SVM) and Pulse-Width Modulation (PWM), are investigated to optimize hybrid filter performance. The study finds that implementing hybrid filters in AC-AC direct converters significantly improves power quality and system stability. These insights contribute to better application and understanding of hybrid filters in enhancing AC-AC direct converter performance.

1. Introduction

The topic of electric power quality, or power quality, has garnered significant attention from both operators and consumers of electrical networks in recent years [1]. It is estimated that the damages resulting from power quality disturbances amount to around $100 billion annually in the United States alone. Therefore, investing in mitigating these disturbances is significantly less than the incurred damages. Undoubtedly, the quality of electric power generation is better today than in the past. Additionally, transmission and distribution networks have become more extensive and rely on newer and more reliable technologies [2]. So, why has the issue of power quality become more important nowadays, receiving serious attention and extensive research?

This issue can be examined from two perspectives. First, technological advancements have led to various nonlinear loads with non-sinusoidal waveform characteristics being dispersed throughout the network [2]. The presence of these loads deviates the waveform from its normal sinusoidal state, leading to power quality disturbances. On the other hand, many loads today are controlled by sensitive electronic and microprocessor-based systems. These systems are sensitive to the various disturbances present in the network and their performance can easily be compromised [3]. These disturbances can lead to significant damages. Therefore, investment and study for improving power quality and preventing the aforementioned damages have received considerable attention today. Consequently, it is necessary to assess and control power quality in power system networks, determine power quality parameters at certain points in the network, and, on the other hand, supplementary electricity tariff regulations oblige subscribers to comply with reducing power quality pollution caused by them. Consumers of electrical power show a significant inclination towards using devices with new technologies [4]. These devices, which enhance the quality and speed of industrial production sectors and improve the standard of living for household consumers, have created two fundamental problems for both producers and purchasers of electrical power [5]. On one hand, these types of loads are highly sensitive to voltage disturbances due to their specific designs. On the other hand, the power electronic circuits used in these devices inject harmonic currents into the distribution network. Current harmonics reduce the lifespan of network components and, upon passing through the network impedance, generate voltage disturbances. Power quality disturbances can be broadly categorized into two main types: 1) voltage disturbances imposed on the load by the network, such as voltage sags and swells, and 2) current disturbances introduced by the load to the network, such as current harmonics.

With the rapid development of the industrial economy, the installation and operation of a multitude of nonlinear loads significantly deteriorate the power

quality of the network. Increased usage of power electronic devices exacerbates the situation further. Low power factor and high harmonics in the network decrease system efficiency, resulting in consumers being unable to receive quality electricity that meets their needs. Harmonic standards like IEEE 519 exist to specify acceptable levels of harmonics. Conventional dynamic VAR compensation solutions, including inverter-based static compensators, have been available in the market for over 20 years, but these technologies are often too costly. Unfortunately, large capacitor banks are typically used on the DC side as energy storage elements in the form of a DC voltage source, leading to very high installation and maintenance costs, which are not acceptable for large-scale industrial applications. As a result, the market penetration of conventional active power filters is very limited.

AC-AC converters, or frequency converters, are a category of power electronic converters used for exchanging energy between two systems with different frequencies or two systems with the same frequency but asynchronous operation. Various applications of these converters include AC drives, HVDC lines, output converters of micro-turbines, external power sources for aircraft, and propulsion systems for modern ships. Different structures of AC-AC converters have been proposed, each with its own advantages and disadvantages. Generally, characteristics such as low weight and volume, high-quality input and output waveforms, high efficiency, high reliability, and ultimately, competitive cost are major requirements for these converters. In a general classification, AC-AC converters can be divided into two types: "direct" and "indirect" [6].

Indirect AC-AC converters involve an intermediate DC circuit and are therefore referred to as DC-AC-AC converters. The quantity of the DC circuit can be either voltage or current. Nowadays, indirect converters with a voltage intermediate circuit are among the most common and widely used AC-AC converters. However, some major drawbacks, such as relatively large size and low efficiency, persist in these converters. Additionally, the electrolytic capacitors used in these converters tend to lose their reliability significantly over time, ultimately compromising the overall performance of the converter. Efforts have been made to replace these capacitors with non-electrolytic capacitors with smaller volumes and longer lifespans, but the results obtained have generally not been confirmed and have not become industrialized.

2. Literature review

In a study conducted by Purwanto et al. [7], the investigation focused on a direct three-phase matrix converter with space vector modulation for driving induction motors [7]. Three-phase induction motors are extensively used in industries and electric vehicles due to their robust and simple construction, relatively low cost with high reliability, and low maintenance expenses. Adjusting the rotational speed of an induction motor can be achieved by controlling the input voltage and frequency. Typically, three-phase inverters are used to change the input voltage and frequency, requiring the conversion of DC voltage to three-phase AC voltage. However, this method has drawbacks, including the non-sinusoidal waveform of the output voltage, which can lead to high harmonics. Harmonics increase losses, which can reduce system efficiency and destabilize power systems. A direct matrix converter with space vector modulation (SVM) offers several advantages that can address these issues and achieve stable performance in driving three-phase induction motors [8].

In another research by Bedoud et al (2018), a dual-fed induction generator was investigated using a matrix converter [9]. With the advancements in power electronics devices, particular attention has been given to a new generation of power converters, namely AC to AC matrix converters. These converters offer direct AC/AC conversion, bidirectional power flow, and nearly sinusoidal input and output waveforms. In this article, the performance of a variable-speed wind turbine based on a dual-fed induction generator powered by a matrix converter is presented. The focus is on maximum power point tracking method to extract maximum power from wind. The entire system is represented in a synchronous d-q reference frame. The control scheme has been tested, and its performance has been evaluated through simulation results. The simulation results obtained using MATLAB/Simulink software demonstrate the effectiveness and validity of the intended control.

3. Methodology

An induction motor is a type of alternating current (AC) motor, specifically an asynchronous AC motor, in which the required power for its moving part is supplied through electromagnetic induction. Induction motors are the most widely used motors in industrial motion control systems as well as household appliances. Their simple and robust design, low cost, low maintenance, and easy and complete connection to an AC power source are fundamental advantages of AC induction motors. Various types of AC induction motors are available in the market, suitable for various applications. Although the design of AC induction motors is simpler than that of DC motors, controlling speed and torque in different types of AC induction motors requires a deeper understanding in their design and manufacturing. An electric motor converts electrical energy into mechanical energy in its rotor. Various methods exist to supply the required power to the rotor. In a DC motor, the armature power is directly supplied by a direct current source, while in an induction motor, this power is induced electromagnetically in the rotor through the stator. Due to their striking similarity to transformers, induction motors are also referred to as rotary transformers, as

their stator closely resembles the primary winding and their rotor resembles the secondary winding of a transformer. Induction motors, especially three-phase induction motors, are widely used in the industry. High power, simple structure, absence of brushes (which require extensive maintenance), and the high controllability of induction motors for speed control are among the reasons for their use. The biggest difference between an AC induction motor and a synchronous AC motor is that in a synchronous motor, the rotor power is directly supplied from an external source. This current in the rotor will also produce its own magnetic field, and due to the interaction of the stator and rotor magnetic fields, the rotor will move in the direction of the stator's rotating field. On the other hand, for inducing current in the rotor, a speed difference between the rotor's rotation speed and the rotating field speed is necessary. Otherwise, the rotating field will not be able to move the rotor, and the rotor's conductors will not cut the magnetic field produced by the stator, resulting in no induced voltage in the rotor. This speed difference between the rotating field speed and the rotor movement speed is called "slip". Slip is a dimensionless quantity. Since the speed difference is a condition and necessity for the operation of induction motors, they are called asynchronous motors.

AC/AC converters have gained a special position in power electronics in recent decades [10]. These converters can be used in power regulators, induction motor drives, and converters related to wind turbines, among other applications. These converters have the capability of bidirectional power transfer, in addition to being unidirectional. With the advancement of technology, high-power switches, commutation strategies, modulation techniques, and corresponding switching techniques, these converters are continuously improving in terms of power conversion quality, efficiency enhancement, and reduction of losses and costs. Structurally, AC/AC converters are classified into two main categories [11]:

A) Structure (AC/DC/AC): Converters with DC energy storage interface, including voltage source inverters (VSI) and current source inverters (CSI). For example, a VSR/VSI inverter, as shown in Figure (1), consists of a rectifier stage and an inverter stage. These two stages are coupled to each other through a large and expensive energy storage element such as a capacitor and an inductor.

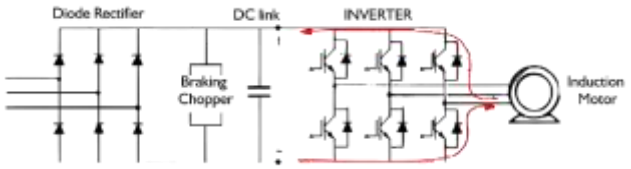


Figure (1), Frequency Converter with AC-DC-AC Structure

VSR/VSI converters have a DC voltage link and a parallel capacitor element, while CSR/CSI converters have a DC current interface and a series inductor element. In addition to these interface elements, these converters are equipped with additional filtering elements to remove harmonics and commutation strategy equipment, etc. Therefore, power factor correction in these converters is significant, and solutions such as using resonant interfaces and high-frequency techniques are recommended.

B) Direct AC/AC: Converters without a DC interface and energy storage, including cycloconverters and matrix converters, which have both direct and indirect structures. Cycloconverters and matrix converters belong to the second category of AC/AC converters, which lack a DC interface and energy storage elements (ZES). Cycloconverters come in two types: three-phase and single-phase, at different power levels, often used in three-phase configurations for high-power and low-frequency applications (Figure 2). In these converters, the output frequency is a fraction of the input frequency [12].

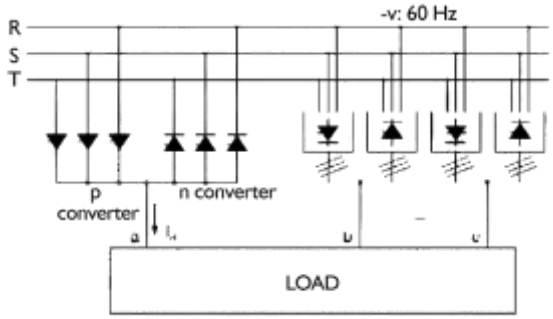


Figure (2), Three-Phase Cycloconverter

The history of matrix converters dates back to 1976 when Gyagy and Pully first introduced the concept as a theoretical and innovative approach to optimize the fundamental operation of cycloconverters. Their goal was to achieve an output voltage with an unlimited frequency and enable direct conversion using controllable bidirectional switches. However, the initial matrix converters faced challenges, including the presence of significant undesired harmonics in the output voltage and input current, which couldn't be easily eliminated by filters [13].

In 1980, Venturini and Al Sina addressed these challenges by proposing a new modulation technique utilizing Pulse Width Modulation (PWM). Despite this advancement, practical applications of matrix converters remained limited at that time due to issues with current commutation and the complexity of control algorithms [14]. Continued research efforts have focused on analyzing mathematical relationships and studying converters at lower frequencies. With the development of suitable modulation techniques and power converter circuits structured as matrices of controllable bidirectional switches, researchers were able to introduce matrix converters with a direct method [15].

Later, in 1983, Rodriguez presented a different control technique based on a virtual DC link. In this method, each output line's switching is performed using PWM

during input lines with minimum values, known as indirect matrix conversion. This evolution marked significant progress in the practical application and control of matrix converters.

The structure of the matrix converter is similar to that of a buck converter. Examining the evolutionary trend of the buck converter helps us understand the performance of matrix converters. Figure 3 illustrates a buck converter where the switch (Sw) is periodically connected to the positive and negative terminals of the DC input voltage source (Vin).

The methodology encompasses the design and evaluation of hybrid filters integrated into AC-AC converters to enhance power quality. Firstly, the design parameters for the hybrid filters are established, including cutoff frequencies and filter orders, crucial for defining their operational range and complexity. Control strategies, namely Pulse-Width Modulation (PWM) and Space Vector Modulation (SVM), are implemented with specific parameters such as modulation index and switching frequency, influencing the converters' output waveform and overall system performance. Converter ratings, including voltage and current specifications, are also considered to ensure compatibility with practical applications.

Following the design phase, the hybrid filter system is evaluated using established performance metrics. Total Harmonic Distortion (THD), voltage stability, and power factor are among the key criteria utilized to assess the effectiveness of the filters in mitigating harmonic distortion and enhancing system stability. The evaluation process involves rigorous testing under various operating conditions, including different load scenarios and harmonic levels. Results are analyzed to determine the extent of power quality improvement achieved through the integration of hybrid filters into the AC-AC converters. This methodology ensures a systematic approach to designing, implementing, and evaluating hybrid filter systems, facilitating reproducibility and comparison with other studies in the field.

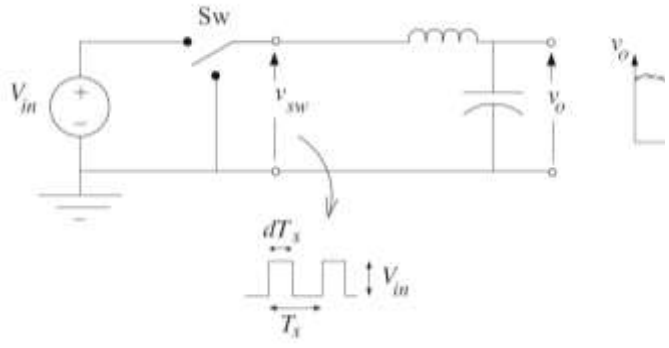


Figure 3, Buck Converter

The DC component of Vsw is obtained using the average waveform over one switching cycle Ts:

$$Vsw = \frac{1}{Ts}\int_0^{Ts} Vsw\, dt = dVin \quad (1)$$

Therefore, by adjusting the duty cycle (d), it is possible to generate a desired DC component from the switching voltage (Vsw). The frequency components (f=1/Ts) and their harmonics present in Vsw can be significantly reduced by an LC filter. The important point is that the desired DC component can only be produced when the output voltage is less than the source voltage (Vin) [2].

The conversion of output voltage from a three-phase sinusoidal to a DC rectifier provides valuable assistance in analyzing converters. Figure 4 illustrates a three-phase diode rectifier and the output voltage.

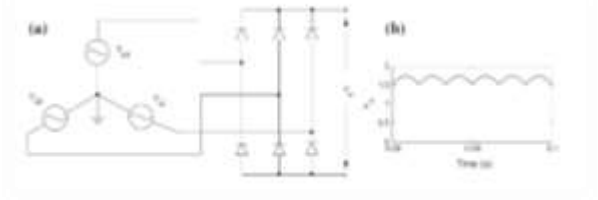


Figure 4 illustrates a three-phase diode rectifier and the output voltage.

The input voltages are as follows:

$$Vsa = \sin 2\pi 50T, \quad (2)$$

$$Vsb = \sin(2\pi 50t - 120), \quad (3)$$

$$Vsc = \sin(2\pi 50t - 240), \quad (4)$$

By replacing three diodes connected to each output terminal with a Single Pole-Triple Throw (SPTT) switch, it is possible to fully control it.

The study employs MATLAB/Simulink to simulate the integration of hybrid filters into AC-AC direct converters, ensuring a detailed analysis of their impact on power quality. The system is modeled to reflect real-world configurations, incorporating both the AC-AC converter and the hybrid filter components. Control strategies, specifically Space Vector Modulation (SVM) and Pulse-Width Modulation (PWM), are implemented within the simulation to optimize the converter's performance. Key parameters such as input voltage, load conditions, and switching frequencies are carefully selected to represent typical operating conditions.

Various test scenarios are simulated to evaluate the hybrid filter's effectiveness under different conditions, including varying loads and harmonic levels. The performance is assessed using metrics like Total Harmonic Distortion (THD), voltage stability, and power factor. The results show significant improvements in power quality, demonstrating the hybrid filter's capability to mitigate harmonic distortion and enhance system stability. This transparent and detailed simulation methodology ensures the study's findings are credible and reproducible, providing a solid foundation for future research and practical applications.

In any engineering study, particularly those involving power electronics, simulation plays a vital role in validating theoretical designs and predicting their real-

world performance. Without specifying the use of software tools, the study lacks a crucial layer of verification that would otherwise strengthen its claims about the effectiveness of hybrid filters in improving power quality. Simulation helps in identifying potential issues, optimizing the design, and ensuring that the proposed solution can achieve the desired outcomes under various operating conditions.

Clarifying whether software tools were used, and providing details about the simulation process, would significantly enhance the study's credibility. Information such as the type of software used (e.g., MATLAB/Simulink, PSpice), the parameters and scenarios tested, and the results obtained from these simulations would provide a more comprehensive understanding of the methodology. This transparency allows other researchers to replicate the study, verify the results, and build upon the findings. It also demonstrates a rigorous approach to design validation, ensuring that the proposed integration of hybrid filters is not only theoretically sound but also practically feasible.

4. Results and discussion

The switches will be turned on for a duration of *d*0*Ts* =*T*0. During this period, all output phases will be connected to one input phase, resulting in zero line voltages. To minimize switching losses, the state before this stage should be considered, ensuring that the least amount of change in the switch states occurs. Therefore, we have:

$V_0(A,B,C) = v(b,a,b) \Rightarrow A = b, B = a, C = b$

5

So, to reduce switching losses during this period, the switching should be performed as follows:

$V_0(A,B,C) = V_0(b,b,b)$

6

Therefore, during this period, switches S2, S5, and S8 are turned on, while the rest of the switches are off.

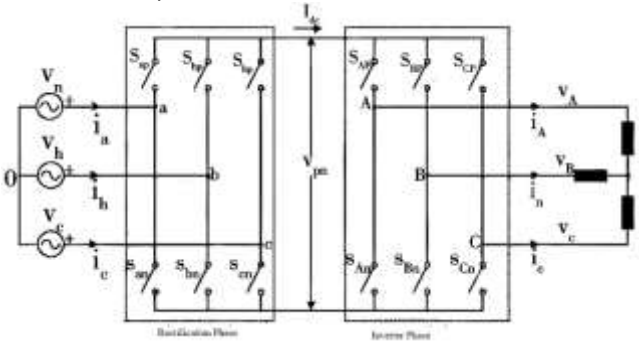


Figure (5), equivalent circuit of the matrix converter used in the control method.

The times are considered symmetrical to reduce the harmonics present in the output voltage. The steps performed were for a scenario where the output voltage vector was in the first sector and the input current vector was in the third sector [16]. For this scenario, the gate signals of the switches are as follows.

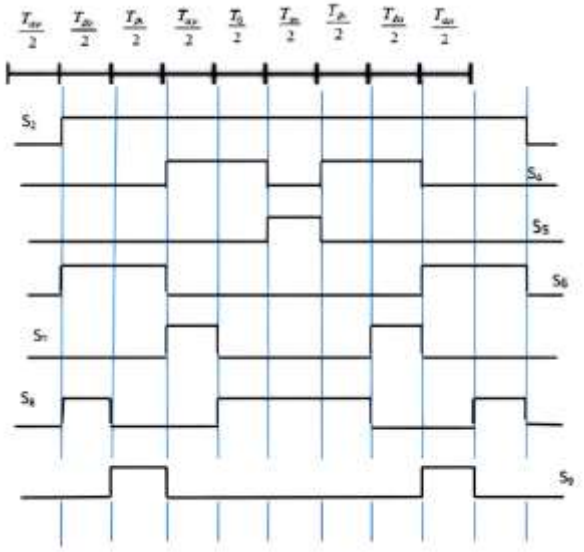


Figure (6), gate signals for the scenario where the output voltage vector was in sector one and the input current vector was in sector three.

Furthermore, the study elucidates the utilization of matrix converters in various industrial applications, such as wind turbine systems and dual-fed induction generators. By employing advanced modulation techniques and control algorithms, matrix converters demonstrate remarkable potential in enhancing power system efficiency and stability. The analysis of gate signals and switching schemes underscores the importance of optimized control strategies to mitigate harmonics and minimize switching losses. Overall, the research provides valuable insights into the evolution, optimization, and practical applications of matrix converters in power electronics. It underscores the importance of advanced modulation techniques and control algorithms in improving efficiency, stability, and performance, paving the way for their wider adoption in diverse industrial and renewable energy systems. The investigation into matrix converters showcases their capability to address challenges associated with traditional power conversion methods, such as harmonics, switching losses, and control complexity. By leveraging vector space modulation and advanced control techniques, matrix converters offer efficient and reliable solutions for power conversion tasks in various industrial sectors.

If software simulation was not conducted in this study, the primary reason could be the focus on validating the proposed design through an experimental setup to ensure real-world applicability. Experimental setups provide direct and tangible results, reflecting actual operational conditions that simulations might not fully capture. This approach can offer more reliable data on how the hybrid filters perform when integrated into AC-AC direct converters, accounting for practical variables such as noise, temperature variations, and other environmental factors that simulations often idealize or overlook.

Despite the strengths of experimental validation, it is important to recognize the limitations of not including software simulations. Simulations offer a controlled environment to test a wide range of scenarios, which can help in identifying potential issues and optimizing the system before physical implementation. The absence of simulations might mean some performance aspects are not thoroughly explored. To mitigate this limitation, future work could incorporate both simulation and experimental phases, providing a more robust and comprehensive evaluation. By explaining these considerations, the study can justify its methodological choices and outline a path for further research enhancements.

5. Conclusions

In this study, we explored the enhancement of power quality in AC-AC direct converters through the integration of hybrid filters. These filters, combining passive and active filtering techniques, offer a promising solution to address power quality issues such as harmonic distortion and voltage fluctuations. Our investigation delved into the historical evolution of matrix converters, providing valuable insights into the development of AC-AC direct converter technology. Through the implementation of sophisticated control strategies including Space Vector Modulation (SVM) and Pulse-Width Modulation (PWM), we aimed to optimize the performance of hybrid filters.

While our study offers valuable insights into the potential of hybrid filters to improve power quality, there are areas for further enhancement. The methodology section lacked clarity on specific design parameters and values, hindering a comprehensive assessment of the proposed hybrid filter integration. Future research should focus on providing detailed design parameters to facilitate a more robust evaluation of the filters' effectiveness. Additionally, incorporating both software simulations and experimental validation would offer a more comprehensive understanding of the hybrid filter performance under various operating conditions.

Overall, this research contributes to advancing the understanding and application of hybrid filters for enhancing the power quality of AC-AC direct converters. By addressing the limitations highlighted and further refining the methodology, future studies can build upon these findings to develop more efficient and reliable power quality enhancement solutions for diverse applications.

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