HARMONIC FILTERS PLANNING OF TRACTION SYSTEM IN TAIWAN HIGH SPEED RAIL

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Abstract - This paper presents a method for combining hybrid differential evolution and orthogonal arrays (HDEOA) in the planning of harmonic filters for the traction system of a distributed generation (DG) system with specially connected transformers in unbalanced three-phase power systems. The objective is to minimize total demand distortion of harmonic currents and total harmonic distortion of voltages. An orthogonal array is first conducted to obtain the initial solution set; the set is then treated as the initial sample. Next, the HDEOA method parameters are determined by using matrix experiments with an orthogonal array, in which a minimal number of experiments have an effect that approximates the full factorial experiments. This HDEOA method is then applied to design optimal harmonic filters in a traction system, where both rectifiers and inverters with IGBT are used. From the results of the illustrative examples, the feasibility of the HDEOA to design an optimal passive harmonic filter of traction system is verified and the design approach can greatly reduce the harmonic distortion. Three design cases are compared that V-V connection suppressing the 3rd order harmonic and Le Blanc for the harmonic improvement is superior to those of the V-V and Scott connection.

Keywords - Power system harmonic, harmonic filter, hybrid differential evolution, power quality, specially connected transformers.

I. INTRODUCTION

The harmonic distortion is one of indexes of power quality for power systems [1, 2]. It is because large nonlinear loads have been used. The nonlinear characteristics introduce harmonic currents [3]. The IEEE Standard 519-1992 provides a solution for the limitation and mitigation of harmonics [4]. Both passive and active filters can be used to reduce harmonic currents. While passive filters provide low impedance paths to absorb harmonic currents, active filters give countervail harmonic components to purify load currents [5-7]. However, passive filters are usually a better choice for customers considering cost. The capacitors of passive filters also provide reactive power compensation to improve power factor. Some special electrical systems usually require strong single-phase power sources to reduce the voltage unbalance disturbances of the three-phase sources. Therefore some specially connected transformers are used, such as V-V, Scott, and Le Blanc connection schemes. These have been employed in the railway electrification systems. The power quality issues in railway electrification systems today include the studies on the influence of traction loads on three-phase utility systems. For example, simplified models of specially connected transformers have been given in three-phase power flow studies [8]. A network model was proposed for investigating unbalance effects [9]. Voltage regulation of railway systems was improved by using Thyristor switched capacitor [10]. In recent years, many researches have appeared in literature involving optimal planning. For example, an advanced computer code technique was used for single-tuned harmonic filter design [11]. The genetic algorithms have also been applied to locating and sizing of passive filters [12]. The optimal design of passive harmonic filters planning was investigated by using the method of HDE, which is a direct and parallel search method that involves accelerating and migrant operations to prevent falling into local optimal solutions [13, 14].In this paper, the optimal planning of a power system with specially connected transformers is studied. The HDE approach is used to determine the parameter values of the passive harmonic filters under abundant harmonic currents. Since the specially connected transformer gives unbalanced characteristics, the harmonic distortion in each phase is different. So the harmonic filter in each phase is also different. The computation results show that the HDE is a good method for filter design to mitigate harmonic distortions of the system with specially connected transformer.

II. HARMONIC FILTER AND OPTIMAL DESIGN

The passive harmonic filters are installed on the 69kV side of the specially connected transformer to improve the harmonic distortion, as shown in Fig. 1.
For the singled-tuned filter, the tuned-point h_0 is

$$h_0 = \frac{1}{2\pi f_b \sqrt{LC}} \qquad (1)$$

For the high-pass and C-type filters, the tuned point h_0 and m are defined

$$h_0 = \frac{1}{2\pi f_b CR} \qquad (2)$$

$$m = \frac{L}{R^2 C} \qquad (3)$$

where f_b: fundamental frequency

h_0: characteristic harmonic order

m : damping time constant ratio

Harmonic filter planning can be formulated as a combinatorial optimization problem as

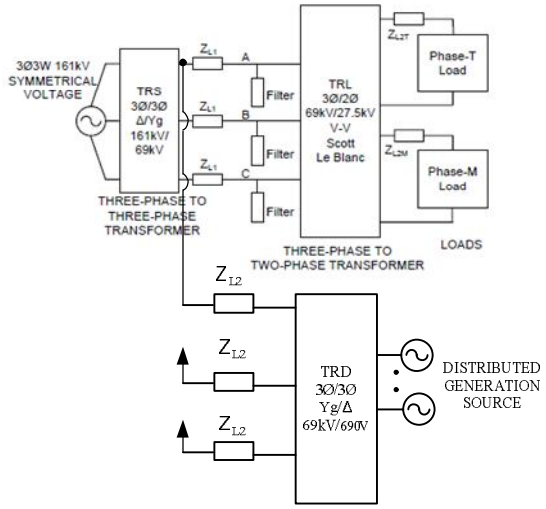


Fig. 1Power system with specially connected transformers.

2.1Objective Function

$$M = \sum_{i=A}^{C} a_i \times I_{TDD-i} + \sum_{i=A}^{C} b_i \times V_{THD-i} + c \times P_F \quad (4)$$

where P_F is the total filter loss.

2.1 Constraints

(1) Harmonic Limitation

The harmonic distortions must follow the IEEE Standard 519.

(2) Reactive Power Compensation

The reactive power of each filter must be limited.

$$Q_{Fj}^{\max} > Q_{Fj} > Q_{Fj}^{\min} \quad (5)$$

where Q_{Fj}^{min} and Q_{Fj}^{max} are the lower and upper limits of reactive power. The totalreactive power compensation at bus A with m filter banks should be

$$Q_F^A = \sum_{j=1}^{m} Q_{Fj}^A \quad (6)$$

2.2 Restrictions on tuning point, characteristic harmonic order and damping time constant ratio

The impedance of all filters must be inductive with respect to the harmonic to be filtered to prevent harmonic amplification.

- For the single-tuned filters

$$ah^* \le h_0 \le bh^* \quad (7)$$

where h^* is the order of harmonic to be filtered.

- For the high-pass filters

$$1 < h_0 \le h^* \sqrt{m - m^2}\ ,\ 0 < m < 1 \quad (8)$$

- For the C-type filters

$$h_0 < \frac{1}{h^*}\sqrt{m(h^{*2}-1)[h^{*2}-m(h^{*2}-1)]}\ \ 0 < m < \frac{h^{*2}}{h^{*2}-1} \quad (9)$$

III. PLANNING RESULTS

The requirement is to improve the power factor of each phase with specially connected transformer to unity. The power and power factor with and without harmonic filters on the 69kV side of the specially connected transformer are shown in Fig. 1 and give the design values of filter parameters of VV, Scott, and Le Blanc scheme, respectively. Three different type filter schemes of per phase with specially connected transformers are compared.

Table 1 indicates the planning results of objective functions and filter losses using the HDEOA approach, where three filter schemes of three transformer schemes are compared. In addition, Table 2, Table 3, and Table 4 also show the comparison of harmonic current distortions each phase of the 69kV side of VV, Scott, and Le Blanc, respectively. It is noted that the harmonic distortion values are greater than the limitation values without the harmonic filter. Table 1 first shows the computation results. From this table, it is obvious that the objective function of the Le Blanc at Case 3 has the smallest objective function. Then, all R, L, C, h_o and m are given in Table 4. Considering the single-tuned filters, high-pass filter and C-type damped filter cost are 36.8×10^4 , 42.52×10^4 and 47.6×10^4 per type, respectively. Finally, three cases are compared with the harmonic currents at MOF as follows.

(1)Case 1: At phase A, the 3rd C-type, 5th and 7th single-tuned filters are used to absorb low-order harmonic currents. At phase B, 3rd and 5th single-tuned filters are installed for suppressing third-order and fifth-order harmonic currents. In addition, the harmonic source at phase B is full of low-order harmonic currents in Scott connection, so that a second 3rd C-type damped filter is necessary. The 7th high-pass filter is used for the 5th, 7th and 9th harmonic currents. The 5th harmonic voltage at phase B in Le Blanc connection is decreased to 0.17% as shown in Table 8. In addition, the 3rd harmonic current flowing into the system at phase B in Scott connection is decreased to 0.12% in Case 1. This Case has a lower cost in Table 4 and therefore capable of improving harmonic distortion and compensating fundamental reactive power.

(2) Case 2: Although Case 1 is enough to satisfy the harmonic limits, it gives higher filter power loss. In Case 2, the low-order and high-order harmonic currents should be filtered when the 3rd and 7th single-tuned, 5th C-type filters are installed at phase B. Table 2 shows that distortions of the 3rd, 5th, and 7th harmonics are 0.17%, 0.02%, and 0.09% at phase B in Scott connection, respectively. In addition, Table 2 also shows that the harmonic current distortions of the 9th, 11th, and 13th are 0.01%, 0.01%, and 0.02%, respectively. Hence, the

individual current harmonics and the total voltage harmonic distortion at each phase are satisfied. It is note that Case 2 has a lower filter loss. Although the limits of harmonic are satisfied, the 7th harmonic current is raised to 0.09% and TDDi is 0.2% at phase

B. It is should be load imbalance caused by the passing of the traction system.

(3) Case 3: Although Case 1 and Case 2 have a higher objective function and filter loss, the filter scheme will increases the installation cost. Hence, Case 3 presents a different type of filters. Table 3 shows that all individual harmonic current distortions slightly increase but still satisfy the limits. About Le Blanc connection, the 3rd, 5th, and 7th harmonic currents at MOF increase to 0.089%, 0.032%, and 0.026% at phase B, respectively. Note that the 11th harmonics current increases to 0.16%. Although the limits of harmonic are satisfied, the filter loss is reduced to 5.13 kW. Hence, Case 3 may not be a perfect candidate for Le Blanc. In addition, the Case 3 has a higher cost in Table 4 for Scott has the smallest TDDi is 0.13% at phase B in Table 3 and objective function is 0.0943% in Table 1, Hence, Case 3 may be a perfect candidate. Fig. 2 also shows the 5th to 7th harmonic distortion are higher than other harmonic orders at phase B with VV connected transformer. It is should be load imbalance caused by the passing of the traction system. Finally, a one-line diagram of the Le Blanc connected transformer with Case 3 for railway's electrification system is also given in Fig. 12. Fig. 4 gives the convergence of objective function of three Cases in VV connection scheme with respect to number of generation. Because migrant and accelerated operations are embedded in the HDEOA, a global optimum and faster convergence are achieved. There is no harmonic amplification problem caused by parallel resonance. It indicates that Case 3 is faster than Case 2 and Case 1. The objective function obtained by GA is higher.

CONCLUSIONS

A comprehensive passive filter planning method has been presented. Three filter cases are compared for the power system with V-V, Scott and Le Blanc connected transformers. The study results satisfy the harmonic limitation and improve the power factor. The sizes and parameter values of single-tuned, C-type, and high-pass filters are determined. The migrant and accelerated operations embedded in HDE are used to verify the global optimal solution and consume less time. Since the specially connected transformer has unbalanced characteristic, the harmonic distortion in each phase is different.

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Table 1Objective functions and filter loss

		Without filter	With filter		
			Case 1	Case 2	Case 3
Number of filters		0	Sight-turned: 6 Damped filter: 3	Sight-turned: 6 Damped filter: 3	Sight-turned: 3 Damped filter: 6
VV	objective function (pu)	0.5861	0.1879	0.1351	0.1168
	Filter loss(W)	-	25.88	24.99	2.55
Scott	objective function (pu)	0.5121	0.1411	0.1354	0.0951
	Filter loss(W)	-	51.89	14.61	4.23
Le Blanc	objective function (pu)	0.5120	0.1444	0.1377	0.0943
	Filter loss(kW)	-	44.37	18.33	5.13

Table2Comparison of harmonic currents at phase B of 69kV side of Scott connected transformer

Harmonic orders	Harmonic distortion (%)				Limitation (%)
	Without filter	With filters			
		Case 1	Case 2	Case 3	
3	10.33	0.12	0.17	0.093	3.5
5	6.40	0.17	0.02	0.038	3.5
7	3.04	0.08	0.09	0.033	3.5
9	0.85	0.04	0.01	0.014	3.5
11	0.82	0.05	0.01	0.021	1.75
13	0.51	0.04	0.02	0.018	1.75
15	0.25	0.03	0.02	0.011	1.75
17	0.18	0.02	0.02	0.010	1.25
19	0.15	0.02	0.01	0.010	1.25
TDDi(%)	13.84	0.25	0.2	0.12	6.89

Table3Comparison of harmonic currents at phase B of 69kV side of Le Blanc connected transformer

Harmonic orders	Harmonic distortion (%)				Limitation (%)
	Without filter	With filters			
		Case 1	Case 2	Case 3	
3	10.25	0.12	0.17	0.089	3.5
5	6.48	0.17	0.02	0.032	3.5
7	2.97	0.08	0.09	0.026	3.5
9	0.88	0.04	0.01	0.012	3.5
11	0.79	0.05	0.01	0.016	1.75
13	0.53	0.04	0.02	0.015	1.75
15	0.25	0.03	0.02	0.009	1.75
17	0.21	0.03	0.02	0.009	1.25
19	0.15	0.03	0.01	0.009	1.25
TDDi(%)	13.78	0.26	0.20	0.13	6.89

Table 4Design of filter parameters of Le Blanc connected scheme

Cases	Element	Filter type	R (Ω)	L (mH)	C (uF)	C_1 (uF)	Q_f (MVA)	Cost ($\times 10^4$ dollars)	CPU time (sec)	Parameters	
										h_0	m
Case 1	Phase A	3rd C-type	660.2	54.8	1.38	128.5	2.478	297	0.16	2.91	0.091
		5th single-tuned	-	509.3	0.59	-	1.101			4.85	-
		7th single-tuned	-	246.7	0.62	-	1.135			6.79	-
	Phase B	3rd single-tuned	-	1910.8	0.43	-	0.885			2.91	-
		5th single-tuned	-	1050	0.28	-	0.534			4.85	-
		7th high-pass	245.2	479	1.59	-	2.8591			6.79	0.005
	Phase C	3rd C-type	737	61.1	1.24	115.1	2.22			2.91	0.091
		5th single-tuned	-	618.9	0.48	-	0.906			4.85	-
		7th single-tuned	-	243.9	0.63	-	1.1481			6.79	-
Case 2	Phase A	3rd single-tuned	-	695.9	1.19	-	2.43	535	0.14	2.91	-
		5th C-type	631.7	31.4	0.87	223.8	1.554			4.85	0.091
		7th single-tuned	-	383.6	0.40	-	0.73			6.79	-
	Phase B	3rd single-tuned	-	757.6	1.10	-	2.232			2.91	-
		5th C-type	693.3	34.5	0.79	203.9	1.416			4.85	0.091
		7th single-tuned	-	444.4	0.34	-	0.6301			6.79	-
	Phase C	3rd single-tuned	-	787.3	1.06	-	2.148			2.91	-
		5th C-type	699.2	34.8	0.78	202.2	1.404			4.85	0.091
		7th single-tuned	-	387.8	0.39	-	0.7221			6.79	-
Case 3	Phase A	3rd single-tuned	-	1878.9	0.44	-	0.9	558	0.13	2.91	-
		5th C-type	1319.4	65.7	0.41	107.2	0.744			4.85	0.091
		7th high-pass	145.3	0.18	1.71	-	3.07			10.67	0.005
	Phase B	3rd single-tuned	-	1910.8	0.43	-	0.885			2.91	-
		5th C-type	1704.3	8.5	0.32	829.5	0.576			4.85	0.0091
		7th high-pass	174.2	0.24	1.57	-	2.8171			9.7	0.005
	Phase C	3rd single-tuned	-	1904.3	0.44	-	0.888			2.91	-
		5th C-type	1759.2	87.6	0.31	80.4	0.558			4.85	0.091
		7th high-pass	192.8	0.29	1.58	-	2.8281			8.73	0.005

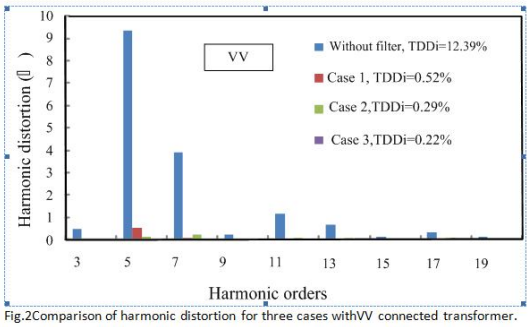


Fig.2Comparison of harmonic distortion for three cases withVV connected transformer.

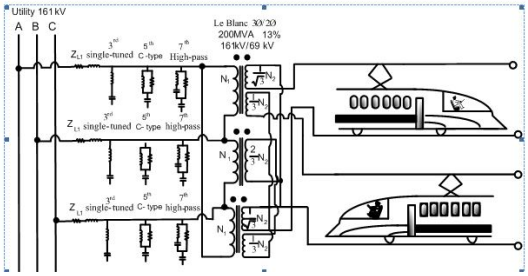


Fig.3One-line diagram of the Le Blanc connected transformer with Case 3 for railway's electrification system.

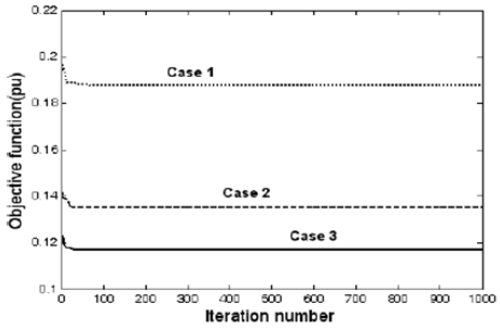


Fig. 4.Convergence of objective function of three cases of VV connection with respect to number of generation.

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