Indonesian Journal of Electrical Engineering and Computer Science
Vol. 18, No. 1, April 2020, pp. 443~451
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v18.i1.pp443-451

Vortex search algorithm for designing hybrid active power filter

Chau Minh Thuyen[1], Truong Khac Tung[2], Nguyen Hoai Phong[3]
[1,3]Faculty of Electrical Engineering Technology, Industrial University of Ho Chi Minh City, Vietnam
[2]Division of Computational Mathematics and Engineering, Institute for Computational Science, Ton Duc Thang University, Vietnam
[2]Faculty of Civil Engineering, Ton Duc Thang University, Vietnam

Article Info

Article history:

Received Jul 10, 2019
Revised Oct 15, 2019
Accepted Nov 1, 2019

Keywords:

Harmonics
Hybrid active power filter
Multi-objective optimization
Passive power filter
Vortex search algorithm

ABSTRACT

This paper proposes a new multi-objective optimization design method for Hybrid Active Power Filter based on the Vortex Search algorithm. The Vortex Search algorithm belongs to the Single-Solution Based algorithm class of Metaheuristics algorithm. This design method has the advantage of fast execution time, high convergence speed and prevent local trap problems. The achieved results are multi-objective, such as minimum total harmonic distortion of the supply current and source voltage and satisfy many constraints such as system stability, resonance conditions of branches and limits of the parameters. Compared with the traditional design method, simulation results have proved that: the proposed design method is given with better results in minimizing total harmonic distortion of the supply current and source voltage.

Corresponding Author:

Truong Khac Tung,
Division of Computational Mathematics and Engineering,
Institute for Computational Science, Ton Duc Thang University,
Ho Chi Minh City, Vietnam.
Email: truongkhactung@tdtu.edu.vn

1. INTRODUCTION

In power systems, the hybrid active power filter (HAPF) is considered as the most effective solution in harmonic filtering and reactive power compensation [1-3]. However, the working efficiency of HAPF depends on many factors such as: correct determination of the parameters [4], control method [5-8], harmonic current detection method [9, 10], control strategy [11, 12] and stabilization of the DC-bus for the inverter [13, 14]. In which, the correct calculation of the parameters of the HAPF is the most important factor, it decided to work efficiency of HAPF.

The structure of a HAPF includes: power circuit part and control circuit part. Therefore, the parameters that need to be designed for HAPF are the parameters of the above circuit parts. Until now, the multi-objective optimization studies of HAPF can be summarized as follows: The application of the genetic algorithm to multi-objective optimization design for passive power filter (PPF) is proposed by [15]. Another algorithm is also commonly used for HAPF design, called the Particle Swarm Optimization (PSO) algorithm. The PSO algorithm is used to design an APF in a four-wire three-phase system in case of balanced and unbalanced loads but only consider to design for PPFs and optimization for the APF but not for the HAPF [16-19]. Another study to multi-objective design on HAPF is using an ant colony and bat algorithm [20, 21] but only aslo multi-objective optimization design for PPFs. Ahmed Faheem Zobaa has used the Fortran Feasible Sequential Quadratic Programming algorithm to solve the multi-objective optimization problem for HAPF with the aim of finding PPF parameters [22].

In summary, the previous research on multi-objective optimization for HAPF was the only multi-objective optimization design of power circuit parts (parameters of the PPF). Meanwhile, the optimized design for the parameters of the control circuit part has not been studied and the calculation of the above parameters without considering the condition of the system stability.

To overcome this disadvantage, in this paper, the Routh's stability standard is used to check the stable condition of the HAPF system. The Vortex search is a new optimization algorithm, that is effecty in solving global optimization [23, 24]. Then a new multi-objective optimization design, based on the Vortex Search (VS) algorithm is proposed to determine the best set of parameters for the HAPF. The proposed algorithm has the advantage of finding a quick solution with little loops. The results achieved will be global optimization such as the minimum of the total harmonic distortion (THD) of the supply current and source voltage and satisfy the stable conditions.

The structure of the paper is divided into five parts. Part 1 is an overview introduction of the issues that need to be investigated. Part 2 is a new multi-objective optimization design method for Hybrid Active Power Filter. The simulation results and discussion are presented in Part 3, and the conclusions are summarized in Part 4.

2. NEW MULTI-OBJECTIVE OPTIMIZATION DESIGN METHOD FOR HYBRID ACTIVE POWER FILTER

The single-phase equivalent circuit of the selected Hybrid Active Power Filter topology is shown in Figure 1. It consists of five parts: U_s and Z_s are the source voltage and the resistance of the source. C_1 and L_1 are capacitance and inductance at the fundamental frequency. C_F is the added capacitance to compensate for reactive power. L_0 is the output filter of the voltage source inverter.

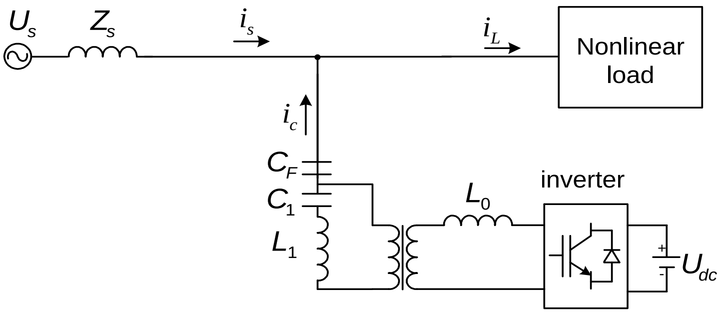

Figure 1. Single-phase equivalent circuit of the selected hybrid active power filter

Starting from the load current i_L (i_{La}, i_{Lb}, i_{Lc}), we use p-q instantaneous power theory [9], [10] to separate the harmonic component of the load current as i_{Lha}, i_{Lhb}, i_{Lhc}. These components will be chosen as the reference components and they are compared to the compensate current components into the grid i_c of HAPF are i_{ca}, i_{cb}, and i_{cc}. The error of the above comparison will be taken through the PI (Proportional - Integral) controller, through pulse width modulation to control ON-OFF switches of the inverter to generate compensate signals on the grid. Thus, the inverter will be controlled to produce a signal similar to the harmonic current signal generated from the load.

The parameters of both the power circuit part and the control circuit part need to be determined in the model in Figure 1 including passive circuit C_F - C_1 - L_1 in which branch C_1 - L_1 resonates at the fundamental frequency, output filter L_0, voltage bus-DC of inverter U_{dc}, parameters of PI controller are K_p and K_i. Currently, these parameters are usually determined based on experience and local calculations, regardless of the stability of the system. Therefore, this paper proposes a new multi-objective optimization design method that has considered the stability of the system.

2.1. Constraints and Objective Function

System stability constraint: Based on the transfer function of the HAPF system in [1], we have the characteristic equation of the control transfer function as follows:

$$D(s) = a_6 s^6 + a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s^1 \quad (1)$$

According to Routh's stability standard, the following conditions must be satisfied.

$$\begin{cases} a_5 a_4 - a_6 a_3 > 0 \\ a_3 a_2 - a_4 a_1 > 0 \\ b_1 a_3 - a_5 b_3 > 0 \\ b_2 b_3 - b_1 b_4 > 0 \\ a_1 b_3 \qquad > 0 \end{cases} \tag{2}$$

With: $b_1 = \frac{a_5 a_4 - a_6 a_3}{a_5}$; $b_3 = \frac{a_3 a_2 - a_4 a_1}{a_3}$; $b_2 = \frac{b_1 a_3 - a_5 b_3}{b_1}$; $b_4 = \frac{b_3 a_1}{b_3}$; $c_1 = \frac{b_3 b_2 - b_1 b_4}{b_2}$; $c_2 = b_4$;
$a_6 = T_i T L_1 C_1 C_F (L_1 L_s + L_1 L_0 + L_1 L_0 L_s)$; $a_5 = T_i T (R_s L_1 C_1 C_F + R_s L_0 C_1 C_F) + T_i (C_1 C_F L_1 L_s + L_1 L_0 C_1 C_F + C_1 C_F L_0 L_s)$;
$a_4 = T_i T (L_0 C_F + L_s C_F + L_1 C_1 + L_0 C_1) + T_i (R_s L_1 C_1 C_F + R_s L_0 C_1 C_F) + C_F C_1 L_1 K_{inv} K T_i)$;
$a_3 = T_i T C_F R_s + T_i (L_0 C_F + L_s C_F + L_1 C_1 + L_0 C_1) + K K_{inv} C_1 L_1 C_F$; $a_2 = T_i T + T_i C_F R_s + T_i K K_{inv} C_F$; $a_1 = T_i + K K_{inv} C_F$;
$T = 0.01 ms$; $T_i = 0.00001$; $K = 10$; $K_{inv} = 1$

Constraints on resonance conditions in PPFs: The L and C parameters in a branch must be resonated at a certain frequency.

$$\omega_n L = \frac{1}{\omega_n C} \tag{3}$$

Constraint of passive power filter values: passive power filter values must be positive and meet system stability and resonance conditions.

$$0 < (R_i, L_i, C_i) \le (R_{max}, L_{max}, C_{max}) \tag{4}$$

the values of R_{max}, L_{max}, and C_{max} are determined under stable conditions (2).

PPFs must be compensated with a maximum capacity but not exceed the required maximum limit

$$Q_{c\min} \le Q_c \le Q_{c\max} \tag{5}$$

constraint of DC-bus voltage value:

$$0 < U_{dc} < U_{dc\text{-}max} \tag{6}$$

Controller parameters constraints: Controller parameters must be positive and satisfy system stability conditions (2).

$$0 < K_p < K_{pmax} \ ; \ \ 0 < K_i < K_{imax} \tag{7}$$

according to [5], the value of K_p and K_i is too small or too large to cause system instability.

Objective function: we consider the main objective as follows:

$$F = \min(THDi_s + THDu_s) \tag{8}$$

2.2. Vortex Search Algorithm and Its Application for Designing Hybrid Active Power Filter

The Vortex search algorithm is first proposed in [23, 24]. Let us consider a two-dimensional optimization problem. In a two-dimensional case, a vortex pattern can be modelled by a number of nested circles. Here, the largest circle of the vortex is first centered on the search space, where the initial center can be calculated using (9). A description of the VS algorithm is also provided in algorithm 1.

$$\mu_0 = \frac{upperlimit + lowerlimit}{2} \tag{9}$$

$$r_0 \approx \sigma_0 = \frac{\max(upperlimit) - min(lowerlimit)}{2} \tag{10}$$

The solutions that exceed the boundaries are shifted into the boundaries, as in (11).

$$s_k^i = \begin{cases} rand\left(upperlimit^i - lowerlimit^i\right) + lowerlimit^i; s_k^i < lowerlimit^i \\ s_k^i; lowerlimit^i \le s_k^i \le upperlimit^i \\ rand\left(upperlimit^i - lowerlimit^i\right) + lowerlimit^i; s_k^i \ge upperlimit^i \end{cases} \quad (11)$$

The initial radius r_0 can be calculated with (10). Because a_0 =1, the resulting function value is 1(x)·*gammaincinv* (x, a_0) ≈1, which means $r_0 \approx \sigma_0$ as indicated before.

$$r_0 = \sigma_0 . \left(\frac{1}{x}\right) . gammaincinv(x, a_0) \quad (12)$$

by methods of (12), the initial radius value r_0 can be computed as $r_0 \approx 10$. Radius at each iteration is calculated by using (13).

$$r_t = \sigma_0 . \left(\frac{1}{x}\right) . gammaincinv(x, a_t) \quad (13)$$

In this algorithm paramater a_t of the inverse incomplete gamma function defines the resolution of the search. By equally sampling values within [1, 0] interval at a certain step size, the resolution of the search can be adjusted. For this purpose, at generation t, a_t is obtained by using (14).

$$a_t = a_0 - \frac{t}{MaxInt} \quad (14)$$

where a_0 is selected as $a_0 = 1$ to ensure full coverage of the search space at the first iteration, t is the iteration index, and *MaxItr* represents the maximum number of iterations.
Vortex Search algorithm flowchart for designing HAPF is shown as in Figure 2.

Algorithm 1.

Inputs: Initial center $\mu_0$is calculated by using (9)
    Initial radius $r_0$or $\sigma_0$is caculated by using (10)
    Best fitness so far $f(s_{best}) = \inf$
Output: Best solution s_{best}
$t = 0$;
Repeat
    /* Generate candidate solutions by using Gaussian distribution around the center $\mu_t$with a standard deviation (radius) r_t*/
    Generate $C_t(s)$;
    If exceeded, then shift the $C_t(s)$ values into the boundaries as in (11);
    /* Select the best solution from $C_t(s)$ to replace the current centerμ_t*/
    $s' = select(C_t(s))$;
    if $f(s') < f(s_{best})$
        $s_{best} = s'$
        $f(s_{best}) = f(s')$
    else
        Keep the best solution found so far s_{best};
    End
    /* Center is always shifter to the best solution found so far*/
    $\mu_{t+1} = s_{best}$;
    /* Decrease the standard deviation (radius) for the next iteration*/
    $r_{t+1} = Decrease(r_t)$;
    $t = t + 1$;
Until the maximum number of iterations is reached

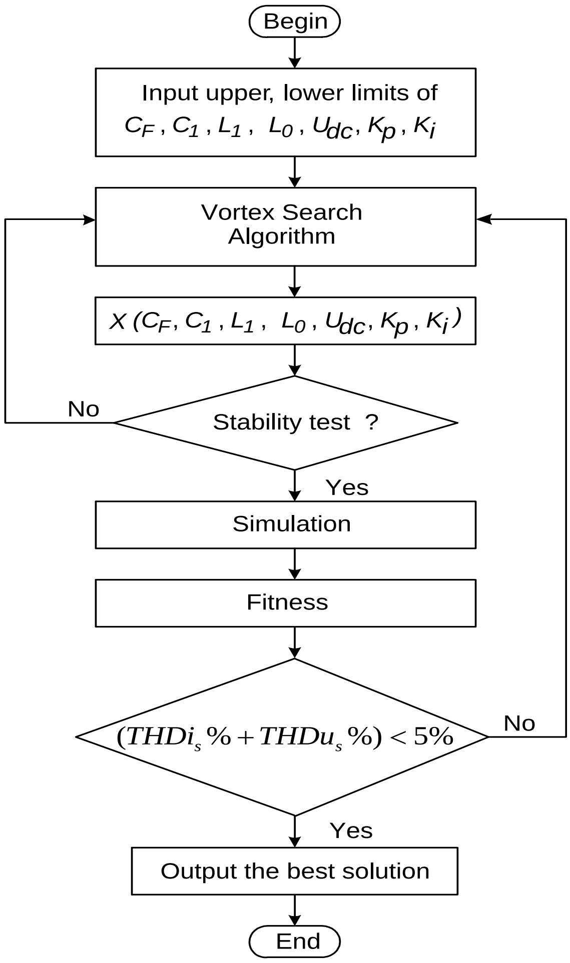

Figure 2. Vortex search algorithm flowchart for designing HAPF

Application of the VS Algorithm for Hybrid Active Power Filter Design is described as follows: The algorithm begins by entering the upper and lower limit values of the parameters to be searched based on the constraints in the formulas from (3) to (7), then these limits will be included in the VS algorithm to find a set of parameters to be searched$X(C_F, C_1, L_1, L_0, U_{dc}, K_p, K_i)$. Next, these parameters will be checked for stable conditions using formula (2), if not stable condition, return to VS algorithm to create a new set of parameters, if stable condition is satisfied, these parameters will be setup into the HAPF simulation model to find the $THDi_s\%$ and $THDu_s\%$ values.

The value of $THDi_s\%$ must be less than ε_1 and $THDu_s\%$ must be less than ε_2, according to IEEE 519 standard [25], the value of ε_1 is less than or equal to 5% and ε_2 is less than or equal to 5%. Therefore, to satisfy ε_1 and ε_2, the objective function F must be less than 5%, then stop and print out the results. Vortex Search algorithm flowchart for designing HAPF is described as in Figure 2.

3. SIMULATION RESULTS AND DISCUSSION

To demonstrate the effectiveness of the proposed design method. Let's consider, let us consider a HAPF model as shown in Figure 1. Three-phase source voltage is 380V-50Hz. THD of the load current is shown in Figure 3.

According to [1], the parameters of the HAPF system with traditional design method are calculated in Table 1. In addition, the controller parameters are randomly selected with the best parameters of K_p = 30 and K_i = 0.1, switching frequency f = 10kHz.

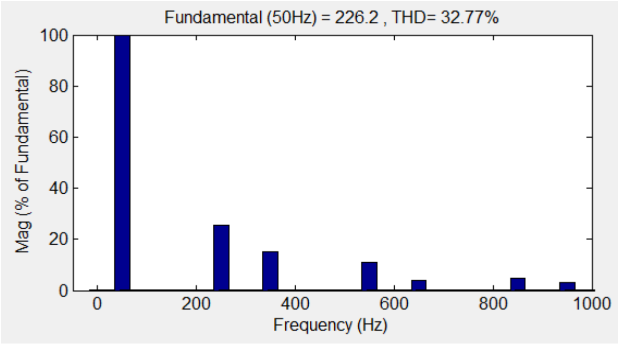

Figure 3. THD of the load current

The parameters in Table 1, we obtain the waveforms of the HAPF system shown in Figure 4. From Figure 4, we see that: THD of the supply current i_s decreases from 32.77% to 2.1%, THD of the source voltage u_s is 1.69%, while the reactive power decreased to 140var from 2359var, that is, the capacity compensated by PPFs is 2219var. THD of the supply current i_s shown in Figure 5. THD of the source voltage u_s is shown in Figure 6.

Table 1. HAPF Parameters by Traditional Design Method

C_F (μF)	C_1 (μF)	L_1 (mH)	L_0 (mH)	U_{dc} (V)	$THDi_s$ (%)	$THDu_s$ (%)
116.8	349.2	29.77	0.2	535	2.1	1.69

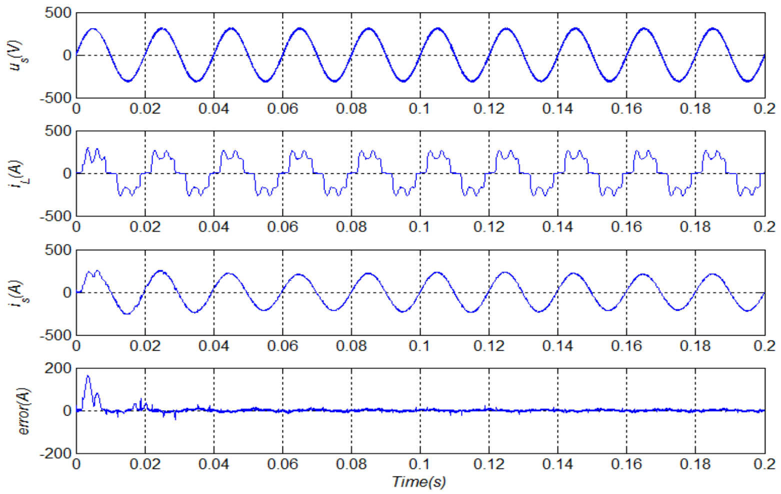

Figure 4. Waveforms of HAPF with traditional design method

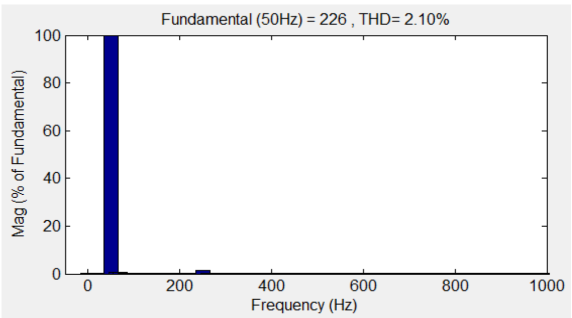

Figure 5. THD of the supply current i_s

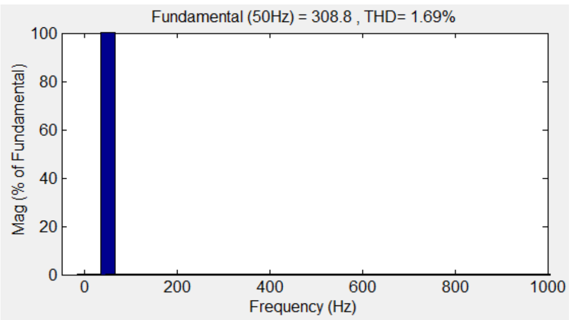

Figure 6. THD of the source voltage u_s

with the proposed design method, the best parameters of HAPF after 10 iterations are shown in Table 2. From the parameters in Table 2, we obtain the waveforms of the HAPF system shown in Figure 7.

Table 2. HAPF Parameters with the Proposed Multi-Objective Optimization Method

C_F (μF)	C_1 (μF)	L_1 (mH)	L_0 (mH)	U_{dc} (V)	K_p	K_i	THD i_s (%)	THD u_s (%)
136.67	301.22	26.6	1.01	674.13	94.95	0.65	1.14	1.28

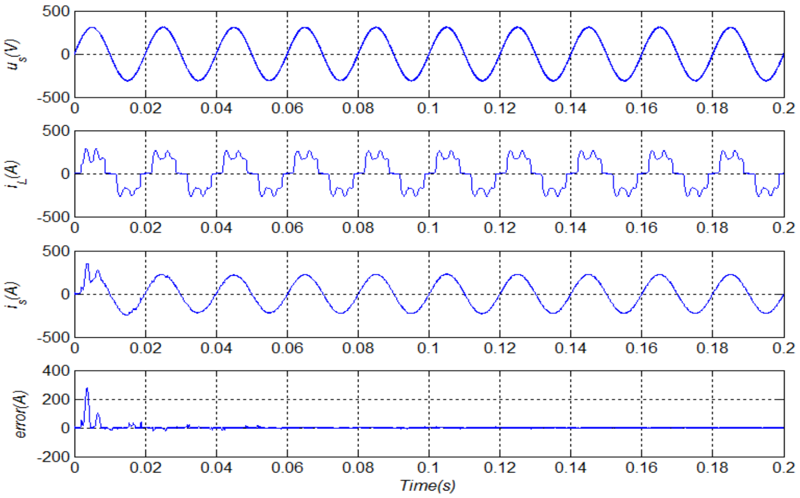

Figure 7. Waveforms of HAPF with the proposed design method

From Figure 7, we can see that: THD of the supply current i_s decreases from 32.77% to 1.14%, while the reactive power decreased to 90var from 2359var, so the compensation power by PPFs is 2269var. THD of the supply current i_s in steady-state is shown in Figure 8, THD of the source voltage u_s in steady-state is shown in Figure 9.

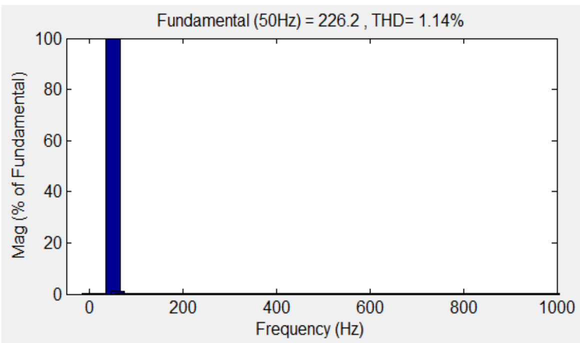

Figure 8. THD of the supply current i_s

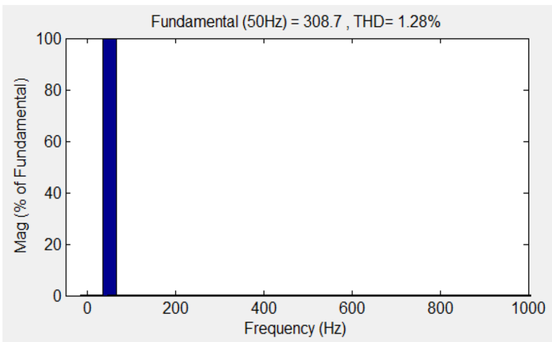

Figure 9. THD of the source voltage u_s

According to IEEE Std. 519-1992 Recommended Practices and Requirements for harmonic control in electrical power systems [25], then total harmonic distortion of current is less than or equal 5%. THD of the supply voltage is less than or equal 5%. From the simulation results, we can see that: the proposed design method is more effective than the traditional design method in reducing the total harmonic distortion of the supply current and source voltage and meet IEEE Std. 519-1992.

4. CONCLUSION

The paper has proposed a new multi-objective optimization design algorithm for HAPF based on the Vortex Search algorithm. This method can determine the parameters of both the power circuit part and the control circuit part of the HAPF. Compared to the traditional design method, simulation results have proved that: the achieved results are multi-purpose, such as: minimize the total harmonic distortion of the supply current and source voltage, maximize the reactive power compensation into the grid and satisfying many constraint conditions. This research can be applied to design for all different types of HAPF.

ACKNOWLEDGEMENTS

This work is supported by the scientific research subject of the Ministry of Industry and Trade of the socialist republic of Viet Nnam No. 081.19.ĐT.BO/HĐKHCN with the title: "Research, design, and manufacture the three-phase active compensation model with 5kW capacity for harmonic filtering for nonlinear loads."

REFERENCES

[1] Chuanping Wu, *et al.*, "*Integrated Mathematical Model and Closed Loop Control Characteristic Analysis of Hybrid Active Power Filter*," in 2009 International Conference on Sustainable Power Generation and Supply, 2009, pp. 1-7.

[2] Minh Thuyen Chau, "Generalized Current Delay Compensation on Hybrid Active Power Filter," *ICIC Express Letters*, vol. 11, pp. 1409-1415, 2017.

[3] MinhThuyen Chau, "Stable Self-Adjustment Control Method for Hybrid Active Power Filter," *International Journal of Applied Engineering Research*, vol. 12, pp. 7162-7168, 2017.

[4] Ibrahim Alhamrouni, et al., "Modeling of Micro-grid with the consideration of total harmonic distortion analysis," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS).* vol. 15, pp. 581-592, 2019.

[5] M. Chau, *et al.*, "Online control method with time-delay compensation for hybrid active power filter with Injection Circuit," *IET Power Electronics*, vol. 5, pp. 1472-1482, 2012.

[6] Minh Thuyen Chau, "Adaptive current control method for Hybrid Active Power Filter," *Journal of Electrical Engineering*, vol. 67, pp. 343-350, 2016.

[7] An Luo, *et al.*, "Development of Hybrid Active Power Filter Based on the Adaptive Fuzzy Dividing Frequency-Control Method," *IEEE Transactions on Power Delivery*, vol. 24, pp. 424-432, 2009.

[8] Z. Shuai, A. Luo, C. Tu, D. Liu, "New control method of injection-type hybrid active power filter," *IET Power Electronics*, vol. 4, pp. 1051-1057, 2011.

[9] Chau Minh Thuyen, "Improved p-q Harmonic Detection Method for Hybrid Active Power Filter," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 8, pp. 2910-2919, 2018.

[10] H. Akagi, *et al.*, "Generalized Theory of Instantaneous Reactive Power and Its Application," *Electrical Engineering of Japan*, vol.103, pp. 483-490, 1983.

[11] Y. K. Latha, *et al.*, "Control Strategy for Three Phase Shunt Active Power Filter with Minimum Current Measurements," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 1, pp. 31-42, 2011.

[12] Pankaj Gakhar and Manoj Gupta, "A novel control strategy for power quality improvement in grid-connected solar photovoltaic system," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 15, pp. 1264-1272, 2019.

[13] Chau Van Bao And Chau Minh Thuyen., "DC-Bus Voltage Stabilization of Hybrid Active Power Filter," *ICIC Express Letters*, vol. 13, no. 1, pp. 27-33, 2019.

[14] An Luo, *et al.*, "Design Considerations for Maintaining DC-Side Voltage of Hybrid Active Power Filter With Injection Circuit," *IEEE Transactions on Power Electronics*, vol. 24, pp. 75-84, 2009.

[15] C. C. M. Moura, *et al.*, "*Determination of the R-L-C parameters of a passive harmonic filter using genetic algorithm*," in 10th International Conference on Harmonics and Quality of Power, 2002, pp. 495-500.

[16] Suresh kumar, Ramesh reddy and Archana, "The application of pso to hybrid active power filter design for 3 phase 4-wire system with balanced & unbalanced loads," *International journal of advances in engineering & technology*, vol. 2, pp. 32-42, 2012.

[17] N. S. Hasan, *et al.*, "Harmonic Suppression of Shunt Hybrid Filter using LQR-PSO based," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 7, pp. 869-876, 2017.

[18] Shengqing Li, *et al.*, "*Multi objective optimal design for passive power filters in hybrid power filter system based on multi-island particle swarm optimization*," in 7th International Conference on Power Electronics and Motion Control, 2012, pp. 2859-2863.

[19] Suresh kumar and K. Ramesh, "The application PSO hybrid active power filter design for 3 phase 4-wire system with variable load," *International Journal of Engineering Inventions*, vol. 1, pp. 39-46, 2012.

[20] Nien-Che Yang and Minh-Duy Le, "Multi-objective bat algorithm with time-varying inertia weights for optimal design of passive power filters set," *IET Generation, Transmission & Distribution*, vol. 9, pp. 644-654, 2015.

[21] Rrachid Dehini and Slimane Sefiane, "Power quality and cost improvement by passive power filters synthesis using ant colony algorithm," *Journal of Theoretical and Applied Information Technology*, vol. 1, pp. 70-79, 2012.

[22] Ahmed Faheem Zobaa, "Optimal multi-objective design of hybrid active power filters considering a distorted environment," *IEEE Transactions on Industrial Electronics*, vol. 61, pp. 107-114, 2014.
[23] Berat Doğan, Tamer Ölmez, "A new metaheuristic for numerical function optimization: Vortex Search algorithm", *Information Sciences*,Volume 293, Pages 125-145, 2015.
[24] Doğan B, Ölmez T. "Modified Off-lattice AB Model for Protein Folding Problem Using the Vortex Search Algorithm," *International Journal of Machine Learning and Computing*. vol. 5, pp. 329-333, 2015.
[25] IEEE Std. 519-1992. *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, 1993.