Indian Journal of Natural Sciences *www.tnsroindia.org.in ©IJONS*
Vol.12 / Issue 68 / October / 2021 *International Bimonthly (Print)* *ISSN: 0976 – 0997*

RESEARCH ARTICLE

3Φ Transformerless Shunt Active Power Filter for Harmonic Compensation

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Received: 07 July 2021 Revised: 20 July 2021 Accepted: 14 August 2021

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ABSTRACT

Power quality decline has an adverse economic impact on utilities and their customers. One of the most well-known power quality challenges is harmonics in current and voltage, which can be handled by using a Hybrid Series Active Power Filter (HSAPF). To make the HSAPF more robust and reliable, a novel controller design based on sliding mode controller-2 is proposed in this study. In this research, an accurate averaged model of three-phase HSAPF is also developed. The resilient HSAPF design concept has been validated by simulation and the results have been discussed.

Keywords: Power Quality, Active Power Filter, Harmonics, controller

INTRODUCTION

Electricity demand is steadily expanding in the modern industrial world, from residential utilities to commercial businesses. Integrating distributed energy resources such as solar photovoltaic systems, wind energy conversion systems, fuel cells, distributed power production systems, and storage devices enhances reliability and power quality while lowering losses of power distribution or transmission networks. The massive expansion in the use of non-linear loads in recent years has resulted in a slew of power quality difficulties on the electrical grid, including excessive current harmonics, voltage distortion, and low power factor, to name a few. Harmonic currents are injected into the AC power lines as a result of the development of non-linear loads in the system. This distorted supply voltage and current causes some protective systems to fail, transformers and motors to burn out, and cables to overheat. As a result, Passive power filters have traditionally been employed as a compensation device to correct for distortion caused by constant non-linear loads. With a simple design and inexpensive cost, these filters [2] are designed to provide a low impedance channel for harmonics while preserving high power quality. Passive filters, on the other hand, have drawbacks such as mistuning, resonance, reliance on power supply system circumstances, and large passive component values, all of which result in bulky implementations. These filters are the most popular because they effectively minimize current distortion and reactive power generated by non-linear loads. However, they are typically costly and have high operational losses. Peng et al. [5] introduced a novel HAPF topology- III in 1988 to overcome these drawbacks and improve compensation performance while lowering the cost of the APFs. In this topology, the APF is connected in series with the source as well as the non-linear load, while the PPF is connected in parallel with the load and acts as a PFC capacitor is proposed. This topology [6] drew a lot of interest since it can withstand high load currents and acts as a harmonic isolator between the source and the non-linear load. The control method is critical for improving HSAPF's performance. Many publications on hybrid power filters have already offered improved approaches for reducing current harmonics caused by non-linear loads. For a hybrid power filter, [7] proposes a linear feedback-feed forward controller. However, because the dynamic model of the HSAPF system comprises multiplication terms of control inputs and state variables, this controller is difficult to get both steady-state and transient state performances with the linear control method. A sliding mode controller is provided in [8] due to the non-linear properties of HSAPF. Furthermore, by decoupling the system into distinct subsystems of lesser dimension, this sliding mode control reduces the complexity of feedback control design. The application of sliding mode control can be found in the domains of power electronic switching devices due to these qualities. The principle of sliding mode control is to use discontinuous control to impose sliding mode motion in a designated switching surface of the system state space. The switching surfaces should be chosen so that sliding motion maintains the desired motion dynamics according to a set of performance criteria. For linear systems, traditional control methods such as Linear-quadratic regulator (LQR) [9] or Linear quadratic Gaussian (LQG) servo controller [10].

The discontinuous control must then be chosen in such a way that all states outside of the discontinuity surface must reach it in a finite amount of time. As a result, the system enters a sliding mode down the surface and follows the intended system dynamics. Chattering is the most difficult aspect of implementing the classic sliding mode control mechanism in hardware. Chattering is a type of oscillation with a finite frequency and amplitude that is restricted. The chattering is dangerous because the system lacks control accuracy, moving mechanical elements wear out quickly, and electrical power circuits lose a lot of heat. The switching frequency in sliding mode control should be high enough to make the controller more robust, stable, and free of chattering, as chattering decreases as the switching frequency of the system increases. Increased switching frequency is a natural technique to prevent chattering when using a sliding mode controller in power converter systems, such as HSAPF. However, due to certain constraints in switching frequency for losses in power converters, it is not practicable in the case of power converters, resulting in chattering. As a result, the chattering problem cannot be blamed on the implementation of sliding mode because it is primarily caused by switching constraints. When the relative degree of the system with actuators or sensors is two, the chattering exponentially decreases to zero, as illustrated in [11]. The HSAPF system has a relative degree of two. This study work presented a novel controller, the sliding mode controller-2, as a result of the relative degree of the HSAPF system and the barriers in the classical sliding mode controller. This proposed controller reduced chattering and improved HSAPF performance. This controller is brand new for this HSAPF system topology. The carrier based PWM (CBPWM) for HSAPF architecture is the subject of a new research publication [12]. However, in the majority of real-world scenarios, the CBPWM-based HSAPF may not be completely measurable. In the case of CBPWM, power system perturbations are not taken into account, and the presence of a temporal delay at the reference tracking point causes the total system to respond slowly. Section II describes the schematic of the system topology of the three-phase HSAPF model. The averaged modelling of the HSAPF system is depicted in Section III. Section IV reveals the HSAPF controller design. Section-V shows the simulation results for harmonic compensation with HSAPF. This work's conclusions are presented in Section VI.

Description of System Topology Schematic and HSAPF Model Hardware Modules

Figures 1 shows a schematic diagram of a hybrid series active power filter (HSAPF). This HSAPF topology is made up of a series connected active power filter (SAPF) and a shunt connected passive power filter (PPF). The PPF is linked in parallel with the load. The PPF is made up of a fifth and seventh tuned LC filter of rating (Lpf = 1.9mH and

Cpf = 80F) for harmonic current compensation on the load side. To ensure galvanic isolation, the SAPF is connected in series with the source via a matching transformer with a turn ratio of 1:2. The high frequency LC filter is used to remove high frequency switching ripples from the inverter's compensating voltage. The HSAPF is controlled by a controller-based algorithm that has been implemented.

HSAPF Average Modelling

The schematic diagram of the 3-phase HSAPF control and power circuit is shown in Fig. 1. The SAPF is made up of a voltage source inverter that is linked to the grid via an LC filter and a three phase linear transformer. The inductors series resistance is ignored.

$$\frac{di_{cd}}{dt} = \frac{V_{cd}}{L_f} + wi_{cq} - \frac{u_d V_{dc}}{L_f} \qquad (1)$$

$$\frac{di_{cq}}{dt} = \frac{V_{cq}}{L_f} - wi_{cd} - \frac{u_q V_{dc}}{L_f} \qquad (2)$$

$$\frac{dV_{cd}}{dt} = wV_{cq} - \frac{i_{cd}}{C_f} + \frac{i_{sd}}{C_f} \qquad (3)$$

$$\frac{dV_{cq}}{dt} = wV_{cd} - \frac{i_{cq}}{C_f} + \frac{i_{sq}}{C_f} \qquad (4)$$

$$\frac{dV_{dc}}{dt} = \frac{3}{2C_{dc}}\left(u_d i_{cd} + u_q i_{cq}\right) \qquad (5)$$

Where u_a, u_b, u_c is the duty cycle (δ) of the inverter legs in a switching period, and V_{ca}, V_{cb}, V_{cc} is the output voltage of a three-phase series active filter, as shown in Fig. 2, and I_{ca} is the three-phase active filter current output, V_{aN}, V_{bN}, V_{cN} is the three-phase phase voltage, I_{sa}, I_{sb}, I_{sc} is the 3Φ source current, and V_{nN} is the neutral voltage. The whole averaged model [13] of the inverter in three phases is obtained by averaging the inverter legs in the circuit diagram, as shown in Fig. 3. The dynamic model of HSAPF under SRF can be expressed by the differential equations shown in this circuit diagram.

Where V_{cd} and V_{cq} are the d-q axis compensating voltages, u_d and u_q are the d-q axis duty ratios, and is the source voltage's angular frequency. The HSAPF system model can be defined as follows to aid controller design:

$$\begin{cases} x^{\cdot} = f(x) + g(x)\,u \\ y = h(x) \end{cases} \qquad (6)$$

Where
$x = [i_{cd}, i_{cq}, V_{cd}, V_{cq}, V_{dc}]^T$ state vector,
vector $u = [u_d, u_q]^T$ system control variables,
vector $y = [y_1, y_2]^T = [V_{cd}, V_{cq}]^T$ system outputs.

It should be noted that the achieved Multi-Input Multi-Output (MIMO) system is non-linear due to the presence of state variable and control variable multiplication terms. Furthermore, the state variables are inextricably linked to one another.

These two difficulties can be precisely controlled by the design of a sliding mode controller, which examines the relationship between the control variables and the system outputs openly.

Control System Development

The reference compensation voltage of the HSAPF system using the hybrid control approach-based SRF method is expressed as follows:

$$V_c^* = KI_{sh} - V_{Lh} \qquad (7)$$

Figure 2 depicts the generation of a reference compensating signal using the combined source current detection and load voltage scheme[14]. Because the additional fundamental components are added to the harmonic components. As a result, the reference compensating voltages are also written as:

HSAPF Sliding Mode Controller Design Proposal

This section describes the synthesis of a sliding mode controller based on the HSAPF system's averaged model. We differentiate the compensating voltage with respect to time using system model (6) until the control variables u_d and u_q appear explicitly. The control signal in this proposed control approach satisfies all of the above conditions, causing the state trajectories to be moved towards the switching surface. As a result of using this proposed controller, the HSAPF system achieves fast response, good robustness, and effective throwaway disturbances.

SIMULATION RESULTS

MATLAB/Simulink software is used to test the reference generation approach (HSRF method) with the switching pattern generation scheme (i.e. sliding mode controller-2) of the HSAPF system shown in Fig. 2. A three-phase source voltage is applied to a non-linear load with a harmonic voltage. This voltage-producing nonlinear load is made up of a three-phase diode bridge rectifier feeding an RL-load. Harmonic distortion occurs in both the source current and the load voltage as a result of this type of non-linear load. Power quality disturbances are caused by harmonic contamination. As a result, HSAPF can eliminate power quality disturbances. MATLAB simulation results for steady-state source voltage Vs, load current IL, source current I_s, and DC voltage V_{dc}, as well as Fig. 3. Without a filter, the nature of the source current is identical to that of the load current. Fig. 4 and Fig. 5 show the MATLAB simulation results for steady state, dynamic condition of load, and parametric variation of the HSAPF system under sliding mode controller-2.

CONCLUSION

For HSAPF, a new robust controller design has been presented in this paper. Sliding mode controller2 establishes the control design by deriving the equivalent control law. This control law is extremely useful for generating switching patterns. The proposed controller's robustness was validated by analysing the performance of the power system under steady-state and transient conditions. The HSAPF's functionalities are improved with the use of this technique. SRF method is found to be the best for reference generation in the presence of switching losses and distortion in both source current and load voltage. Furthermore, the variable structure control method of the sliding mode controller-2 reduces tracking error distortion, suppresses chattering, and noise, and thus achieves perfect gain stability of the HSAPF system.

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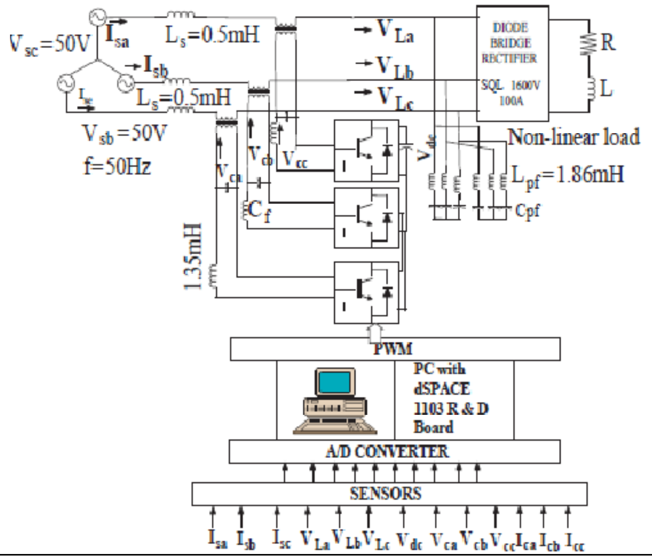

Fig. 1 Schematic diagram of a Hybrid Series Active Power Filter (HSAPF)

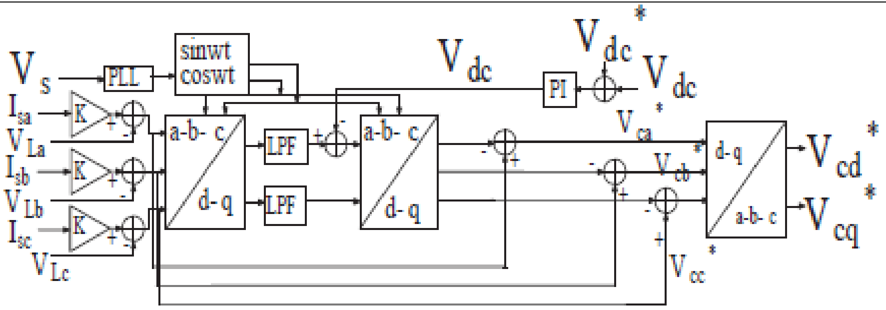

Fig. 2 Reference Generation Scheme

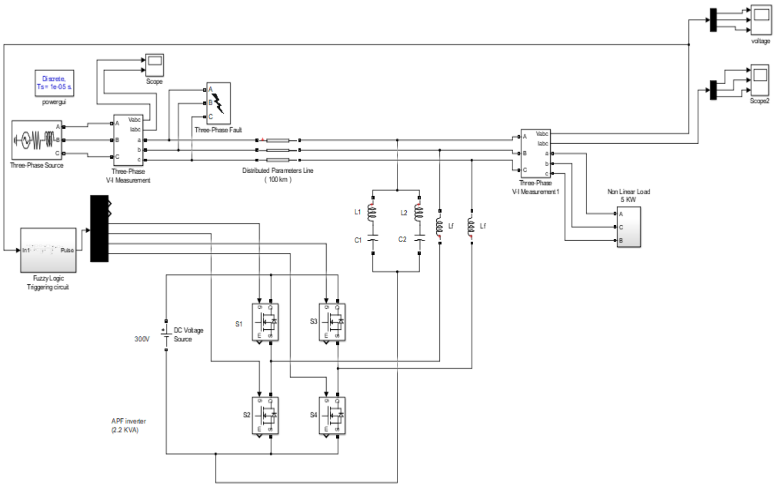

Fig.3 Simulation Diagram

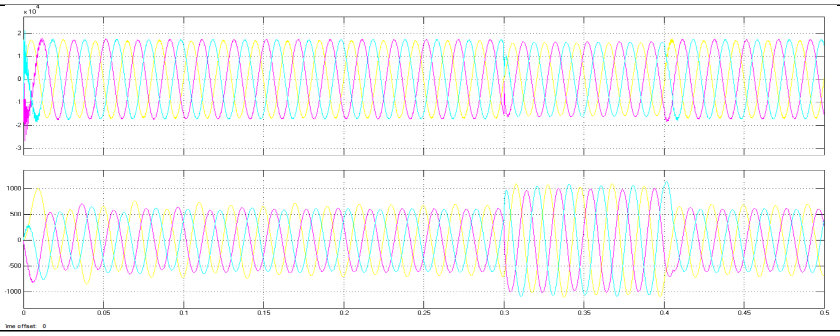

Fig. 4 Simulation Waveforms (Before Fault)

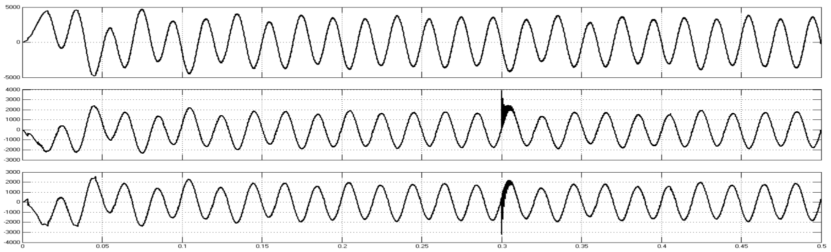

Fig. 5 Simulation Waveforms (After Fault)

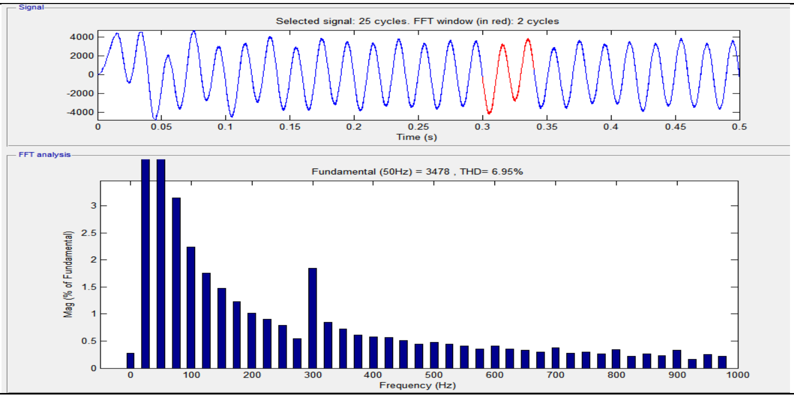

Fig. 6 THD Analysis (Before Fault)

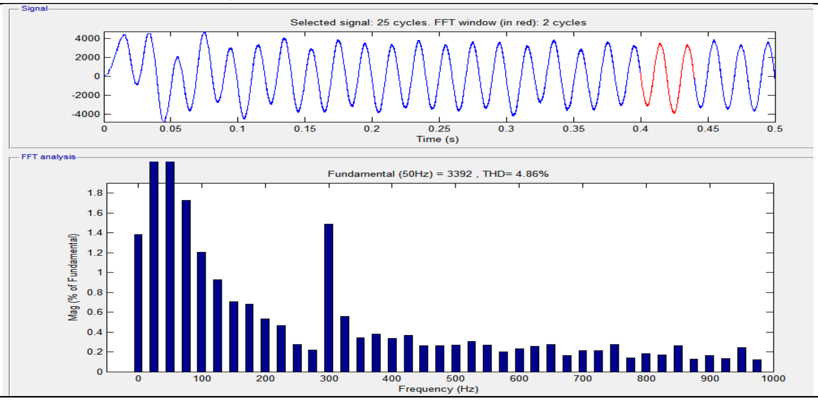

Fig. 7 THD Analysis (After Fault)