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# A NEW APPROACH IN DESIGN FOR HYBRID ACTIVE POWER FILTER

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Abstract. *This paper proposes a new approach in the design of Hybrid Active Power Filter (HAPF). First, a stable analysis for HAPF was performed to find the stable domain of HAPF system. Then a multi-objective optimization method based on particle swarm optimization algorithm will be used to select a set of the best parameters in the stable domain and constraints that still satisfy the objective function. The process of finding the best set of parameters for HAPF was done by embedding between the multi-objective optimization algorithm and the HAPF model. This approach provides the optimal values of both the passive circuit and the active circuit of the HAPF. By comparing the performance of the HAPF model with traditional design, the HAPF model with new design has demonstrated superior advantages in reducing harmonics, minimum error compensation and maximum reactive power compensate into the system.*
**Keywords:** Hybrid active power filter, Multi-objective optimization, Harmonic filter, Particle swarm optimization

1. **Introduction.** Today, power quality has become one of the important criteria in power systems. The cause of poor power quality is due to an increasing number of nonlinear loads connected to the grid. In order to improve power quality, Active Power Filter (APF) is born, in which the Hybrid Active Power Filter (HAPF) is an improved form of APF [1-4].

Proper determination of HAPF parameters will directly affect the effectiveness of HAPF. At present, the parameters of the HAPF are often determined based on experience and locality, without scientific basis. Therefore, the achieved results may not be a satisfactory condition of stability system. Multi-objective optimization studies of HAPF can be summarized as follows. The application of genetic algorithm to multi-objective optimization design for Passive Power Filter (PPF) is proposed by [5-7]. Yang and Le have studied the multi-objective optimization design for passive power filters with variable time [8]. 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 not for the HAPF [9-13]. Another study to multi-objective design on HAPF is using an ant colony algorithm [14] but only also multi-objective optimization design for PPFs. Zobaa has used the Fortran feasible sequential quadratic programming algorithm to solve the multi-objective optimization problem for HAPF with the aim of finding passive power filter parameters [15].

In summary, the previous research on multi-objective optimization for HAPF was the only multi-objective optimization design of Passive Power Filters (PPFs). Meanwhile,

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the optimized design for the parameters of the Active Power Filter (APF) has not been studied.

To overcome this disadvantage, in this paper a stability analysis on the HAPF is done to find the stability of the HAPF system. Then a multi-objective optimization design based on particle swarm optimization is proposed to determine the best set of parameters for the HAPF. The proposed algorithm has the advantage of finding a quick solution with few loops. The results achieved will be global optimization such as the minimum error in steady-state, the minimum of the total harmonic distortion and satisfying the stable conditions.

The structure of the paper is divided into five parts. Part 1 presents an overview of the issues that need to be investigated. The stability analysis of the hybrid active power filter is presented in Part 2. Part 3 gives a multi-objective optimization design for hybrid active power filter. The simulation results are presented in Part 4, and the conclusions are presented in Part 5.

2. **Stable Analysis for Hybrid Active Power Filter.** The structure of HAPF is expressed as in Figure 1. $U_s$ 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, the transformer has ratio $n$:1 to protect, insulate between the source and the voltage source inverter. $L_0$, $C_0$ are the output filters of the voltage source inverter.

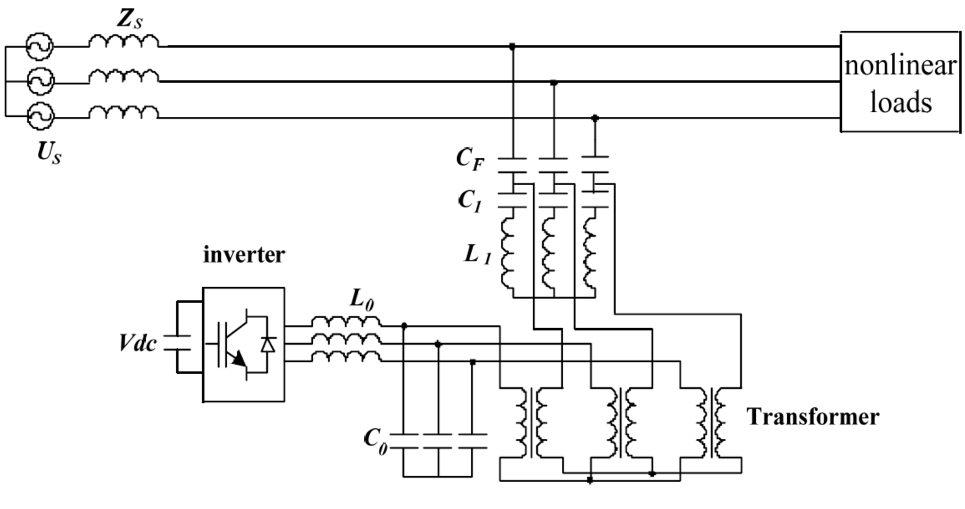


FIGURE 1. Topology of HAPF

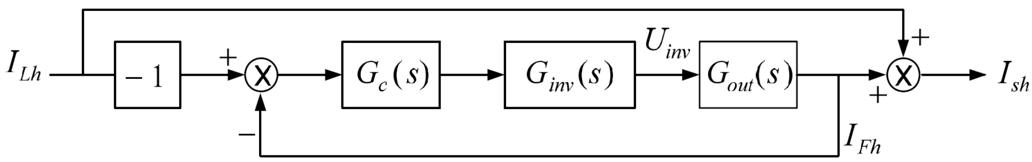


FIGURE 2. Control block diagram of HAPF

According to [1], the control block diagram of HAPF is shown in Figure 2.

In Figure 2, $G_{out}(s)$ is the transfer function of compensation harmonic current $I_{Fh}$ to inverter output voltage $U_{inv}$.

$$G_{out}(s) = \frac{I_{Fh}}{U_{inv}} = \frac{n \cdot Z_2}{Z_2(Z_1 + Z_s) + n^2 Z_{L_0}(Z_1 + Z_2 + Z_s)} \tag{1}$$

with $Z_s = R_s + L_s s$; $Z_1 = Z_{L_1}C_1//n^2 Z_{C_0}$; $Z_2 = \frac{1}{C_F s}$; $Z_{L_0} = R_0 + L_0 s$.

$G_c(s)$ is the transfer function of the traditional PI controller.

$$G_c(s) = K_p\left(1 + \frac{1}{T_i s}\right) \tag{2}$$

with $K_p$ and $T_i$ being proportional and integral coefficients.

The inverter can be treated as an inertia link, so its transfer function can be described based on experimental result [1] as follows:

$$G_{inv}(s) = \frac{K_{inv}}{T_{inv}s + 1} \tag{3}$$

where $K_{inv}$ is inverter gain, and $T_{inv}$ is time constant.

According to the diagram scheme of HAPF in Figure 2, the transfer function of load harmonic current $I_{Lh}$ to supply harmonic current $I_{sh}$ as:

$$G(s) = \frac{I_{sh}}{I_{Lh}} = \frac{1}{1 + G_c(s) \cdot G_{inv}(s) \cdot G_{out}(s)} \tag{4}$$

From (4), the characteristic function of the control transfer function is as follows:

$$D(s) = a_6 s^6 + a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s^1 + a_0 \tag{5}$$

where the coefficients from $a_0$ to $a_6$ are the coefficients of the characteristic Equation (5).

$$\begin{aligned}
a_6 &= L_0 C_F C_1^2 L_1^2; \quad a_5 = C_F L_1 C_1 (C_0 L_0 + C_1 L_0 + L_s L_0 + R_0 L_1 C_1) \\
a_4 &= L_0 L_1 C_F C_1 + L_0 C_F L_1 C_1 R_s + L_0 L_s C_0 C_F + L_0 L_s C_1 + R_0 C_1 L_1 C_0 \\
&\quad + R_0 C_F L_1 C_1 + R_0 L_s L_1 C_1 \\
a_3 &= L_s L_1 C_0 + R_0 C_F L_1 C_1 + R_0 C_F L_1 C_1 R_s + R_0 L_s C_0 C_F + R_0 L_s C_1 + L_0 C_F C_1 \\
&\quad + L_0 C_F R_s C_0 + L_0 R_s C_F C_1 + R_1 L_0 C_0 \\
a_2 &= R_s L_1 C_0 + L_s C_0 + L_s C_1 + L_1 C_1 + R_0 C_F C_1 + R_0 C_F R_s C_0 + R_0 R_s C_F C_1 \\
&\quad + R_0 L_1 C_0 + L_0 C_0 + L_0 C_1 \\
a_1 &= R_s (C_0 + C_1); \quad a_0 = 1
\end{aligned}$$

From (5), we can establish Routh table as in Table 1.

Table 1. Routh stable standard

| | | | | |
|---|---|---|---|---|
| $s^6$ | $a_6$ | $a_4$ | $a_2$ | $a_0$ |
| $s^5$ | $a_5$ | $a_3$ | $a_1$ | 0 |
| $s^4$ | $b_0$ | $b_2$ | $b_4$ | |
| $s^3$ | $b_1$ | $b_3$ | $b_5$ | |
| $s^2$ | $c_0$ | $c_2$ | $c_4$ | |
| $s^1$ | $c_1$ | $c_3$ | | |
| $s^0$ | $d_0$ | | | |

Therefore, in order that the system is stable, all elements in the first column must be positive. We have:

$$\begin{cases} a_5 a_4 - a_6 a_3 > 0 \\ b_0 a_3 - a_5 b_2 > 0 \\ b_1 b_2 - b_0 b_3 > 0 \\ c_0 b_3 - b_1 c_2 > 0 \\ c_1 c_2 - c_0 c_3 > 0 \end{cases} \tag{6}$$

with $b_0 = \dfrac{a_5a_4 - a_6a_3}{a_5}$; $b_2 = \dfrac{a_3a_2 - a_4a_1}{a_3}$; $b_1 = \dfrac{b_0a_3 - a_5b_2}{b_0}$; $b_3 = \dfrac{b_2a_1 - b_4a_3}{b_2}$; $b_4 = a_0$; $b_5 = 0$; $c_0 = \dfrac{b_1b_2 - b_0b_3}{b_1}$; $c_2 = \dfrac{b_3b_4 - b_2b_5}{b_3}$; $c_4 = 0$; $c_1 = \dfrac{c_0b_3 - b_1c_2}{c_0}$; $c_3 = 0$; $d_0 = c_2$.

## 3. Multi-Objective Optimization Design for Hybrid Active Power Filter.

**3.1. Constraints and objective function.** When designing an HAPF system, all of the following constraints need to be considered:
+ System stability constraints: For a stable HAPF system, condition (6) must be satisfied.
+ Constraints on resonance conditions in PPFs: The $L$ and $C$ parameters in a branch must resonate at a certain frequency.

$$\omega_n L = \frac{1}{\omega_n C} \tag{7}$$

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

$$0 < (R_i, L_i, C_i) \leq (R_{\max}, L_{\max}, C_{\max}) \tag{8}$$

The values of $R_{\max}$, $L_{\max}$ and $C_{\max}$ are determined under stable conditions (6).
+ PPFs must be compensated with a maximal capacity but not exceed the required maximum limit

$$Q_{b\min} \leq Q_{bi} \leq Q_{b\max} \tag{9}$$

+ Constraint of DC bus voltage value:

$$V_{ac} < V_{dc} < V_{dc\text{-}\max} \tag{10}$$

where $V_{ac}$ is the AC voltage amplitude at the output of the VSI.
+ Controller parameters constraints: Active circuit values must be positive and satisfy system stability conditions (6).

$$0 < K_p < K_{p\max} \qquad 0 < K_i < T_{i\max} \tag{11}$$

+ Objective function: Here we consider the two main objective functions as follows

$$\begin{cases} \min THDi_s \\ \min Error \end{cases} \tag{12}$$

**3.2. Application of particle swarm optimization for hybrid active power filter.** In order to design a hybrid active power filter system, a new multi-objective optimization algorithm based on Particle Swarm Optimization (PSO) is proposed in Figure 3.

At the beginning, we enter the upper and lower limits of the parameters $C_F$, $C_1$, $L_1$, $R_1$, $L_0$, $C_0$, $V_{dc}$, $K_p$ and $K_i$, and then the PSO algorithm begins by creating the initial populations $C_F$, $C_1$, $L_1$, $R_1$, $L_0$, $C_0$, $V_{dc}$, $K_p$ and $K_i$, and assigning them initial velocities. After that, checking the stability condition in Equation (6) is implemented, if satisfied, the algorithm evaluates the objective function at each particle location, and determines the lowest value and the best location. Based on the current velocity, the particles individual best locations, and the best locations of their neighbors, it chooses new velocities. It then iteratively updates the particle locations, velocities, and neighbors. Iterations proceed until the algorithm reaches a stopping criterion. If the stop is not satisfied, then the algorithm returns to step create new populations.

In Figure 3, $\varepsilon_1$ and $\varepsilon_2$ are small values given. According to IEEE Recommended Practices and Requirements for harmonic control in electrical power systems [16], then Total Harmonic Distortion (THD) of current is less than or equal to 5%. So, the value of $\varepsilon_1$ is selected as 0.03 (i.e., 3%). The value of error compensation $\varepsilon_2$ is selected as ±3A.

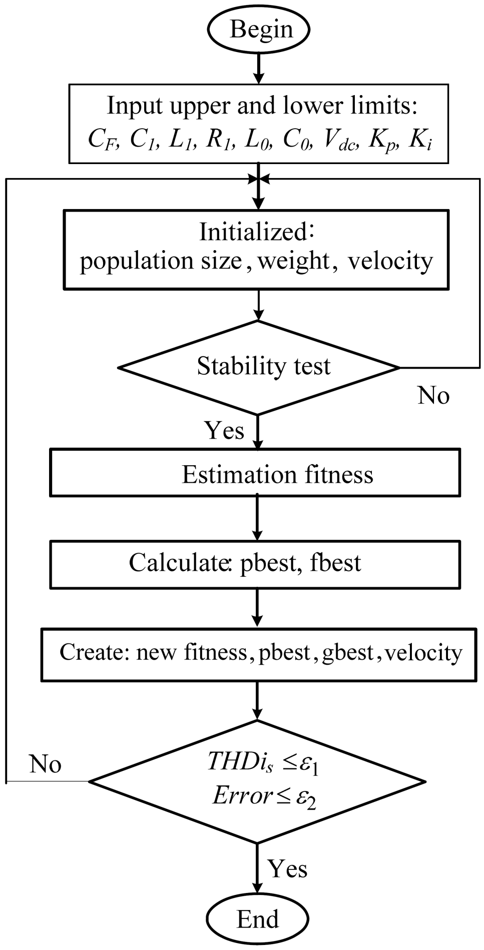


Figure 3. Flowchart of multi-objective optimization algorithm based on PSO for HAPF

4. **Simulation Results.** Let us consider an HAPF model as shown in Figure 1, The nonlinear load here is made by a three-phase uncontrolled bridge rectifier with load $R_L = 3\Omega$ in series with $L_L = 0.3$mH. Three-phase voltage is 380V-50Hz. According to [1,2], the parameters of the HAPF system with traditional design method are summarized in Table 2. In addition, the control parameters are randomly selected with the best parameters of $K_p = 100$ and $K_i = 0.1$, switching frequency $f = 10$kHz.

Table 2. HAPF parameters by traditional design method

| $C_F$ ($\mu$F) | $C_1$ ($\mu$F) | $L_1$ (mH) | $R_1$ ($\Omega$) | $L_0$ (mH) | $C_0$ ($\mu$F) | $V_{dc}$ (V) | $THDi_s$ % | Error (A) |
|---|---|---|---|---|---|---|---|---|
| 116.8 | 349.2 | 29.77 | 0.01 | 0.2 | 80 | 535 | 1.963 | $\pm 8$ |

The waveforms of HAPF in steady-state with the traditional design method are shown as in Figure 4. From Figure 4, we find that: THD of $i_s$ decreases from 32.13% to 1.963%. while the reactive power decreased to 1490Var from 4820Var, that is, the capacity compensated by PPFs is 3330Var. Error of compensation is reduced to $\pm 8$A from $\pm 100$A.

With switching frequency being 10kHz, the proposed design method, the process of finding the best set of parameters for HAPF was done by embedding between the multi-objective optimization algorithm based on PSO and the HAPF model. In HAPF model, we have the following parameters: $C_F$, $C_1$, $L_1$, $R_1$, $L_0$, $C_0$, $V_{dc}$, $K_p$ and $K_i$, corresponding to variables $f_1$, $f_2$, $f_3$, $f_4$, $f_5$, $f_6$, $f_7$, $f_8$ and $f_9$. In order to connect between the multi-objective optimization algorithm based on PSO and the model of HAPF system, the names of the variables, models, objective function, etc., must be the same. So when we

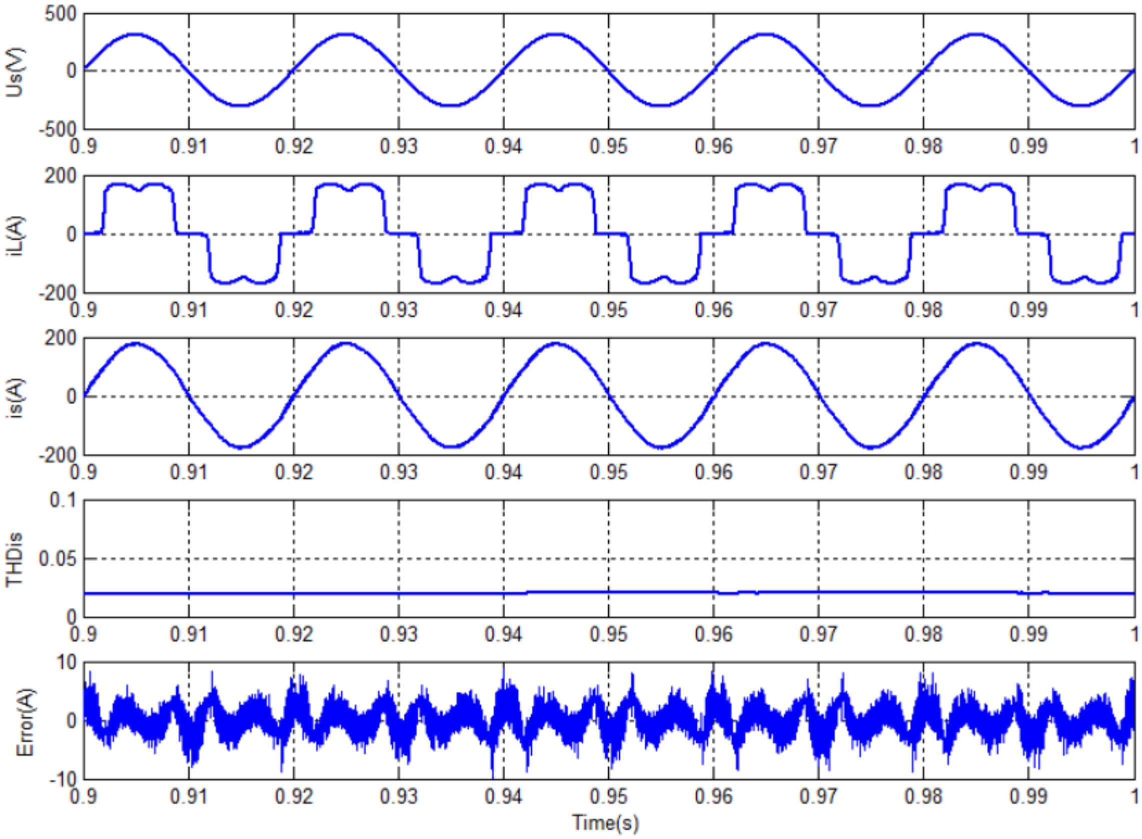


Figure 4. Waveforms of HAPF with traditional design

Table 3. HAPF parameters by multi-objective optimization method

| $f_1$ ($\mu$F) | $f_2$ ($\mu$F) | $f_3$ (mH) | $f_4$ ($\Omega$) | $f_5$ (mH) | $f_6$ ($\mu$F) | $f_7$ (V) | $f_8$ | $f_9$ | $THDi_s$ % | Error (A) |
|---|---|---|---|---|---|---|---|---|---|---|
| 170.32 | 382.3 | 25.92 | 0.035 | 1.31 | 60.2 | 687.2 | 59.9 | 0.86 | 0.93 | ±3 |

run algorithm it will automatically pull the HAPF model run at each iteration and the best results for each iteration will be saved and exported. Parameters with the proposed algorithm over 100 iterations are shown in Table 3.

The waveforms of HAPF in steady-state with the proposed design are shown as in Figure 5.

From Figure 5, we see that: THD of $i_s$ decreases from 32.13% to 0.93%, while the reactive power decreased to 780Var from 4820Var, so the compensation power by PPFs is 4040Var, the compensation error value is reduced to ±3A from ±100A.

From Figure 4 and Figure 5, we can see that: the proposed design is more efficient than traditional design in minimizing the $THDi_s$ and the error compensation in steady-state.

5. **Conclusions.** This paper presents a new approach in the design of HAPF. This approach allows us to determine all the parameters of both the passive circuit and the active circuit of the HAPF. The results are satisfying both optimally global and stability of the system. This research can be applied to design for all different types of HAPF. Furthermore, in the near future this method will be developed for the design of HAPF with different types of load, whereby the algorithm will online adjust the control coefficients. The research result has practical implications, which contribute to the improvement of the power quality in the electrical system.

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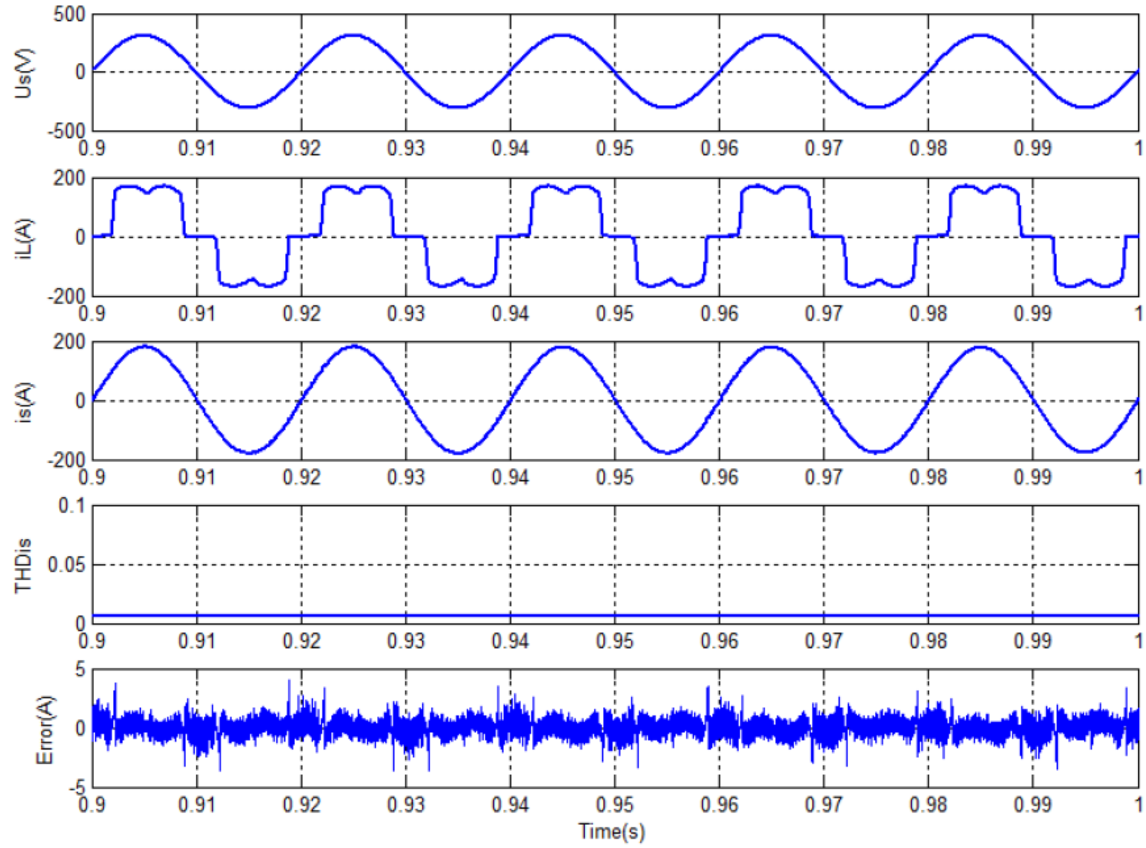


Figure 5. The waveforms of HAPF in steady-state with the proposed design

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