ADVANCEMENTS IN SERIES ACTIVE POWER FILTERS: A COMPARATIVE REVIEW OF INTELLIGENT CONTROL STRATEGIES AND TRANSFORMER-LESS TOPOLOGIES

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ABSTRACT

Power quality issues such as harmonics, voltage sags, swells, and waveform distortions have become increasingly critical with the proliferation of nonlinear loads and electronic converters. To address these challenges, Active Power Filters (APFs) have emerged as effective solutions, with the Series Active Power Filter (SeAPF) playing a significant role in mitigating voltage-related disturbances. Both the proposed works—one focusing on a fuzzy logic-based controller in MATLAB Simulink and the other presenting a transformer-less SeAPF prototype validated experimentally—highlight innovative approaches for reducing harmonics and improving system performance. The first study emphasizes advanced control strategies, replacing conventional PI control with fuzzy inference rules to achieve better adaptability and robustness. The second work validates a novel hardware topology, eliminating coupling transformers and external power sources, thereby improving compactness and efficiency. Together, these studies demonstrate complementary contributions: simulation-based validation of intelligent control methods and experimental verification of practical hardware designs. This review compares their methodologies, control strategies, and outcomes, thereby offering a comprehensive perspective on advancements in SeAPF design for future smart grids.

Keywords— Active Power Filters, Power Quality, Harmonics, Series Active Power Filter, Fuzzy Logic Control, Transformer-less Topology.

1. INTRODUCTION

1.1INTRODUCTION TO POWER GRID

An interconnected network used for delivering electricity starting from producers to consumers is termed as an electrical grid.

The main components are generating stations which produce electrical power, high voltage transmission lines which carry power to demand centers from distant sources, and distribution lines which connect the individual customers. An AC-AC converter with approximate sinusoidal input current and bidirectional power flow can be grasped by coupling a PWM inverter and a

PWM rectifier to the DC-link. Then the DC-link quantity impressed energy storage element, which is common to both the stages[1].

1.2 POWER GRID HARMONICS

In today's scenario that showcases technological advancements, electronic equipments play a major role. Additionally, the industrial development longs for better quality and quantity that calls for modernization which requires automated equipment based on power electronic converters. But when these equipment get connected to the grid, it leads to the generation of harmonics that further results in the power quality problems [2].

Harmonics are sinusoidal steady-state voltages or currents having frequencies that are integral multiples of the basic frequency. The nonlinear characteristics of systems and loads on the power grid, prompts harmonic distortion. Speed drives, welding machines electronic ballasts, smart phones, refrigerators and other high power electronic devices are some of the examples of harmonic instigating leads. Most of these equipments have a non-controlled diode rectifiertrailed by a DC-Link, which leads to high harmonic contents in the system. This further leads to harmonic distortion in the power grid voltage via the line impedances. This is a major problem for both the provider and consumer in terms of capital.Various journals show that around 30% of the most susceptible industry sectors may invite a power quality cost of about 4% of their turnover with about 60% of the cost contribution from the voltage sags and momentary interruptions.

1.3 INTRODUCTION TO POWER FILTERS

The networks that hold the property of differentiating between the signals of various frequencies and passing the signals of specific frequency only while the signals of the other frequencies not belonging to this range are suppressed or attenuated are termed as filters.

The frequencies that are permitted to pass through the filters are termed as **pass band** and the frequencies that are entirely attenuated or repressed are phrased as **stop band** or attenuation band. The frequency that separates both these frequencies, i.e., stop band and pass band is termed as **cut-off frequency**.

1.4 INTRODUCTION TO ELECTRIC POWER QUALITY

Electric power quality is the extent to which the voltage, frequency, and waveform of a power supply system match to established specifications. Good power quality can be termed as a steady supply voltage that settles within the set range, steady ac frequency near to the rated value, and a smooth voltage curve waveform that looks like a sine wave. Generally, it is practical to deem power quality as the compatibility between output of an electric outlet and the load that is connected to it. Power quality is also used to portray electric power which drives an electrical load and the load's ability to taskaccurately. In the absence of proper power, electrical loads may breakdown, fail too early, or not at all operate. Electric power can be of poor quality in many ways and the causes can be different.

The electric power industry mainly consists of electricity generation (AC power), electric power transmission and finally electric power distribution to an electricity meter placed at the site of the end user of the electric power. Thenthe electricity moves through the end user's wiring system until it reaches the load. The intricacy of the system to move electric energy from the production point to the consumption point in combination with disparities in generation, weather, demand and other factors offer many opportunities for the quality of supply to be compromised.

While "power quality" is a suitable term for a lot, it is actually the quality of the voltagerather than electric current orpower that is essentiallydepicted by the term. Power that is basically the flow of energy and the current required by a load is largely uncontrollable [4] .

2. LITERATURE REVIEW

This chapter throws light on the literature review of various types of active filters, as well as active advances of these filters.

F. Jiang, Y. Li, C. Tu, Q. Guo and H. Li et al. [1] states that the series voltage source converter(SVSC) is widely used in the power electronic equipment, such as series active power filter, dynamic voltage restorer, unified power flow controller and so on. However, while the SVSC is more vulnerable to the impact of fault current, its applications are increasing, bringing huge challenges to the safe operation of the grid. In recent years, the topology and control strategy of the series voltage source converter with fault current limiting(SVSC-FCL) are a research hotspot. In this paper, it suggests classifying SVSC-FCL based SVSC into two groups: the control scheme optimization group and the existing topology improvement group. The research challenges and perspectives of the SVSC-FCL are commenced in detail. This paper also aims to illustrate current research progress on SVSC-FCL and enrich the available pool of the multi-functional power electronic equipment.

H. Akagi et al. [2] active filters'basic compensation principles were proposed around 1970 and since then have been studied by many researchers and engineers aiming to put them into practical applications. Shunt active filters for harmonic compensation with or without reactive power compensation, flicker compensation or voltage regulation have been put on a commercial base in Japan, and their rating or capacity has ranged from 50 kVA to 60 MVA at present. In near future, the term of active filters will cover a much wider sense than that of active filters in the 1970s did. The function of active filters will be expanded from voltage flicker compensation or voltage regulation into power quality improvement for power distribution systems as the capacity of active filters becomes larger. This paper depicts the present states of the active filters based on state-of-the-art power electronics technology, and their future prospects toward the 21st century, including the personal view and expectation of the author.

M. Simicet al.[3]This paper showcases the software oriented approach in generation and analysis of complex signal waveforms, suitable for testing the instruments for detection of typical power quality (PQ) problems. This approach is based on virtual instrumentation software for definition of signal parameters, data acquisition card NI PCI 6343 for signal generation and power amplifier for amplification of output voltage level to the nominal RMS value of 230 V. Definition of basic signal parameters is enabled using LabViewsoftware support, which allows simple repetition of test signals and various combinations of more test sequences in final complex test signals. The basic advantage of this approach compared to similar solution for signal generation is possibility for providing test signal sequences according to the predefined algorithms, including variations of real PQ disturbances and problems in accordance with the European standard EN 50160.

S. Unnikrishnan and G. Biji et al. [4]this paper presents various power quality problems and its mitigation through a hybrid series active power filter. Series filters have less attention in the power quality area due to its high cost of compensation, bulky transformers etc. Even though hybrid series active power filters are used in three phase system it is less utilized in single phase system. So for above mentioned purposes a transformer less single phase hybrid series active power filter is studied. A novel chattering less sliding mode control algorithm is developed and is incorporated with voltage and current control loop which provide source current harmonics elimination coming from voltage fed by that of non linear load and other voltage distortions like voltage harmonics, voltage sag/swell initiated through grid. Thus, it helps in clearing point of common coupling and enhancing power quality and also in providing reactive power regulation. Main advantage of the filter is that only less dc voltage is needed for compensation and only small compensation gain is used. Voltage disturbances initiated from power system are obstructed by the compensator and PCC becomes free of voltage harmonics and is protected from voltage sag/swell. For tracking and reducing chattering auto-tuning of sliding mode control parameters using fuzzy logic are used.

M. I. M. Montero, E. R. Cadaval and F. B. Gonzalez et al. [5]Strategies for extracting the three-phase reference currents for shunt active power filters are compared, evaluating their performance under different source and load conditions with the new IEEE Standard 1459 power definitions. The study was applied to a three-phase four-wire system in order to include imbalance. Under balanced and sinusoidal voltages, harmonic cancellation and reactive power compensation can be attained in all the methods. However, when the voltages are distorted and/or unbalanced, the compensation capabilities are not equivalent, with some strategies unable to yield an adequate solution when the mains voltages are not ideal.

B. Expostoet al. [6] This paper presents a Shunt Active Power Filter that is built using a current-source inverter. The control of the Active Filter relies in the p-q Theory with the "Sinusoidal Currents at Source" algorithm implemented. The Active Power Filter was simulated using two modulation techniques: Periodic Sampling and Carrier-Based Pulse Width Modulation (CBPWM). To assess the performance of the Active Filter, the simulations were made using two different loads. The first load was a RL balanced load. The second was a non-linear load, namely a full bridge rectifier with a RL load in the DC side. These loads allowed determining the performance of the Active Filter when compensating current harmonics and power factor, using the two modulation techniques**.**

3. THREE PHASE FOUR WIREACTIVE POWER FILTER

A three phase four wire active power filter finds wide applications practically. It was mainly developed to suppress harmonics due to currents from non linear loads, for compensation of reactive power ,non linear load current, harmonic neutral current mainly third order.Since, in three-phase systems, triple harmonic currents are in phase and whose strengthening leads to excessive neutral currents that leads to overheated transformers, loss of insulation, high neutal top ground voltage, wiring failure etc.

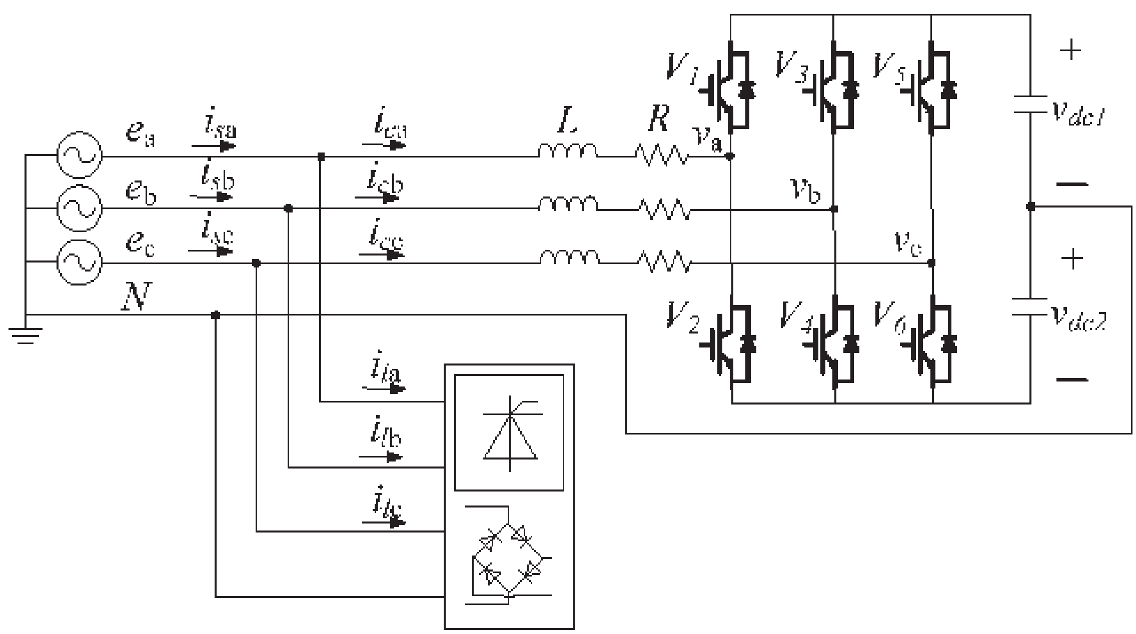

Figure 1. Three-phase four-wire APF

3.2. SERIES ACTIVE POWER FILTER(SeAPF)

The series active power filters compensate for the current distortions that are induced by non-linear loads. This is done by applying high impedance path to the current harmonics which are responsible for high frequency currents flow through the passive LC filter connected in parallel to the load. The active power filter imposes high impedance, by generating a same frequency voltage as that of the current harmonic portion that is required to be removed.

The SeAPF is the basic topology that is widely used to compensate voltage and current issues such as momentary interruptions, voltage sags, voltage swells, voltage fluctuation, notches, transients and voltage unbalances etc. It acts similar to an ideal voltage source by proving a voltage in phase opposition to the harmonic content of power grid, thereby letting a sinusoidal voltage waveform at the load. The conventional topology of single phase SeAPF along with coupling transformer and an auxiliary external power source is shown below. The presence of coupling transformer provides isolation in between APF and power grid whereas the external power source assists in voltage compensation. Since, the coupling transformer injects voltage harmonics in the system, it leads to high loss, reduced life and overheating of components in the system and the use of external power source in combination makes the whole system bulky and expensive which is the main drawback of the conventional topology.

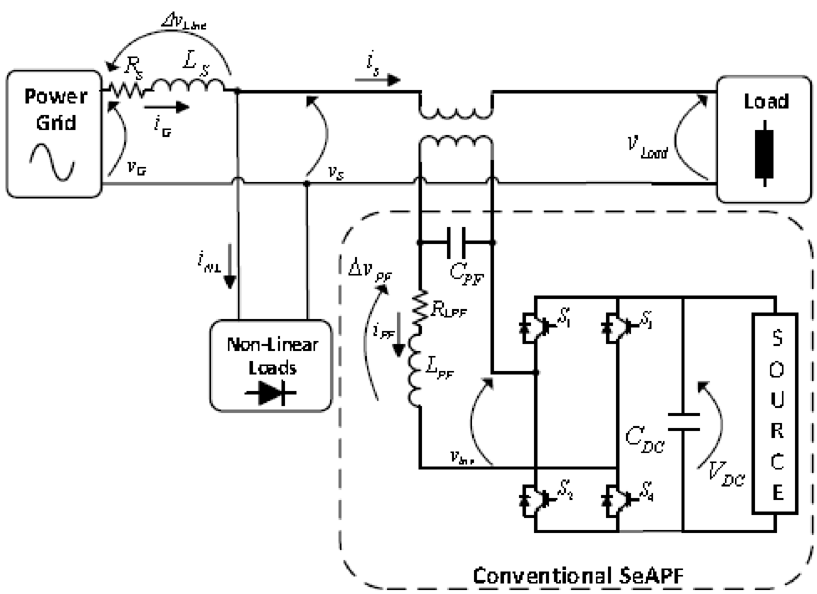

Figure 2. Conventional Topology of SeAPF

A new (proposed) topology is developed so as to overcome the above problems. In this there is no requirement of external power source or coupling transformers rather it makes use of more sophisticated control system. The implementation method is easer due to advancements in the field of power electronics. For this a synchronization method is used to keep the reference voltage immune to the power grid distortions and also to regulate the SeAPF DC-Link to the reference voltage. This along with the information recovered fromthe sensors in the system can be used to control SeAPF so as to alleviateassociated power quality problems and provide sinusoidal voltage waveform to the loads.

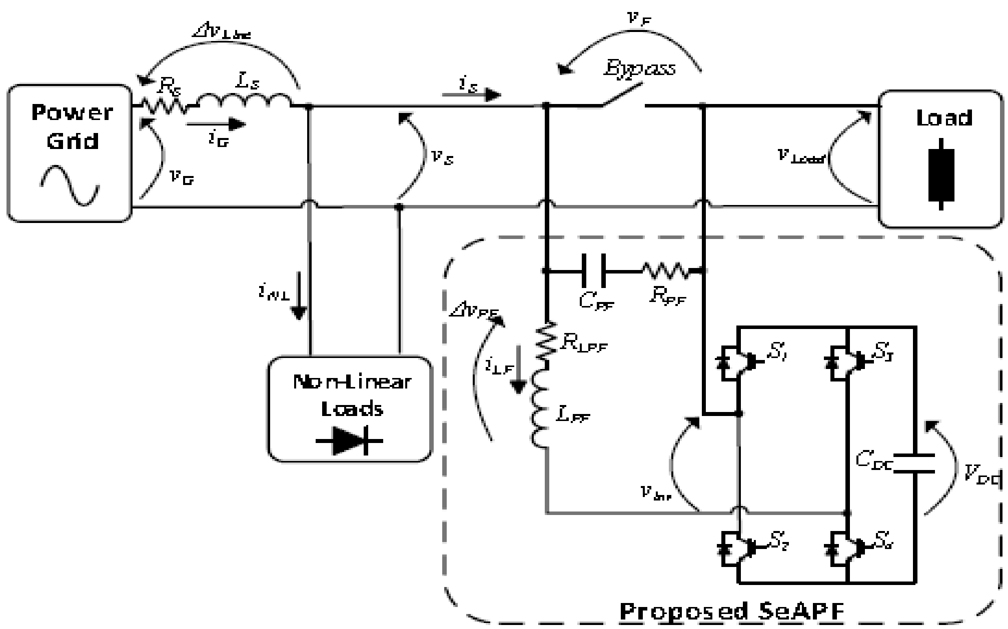

Figure 3.Proposed SeAPF Topology

4. METHODOLOGY

4.1 FUZZY LOGIC CONTROLLER

Fuzzy control gives a formal method to represent, manipulate and implement human's heuristic knowledge regarding the control of a system. The slab diagram of a fuzzy logic controller, in which there is an embedded a closed-loop control system is discussed below. The process outputs are indicated by y (t); its inputs are indicated by u (t); and the reference input to the fuzzy controller is indicated by r (t).

The fuzzy controller has got four main components: The rule-base, that holds the knowledge in the pattern of a set of rules that, describes the finest way for a system control. The membership functions are used to quantify knowledge. The inference mechanism states control rules which are relevant next to the present time and then decides which input of the plant should be enabled. The fuzzification interface modifies the inputs, such a way that they can be interpreted and compared to the rules in the rule-base. The defuzzification interface transforms the conclusions reached by the inference mechanism into the inputs of the plant.

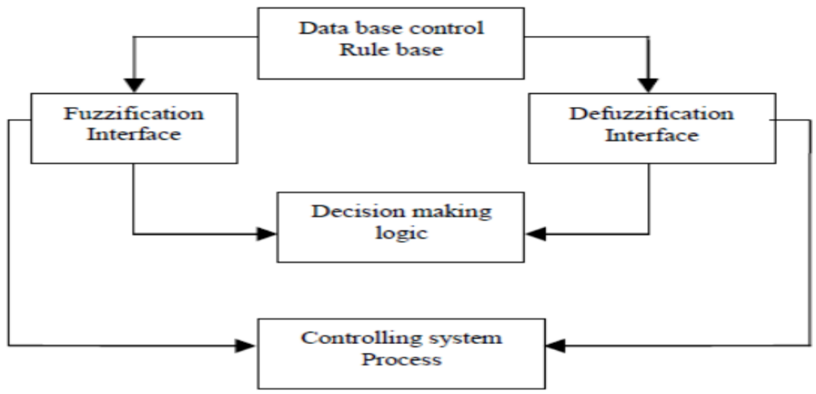

Figure 0 Fuzzy Inference System

4.2 FUZZY LOGIC TOOLS

Unlike Boolean or crisp logic Fuzzy logic, deal with vague, imprecise and uncertain problems and uses membership functions whose values vary between 0 and 1. Figure 4.2 shows a schematic block diagram of fuzzy inference system or fuzzy controller. It consists of following working blocks:-

- Fuzzification Interface
- Knowledge base
- Decision making logic
- Defuzzification

Since it is a two dimensional fuzzy control, a fuzzy logic controller must possess proportional integral control effects. An integral action is usually needed to achieve the best performance in practical situation

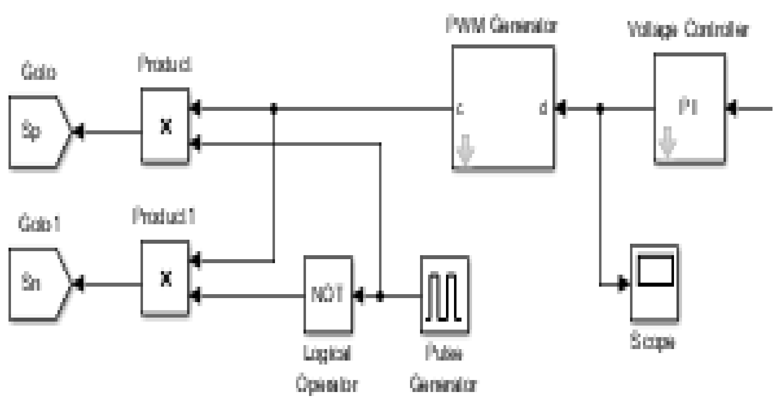

Figure 0. PWM pulse generator

4.3 DESIGN OF CONTROL RULES

The fuzzy control rule design involves defining the rules that relate the input variables to the output model properties. Since fuzzy logic controller is independent of system model, the design is majorly dependent on the intuitive feeling and understanding of the process. The rules are expressed in English like language with syntax such as If {error e is A and change of error Δeis B} then {control output is C}. For better control performance finer fuzzy petitioned subspaces(NL, NM, NS, ZE, PS, PM, PB) are used, and summarized in table 4.1. These seven membership functions are same for input and output and are characterized using triangular membership functions.

5. CONCLUSION

The comparative analysis of the two approaches reveals that both simulation-driven and experimental strategies hold unique strengths in advancing Series Active Power Filters. The fuzzy logic-based MATLAB study contributes by enhancing **controller intelligence and adaptability**, ensuring superior harmonic suppression compared to traditional PI controllers. In contrast, the IEEE experimental work contributes by validating a **cost-effective, compact, and transformer-less topology** through hardware implementation, proving the feasibility of real-world applications. While the simulation-based approach excels in exploring advanced control algorithms and theoretical validation, the experimental prototype confirms practical viability and robustness against real grid disturbances such as sags and swells. Hence, the integration of **intelligent fuzzy control** into a **hardware-validated transformer-less topology** could represent the next step in developing highly efficient, compact, and reliable SeAPFs for modern power distribution systems.

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