Optimal Design of Passive Power Filters Based on Pseudo-parallel Genetic Algorithm

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Abstract. The economic costs together with filter efficiency are taken as targets to optimize the parameter of passive filter. Furthermore, the method of combining pseudo-parallel genetic algorithm with adaptive genetic algorithm is adopted in this paper. In the early stages pseudo-parallel genetic algorithm is introduced to increase the population diversity, and adaptive genetic algorithm is used in the late stages to reduce the workload. At the same time, the migration rate of pseudo-parallel genetic algorithm is improved to change with population diversity adaptively. Simulation results show that the filter designed by the proposed method has better filtering effect with lower economic cost, and can be used in engineering.

1. Introduction

Due to low price, simple structure and reliable operation, passive filter is still widely used in electrical system, whose design requires comprehensive consideration of economic and technical and other factors. In the existing designs of filter, genetic algorithm is used to optimize the parameters of the filter in the literature [1], who has some disadvantages such as "premature" falling into local optimal solution. The simulated annealing optimization method used in [2] reduces the diversity of the individuals by making the feasibility of the constraints, so that the individuals with potential ability are eliminated prematurely, and too many parameters to choose lead to the filter configuration unreasonable.

The pseudo-parallel genetic algorithm [3] is introduced in this paper for the first time to realize the optimization of the filter parameters. In the early stage of evolution, the pseudo-parallel genetic algorithm (GA) is used to separate the three initial populations, and the population migration is carried out every algebra to increase the population diversity and improve the quality of the optimal solution. When the population evolved to a certain degree, the similarity of the three populations is high, and the adaptive genetic algorithm is implemented after merging into a population. In this paper, the mobility of the population is improved which changes with the diversity of the population, and improve the diversity of the population effectively. At the same time, with the decrease of population diversity, the population size gradually decreased [4].

2. Principles of genetic algorithm

2.1. Adaptive genetic algorithm[5]

2.1.1. Selection method - proportional fitness allocation. If an individual i, its fitness is f_i, then the probability of being selected is:

$$p_i = f_i / \sum_{i=1}^{M} f_i, \quad i = 1, 2, \cdots, M \tag{1}$$

When the probability of selection is given, a uniform random number of [0,1] interval is generated to determine which individual participates in the intersection.

2.1.2. Crossover and mutation methods.(1) Arithmetic crossover: Assuming that the two individuals cross-arithmetic, the cross-produced after the new individual is:

$$\begin{cases} X_A^{t+1} = \alpha X_B^t + (1-\alpha) X_A^t \\ X_B^{t+1} = \alpha X_A^t + (1-\alpha) X_B^t \end{cases} \tag{2}$$

Where: α is a random number within the range of (0, 1) consistent with the uniform probability distribution. X_A^t, X_B^t are two individuals to be exchanged for the t generation. X_A^{t+1}, X_B^{t+1} represents two new generation of t+1 generation.

(2) Uniform variation: An individual $X = x_1 \cdots x_k \cdots x_l$, if x_k is the point of variation, the value range is $[U_{min}^k, U_{max}^k]$, then the variation of x_k:

$$x_k' = U_{min}^k + \alpha(U_{max}^k - U_{min}^k) \tag{3}$$

(3) Adaptive crossover and mutation

Population crossover probability Pc and mutation probability Pm can change automatically with the fitness. When the population has a tendency to fall into the local optimal solution, the population increases Pc and Pm and decreases them when the population diverges in the solution space. For the minimum fitness of the passive filter, the fitness value is lower than the average fitness value of the population, which corresponds to the lower Pc and Pm and protects the solution to the next generation. The individuals above the mean fitness value correspond to the higher Pc and Pm, so that the solution is eliminated. And the selection formula is as follows:

$$P_c = \begin{cases} P_{c1} - \dfrac{P_{c1} - P_{c2}}{f_{avg} - f_{min}}(f_{avg} - f_0) & f_0 \leq f_{avg} \\ P_{c1} & f_0 > f_{avg} \end{cases} \tag{4}$$

$$P_m = \begin{cases} P_{m1} - \dfrac{P_{m1} - P_{m2}}{f_{avg} - f_{min}}(f_{avg} - f) & f \leq f_{avg} \\ P_{m1} & f > f_{avg} \end{cases} \tag{5}$$

Where: f_{avg} is the mean fitness value of each generation population; f_{min} is the fitness value of the smallest individual in the population; f_0 is the smaller fitness value of the two individuals to be crossed; and f is the fitness value of the individual of the mutation.

2.2. Pseudo-parallel genetic algorithm implementation

2.2.1. Crossover and mutation methods. In this paper, the spatial variance of individual fitness is used to measure the population diversity.

Assuming that the individual of the generation t is $x_t^1, x_t^2 \cdots x_t^N$ and the fitness of the individual is $f_t^1, f_t^2 \cdots f_t^N$. The average fitness of the individual is $\bar{f}_t = \frac{1}{N} \sum_{i=1}^{N} f_t^i$. The maximum fitness of the individual in the population is $f_{t,max} = \max\{f_t^i : i = 1, 2 \cdots N\}$ and the minimum fitness is $f_{t,min} = \min\{f_t^i : i = 1, 2 \cdots N\}$. The variance of the fitness is $D_t = \frac{1}{N} \sum_{i=1}^{N} (f_t^i - \bar{f}_t)^2$. The maximum fitness variance in the population from population evolution to generation t is $D_{max} = \max\{D_j : j = 1, 2 \cdots N\}$. Definition: $\Omega = D_t / D_{max}$, which can be used to characterize the diversity of the generation t population. The value of Ω is within the range [0,1] and the higher the diversity of the population, the greater the Ω.

2.2.2. Mobility selection. Pseudo-parallel genetic algorithm evolution process, the individual exchange between groups, used to increase the diversity of groups. In the prior art, the mobility (the number of individuals migrating in a population) is conventionally set to be constant.

In this paper, the number of individuals is adjusted according to population diversity and the individuals of the population are exchanged every 10 generations. Generally, if the diversity of the population is more than 90%, it is considered as a high diversity and the population need not be migrated . When the population diversity is less than 90%, the population migrates as described above. Mobility starts at 1 until not less than 90%, and migration terminates. However, mobility is not too large, so as to avoid the similarity of the two populations is too high.

2.3. An optimization method based on pseudo-parallel genetic algorithm and adaptive genetic algorithm

In this paper, the pseudo-parallel genetic algorithm and adaptive genetic algorithm are combined to optimize the filter parameters. In the early stage of evolution, the pseudo-parallel genetic algorithm is used to separate the three populations. After a certain period of time, the individuals are exchanged and the diversity of the population is enhanced. The disadvantages of the genetic algorithm and the local optimal solution are avoided. With the progress of evolution, the similarity of the three populations gradually increased, and the significance of population migration is not significant. In the later stage of evolution, the three populations are combined into one population to implement the adaptive genetic algorithm, which effectively reduces the workload.

In this paper, a pseudo-parallel genetic algorithm with variable scale is adopted. The population size at the beginning of the subpopulation is 40 individuals, which is gradually reduced to 30 individuals within 50 generations. The size of each sub-population is reduced by a number of individuals every 10 generations according to the following sequence:

$$\{1，2，3，4\}$$

3. Passive filter optimization

3.1. An optimization method based on pseudo-parallel genetic algorithm and adaptive genetic algorithm

Passive power filter is combined by the power capacitors, reactors and resistors. Filter devices are usually connected by a number of parallel passive filters, which exhibit a low resistance characteristic in the vicinity of a harmonic frequency or a certain frequency band to absorb the harmonic current, and reduce the harmonic current flowing into the AC system.

The commonly used passive power filters are single-tuned filter, dual-tuned filter and high-pass filter. The single-tuned filter is most widely used.

In the design of single tuned filter, the selection of parameter L C has a great influence on the filtering effect. According to the experience, the quality factor q of single tuned filter is generally 30 ~60. Because of the quality factor and the number of tuning, the inductance capacitance and resistance of the filter can be established and the quality factor of each filter circuit and the capacitance can be used as the optimization variables.

$$X = (C_1, C_2, C_3, C_4, q_1, q_2, q_3, q_4) \tag{6}$$

3.2. Optimization algorithm model

3.2.1. Mobility selection. Passive filter has two functions, to filter the harmonic and to provide reactive power compensation. With the constraints of reactive power compensation, safe operation and state variable constraints, the minimum harmonic distortion and the minimum economic input are taken as the optimization objectives. The optimized model is:

(1) The lowest investment cost:

$$\min F_1, \quad F_1 = \sum_{i=1}^{n}(k_1 R_i + k_2 L_i + k_3 C_i) \tag{7}$$

Where: k_1, k_2, k_3 is the unit price factor corresponding to the resistance, inductance and capacitance of the passive filter, n is the number of passive filters.

(2) After installing the filter, the harmonic content of the grid is lower than the national standard and the lower ,the better.[6]

$$F_2 = THD_U = (\sqrt{\sum_{h=2}^{H} U_h^2} / U_1) \tag{8}$$

It is not possible to obtain the optimal solution for the two independent objective functions at the same time. Therefore, it is necessary to coordinate these independent objective functions, so as to make the overall performance to achieve better.

In this paper, the method of proportional weighting is used to realize the coordination between multi-objective functions. Due to the various orders of magnitude are not uniform, so the first two indicators are normalized.

$$F_1^* = (F_1 - F_{1\min}) / (F_{1\max} - F_{1\min}) \tag{9}$$

$$F_2^* = (F_2 - F_{2\min}) / (F_{2\max} - F_{2\min}) \tag{10}$$

This limits the value of F_1^* F_2^* between (0,1). The overall objective function for weighting the two objective functions is:

$$F = \omega_1 F_1^* + \omega_2 F_2^* \tag{11}$$

ω_1 ω_2 are the weight of each target, which meet $\omega_1 + \omega_2 = 1$; $\omega_1 \geq 0$; $\omega_2 \geq 0$ and they value according to the importance of each sub-goal.

*3.2.2. Restrictions[7](*1) The reactive power compensation provided by the filter should make the power factor of the system as close as possible 1, but at the same time it can not appear the situation of reactive overcompensation, namely:

$$Q_{\min} \leq \sum_{i=1}^{n} Q_i \leq Q_{\max} \tag{12}$$

(2) State variable constraint

The state variable mainly refers to the voltage total harmonic distortion rate THD_U and each harmonic voltage content rate HRU .

$$HRU_h = (U_h / U_1) \times 100\% \leq c_{HRU} \tag{13}$$

$$THD_U = (\sqrt{\sum_{h=2}^{H} U_h^2} / U_1) \times 100\% \leq c_{THD_U} \tag{14}$$

Equations (13) and (14) are constrained by harmonic voltage content and total harmonic distortion, respectively and c_{HRU}, c_{THD_U} are the limiting value of the specified h harmonic voltage and the total harmonic distortion rate.

4. Example analysis

In the design of this paper, on the basis of satisfying all the constraints of the filter, the capacity and quality factor are optimized, and the better filtering effect is obtained under the condition of low economic cost. In the early stage of evolution, pseudo-parallel genetic algorithm is used to prevent premature generation. In the latter stage of evolution, adaptive genetic algorithm is used to reduce the computational load and find the optimal solution faster and better.

The load of a steel plant is mainly AC motor and DC motor. Most of the AC motors are controlled by AC-DC -AC inverter, and the DC motors are controlled by three phase fully controlled thyristor rectifier (including 6 pulse rectification and 12 pulse rectification). In the factory, there are 5, 7, 11

and 13 harmonics in the 10kV side of the 35kV substation. The 4 sets of single tuned filters are to be installed, which are 5, 7, 11, 13 Sub-single-tuned filter.

According to the data provided by the factory, the natural power factor $\cos\varphi_1 = 0.8$, the required compensation power factor $\cos\varphi_2$ is not less than 0.9, and it can not appear power over compensation, which is 0.95 in this paper. Active power mean value P = 12500 × 0.8 = 10000kW, and the reactive power Qc= 2657kvar ~ 4214kvar by calculating the required compensation of the fundamental $Q_c = P(\tan\varphi_1 - \tan\varphi_2)$. The minimum short-circuit capacity of system is 143MVA. The parameters of the capacitor and the inductance coil will vary during operation due to changes in ambient temperature, self-heating and aging of the capacitor insulation, and there may be errors during installation and commissioning so that the actual parameters and the corresponding resonance frequency deviation from its design value and it may cause the filter detuning. Considering all the factors above, the design of the resonant frequency is setted lower 3% than harmonic characteristic frequency.

In this paper, the combination of pseudo-parallel genetic algorithm and adaptive genetic algorithm is used to optimize the parameters of the filter （$\omega_1 = 0.4, \omega_2 = 0.6$） and the results are in Tab.1:

Table1. the optimization parameters of the filter

	$C(\mu F)$	$L(mH)$	$R(\Omega)$	q	$Q(kvar)$
4.85filter	56.74	7.6	0.2076	55.74	599.95
6.79filter	21.27	10.2	0.3929	55.61	222.45
10.67filter	19.75	4.5	0.2712	55.73	202.15
12.61filter	24.66	2.6	0.1813	55.93	251.78

In the table, L, C, R, q are the inductance, the capacitance, the resistance value (single-phase value) and the quality factor of the filter branch. Q is the reactive power (single phase) compensated for the filter branch.

After the filter is putted into operation, the main harmonic current of 5 times, 7 times, 11 times and 13 times has good filtering effect, and the harmonic voltage distortion rate after filtering meets the national standard (odd voltage limit is 3.2% and even voltage limit is 1.6%). The total harmonic voltage distortion rate reduce from 9.59% to 1.75%. The total reactive power compensation can be 3828.9kvar, and the power factor is 0.938.The effect of harmonic filtering is showed in Tab.2.

Table 2. The table of harmonic filtering effect

	5	7	11	13	17
Prefilter system current	87.5	34.3	37.5	24.9	12.9
System allowable current	28.6	21.4	13.3	11.3	8.58
Filtered system current	16.8	7.92	5.25	1.45	2.99
i	5.29	2.91	4.98	3.91	2.66
Filtered HRU(%)	1.02	0.68	0.7	0.23	0.62

Table 3. Table of filter parameters

	$C(\mu F)$	$L(mH)$	$R(\Omega)$	q
4.85filter	50.75	8.5	0.5176	25
6.79filter	19.98	11	0.939	25
10.67filter	21.7	4.1	0.55	25
12.61filter	32.74	1.9	0.31	25

According to the initial investment objective function formula $F_i = \sum_{i=1}^{n}(k_1 R_i + k_2 L_i + k_3 C_i)$, and the value of each price factor is provided by the actual project. The value of k_2, k_3 in this paper is k2=320yuan/ mH, k3=320yuan/ mH.

According to the traditional method to design the filter (the same capacity, according to the size of the harmonic current to determine the size of each branch filter), the parameters are as Tab.3.

After filtering, the harmonic voltage distortion rate is 1.96%, in line with the national standards. The harmonic currents of the injection system are 21.49A, 10.07A, 5.69A, 1.29A, 2.6A for the 5,7,11,13,17 harmonic currents respectively. In this paper, the filter parameters are optimized through the combination of pseudo-parallel genetic algorithm and genetic algorithm, considering the economic cost and filter efficiency, and the filtering effect is ideal.

Filter design is a typical multi-objective optimization problem. The method of proportionality is used to achieve the goal of coordination in this paper. The different weights have certain influence on the optimization results. Based on the filter effect and economic costs and other factors of different considerations, type (11) in the selection of the weights are different and the effect is shown in Figure 1.
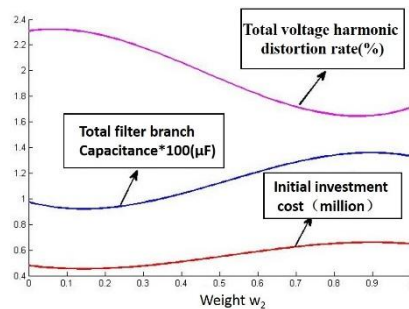
Figure 1. Comparison chart with different weights
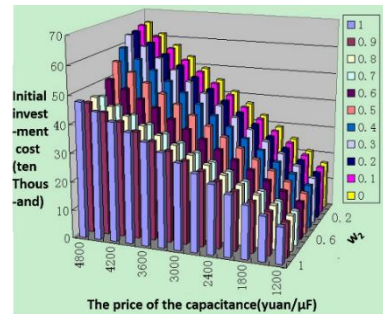
Figure 2. The investment cost when considering the weight and capacitance price

In the actual project, the investment of the filter capacitor may change to a certain extent. The initial investment of the filter is given in the Fig.2 when the price of the capacitor changes and the weight changes for practical engineering reference.

5. Conclusion

Passive filter design is a multi-constrained, non-linear mixed-type planning problem. In this paper, the pseudo-parallel genetic algorithm is used to optimize the parameters of the filter, taking the economic input, the benefit of the filter and the reactive power compensation. This method enhances the diversity of population and can find the optimal parameters of the filter faster. At the same time, the mobility of pseudo-parallel GA is improved to adaptively change with the diversity of population, so as to prevent the blind migration in the evolution process leading to the decline of population diversity. Considering the difference between the investment and the technical performance of the actual project, this paper gives the corresponding optimal design of the filter, which can provide reference for the selection of the filter parameters in practical engineering.

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