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HARMONIC MITIGATION IN SMART POWER SYSTEMS USING DATA-DRIVEN DQ-FRAME INSTANTANEOUS POWER CONTROL OF SHUNT ACTIVE POWER FILTERS: A REVIEW

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ABSTRACT

Increasing use of non-linear loads, renewable energy sources, and the use of power electronics converters on today's electric grids have placed greater demands on power quality. The main issues that affect the stability and efficiency of today's electrical systems include harmonic distortion, reactive power imbalance, and distortion of current waveforms. To compensate for harmonic currents and improve power quality, Shunt Active Power Filters (SAPF) have been developed. This chapter outlines a comprehensive review of multivariable control strategies based on synchronous dq-reference frame transformations and instantaneous power theory used for SAPF harmonic mitigation. Special attention is given to nonlinear hysteresis-based current regulation methods for their rapid dynamic response capability and excellent accuracy in tracking harmonic currents. This chapter outlines the theoretical basis for SAPF harmonics mitigation, system models, control architectures, and comparisons of existing advanced control methodologies for SAPF's. Additionally, the chapter reviews the application of intelligent and data-driven control methodologies for improving active filtering methods in smart and sustainable energy systems. The chapter describes how these modern control approaches help to improve grid reliability, reduce harmonic distortion, and support the integration of distributed energy resources in the next generation of smart grids.

Keywords: *Shunt Active Power Filter[1]; Harmonic Current Compensation[2]; dq Reference Frame Control[3]; Instantaneous Power Theory[4]; Nonlinear Hysteresis Current Control[5]; Power Quality Improvement[6]; Harmonic Mitigation[7]; Smart Grid Systems[8]; Power Electronics Converters[9]; Sustainable Energy Systems[10].*

1. INTRODUCTION

Modern power systems are undergoing rapid transformation due to the widespread integration of power electronic converters, renewable energy sources, and intelligent energy management systems. While these technologies allow for more efficient and flexible operation, they also present serious challenges to the quality of electrical power. Nonlinear loads, including adjustable-speed drives, switched-mode power supplies, electric vehicle chargers, and renewable energy inverters, create non-sinusoidal currents that distort the waveform of the electrical supply. This causes harm to transformers by overheating them; increasing losses (losses)/increasing losses, malfunctioning of protective devices, as well as causing an improper operation of communications systems. Therefore, harmonic mitigation and improving the quality of electric power have become essential areas for research today in the field of electrical power engineering. In this regard, active power filter (active power filter) technologies have been very effective in reducing the adverse effects of harmonics on electrical systems. One of the most widely studied active filtering technologies is the Shunt Active Power Filter (SAPF), due to its capability of dynamically compensating for both harmonic currents and reactive power at the point of common coupling. Unlike passive filters, which are comprised exclusively of fixed passive (inductive/capacitive) elements, SAPFs incorporate an active power electronic converter along with a sophisticated control algorithm that generates compensating currents in order to counteract harmonic components created by non-linear loads.In addition, the pioneering work of Akagi regarding the fundamental principles of active filtering and their modem implementation has become the basis for the development of all modern active filtering techniques [1]. Numerous control techniques have been developed over the years for SAPF operations. The dq-frame (synchronous reference frame) has been a very successful means of detecting and compensating for harmonics. This process involves transforming three-phase currents from an independent abc stationary coordinate system into a rotating dq reference frame that is synchronized with the grid voltage. In the dq frame, fundamental frequency components are represented as constant direct-current (DC) values while harmonic components are oscillatory signals, allowing straightforward extraction of the harmonic components via filtering methods. The use of an instantaneous power theory allows for further enhancement of the dq control scheme's ability to mitigate harmonics and compensate for reactive power. Another critical aspect of the control logic associated with SAPFs is the method employed for tracking currents to accurately inject compensating currents. One of the most widely employed methods for tracking current is hysteresis current control due to its ease of use, rapid dynamic response, and robustness against variations in the parameters of the electrical system. Kale and Ozdemir proposed an adaptive hysteresis band current controller that automatically adjusts the width of the hysteresis band to control the switching frequency of the inverter in order to increase the overall efficiency of the system [3]. Nonlinear current regulation techniques such as hysteresis provide fast response times to transient disturbances and high accuracy of tracking. Advanced control strategies have also been suggested to improve the performance of SAPFs in complex power systems. Rahmani et al. proposed a new control method for three-phase shunt active power filters that improves harmonics compensation and improves the stability of the overall system under varying loading conditions [4]. Hoon et al. have studied various control methods for SAPFs and have demonstrated how each method is effective at reducing harmonic currents in power distribution systems [5]. The following studies illustrate how important it is to have efficient control techniques in order to achieve a good level of active power filter harmonic mitigation. In addition, combining dq-based control methods with hybrid and adaptive filter architectures has produced a better performance from active power filters. Dey and his colleagues have investigated an experimental dq control technique for hybrid active power filters with three-phase four-wire and neutral current distortion to help improve harmonic compensation [6] Research is being conducted to improve dq control techniques using more advanced signal processing techniques and intelligent methods of control. For instance, Al-Gahtani and Elbarbary have proposed an optimised dq control technique for SAPF systems to enhance power quality performance by conducting better reference current extraction [7]. The theoretical basis for many of these techniques is based on instantaneous power theory formulated by Akagi and have been further elaborated by Akagi, Watanabe, and Aredes. They provide an overall framework for analysing the power components of three-phase systems and have become a significant reference point for all those studying to try to find new ways to filter out unwanted harmonic currents [8]. Advanced SAPF control procedures are important for enhancing the overall power quality as well as the overall quality of the electrical grid. The implementation of many distributed energy resources, electric vehicles, and intelligent energy management systems requires robust methods of harmonic mitigation, which will react to varying operating conditions. Data-driven control and monitoring systems along with new types of power electronics will help to improve the performance of active filtering technology used in the future developments of smart grids.

2. HARMONIC DISTORTION IN POWER SYSTEMS

Harmonic voltages and currents are multiples of system's fundamental frequency (50 or 60 Hz). For example, at 50 Hz, we would see harmonics at 150 Hz, 250 Hz etc. Harmonic distortion is caused mainly by non-linear loads drawing current non-sinusoidally. There are many different types of non-linear equipment contributing to harmonic distortion in today's power systems (e.g., power electronic converters, adjustable speed drives, uninterruptible power supplies, electric arc furnaces, and renewable energy conversion systems), and the rapid switching of semiconductors creates current harmonics that propagate throughout the electric power network. Harmonic distortion produces a number of negative effects within the electric power system. The added heat created by harmonic voltages and currents causes more losses in transmission & distribution systems. Excessive temperature rises in transformers and rotating machines shorten their lifespan. Harmonic currents can cause protective devices to malfunction and measurement devices to give faulty readings. Voltage distortion can cause problems in communications and sensitive electronic equipment. There are many different techniques available to reduce the negative effects of harmonics; however, the use of passive harmonic filters was historically the most common method because of their ability to reduce harmonics/resonance in electric power systems. The performance of these filters is typically very limited by their inability to adjust to varying conditions and/or provide flexible compensation. Active harmonic filtering techniques have been developed to provide greater flexibility and adaptability to modern electric power systems than passive harmonic filters could provide.

3. SHUNT ACTIVE POWER FILTERS

Harmonics refers to currents or voltages whose frequencies are integer multiples of the fundamental system frequency; for example, harmonic frequencies occur at frequencies such as 150 Hz, 250 Hz, etc. in a 50 Hz (or 60 Hz). Harmonic currents are primarily caused by nonlinear loads or devices that draw current in a non-sinusoidal manner. Modern power systems have large numbers of nonlinear devices contributing to harmonic currents including: 1) Power Electronic Converters - 2) Adjustable Speed Drives - 3) Uninterruptable Power Supplies (UPS) - 4) Electric Arc Furnaces - 5) Renewable Energy Conversion Systems. These devices contain semiconductor devices which have very high transient currents during switch-on and will generate harmonic currents that propagate through the power systems. Harmonic currents have several adverse effects on electric power systems. Harmonics lead to higher power loss in the transmission and distribution lines due to excessive heating. Excessive heating also causes excessive aging of transformers and rotating machines. Additionally, excessive harmonic currents may also cause improper operation of the protection devices and measurement devices. In addition, voltage distortion caused by harmonics can interfere with communication systems and sensitive electronic apparatus. There are several methods of filtering harmonics. In early years of power systems, passive filters were used for filtering; however, since passive filters have limitations associated with resonance and fixed compensation capability they are not used as much. Active filtering techniques have proven to provide more flexibility and adaptability, and are, therefore, more applicable to today's power systems. Active Power Filter provided the functions of actively eliminating the higher order active current component. Active filters were typically used in conjunction with other filter types to improve the quality of the current. As an example, an active filter would typically provide for the removal of harmonics produced by an a.c. surge source with a pure electrical load connected to it. Because an active filter is not dependent on the load characteristics, they were used for compensating current due to the a.c. surge on the system. The active filter produced compensating currents which were added back to the load current i.e. the active filter created additional (artificial) loads/impedances for the higher harmonics. The compensation current from the active filter also caused the supply current to be nearly sinusoidal and to remain in phase with the power supply voltage, due to the energy extracted from the power supply. Power filter systems utilize inverters to create compensating currents from the reference signals based on the current measured by the active filter (load) sensor. The reference compensating currents are injected into the power line (the coupling inductors).There are several significant steps that must be accomplished during the operation of an active filter system. The first step is that the active filter must measure the load current and the supply voltage using the sensors. The second step is to process the load and supply currents by the control algorithm (filter) to identify the total harmonic current and to define the reference compensating current. The final step is for the inverter to create the switching signals that will produce the required current.Active filters provide additional benefits versus passive filters. Active filters provide dynamic compensation for a wide range of conditions and provide simultaneous correction for harmonics, reactive power compensation and balancing loads. Active filters will effectively eliminate problems associated with resonance often encountered with passive filters.

4. INSTANTANEOUS POWER THEORY

For analysing three phase electrical systems with respect to how power flows through them and their component parts, instantaneous power theory provides a mathematical method (or mathematical framework) of accomplishing this task. Developed by Akagi, instantaneous power theory has been extended by others to include many different uses in power conditioning systems. With the use of Clarke transformation, three-phase voltage and current signals are transformed from the three-phase abc coordinate system into a stationary two-phase αβ coordinate system. Using these transformed signals, the instantaneous active (real) and instantaneous reactive (oscillatory) power components can be measured. The active instantaneous power represents the actual power being transported between the electrical source and load while instantaneous reactive power corresponds to the oscillatory power components associated with the exchange of reactive energy. By determining what each of these types of power are, it is possible to easily identify and compensate for any harmonic currents that may be present. Many active filtering control algorithms, in particular those that require real-time harmonic detection, rely on instantaneous power theory for their basis.

5. dq-FRAME CONTROL STRATEGY

The synchronous reference frame control technique converts three-phase electrical measurements into a rotating reference frame synchronized to the grid voltage. The Park transformation is used to accomplish this transformation of the three-phase (abc) coordinate system into a direct-quadrature (dq) coordinate system. The fundamental current components in this dq reference frame will appear as a constant DC value, while the harmonic current components will be signaled by an alternation to one another. This property allows for easy separation of harmonic currents from the fundamental currents using a low-pass filter. The dq-frame controller typically utilizes the following steps: The load currents from the three-phase system are first measured, and then transformed into the dq reference frame. Then, the fundamental components of the load current are extracted using filter techniques, while the harmonic components are identified as the deviation from the DC value. After this extraction is complete, reference compensating currents are produced and converted back to the abc frame. The reference current produced will be used by the inverter control system to provide the appropriate drive signals for the inverter. A number of studies have shown that dq control strategy has advantages over traditional control strategies with regard to harmonic mitigation.

6. NONLINEAR HYSTERESIS CURRENT CONTROL

Hysteresis current control is widely used in active power filter systems because of its fast dynamic response and ease of implementation. The Hysteresis current control method is defined by forcing the actual current to follow the reference(current) by using a defined band of hysteresis. When the actual current is greater than the upper limit of the hysteresis band, the inverter switches are turned on in an effort to return the actual current to (below) the upper limit of the hysteresis band. Inversely, when the actual current is less than the lower limit of the hysteresis band, the inverter switches are turned on in an effort to return the actual current to the upper limit of the hysteresis band. Thus, the hysteresis current control method keeps the actual current within an acceptable tolerance band about the reference current. Additionally, adaptive hysteresis control techniques improve system performance by modifying the hysteresis band width according to operating conditions, allowing for a nearly constant switching frequency while still obtaining a fast dynamic response.

7. PERFORMANCE EVALUATION OF SAPF SYSTEMS

There are several ways to rate SAPF systems based on the number of measurable performance indicators that can be used to judge overall harmonic mitigation performance. Currently the most frequently used performance metric is total harmonic distortion (THD), which is a measure of the relative amount of harmonic content to fundamental current or voltage, expressed as a percentage of root mean square values. The design of properly functioning high-quality SAPF systems allows the THD of current to be reduced such that it is often less than what is permitted according to IEEE-519 standards. Some of the other measurable parameters include dynamic response time, power-factor improvement, and system efficiency. The performance of hysteresis current regulated, dq-frame controlled SAPFs for harmonic compensation has been evaluated in simulation studies and experimental work and has been shown to provide excellent harmonic compensation performance for many different loading configurations.

8. ROLE OF ACTIVE FILTERS IN SMART AND SUSTAINABLE ENERGY SYSTEMS

The development of smart grids and sustainable energy systems has increased the importance of power quality management. Renewable energy sources such as solar photovoltaic systems and wind turbines rely heavily on power electronic converters, which introduce harmonic distortions into the grid.Active power filters play a crucial role in maintaining power quality in such systems. They enable reliable integration of distributed generation units, electric vehicle charging infrastructure, and energy storage systems. By mitigating harmonic distortion and improving power factor, SAPFs enhance the stability and efficiency of modern power networks. The integration of advanced monitoring technologies and data analytics with active filtering systems further enhances their effectiveness. Intelligent controllers can analyze system conditions in real time and adapt compensation strategies accordingly the development of smart grids and renewable energy systems has intensified the need for quality power management in order to ensure the continued success and viability of electric utility company operations. The majority of distributed generation resources such as solar photovoltaic systems and wind-power generating equipment utilize power electronics for interconnection to the electric grid, with the result being that these resources contribute harmonics to the grid. Active power filters play a critical role in ensuring that the power produced by these resources supports the quality of power delivered through the electric grid. SAPFs support the reliable integration of distributed generation resources, electric vehicle charging infrastructure, and battery energy storage systems. SAPFs support overall grid stability and improve overall electric utility operational efficiencies by mitigating harmonic levels and improving power factor. The implementation of advanced monitoring technologies and data analytics will further enhance the performance of active filtering systems. With real-time analysis of electric circuit operating conditions, intelligent controls have the ability to modify the parameters of the SAPF system to provide optimized compensation.

9. CONCLUSION

Harmonic currents are one of the biggest challenges to today's electric power systems due to the number of non-linear loads and power electronics being utilized. Shunt Active Power Filters (SAPFs) are an effective way to reduce harmonic current in electric power systems and improve the quality of power produced and supplied. Using the dq-frame instantaneous power control method for the detection and compensation of harmonics provides a number of advantages when compared to other methods. By utilizing the nonlinear hysteresis current control method with the SAPF control strategy, these systems provide fast dynamic response times and accurate current tracking; both attributes are critical for ensuring reliable operation of smart and sustainable energy systems.

10. FUTURE RESEARCH DIRECTIONS

The focus of future research in this area will be on the use of intelligent control strategies and digitalized architectural designs for power system operations. Using artificial intelligence and machine learning algorithms to implement adaptive control methods for active power filters is feasible, as are using digital twin technology to simulate and continuously monitor the condition of electric power quality in real-time. There has been some research on using model predictive control and neural networks to enhance the overall performance of SAPFs, but research in this area should continue. By using these methods in combination, next generation electric power systems with high penetrations of renewable generation will experience unprecedented levels of reliability and adaptability in their operation.

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