Sakarya University Journal of Science, 22(4): 1071-1079, 2018.

SAKARYA UNIVERSITY
JOURNAL OF SCIENCE

e-ISSN: 2147-835X
http://www.saujs.sakarya.edu.tr

Received	Revised	Accepted	DOI
22.05.2017	02.07.2018	07.08.2017	10.16984/saufenbilder.315352

Mathematical Modelling of PAF with Voltage Supply for Non-linear Loads by GSSA Method

Murat Tuna*[1] , Ayşe Ergün Amaç[2], Süreyya Kocabey[3]

ABSTRACT

This work aims to improve well known generalized averaged models for mathematical modelling of parallel active filter (PAF) with voltage supply. To achieve this task, the method is adopted to generalized state space averaging (GSSA) method. Non-linearity of the system is removed by using GSSA method. Relation between the state variables of the system is expressed by linear equations. An exact and fast approximation of the system parameters is achieved. Non-linearity of real elements that causes many problems such as long execution time, divergence, and huge produced files do not exist thanks to the method. A single phase full-bridge voltage supply inverter is proposed as a parallel active filter. A diode rectifier with RL load is used as a nonlinear load. In this study, simulation results of parallel active filter mathematically modeled with GSSA model are compared to real-time designed simulation results of parallel active filter realized power simulation with PSIM software. In the results obtained through mathematical models with real model has been observed that a good match.

Keywords: generalized state space averaging method (GSSA), harmonic filter, parallel active filter (PAF), PSIM

1. INTRODUCTION

Nowadays, using of nonlinear loads such as switching power supply, arc and pot furnaces, motor drives, AC/DC converters, and inverters etc. in industry, increases thanks to advances of power electronics and semiconductors [1,2]. Also, renewable generation affects power quality due to its nonlinearity [2], since solar generation plants and wind power generators must be connected to the grid through high-power static PWM converters [2–5]. They cause distortions in power quality (voltage regulation and creates voltage distortion in power systems) of transmission and distribution systems substantially [6]. However, critical loads which sensible of power quality in the system continuously rise in parallel increasing of nonlinear loads usage [6,7]. Therefore, these distortions are important issues for many countries which need to be solved. IEEE 519-1992 (IEC61000) standards are defined limitation of the harmonics to prevent problems. Harmonics above from defined limits dangerously and costly damage electrical systems such as overheating in electromechanical devices, transformers and cables, breakdown in triggering circuits, power loss, perforation and eruption in power capacitors, fuse blowing of compensation systems, mechanical vibrations in machines,

* Sorumlu Yazar / Corresponding Author
[1] Kirklareli University, Technical Sciences Vocational School, Department of Electric, Kirklareli-murat.tuna@klu.edu.tr
[2] Kocaeli University, Faculty of Technology, Department of Energy Systems Engineering, Kocaeli-ayseergun@kocaeli.edu.tr
[3] Kirklareli University, Faculty of Technology, Department of Energy Systems Engineering, Kirklareli-sureyyakocabey@klu.edu.tr

malfunctioning of measurement and protection systems, energy loss and thus rising energy cost in whole system [8]. To eliminate of these negativities, harmonics should be removed from the system. Therefore, filters are developed by engineers for suppressing harmonics [9]. Although passive filters are economic solution, their performances depend on system parameters and they occupy big place and offer constant compensation [10]. Most importantly, they create resonance circuit between grid and/or load. To overcome the disadvantages of passive filters, Active Power Filters (APF) are proposed by engineers for harmonic elimination [11,12]. APF is in used of compensate current and voltage harmonics generally. Moreover, it provides harmonic isolation between grid and load, compensates reactive power and neutral current, regulates voltage, makes flicker compensation, and suppresses resonances [11,13].

Consequently, APF provides high quality energy for both grid and load side that demand by them. Working principle of APF is to add the system an opposite current with same magnitude of the harmonics which is produced by load. There are different kinds of APF according to connection types with the system. Parallel Active Filter (PAF) and Series Active Filters (SAF) are two of them that widely used in industrial area. Topology of PAF is connected with load in parallel for harmonics filtering, reactive power compensation, current stabilization, and neutral current removing [14–16]. There are two kinds of PAF as voltage supply and current supply. While a capacitor for energy storage is implemented in DC side of inverter that works as voltage supply PAF, an inductor for energy storage is performed in DC side of inverter that works as current supply PAF [17]. PAF is shown in Figure 1.

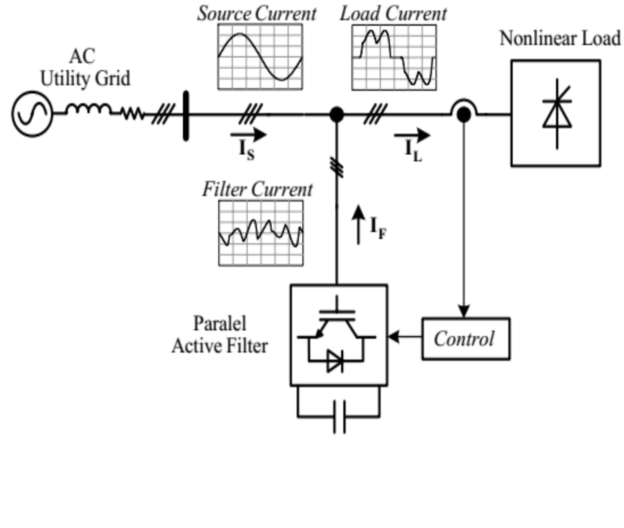

Figure 1. Topology of the parallel (shunt) active filter with single phase voltage supply

PAF are the most common active filter types in industrial field. These filters are in used of compensate current based deformations, current harmonics, load imbalances, reactive current, and neutral current deformations due to nonlinear loads such as DC/DC converters, AA drivers, rectifiers, uninterruptible power supplies and frequency converters [18–22]. The configurations of PAF change according to the supply such as single phase or three phases, or according to the energy storage component of DC side such as current or voltage based. PAF cancel harmonic currents flowing to the supply due to nonlinear load by operating as a current supply. Therefore, they protect the system from harmonics by generating currents at the same amplitude which are in opposite phase to harmonic currents [21–23]. Thus, sum of currents generated by load and active filter eliminates each other, and harmonic currents flowing into the mains are prevented for this way.

GSSA method proposed by Sanders [24] is valid for modeling of converters although the process is more difficult than conventional SSA method [21,22]. In recent years, the GSSA method, AC/DC inverter is used quite a lot of mathematical modeling in the literature [21–23]. A new approach is presented as a novel GSSA model for the system analysis, control and characterization of Advanced Aircraft Electric Power Systems AAEPS by Ebrahimi et al in their study [24–25]. GSSA method is employed to the modelling of a witricity (transferring medium power electricity with high efficiency and wireless) system and calculations are presented by Jianyu et al. in detail [26]. For modeling of an ideal boost DC/DC converter connected to the output of a fuel cell, GSSA method that eliminates disadvantages of conventional SSA method is applied by Tuna et al. in their study [27]. Average of harmonic state variables is also taken into account in the method.

2. Generalized State-Space Averaging Method (GSSA) Method

GSSA method is taken out from Fourier Transformations for a non-periodic signal [28–30]. The method is based upon a principle that an *x(t)* waveform between infinite time interval of (*t-T, t*] can be approached with arbitrary accuracy using finite coefficients of Fourier Transformation

[31,32]. The relation is expressed by eq. 1 and calculated by eq. 2 and 3:

$$x(t) = \sum_{k=-n}^{n} < x >_k (t) * e^{j\omega kt} \tag{1}$$

$$\omega = \frac{2\pi}{T} \tag{2}$$

$$< x >_k (t) = \frac{1}{T} \int_{t-T}^{t} x(\tau) * e^{-j\omega k\tau} * d\tau \tag{3}$$

The value of n depends on degree of accuracy as given by eq.1. If n goes to infinite, error of the approach goes to zero. If a state variable doesn't have any kind of oscillation and it is stable, the result obtained by only using term of k=0, gives the result obtained by SSA method [18–22]. However, if a state variable has only one oscillation similar to sine wave, term of k= -1, 1 is used. This method is called first harmonic approach. If a state variable has one DC value, and an oscillation, term of k= -1, 0, 1 is used. The more term is taken into account, the more we get close to accuracy [19,20,24] in here.

$<x>_k$ (t) is complex Fourier coefficient. The coefficients change as a function of time in the considered interval. Purpose of the approach is to determine proper state space model that includes coefficients of state variables given by eq. 3. In order to specify characteristics of Fourier transformation coefficients, transformations for derivatives of state variables given by eq. 4 and multiplications of them stated by eq.5, which depend on time, are required to be found [16].

$$\frac{d}{dt} < x >_k (t) = \langle \frac{d}{dt} x \rangle_k (t) - jk\omega * \langle x \rangle_k (t) \tag{4}$$

$$< x.y >_k (t) = \sum_{n=-\infty}^{n=+\infty} < x >_{k-n} (t) * < y >_n (t) \tag{5}$$

3. Basic Equations for a PAF with Single Phase Voltage Supply

PAF works as a current harmonic supply and injects harmonic currents to the mains. The currents produced by PAF are in opposite direction of the currents produced by load. Therefore, passing of harmonic currents to the mains side is prevented. Also, PAF compensates reactive components and stabilizes unbalanced currents, which occurred in phases. Consequently, currents drawn from the mains are sinusoidal as it should be thanks to PAF. The schematic for a single phase voltage supply PAF is shown by Figure 2 [16].

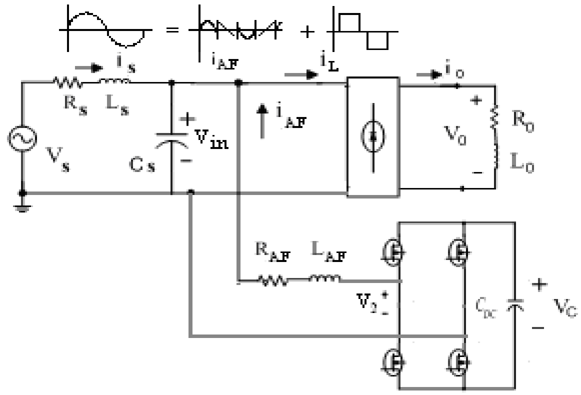

Figure 2. Schematic of the proposed PAF with Single Phase Voltage Supply by PSIM

R_S and L_S are resistance and inductance of the supply in here. R_{AF} and L_{AF} are passive elements that in used of compensating harmonics caused by switching devices in inverter circuit. As a nonlinear load, diode rectifier with *R-L* load has been used. To provide continuous load current, load inductance must be at sufficient magnitude and taken into account.

For GSSA modeling of load and active filter, two different switching functions are used and their analytical statements are determined [16]. For diode rectifier used as a nonlinear load, input-output current and voltage relations which depend on $u_1(t)$ switching function (Figure 3), are given by eq. 6 and 7. Switching function $u_2(t)$ for active filter is demonstrated by Figure 4.

$$i_L = i_0 * u_1(t) \tag{6}$$

$$V_0 = V_{in} * u_1(t) \tag{7}$$

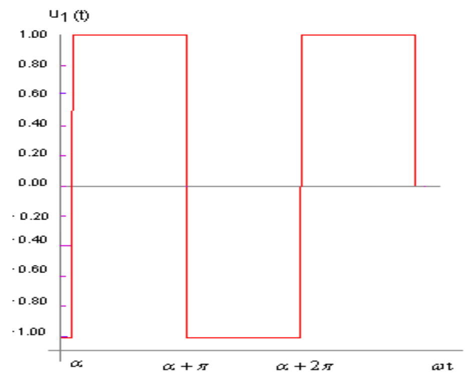

Figure 3. Switching function $u_1(t)$ for rectifier

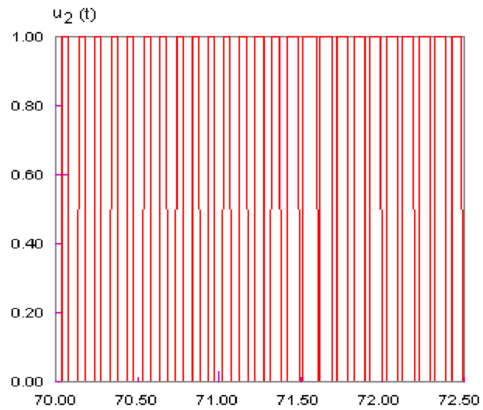

Figure 4. Switching function $u_2(t)$ for the active filter inverter circuit

Correlation between input current and output voltage that depends on switching function are expressed by eq.8 and 9 respectively.

$$i_C = -i_{AF} * u_2(t) \tag{8}$$

$$V_2 = V_C * u_2(t) \tag{9}$$

In suggested voltage supply PAF based on $u_1(t)$ and $u_2(t)$ switching functions, all components are transformed into passive elements, dependent voltage and current supplies as shown by Figure 5.

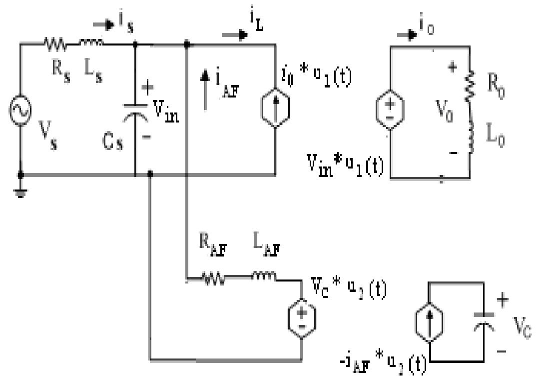

Figure 5. Schematic of the proposed PAF with Single Phase Voltage Supply by GSSA model

State equations of the proposed PAF with single phase voltage supply are expressed with equation 10-14.

$$\frac{di_0}{dt} = \frac{1}{L_0}\left[V_{in} * u_1(t) - R_0 * i_0\right] \tag{10}$$

$$\frac{dV_C}{dt} = -\frac{1}{C} * i_{AF} * u_2(t) \tag{11}$$

$$\frac{di_{AF}}{dt} = \frac{1}{L_{AF}}\left[V_{in} - V_C * u_2(t) - R_{AF} * i_{AF}\right] \tag{12}$$

$$\frac{di_S}{dt} = \frac{1}{L_S}\left[V_S - V_{in} - R_S * i_S\right] \tag{13}$$

$$\frac{dV_{in}}{dt} = \frac{1}{C_S}\left[i_S - i_{AF} - i_0 * u_1(t)\right] \tag{14}$$

4. Modelling of PAF with GSSA Method

For rectifier output current (i_o) and inverter supply voltage (V_C), only DC values are calculated by eq. 15 and 16. Capacitor and inductance values are considered as quite high.

$$< i_o >_0 = x_1 \tag{15}$$

$$< V_C >_0 = x_2 \tag{16}$$

For supply current calculation, fundamental frequency of supply current (i_s) is only taken into account. Because PAF meets 3th, 5th and 7th harmonics in the supply current in GSSA model. State variables used in the 1st harmonic approach for GSSA model are expressed by eq. 17 and 18.

$$< i_s >_1 = x_3 + jx_4 \tag{17}$$

$$< i_s >_{-1} = < i_s >_1^* = x_3 - jx_4 \tag{18}$$

Active filter current (i_{AF}) with fundamental frequency that compensates reactive current and recharges the capacitor, is calculated by eq. 19 and 20.

$$< i_{AF} >_1 = x_5 + jx_6 \tag{19}$$

$$< i_{AF} >_{-1} = < i_{AF} >_1^* = x_5 - jx_6 \tag{20}$$

Also the 3rd, 5th and 7th degree current harmonics, which are the most influential ones to the system, are calculated by equation 21-26.

$$< i_{AF} >_3 = x_7 + jx_8 \tag{21}$$

$$< i_{AF} >_{-3} = < i_{AF} >_3^* = x_7 - jx_8 \tag{22}$$

$$< i_{AF} >_5 = x_9 + jx_{10} \tag{23}$$

$$< i_{AF} >_{-5} = < i_{AF} >_5^* = x_9 - jx_{10} \tag{24}$$

$$< i_{AF} >_7 = x_{11} + jx_{12} \tag{25}$$

$$< i_{AF} >_{-7} = < i_{AF} >_7^* = x_{11} - jx_{12} \tag{26}$$

For the capacitor voltage in AC side, 1st harmonic is calculated and it is expressed by eq. 27 and 28.

$$< V_{in} >_1 = x_{13} + jx_{14} \tag{27}$$

$$< V_{in} >_{-1} = < V_{in} >_1^* = x_{13} - jx_{14} \tag{28}$$

Fourier transformation is applied to the supply and switching functions as shown in eq. 29-37.

$$V_S(t) = v_S * \sin(\omega t) \tag{29}$$

$$< V_S(t) >_0 = 0 \tag{30}$$

$$< V_S(t) >_1 = \frac{-jv_S}{2} \tag{31}$$

$$< u_1(t) >_0 = 0 \tag{32}$$

$$< u_1(t) >_1 = \frac{-j2}{\pi} \tag{33}$$

$$< u_2(t) >_1 = 0.427 + j0.337 \tag{34}$$

$$< u_2(t) >_3 = -0.0239 + j0.087 \tag{35}$$

$$< u_2(t) >_5 = 0.336 + j0.135 \tag{36}$$

$$< u_2(t) >_7 = 0.0219 - j0.295 \tag{37}$$

Equation sets of 15-37 are placed in state space equation sets of 10-14 to obtain new equations for the system. Fourier transformations are implemented to obtained new equations at new triggering angle as shown by eq. 4 and 5. Thus, GSSA model for whole system is found. To define unknown variables for GSSA model of the system, matrix is given by equation 38.

$$\frac{d}{dt}\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \\ \dot{x}_7 \\ \dot{x}_8 \\ \dot{x}_9 \\ \dot{x}_{10} \\ \dot{x}_{11} \\ \dot{x}_{12} \\ \dot{x}_{13} \\ \dot{x}_{14} \end{bmatrix} = \begin{bmatrix}
-\frac{R_s}{L_s} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{4}{\pi L_s} \\
0 & 0 & 0 & 0 & \frac{0.189}{C} & \frac{0.113}{C} & \frac{0.0005}{C} & \frac{-0.0007}{C} & \frac{-0.112}{C} & \frac{-0.0182}{C} & \frac{-0.0045}{C} & \frac{0.087}{C} & 0 & 0 \\
0 & -\frac{R_s}{L_s} & \omega & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_s} & 0 & 0 & 0 & 0 & 0 \\
0 & -\omega & -\frac{R_s}{L_s} & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_s} & 0 & 0 & 0 & 0 \\
0 & \frac{0.427}{L_f} & 0 & 0 & -\frac{R_f}{L_f} & \omega & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_f} & 0 \\
0 & \frac{0.337}{L_f} & 0 & 0 & \omega & -\frac{R_f}{L_f} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_f} \\
0 & \frac{0.0239}{L_f} & 0 & 0 & 0 & 0 & -\frac{R_f}{L_f} & 3\omega & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{-0.087}{L_f} & \frac{1}{C_s} & \frac{2}{\pi C_s} & 0 & 0 & -3\omega & -\frac{R_f}{L_f} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{-0.336}{L_f} & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{R_f}{L_f} & 5\omega & 0 & 0 & 0 & 0 \\
0 & \frac{-0.135}{L_f} & 0 & 0 & 0 & 0 & 0 & 0 & -5\omega & -\frac{R_f}{L_f} & 0 & 0 & 0 & 0 \\
0 & \frac{-0.0219}{L_f} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_s} & 0 & -\frac{R_f}{L_f} & 7\omega & 0 & 0 \\
0 & \frac{0.295}{L_f} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -7\omega & -\frac{R_f}{L_f} & 0 & 0 \\
0 & 0 & \frac{1}{C_s} & 0 & -\frac{1}{C_s} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \omega \\
\frac{2}{\pi C_s} & 0 & 0 & \frac{1}{C_s} & 0 & -\frac{1}{C_s} & 0 & 0 & 0 & 0 & 0 & 0 & -\omega & 0
\end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{-v_s}{2L_s} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{38}$$

The matrix can be solved with MATLAB easily. After the variables in eq. 15-28 are analyzed by eq. 1, harmonic extensions for the state variables are found by eq. 39-43.

$$i_o(t) = x_1 \tag{39}$$

$$V_c(t) = x_2 \tag{40}$$

$$i_S(t) = 2x_3 \cos\omega t - 2x_4 \sin\omega t \tag{41}$$

$$\begin{aligned} i_{AF}(t) = {} & 2x_5\cos\omega t - 2x_6\sin\omega t + 2x_7\cos 3\omega t \\ & - 2x_8\sin 3\omega t + 2x_9\cos 5\omega t - 2x_{10}\sin 5\omega t \\ & + 2x_{11}\cos 7\omega t - 2x_{12}\sin 7\omega t \end{aligned} \tag{42}$$

$$V_{in}(t) = 2x_{13}\cos\ \omega t - 2x_{14}\sin\omega t \tag{43}$$

When the variables that come from solution of the matrix are placed to the obtained results, all parameters of the circuit are solved.

5. GSSA and Real-Time Simulation Results

To confirm the results obtained by GSSA method for modeling voltage supply PAF mathematically, real-time simulation of the system is realized by PSIM software. The proposed single phase voltage-supply PAF is carried out via PSIM software as shown by Figure 6 and the results are given by Figure 7. Besides, the system parameters used in simulations are given by Table 1.

Table 1. The system parameters used in simulations

Parameter	**Value**
Supply Voltage (V_S)	50 Hz, 220 V
Supply Impedance(R_S-L_S)	0.4 Ω, 0.2 mH
Load (P, L_{fDC}, R_L)	50 W, 0.2 H, 100Ω
PAF inductance (L)	10 mH
Energy storage part of active filter (L_{AF},V_{DC})	0.5 mH, 300V
Switching Frequency (fs)	50 kHz

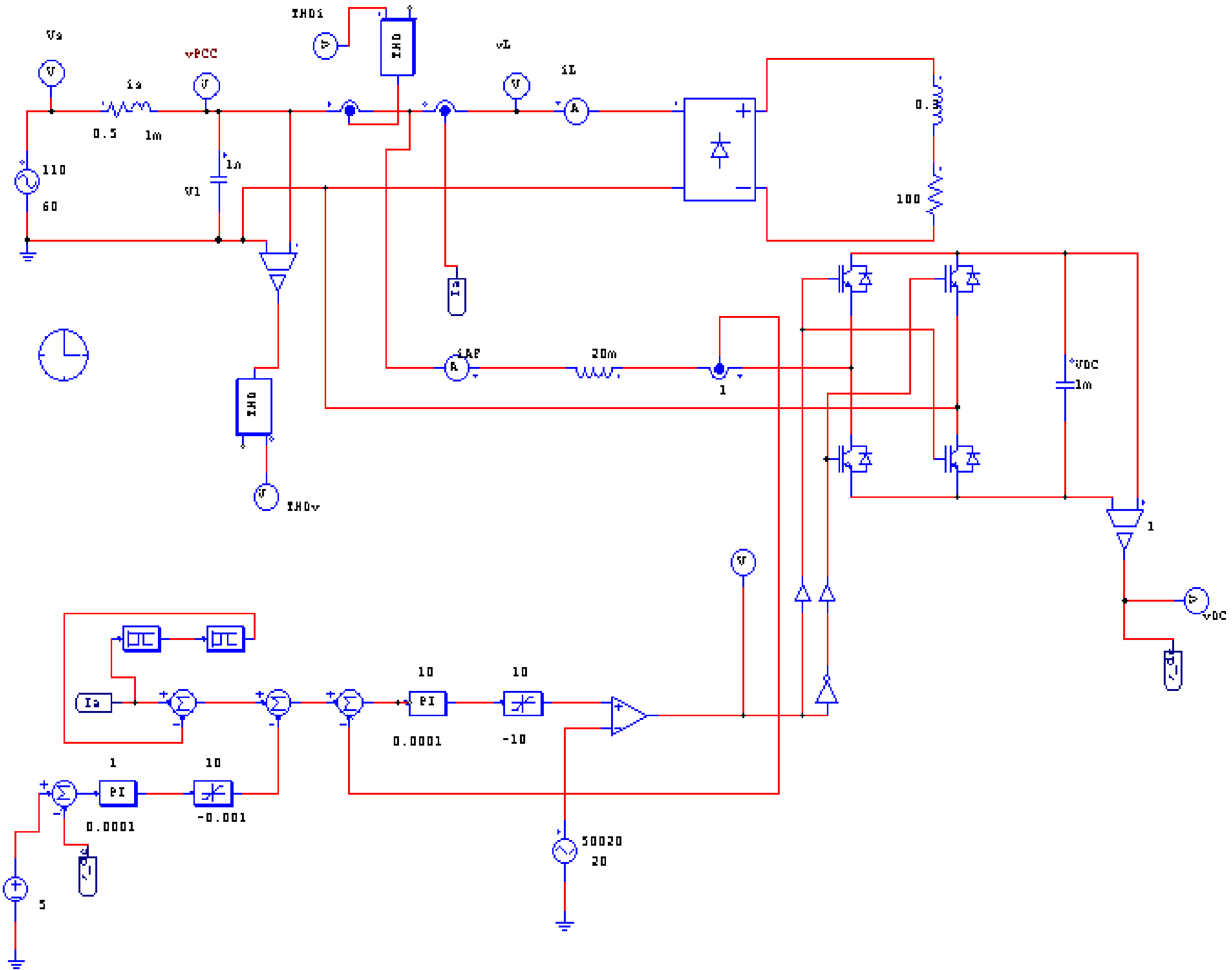

Figure 6. The proposed PAF with Single Phase Voltage Supply by PSIM

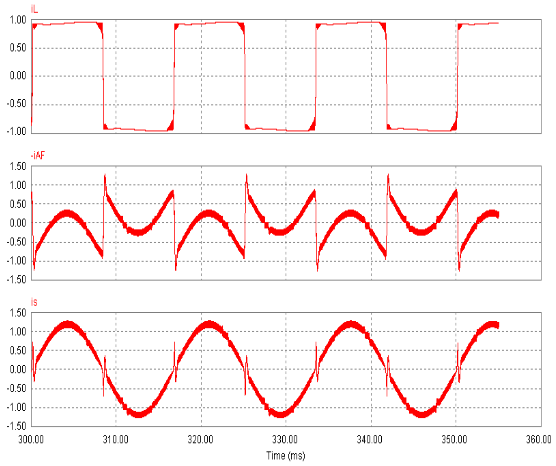

Figure 7. Obtained results from the proposed single phase PAF system with PSIM model. (top load current (i_L), middle parallel filter current (i_{AF}), and bottom supply current (is))

Before active filter is connected to the system, the current waveform drawn by rectifier with RL load is shown by Figure 8.

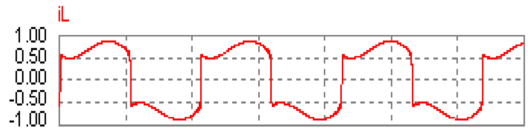

Figure 8. Current waveform of rectifier with RL load

After PAF is connected to the system, GSSA results for the current given by active filter to the grid are shown by Figure 9 respectively.

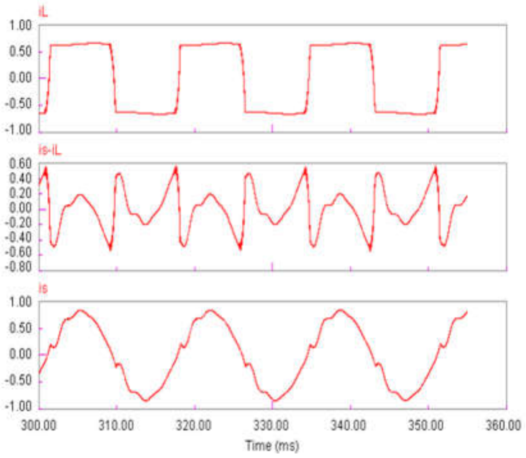

Figure 9. Obtained results from the proposed single phase PAF system with GSSA model. (top load current (i_L), middle parallel filter current ($i_{AF}=i_S-i_L$), and bottom supply current (is))

Consequently, after PAF is connected to the system, the current drawn by nonlinear load from the main becomes pure sinusoidal. Waveforms of the grid current found by PSIM simulations and GSSA methods are shown by Figure 10 and Figure 11 respectively. The results taken from both applications have rather similar characteristics. This proves that the GSSA method used in modelling active filters mathematically has been valid. However, the difference between them stems from not taking switching frequency of active filter and high degree harmonics into account in the application of mathematical method. But, in the equation 1, when we increase in coefficient, both results will have more similarities.

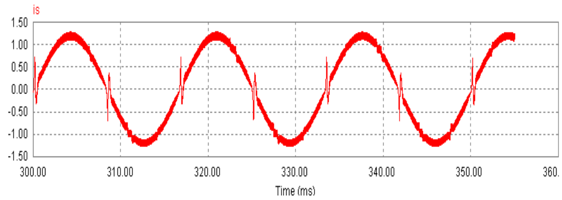

Figure 10. The main current (i_S) waveform obtained via PSIM after PAF

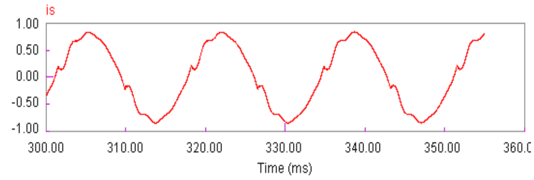

Figure 11. Grid current (i_S) waveform obtained via GSSA method after PAF

6. Conclusion

The power electronic converters are the circuits which include inductor, capacitor, resistance, thyristor, transistor, and diode mainly. These converters are nonlinear loads for the system because of their switching nature. In this case, simulation and/or mathematical modelling of the converters are most important issues for their analysis and design process. These provide great benefits for the designer to understand the system. However, the existing models cannot be in used for determining big signal distortions and estimating harmonic components. These problems can be solved by the GSSA method.

In this study, single phase PAF is mathematically modeled by GSSA method. In order to prove accuracy of the method, PAF is also designed by PSIM software program. Afterwards, the obtained results are compared comprehensively. Simulation and analysis of power electronic converters are realized using software packages such as MATLAB, PSPICE, Saber and PSIM. Nonlinear actual elements such as switches and passive components are used for simulating active filter systems. Nonlinear models are used in the model with time-based software for the simulation accuracy of the system. In this case, nonlinear properties of real elements; require long simulation period, conversion problems and large program files. Also, temporary simulations with the switching models of the transformers bring about the same problems. For this reason, mathematical average methods are traditionally used in the modeling of power electronic systems.

This method is derived from Fourier transform for non-periodic signals. By using this method, the non-linearity of the system is removed. Thus, relationship among the state equations of system is expressed by linearized equations. In the modeling system, there is no need for the actual model of the key or switch. An exact and fast approximation of the system parameters is achieved. Unlike the conventional simulation methods; require long simulation period, conversion problems and large program files are eliminated for modeling of active filters by means of GSSA method. In addition, linear state equations are drawn by nonlinear equations of active filters via using the method. Furthermore, harmonic oscillations are obtained for all state variables in the system.

References

[1] G. Nirmal, A. Vineesha, and A. Professor, "Design and Implementation of Shunt Active Power Filter Based Predictive Control Algorithm," *International Journal of Advanced Research in Electrical*, vol. 4, no. 3, pp. 1531-1538, 2015.

[2] Surendhar, B., Ramu, K., "Shunt Active Power Filter for Power Quality Improvement By SAPF Using PV System," *International Journal & Magazine of Engineering, Technology, Management and Research*, vol. 2, no. 12, pp. 75–81, 2015.

[3] A. Singh and P. Baredar, "Power quality analysis of shunt active power filter based on renewable energy source," in *2014 International Conference on Advances in Engineering & Technology Research (ICAETR - 2014)*, 2014, pp. 1–5.

[4] M. Vijayakumar and S. Vijayan, "PV Based Three-Level NPC Shunt Active Power Filter with Extended Reference Current Generation Method," *International Journal of Electrical Energy,* vol. 4, no. 2, pp. 258–267, 2014.

[5] B. Majhi, "Design of a Shunt Active Power Filter with Grid connected Inverter Control for a Photovoltaic System," M.S. thesis, Dept. Elect. Eng., National Institute of Technology, Rourkela-Odisha, India, 2015.

[6] E. Srinivasulu Reddy and P. R. Chandra, "Design and Analysis of Shunt Active Power Filter for Grid Connected RES System," *International Journal of Innovative Technologies*, vol. 4, no. 6, pp. 0963–0968, 2016.

[7] A. J. Viji and T. A. A. Victoire, "A comparative study of 3 Phi SAPF with Different reference current generation," *Control Engineering and Applied Informatics*, vol. 16, no. 4, pp. 99–106, Dec. 2014.

[8] Y. Chen, T. Ji, M. Li, Q. Wu, and X. Wang, "Power System Harmonic Estimation Based on Park Transform," *J Electr Eng Technol*, vol. 11, no. 1, pp. 1921–718, 2016.

[9] H. Akagi, "New trends in active filters for power conditioning," *IEEE Transactions on Industry Applications*, vol. 32, no. 6, pp. 1312–1322, 1996.

[10] H. Akagi, "Active Harmonic Filters," *Proceedings of the IEEE*, vol. 93, no. 12, pp. 2128–2141, Dec. 2005.

[11] V. A. Jeraldine and M. Sudhakaran, "Reduction of THD in Single Phase PAF With PSD Method for Reference Current Generation," *International Journal of Engineering*, vol. 1, no. 5, pp. 31–34, 2012.

[12] A. K. Al-Othman, M. E. Alsharidah, N. A. Ahmed, and B. N. Alajmi, "Model Predictive Control for Shunt Active Power Filter in Synchronous Reference Frame," *J Electr Eng Technol*, vol. 11, pp. 1921–718, 2016.

[13] B. Sun, Y. Xie, H. Ma, and L. Cheng, "Analysis and Application of Repetitive Control Scheme for Three-Phase Active Power Filter with Frequency Adaptive Capability," *J Electr Eng Technol*, vol. 11, pp. 1921–718, 2016.

[14] T. Platek, "Power system stability with parallel active filter ensuring compensation of capacitive reactive power of a resonant LC circuit," *Bulletin Of The Polish Academy Of Sciences Technical Sciences*, vol. 60, no. 2, 2012.

[15] H. Nawar, A. Alobidi, and M. Ismail, "Parallel Active Filter Modelling and control strategy for harmonic elimination," *International Journal of Innovative Research in Advanced Engineering*, vol. 2, no. 2, pp. 2349–2163, 2015.

[16] M. Gwóźdź, "Power electronics parallel active filter with controlled dynamics and improved EM immunity," *Przegląd Elektrotechniczny (Electrical Review)*, vol. 87, no. 1, pp. 33–2097, 2011.

[17] A. Nasiri, A. E. Amac, and A. Emadi, "Series-Parallel Active Filter/Uninterruptible Power Supply System," *Electric Power Components and Systems*, vol. 32, no. 11, pp. 1151–1163, Nov. 2004.

[18] A. Emadi, "Modeling and Analysis of Multiconverter DC Power Electronic Systems Using the Generalized State-Space Averaging Method," *IEEE Transactions on Industrial Electronics*, vol. 51, no. 3, pp. 661–668, Jun. 2004.

[19] A. Emadi, "Modeling of Power Electronic Loads in AC Distribution Systems Using the Generalized State-Space Averaging Method," *IEEE Transactions on Industrial Electronics*, vol. 51, no. 5, pp. 992–1000, Oct. 2004.

[20] J. Mahdavi, A. Emaadi, M. D. Bellar, and M. Ehsani, "Analysis of power electronic converters using the generalized state-space averaging approach," *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 44, no. 8, pp. 767–770, 1997.

[21] S. Rahmani, K. Al-Haddad, and H. Y. Kanaan, "A comparative study of shunt hybrid and shunt active power filters for single-phase applications: Simulation and experimental validation," *Mathematics and Computers in Simulation*, vol. 71, no. 4–6, pp. 345–359, Jun. 2006.

[22] A. Nasiri and A. Emadi, "Modeling, simulation, and analysis of active filter systems using generalized state space averaging method," in *IECON'03. 29th Annual Conference of the IEEE Industrial Electronics Society (IEEE Cat. No.03CH37468)*, 2003, vol. 3, pp. 1999–2004.

[23] S. Rechka, É. Ngandui, J. Xu, and P. Sicard, "Performance evaluation of harmonics detection methods applied to harmonics compensation in presence of common power quality problems," *Mathematics and Computers in Simulation*, vol. 63, no. 3–5, pp. 363–375, Nov. 2003.

[24] S. R. Sanders, J. M. Noworolski, X. Z. Liu, and G. C. Verghese, "Generalized averaging method for power conversion circuits," *IEEE Transactions on Power Electronics*, vol. 6, no. 2, pp. 251–259, Apr. 1991.

[25] H. Ebrahimi and H. El-Kishky, "A novel Generalized State-Space Averaging (GSSA) model for advanced aircraft electric power systems," *Energy Conversion and Management*, vol. 89, pp. 507–524, Jan. 2015.

[26] L. J. Yu, T. Houjun, and G. Xin, "Modelling of a Witricity System Using GSSA Method," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 12, no. 5, pp. 3697–3704, 2014.

[27] M. Tuna, A. E. Amac, and M. Ak, "The comparative analysis of boost DC/DC converter used in hybrid electric vehicles," *Energy Education Science and Technology Part A: Energy Science and Research*, vol. 30, no. 1, 2012.

[28] L. Dong, H. Ma, and F. Xu, "Modeling and analysis of PWM converters with a new GSSA method," in *2008 34th Annual Conference of IEEE Industrial Electronics*, 2008, pp. 821–826.

[29] P. T. Krein, J. Bentsman, R. M. Bass, and B. L. Lesieutre, "On the use of averaging for the analysis of power electronic systems," *IEEE Transactions on Power Electronics*, vol. 5, no. 2, pp. 182–190, Apr. 1990.

[30] H. E. Darkhaneh, J. R. Gatabi, and H. El-Kishky, "A novel GSSA method for modeling of controllers in the multi-converter system of an Advanced Aircraft Electric Power System (AAEPS)," in *2012 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, 2012, pp. 795–798.

[31] A. Yazdani and R. Iravani, "A Generalized State-Space Averaged Model of the Three-Level NPC Converter for Systematic DC-Voltage-Balancer and Current-Controller Design," *IEEE Transactions on Power Delivery*, vol. 20, no. 2, pp. 1105–1114, Apr. 2005.

[32] C. Q. Lee, "Generalized state-space averaging approach for a class of periodically switched networks," *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 44, no. 11, pp. 1078–1081, 1997.