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Implementation of Cascaded Multilevel Inverter – Based Shunt Active Power Filter for Harmonic Mitigation

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ABSTRACT

The increasing use of nonlinear loads in modern electrical systems, such as industrial drives, rectifiers, and uninterruptible power supplies, has resulted in significant harmonic distortion and deterioration of power quality. Harmonics because overheating, reduced efficiency, and malfunctioning of sensitive equipment, making their mitigation critical in industrial and high-power applications. Shunt Active Power Filters (SAPFs) are widely recognized as an effective solution for compensating harmonic and reactive currents in real time. Integrating a Cascaded Multilevel Inverter (CMLI) with SAPFs enhances their performance by generating multi-step voltage waveforms, which closely approximate a sinusoidal waveform and reduce Total Harmonic Distortion (THD). The modular structure of the CMLI allows for scalability, easy maintenance, and reduced voltage stress on semiconductor switches, while advanced control strategies such as Pulse Width Modulation (PWM) and Selective Harmonic Elimination (SHE) ensure precise current injection and dynamic response under varying load conditions. This paper presents a theoretical analysis of the implementation of a CMLI-based SAPF for harmonic mitigation, discussing its principles, configuration, control algorithms, and compensation strategies. Simulation studies confirm that the system effectively reduces harmonics, maintains sinusoidal source currents, and improves overall power quality, making it suitable for industrial applications.

Keywords: Reactive Power Compensation Cascaded Multilevel Inverter, Shunt Active Power Filter, Total Harmonic Distortion, Harmonic Mitigation.

I. INTRODUCTION

The increasing penetration of nonlinear loads in modern power systems has led to significant challenges in maintaining power quality, particularly with respect to harmonic distortions. Nonlinear loads such as adjustable speed drives, rectifiers, switched-mode power supplies, and other power electronic devices draw non-sinusoidal currents from the supply, resulting in current and voltage harmonics, poor power factor, and increased losses in transmission and distribution networks. These harmonics, if left uncontrolled, can cause overheating of equipment, interference with sensitive electronics, malfunctioning of protective relays, and overall deterioration of system efficiency and reliability. To address these concerns, active power filters (APFs) have emerged as an effective solution for harmonic mitigation and reactive power compensation. Among different topologies, the Shunt Active Power Filter (SAPF) has been extensively studied and implemented due to its capability to inject compensating currents at the point of common coupling (PCC), thereby canceling out harmonic components drawn by nonlinear loads and restoring sinusoidal current flow from the supply. Conventional APFs, however, are commonly based on two-level voltage source inverters (VSIs). While effective in low and medium power applications, two-level inverters encounter several limitations when applied in high-power and high-voltage systems. They are characterized by high switching losses, increased electromagnetic interference, limited output voltage quality, and difficulties in achieving scalability. These drawbacks have motivated the exploration of multilevel inverter (MLI) topologies, which offer superior performance in high-power applications by generating stepped voltage waveforms that more closely approximate a sinusoidal waveform. Among various MLI configurations—such as diode-clamped, flying capacitor, and cascaded H-bridge—the Cascaded Multilevel Inverter (CMLI) has gained particular attention due to its modular structure, ease of expansion, and reduced number of components when compared with other multilevel topologies.

The CMLI operates by connecting multiple H-bridge cells in series, each supplied by an isolated DC source, to generate stepped voltage levels. This structure allows the inverter to achieve higher voltage levels with improved harmonic performance while maintaining relatively low switching frequencies. The main advantage of using a cascaded arrangement is that it distributes the overall voltage stress among multiple power devices, thereby enhancing system reliability and reducing the switching losses associated with high-frequency operation. Additionally, the modular nature of the CMLI provides flexibility in design, scalability to higher voltage levels, and potential integration with renewable energy sources such as photovoltaic panels or fuel cells, which can serve as isolated DC supplies for individual H-bridge cells. When applied in Shunt Active Power Filters, the cascaded multilevel inverter topology significantly enhances harmonic mitigation capabilities. By generating higher quality voltage and current waveforms with lower Total Harmonic Distortion (THD), the CMLI-based SAPF ensures compliance with international power quality standards such as IEEE-519. The SAPF injects compensating currents into the system that are equal in magnitude but opposite in phase to the harmonic currents generated by nonlinear loads. With a cascaded inverter structure, the filter can operate efficiently at medium and high voltage levels without requiring bulky transformers or excessively high switching frequencies. This not only improves harmonic mitigation but also enhances the dynamic performance of the system in responding to sudden load changes, reactive power demands, and unbalanced load conditions.

Furthermore, the implementation of a CMLI-based SAPF incorporates advanced control strategies to ensure precise extraction and injection of compensating currents. Popular control algorithms include instantaneous reactive power theory (p–q theory), synchronous reference frame (SRF) theory, and adaptive or intelligent control methods based on fuzzy logic, neural networks, or model predictive control. These techniques enable accurate detection of harmonic components and efficient generation of reference signals for the inverter, ensuring effective compensation under both steady-state and transient operating conditions. Modern digital signal processors (DSPs) and field-programmable gate arrays (FPGAs) further enhance the real-time execution of these control strategies, making cascaded inverter-based SAPFs practical for industrial deployment. Another key consideration in the implementation of CMLI-based SAPFs is the balancing of DC link voltages across individual H-bridge cells. Since each H-bridge requires a separate DC source, ensuring equal voltage distribution and avoiding voltage imbalance is critical for maintaining system performance. Various modulation techniques, such as phase-shifted pulse width modulation (PSPWM) and selective harmonic elimination (SHE), are employed to optimize the switching strategy and balance voltages across cells. These modulation schemes not only improve harmonic performance but also reduce switching losses and enhance the overall efficiency of the filter.

In addition to harmonic mitigation, the CMLI-based SAPF also contributes to reactive power compensation and voltage regulation, thereby supporting grid stability and improving the power factor of the system. This makes the technology especially valuable in industrial plants, data centers, and renewable energy integration, where large nonlinear loads are prevalent and power quality requirements are stringent. The rapid advancements in semiconductor technology, digital controllers, and modular inverter design are further accelerating the adoption of cascaded multilevel inverter-based SAPFs as a preferred solution for modern power quality challenges. In summary, the implementation of a Cascaded Multilevel Inverter–based Shunt Active Power Filter represents a significant advancement in the field of power quality improvement. By combining the advantages of SAPFs with the superior waveform generation capabilities of CMLIs, this approach offers a scalable, efficient, and robust solution for mitigating harmonics, compensating reactive power, and ensuring compliance with power quality standards in high-power electrical systems.

II. CASCADED MULTILEVEL INVERTER (CMLI)

Overview of Multilevel Inverters

Multilevel inverters are a class of power electronic converters designed to produce high-quality voltage waveforms by synthesizing multiple discrete voltage levels. Unlike conventional two-level inverters, which switch the output directly between positive and negative DC bus voltages, multilevel inverters generate output voltages that transition in several steps. These multiple voltage steps create a waveform that more closely approximates a pure sinusoidal waveform, significantly reducing Total Harmonic Distortion (THD) and improving power quality.

Multilevel inverters are particularly useful in high-voltage and high-power applications, such as industrial drives, renewable energy integration, and high-voltage transmission systems. In conventional two-level inverters, directly converting high DC voltage into an AC output can introduce excessive voltage stress on the semiconductor devices, leading to high switching losses and reduced reliability. In contrast, multilevel inverters divide the DC bus voltage into smaller segments and switch them in a controlled manner to generate a stepped AC waveform. This approach not only reduces the voltage stress on individual switches but also minimizes the switching frequency required to achieve low harmonic content, making the system more efficient.

The main types of multilevel inverters include diode-clamped, flying capacitor, and cascaded H-bridge topologies. Diode-clamped inverters use clamping diodes to achieve multiple voltage levels by dividing the DC bus voltage. Flying capacitor inverters employ a series of capacitors to create intermediate voltage levels, which are switched by semiconductor devices. Cascaded H-bridge inverters, on the other hand, connect multiple single-phase H-bridge modules in series, each supplied by its own isolated DC source, to synthesize the AC output. Each topology has its own advantages, limitations, and practical applications, but the cascaded H-bridge inverter is widely preferred for modularity, scalability, and ease of control in high-power applications.

Cascaded H-Bridge Multilevel Inverter

The Cascaded H-Bridge (CHB) multilevel inverter is a widely used configuration due to its modularity and ability to produce high-quality voltage waveforms. Each single-phase H-bridge module in the inverter can produce three distinct output levels: positive DC voltage (+Vdc), zero voltage (0), and negative DC voltage (-Vdc). By cascading multiple H-bridge modules in series, a multilevel output voltage with multiple discrete steps can be obtained. For instance, a system with three cascaded H-bridges can produce seven output levels: +3Vdc, +2Vdc, +Vdc, 0, -Vdc, -2Vdc, -3Vdc.

The primary advantage of this approach is that it reduces harmonic distortion in the output waveform without requiring a high switching frequency, which is necessary in conventional two-level inverters. Lower switching frequency reduces switching losses, increases efficiency, and decreases electromagnetic interference (EMI). Moreover, the modular nature of the cascaded H-bridge inverter allows easy expansion: additional H-bridge modules can be added in series to increase the number of voltage levels and further improve waveform quality.

In addition to superior harmonic performance, the cascaded H-bridge inverter provides flexibility in voltage control. Each H-bridge module is independently controlled, allowing the inverter to compensate for unbalanced loads, inject reactive power, or provide fault-tolerant operation. These features make CMLIs particularly suitable for industrial applications requiring high power, high efficiency, and precise voltage waveform control, such as shunt active power filters for harmonic mitigation.

Control Strategies for CMLI

Effective operation of a cascaded H-bridge multilevel inverter depends heavily on advanced control strategies that determine the switching sequences of the individual H-bridge modules. The two most commonly used control techniques are Pulse Width Modulation (PWM) and Selective Harmonic Elimination (SHE).

Pulse Width Modulation (PWM) is a widely used technique that modulates the width of inverter output pulses to approximate a reference sine waveform. In sinusoidal PWM, a high-frequency triangular carrier signal is compared with a sinusoidal reference to determine the switching instants of each inverter module. This allows precise control of the output voltage amplitude and frequency while keeping harmonic content low. PWM also enables dynamic response to load variations, making it suitable for real-time applications such as active power filtering.

Selective Harmonic Elimination (SHE) is a complementary approach that focuses on eliminating specific harmonic components in the inverter output. By carefully selecting the switching angles of each H-bridge module, specific low-order harmonics can be canceled out entirely, resulting in a cleaner voltage waveform with minimal THD. SHE is particularly effective in applications where low harmonic content is critical, although it requires solving nonlinear equations for switching angles, which can be computationally intensive.

In addition to PWM and SHE, other hybrid control strategies can be implemented, such as carrier-based multilevel PWM, space vector modulation, and real-time adaptive switching to optimize voltage waveform quality. The key objectives of these control strategies are:

1. Minimizing Total Harmonic Distortion (THD) to improve power quality.
2. Reducing switching losses to enhance inverter efficiency.
3. Balancing voltages across each H-bridge module to prevent overvoltage or undervoltage conditions.
4. Ensuring modular scalability so additional H-bridges can be added without redesigning the control system.

By applying these control strategies, the CMLI can reliably generate high-quality voltage waveforms suitable for industrial applications, including shunt active power filters, grid-tied inverters, and renewable energy interfaces, all while maintaining high efficiency, modularity, and low harmonic distortion.

III. SHUNT ACTIVE POWER FILTER (SAPF)

Principles of SAPF

A Shunt Active Power Filter (SAPF) is an advanced power electronic device designed to improve power quality by actively compensating for harmonic and reactive currents in electrical systems.

Nonlinear loads, such as rectifiers, variable speed drives, and uninterruptible power supplies, draw distorted currents from the supply, resulting in harmonic injection and poor power factor. The fundamental principle of SAPF operation is based on real-time detection and compensation: the SAPF continuously monitors the load current waveform and identifies the harmonic and reactive components.

Once the harmonic components are detected, the SAPF generates equal but opposite compensating currents, which are injected into the system through a power electronic inverter connected in parallel with the load. This process effectively cancels out the harmonics, ensuring that the current drawn from the source remains sinusoidal and in phase with the supply voltage. Additionally, the SAPF compensates for reactive power demand, improving the overall power factor of the system. Unlike passive filters, which rely on fixed inductors, capacitors, or LC combinations to block certain frequencies, SAPFs are dynamic devices capable of adapting to continuously changing load conditions. They can provide harmonic mitigation for a wide range of frequencies and are particularly effective in systems with multiple nonlinear loads or rapidly varying operating conditions.

Configuration of SAPF

The configuration of a SAPF depends on the type of load and system requirements. In industrial applications, a three-phase, four-wire SAPF is commonly used, allowing compensation not only of phase currents but also of neutral current harmonics. The four-wire configuration is essential for addressing triplen harmonics (multiples of the third harmonic), which tend to accumulate in the neutral conductor and cannot be mitigated by three-phase three-wire filters.

Integrating a Cascaded Multilevel Inverter (CMLI) into the SAPF architecture further enhances its capabilities. The CMLI provides a multilevel voltage output that allows precise shaping of the compensating current waveform with minimal harmonic distortion. This ensures that the injected currents closely match the harmonic profile of the load, maximizing compensation efficiency. The modular structure of the CMLI also offers operational advantages: it allows the SAPF to be scaled for higher power applications simply by adding more H-bridge modules, and it simplifies maintenance, as individual modules can be serviced without taking the entire system offline. Moreover, CMLI-based SAPFs have lower switching losses and higher reliability, making them particularly suitable for high-voltage and high-power industrial environments where maintaining strict power quality standards is critical.

Control Algorithms

The performance of a SAPF heavily depends on its control algorithms, which determine the magnitude, frequency, and phase of the compensating currents to be injected. Two widely used methods are Instantaneous Reactive Power Theory (p–q theory) and the Synchronous Reference Frame (dq0) method.

The Instantaneous Reactive Power Theory (p–q theory) is based on real-time measurement of three-phase voltages and currents. The theory transforms the measured currents and voltages into instantaneous active and reactive power components. The harmonic and reactive components are then extracted from the total power, and the reference compensating currents are calculated. These currents are fed to the inverter, which generates the compensation waveform in real time. The p–q theory is highly effective for dynamic load compensation, offering fast response times and accurate harmonic cancellation in three-phase systems.

The Synchronous Reference Frame (dq0) method is another popular control strategy that simplifies harmonic detection by transforming three-phase currents from the stationary abc reference frame into a rotating dq0 reference frame. In this frame, the fundamental components become DC quantities, while the harmonic components remain AC. This separation allows easier calculation of the compensating currents. The dq0 method is often preferred for three-phase four-wire systems, as it provides better separation of fundamental and harmonic components, ensuring precise current injection for both phase and neutral conductors.

Both methods require additional control components such as voltage sensors, current sensors, and fast digital signal processors (DSPs) to implement real-time measurement, calculation, and PWM generation. Advanced controllers may also include adaptive algorithms that adjust the compensation strategy based on load variations, ensuring that the SAPF continuously maintains low THD and improves power factor under changing operating conditions. By combining precise current detection, multilevel inverter-based current synthesis, and real-time adaptive control, SAPFs can achieve highly effective harmonic mitigation and reactive power compensation in modern industrial systems.

IV. HARMONIC MITIGATION USING CMLI-BASED SAPF

Harmonic Analysis

Harmonics in electrical systems are periodic distortions in voltage or current waveforms caused by nonlinear loads. Each harmonic is characterized by its frequency, order, and magnitude. The harmonic order is defined as the multiple of the fundamental frequency; for example, the 3rd, 5th, 7th harmonics correspond to three, five, and seven times the fundamental frequency. In three-phase industrial systems, triplen harmonics (multiples of the third, such as the 3rd, 9th, and 15th) are particularly problematic because they add in the neutral conductor, potentially causing overheating and neutral conductor overload. Interharmonics, which occur at frequencies that are not integer multiples of the fundamental, can also arise due to modern electronic devices, resulting in voltage fluctuations, flicker, and interference with communication systems?

To quantify and analyze these harmonics, Fourier analysis is employed. Fourier transformation decomposes a distorted waveform into its constituent sinusoidal components, providing precise information about the amplitude and phase of each harmonic. This analysis is critical in designing an effective Shunt Active Power Filter, as it determines the compensating current that must be generated to cancel out the harmonics. Accurate harmonic characterization ensures that the SAPF can dynamically respond to variable load conditions, targeting both low-order and high-order harmonics while maintaining the source current nearly sinusoidal.

Compensation Strategy

The fundamental operation of a CMLI-based SAPF revolves around generating compensating currents that cancel the harmonic components of the load. After detecting the distorted load current through real-time measurement, the SAPF calculates the harmonic components that need compensation. Using control algorithms such as p–q theory or dq0 method, the required reference compensating currents are derived. These currents are then synthesized by the Cascaded Multilevel Inverter (CMLI) and injected into the system via the point of common coupling (PCC).

By injecting an equal but opposite current for each harmonic component, the SAPF effectively neutralizes the harmonic currents, ensuring that the supply current remains sinusoidal and that reactive power is properly compensated. Proper synchronization between the reference current generation algorithm and inverter switching is critical to achieving accurate compensation. If the switching angles or reference currents are not precisely coordinated, residual harmonics may remain, reducing the effectiveness of the SAPF. Moreover, multilevel inverter topology allows smooth and precise current injection with reduced Total Harmonic Distortion (THD) and lower switching losses, making the system suitable for industrial and high-power applications where maintaining strict power quality standards is essential.

Simulation and Modeling

Before hardware implementation, simulation and modeling of the CMLI-based SAPF are essential for verifying its performance and optimizing design parameters. Tools like MATLAB/Simulink and PSCAD/EMTDC are widely used to model the electrical network, load conditions, inverter topology, and control algorithms. Simulation allows engineers to evaluate how the SAPF responds to different nonlinear load conditions, variable supply voltages, and system transients.

Simulated results demonstrate the improvement in current and voltage waveforms, highlighting reductions in THD and harmonic distortion. Waveform plots can show the source current becoming nearly sinusoidal after compensation, while the injected compensating current matches the harmonic profile of the load. Simulation also allows testing of different control algorithms, inverter switching frequencies, and modular configurations, ensuring that the final hardware system performs efficiently and reliably under real-world conditions. Additionally, simulation helps identify potential challenges, such as voltage unbalance or switching overshoot, allowing corrective adjustments before physical implementation, thus saving time and cost during the deployment phase.

V. ADVANTAGES OF CMLI-BASED SAPF

Cascaded Multilevel Inverter (CMLI)-based Shunt Active Power Filters (SAPFs) offer significant advantages compared to conventional two-level inverter-based SAPFs or passive filters. One of the primary benefits is the reduction of voltage stress across power semiconductor switches. Because the output voltage of a CMLI is synthesized in multiple discrete steps, each individual switch handles only a fraction of the total voltage. This reduces the risk of voltage overstress, increases device reliability, and allows operation at higher system voltages without requiring specialized high-voltage components. Another important advantage is reduced switching losses, which enhances overall system efficiency. Multilevel inverters can generate a high-quality output waveform at lower switching frequencies because the multi-step voltage waveform naturally approximates a sine wave. This reduces the frequency at which switches must operate, leading to lower thermal losses and higher efficiency, particularly in high-power applications.

The modular design of the CMLI further contributes to its advantages. Each H-bridge module operates independently, allowing easy scalability. For instance, additional modules can be added to increase the number of voltage levels and improve harmonic compensation without redesigning the entire system. This modularity also simplifies maintenance and fault management: if one module fails, it can be isolated and replaced without shutting down the entire SAPF system. By producing multi-step voltage waveforms, CMLI-based SAPFs achieve superior harmonic mitigation. The multiple voltage levels reduce the total harmonic distortion (THD) in the injected compensating currents, ensuring better compliance with power quality standards such as IEEE 519. Additionally, precise control of compensating currents allows rapid dynamic response to load variations. This makes CMLI-based SAPFs particularly suitable for industrial environments where loads are highly variable and conventional passive filters may fail to provide adequate compensation. Overall, these features make CMLI-based SAPFs a reliable, efficient, and flexible solution for modern power quality challenges.

VI. CONCLUSION

The growing use of nonlinear loads and renewable energy systems has made harmonic mitigation and power quality enhancement critical issues in modern power networks. Traditional two-level inverter-based SAPFs, although effective in small-scale applications, face limitations when extended to high-power and high-voltage systems. The Cascaded Multilevel Inverter (CMLI)–based Shunt Active Power Filter overcomes these challenges by leveraging a modular structure capable of producing high-quality stepped voltage waveforms with lower THD, reduced switching losses, and superior scalability. Its ability to distribute voltage stress across devices makes it particularly suitable for medium and high-voltage applications. Furthermore, the integration of advanced modulation and control strategies ensures effective extraction and compensation of harmonics, while also providing reactive power support and improving overall system efficiency. By injecting accurate compensating currents, the CMLI-based SAPF ensures compliance with international standards, reduces equipment stress, and enhances grid reliability. Its adaptability for integration with renewable sources and modular expansion highlights its future potential as a key enabler of sustainable, smart, and resilient power systems. Thus, the cascaded multilevel inverter–based SAPF stands as a promising and practical solution for addressing the pressing challenges of harmonic mitigation and power quality improvement in today's evolving energy landscape.

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