Power Quality Enhancement in Grid Integrated System

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***Abstract-*** The proliferation of distorting loads has witnessed an exponential surge, consequently giving rise to power quality predicaments within electrical power systems. The seamless transmission of untainted electric power stands as a pivotal mission for power engineers. The repercussions of power quality anomalies can be keenly felt on end-user apparatus, encompassing electronic appliances and digital meters, thereby culminating in product impairment. In a bid to counteract these power quality apprehensions, bespoke power devices have assumed a decisive role in contemporary power systems. This discourse primarily centers on the investigation and configuration of Shunt Active Power Filters (SAF) as a means to enhance the power quality for delicate industrial loads, electrical distribution networks, transmission facilities, and power generation systems.

***Keywords:*** *Power Quality Improvement, Active and Reactive power, Power Factor improvement, Shunt Active Filter (SAF), STATCOM, power grid integrated system systems, Current Harmonics.*

1. **Introduction:**

The efficient transmission of clean power to end-users stands as a pivotal challenge for electrical power engineers. In the current landscape, electrical distribution systems contend with a multitude of distorting or nonlinear loads, as well as reactive loads. The prevalence of reactive loads contributes to an excessive demand for reactive power, leading to increased feeder losses and a reduction in the overall efficiency of active power flow within the distribution network. Concurrently, non-linear loads like single-phase and three-phase power converters, electronic appliances, electric arc furnaces, and digital meters introduce significant asymmetric disturbances into the AC mains. These disturbances, often termed power quality issues, can cause voltage fluctuations, waveform distortions (harmonics), transients, flickering, variations in supply frequency, DC offsets, noise, and notches. Both balanced and unbalanced non-sinusoidal currents produce a slew of adverse effects including harmonics, elevated neutral currents, reactive power inefficiencies, low power factors, and unbalanced loading of the AC mains. Poor power quality not only leads to substantial power losses but also deteriorates consumer services, system efficiency, productivity, economic conditions, and the performance of telecommunication networks.

In the early stages, LC passive filters were instrumental in mitigating power quality concerns in electrical power systems. However, the drawbacks of passive filters – their bulky size, limited dynamic performance, fixed compensation requirements, and susceptibility to resonance – prompted power engineers to focus on innovative solutions. This led to significant advancements in the field of power electronics devices, paving the way for the emergence of active filters. Active filters rapidly replaced passive counterparts due to their agility and dynamism.

Among the various types of active filters, Shunt Active Filters (SAFs) have emerged as a cornerstone in power quality enhancement. SAFs have proven highly effective in rectifying disturbances related to electric power in distribution systems. Nearly all power quality issues associated with consumer loads can be resolved through the implementation of SAFs, including the utilization of STATCOMs.

The structure of the present article unfolds as follows: Section II delves into power quality concerns, their implications, and industry standards. Sections III, IV, V, and VI sequentially present the system configuration, control strategies, merits, and applications of shunt active filters (SAFs), culminating in the concluding section.

1. **POWER QUALITY STANDARDS AND POWER QUALITY ISUUES, CONSEQUENCES**

**A. Power Quality Standards:**

At both national and international levels, organizations such as IEEE and IEC collaborate with power engineers and research institutions to establish a cohesive platform for cooperation. Their aim is to ensure compatibility between end-use equipment and the power system. International standards guidelines stipulate that electrical equipment's energy consumption must adhere to specified harmonic content limits. The injection of current or voltage is restricted based on the load and power system size. Working group members develop standards that define the parameters for power quality. According to IEEE Standard 519-1992 for systems below 69KV, the Total Harmonic Distortion (THD) value should not exceed 5%. Harmonic load currents should not coincide with system resonances. As per IEC Standard 61000-2-2\*, the compatibility level of harmonic voltage, particularly the third harmonic and its multiples, should be below 5%.

**B. Power Quality Issues:**

"Power quality" has emerged as a prominent term in the realm of electric power systems. In the present scenario, the growing utilization of non-linear or sensitive loads that draw non-sinusoidal currents significantly impacts end-use equipment. This growing demand for highly reliable and quality electric power has led to increased awareness among both utilities and end-users. Key power quality concerns encompass:

**i. Voltage Variations:**

Fluctuations in power system loads lead to voltage variations. Real and reactive powers are intricately linked to load variations. These variations are classified based on the root mean square (rms) voltage and duration into short and long-duration voltage variations. The subclasses include voltage rise/swell, voltage dips/sags, voltage interruptions, and long-duration voltage variations. Voltage fluctuations are commonly termed voltage flicker, depicting dynamic variations caused by load changes in power networks.

**ii. Wave Distortion / Harmonics:**

Harmonics, defined as integer multiples of the system's fundamental frequency, have been a subject of technical study since the 1930s and 1940s. They fall within the category of waveform distortion. Harmonics stem from sensitive or distorted loads like power electronics devices, arc furnaces, and induction furnaces within power networks. Distorted loads exhibit non-proportional relationships between current and voltage. Waveform distortion is further classified into notching, noise, DC-offset, and interharmonics. The presence of DC content in AC current or voltage, termed DC-offset, is caused by factors such as geomagnetic disturbances and DC currents in AC networks, resulting in transformer saturation.

**C. Consequences of Power Quality Issues:**

Power quality issues such as voltage variations, transients, flickers, interharmonics, and harmonics yield consequences like overloading, overheating, increased losses, transformer saturation, data errors or losses, and malfunctions in equipment like logic controllers, microprocessor-based controllers, and power meters. Specifically, harmonics induce overheating, proximity effects, and skin effects in electric conductors.

1. **SYSTEM DISCRIPTION**

Even with a variety of options available to enhance power quality, shunt active filters (SAFs) have gained widespread adoption due to their versatility and robust performance. Shunt active filters are primarily realized through pulse width modulated voltage source inverters (VSI) and current source inverters (CSI). These active filters are categorized based on phase numbers, converter topology (CSI or VSI), power ratings, and response speed.

**A. Converter-Based Classifications:**

Shunt active filters can be classified into two main types: voltage-fed type and current-fed type. The voltage-fed PWM power converters are favored due to their expandability, cost-effectiveness, and improved efficiency. They employ a bridge-structured configuration as depicted in Fig. 2. This type of inverter serves as a non-sinusoidal current source, fulfilling the harmonic current requirements of distorting loads. The inclusion of a diode in series with the IGBT prevents reverse voltage flow, albeit at the cost of restricted switching frequency.

**B. Phase-Based Classifications:**

Shunt active filters are further categorized based on phase levels, encompassing 1-phase (2-wire) and 3-phase (3-wire or 4-wire) systems.

**B.1) 2-Wire Active Filters:**

Many distorting loads, typically found in domestic appliances, are connected to 1-phase supply systems. The deployment of 2-wire active filters in series, shunt, or combined configurations effectively addresses power quality concerns. Both current-fed and voltage-fed PWM converters amplify input characteristics on the supply side. The setup using a bridge-structured current source inverter (CSI) with inductive storage is illustrated in Fig. 3. An analogous configuration can be achieved with a voltage source bridge using capacitive storage for shunt active filters.

**B.2) 3-Phase, 3-Wire Active Filters:**

Numerous publications have explored 3-phase, 3-wire shunt active filters. These filters are employed when 3-phase nonlinear loads, such as adjustable speed drives (ASDs), utilize solid-state power converters. Fig. 4 illustrates the configuration of a 3-phase, 3-wire shunt active filter. Some designs involve three 1-phase active filters coupled with an isolation transformer for independent phase control, voltage matching, and effective compensation in unbalanced systems.

**B.3) 3-Phase, 4-Wire Active Filters:**

In situations where a three-phase supply system incorporates a neutral conductor to power numerous 1-phase loads, issues like reactive power burden, excessive neutral current, harmonics, and unbalance may arise. 4-wire shunt active filters are designed to address these concerns. These filters can be implemented using both voltage-fed and current-fed converters. Figs. 5-7 depict the configuration of 3-phase, 4-wire active filters. The midpoint configuration with capacitors is suitable for lower rating applications, whereas the switch-type filters stabilize the neutral of the active filter. Another configuration employs three 1-phase bridge converters to ensure proper voltage matching and enhance reliability. The classification of shunt active filters based on converter type and phase configuration underscores their adaptability and effectiveness in mitigating power quality issues.

The conceptual model for evaluating harmonic compensation, as illustrated in Figure 1, encompasses the primary power circuits and a DC link voltage control unit. This configuration incorporates a voltage source control-based active filter designed to address harmonic issues and is connected in parallel with a grid-integrated system. The inherent dynamic capabilities of shunt active power filters make them the prominent choice for mitigating harmonics within the envisaged electrical distribution system.



**Fig.1.** The proposed model for harmonic mitigation in a grid-tie system.

1. **CONTROL STRATEGY FOR GENERATION OF GATE PULSES**

The efficacy of active filters heavily relies on their control strategies, which serve as the core of their operation. These strategies are pivotal in generating the necessary compensation current and are integral to the design of shunt active power filters (SAFs). Within the realm of 3-phase source systems supplying distorting loads, various control strategies exist, including instantaneous reactive power theory (p-q theory), synchronous reference theory (Id-Iq theory), perfect harmonic cancellation method (PHC), and Unity Power Factor method (UPF). This paper primarily focuses on p-q theory and Id-Iq theory.

**4.1 P-Q Theory:**

The p-q theory was initially introduced by Akagi and collaborators in 1984. This control strategy operates in the time domain and is applicable to both 3-phase, 3-wire systems and 3-phase, 4-wire systems. Its validity extends to steady-state as well as transient conditions. By employing α-β transformation, the set of voltages and currents are converted from the abc to α-β-0 coordinates. The phase voltages supplied by the source are represented as:

Similarly reactive load currents are given by the equations

=

=

Where +. The powers p and q can decomposed as p = , q =. The reference source currents for ***α-β*** and ***abc*** transformations can be expressed [8] as

=

=

**4.2 Id-Iq Theory:**

Also known as synchronous reference frame theory (SRF), this theory involves transforming the 3-phase stationary (abc) system into a rotating coordinate (dq0) system. The d-q reference frame is determined by the angle θ relative to the α-β frame, which is utilized in the p-q theory. The Park's transformation is defined as:

=

=

Where voltage and currents are

=

1. **PRACTICLE IMPLEMENTATION AND CONSIDERATIONS**

This section presents the MATLAB simulation outcomes of a proposed test model designed to enhance power quality using an active filter. In order to meet the total load demand, the current is supplied from both the primary grid source and a green energy source as depicted in Figure 1. The shunt active filter integrated into the grid system effectively eliminates the current harmonics generated by nonlinear loads. The system enumerates the parameter values utilized in the MATLAB simulation study aimed at nullifying current harmonics within this research endeavor. The single-phase source voltage is illustrated in Figure 2.



**Fig.2.** Source voltage for *Phase-a* in three-phase *abc* system.

The source current for Phase-a in a three-phase abc system is depicted both with and without the STATCOM (Static Synchronous Compensator) as follows:

***With Shunt Active Filter (Statcom):***

When the STATCOM is employed, it actively regulates the reactive power in the system, leading to a more controlled and balanced operation. The source current in Phase-a exhibits reduced harmonic content and improved power factor due to the compensating effects of the STATCOM.

***Without Shunt Active Filter (Without-Statcom):***

In the absence of the STATCOM, the source current in Phase-a tends to exhibit higher harmonic distortion and a potentially lower power factor due to the impact of nonlinear loads or other power quality issues.

The implementation of the STATCOM helps to mitigate these adverse effects, resulting in a more stable and harmonically cleaner source current in Phase-a of the three-phase abc system. As shown in Figure.3.



**Fig.3.** Source Current for *Phase-a* in three-phase *abc* system with & without Statcom.



**Fig.4.** Compensating Current for *Phase-a* in three-phase *abc* system for mitigation of Harmonics.

Figure.4 represents injection of current by shunt active power filter for mitigation of current harmonics into the grid integrated system.

1. **CONCLUSION**

This chapter underscores the significance, research, and advancement of shunt active filters in the context of non-linear loads within power systems. Specifically, the utilization of STATCOM (Static Synchronous Compensator) is explored, where it is strategically connected at the load end to mitigate the current harmonics introduced by distorting loads. Beyond harmonics suppression, STATCOM demonstrates its capability in enhancing power factor and voltage regulation. The paper delves comprehensively into various aspects, providing clear insights into power quality concerns, the establishment of power quality standards, the repercussions of compromised power quality, system configurations, diverse control strategies, and the crucial advantages and applications associated with shunt active filters, particularly STATCOM. Over the past two decades, the continuous and diligent research efforts in the domain of static reactive compensation technology, represented by shunt active filters, have yielded remarkable benefits. These advancements have rippled across end-users, utility companies, and wind farm developers. The integration of such technology has ushered in significant enhancements in power quality, operational efficiency, and the overall reliability of power systems.

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