Harmonic Filters Design of a Power System with Specially Connected Transformers Using Hybrid Differential Evolution Method

Yao-Hung Chan and Chi-Jui Wu

Abstract — This paper is used to investigate the harmonic filters planning of a power system with three-phase to two-phase specially connected transformers. The hybrid differential evolution (HDE) method is used to obtain the filter parameter values. The migrant and accelerating operations embedded in HDE are used to overcome the traps of local optimal solutions and problems of time consumption. The design purposes are to minimize the total demand distortion of harmonic currents and total harmonic distortion of voltages. The reactive power compensation and constraints of individual harmonics are also considered. Three design cases are compared to demonstrate the design results. The study results shows that the scheme type of three-phase to two-phase specially connected transformers have significant effects on the harmonic distribution. The design approach can greatly reduce the harmonic distortion.

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 of a power system [1-6]. It is because large nonlinear loads have been used. The IEEE Standard 519-1992 provides a solution for the limitation and mitigation of harmonics [7]. 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 [8-10]. 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 [11]. A network model was proposed for investigating unbalance effects [12]. Voltage regulation of railway systems was improved by using Thyristor switched capacitor [13].

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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 [14]. The genetic algorithms have also been applied to locating and sizing of passive filters [15]. 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 [16-19]. The HDE has been applied to the optimal control problems of a bioprocess system [20], parameter estimation of the recombinant fermentation process [21], plant scheduling and planning evolution with multiplier updating [22], and evolutionary algorithms for mixed-integer nonlinear optimization problems [23]. The important alternative to multi-objective optimization is not to obtain the best solution, but to derive a good compromise solution [24].

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. Specially Connected Transformer Scheme

There are three schemes of specially connection transformer, which are the V-V, Scott, and Le Blanc. Let $k_1 = \frac{N_1}{N_2}$ and $k_2 = \frac{N_2}{N_1}$ denote the turn ratios of each phase.

The V-V connection scheme is composed of two single-phase transformers. The transformer uses three-phase power on the primary side, and supplies two single-phase loads on the secondary side. Fig. 1 shows the circuit diagram of the V-V connected transformer.

Fig. 2 shows the circuit diagram of the Scott connected transformer. It also transforms three-phase power to two-phase power. The main Transform (phase M) has a middle-tapped winding on its primary side, and a single winding on its secondary side. The teaser transformer (phase T) is a single-phase transformer.

The connection scheme of the Le Blanc transformer is shown in Fig. 3. The primary windings are the same as those of a common three-phase transformer in delta connection. The secondary side consists of five windings, which are separated into two phases.

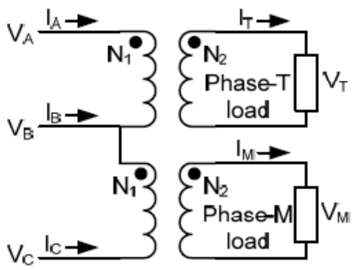

Figure 1. V-V connection scheme.

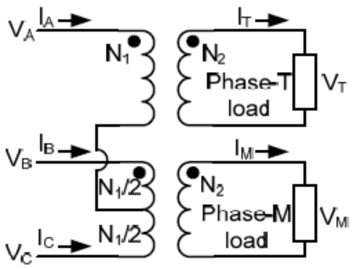

Figure 2. Scott connection scheme.

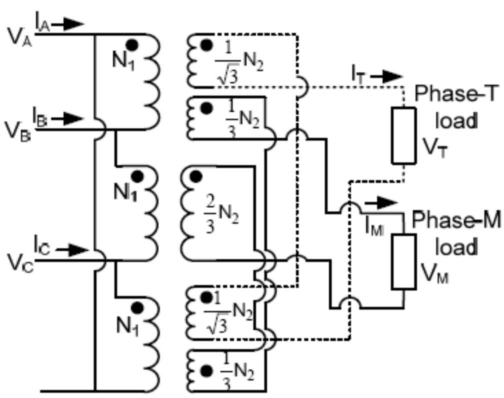

Figure 3. Le Blanc connection scheme.

III. Harmonic Distortion and Simulation

The distorted waveform in a circuit under non-sinusoidal condition is given by

$$a(t)=\sqrt{2}\left[\sum_{h=1}^{\infty} A_h \sin(2\pi f_h+\theta_h)\right] \tag{1}$$

where a(t)：instantaneous voltage or current

A_h：RMS value of the hth order harmonic

f_h：frequency of the hth order harmonic

θ_h：angle of the hth order harmonic

Then, the harmonic distortion and total harmonic distortion is given by

$$HD(\%)=\frac{A_h}{A_1}\times 100\% \tag{2}$$

$$THD(\%)=\frac{\sqrt{\sum_{h=2}^{\infty} A_h^2}}{A_1}\times 100\% \tag{3}$$

If A_1 in (2) is given the demand current, it is called the total demand distortion (TDD).

Figure 4 reveals a power system with a three-phase to two-phase, 69/27.5-kV specially connected transformer. The system data is given in TABLE I. The utility source is a balanced three-phase Y connection 161-kV power system. The nonlinear loads in phase T and phase M cause harmonic distortion on the 69-kV level.

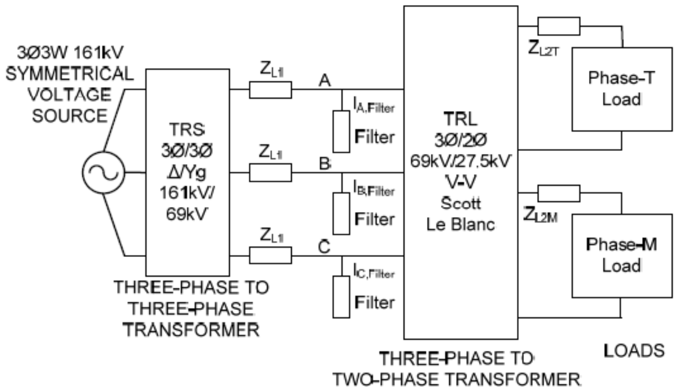

Figure 4. Power system with specially connected transformers.

The harmonic simulation procedures are as follows.

(1) The utility side is a symmetrical three-phase 161-kV voltage source.

(2) The three-phase to two-phase transformer is constructed by using corresponding windings with adequate turn ratios.

(3) The linear loads on the two-phase side are composed of parallel RLC load, which consists of active and reactive powers.

(4) The nonlinear loads on the two-phase side are composed of power electrical equipments, which convert single-phase power into three-phase power by using PWM inverter structure, as shown in Figure 5.

(5) The fundamental and harmonic components of the voltages and currents can be obtained by using the FFT calculation.

TABLE II gives the harmonic distortion results on the phase T and phase M of the specially connected transformer. Although the loading conditions are the same, the harmonic distortion results are different. TABLE III shows the harmonic distortion results on the 69-kV side of the specially connected transformer. It can be found that the transformer connection scheme has significant effect on the harmonic distribution. It is caused by the unbalanced characteristics of the specially connected transformer.

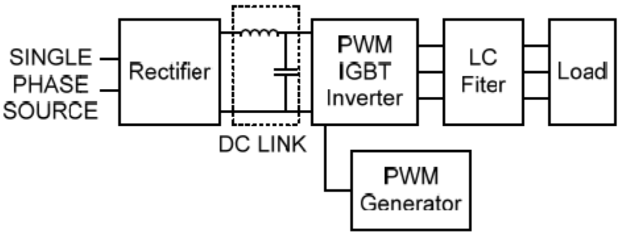

Figure 5. Nonlinear loads.

TABLE I
SYSTEM DATA

Utility Power Source	Three-phase balanced, 161kV, Y connected, X/R=33.25, MVA_{sc}=10935MVA.	
Transformer	TRS：3Φ/3Φ, 161/69-kV, 200-MVA, X_{TRS}=13%, X/R=40, △/Y-g connected, Z_{g1}= 20Ω.	
	TRL：3Φ/2Φ, 69/27.5-kV, 30-MVA, X_{TRL} =10%, X/R=10, V-V,.	
Line	Z_{L1}=1.1869+j3.9108 Ω	
	Z_{L2T}= Z_{L2M}=0.97+j2.55 Ω	
Load	Phase T linear load: 7.5MW+j7MVAR Phased T nonlinear load: 2.5MW+j1.2MVAR	
	Phase M linear load: 7.5MW+j6MVAR Phase M nonlinear load: 1.75MW+j1.05MVAR	
Base Value	30 MVA, rated voltages	

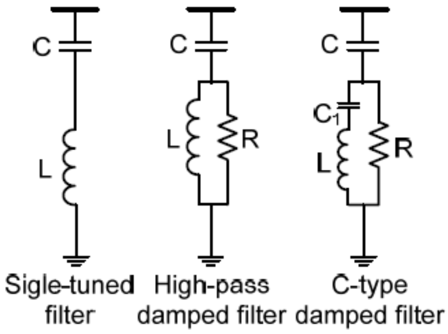

Figure 6. Typical passive filters.

IV HARMONIC FILTER AND OPTIMAL DESIGN

The passive harmonic filters are installed on the 69-kV side of the specially connected transformer to improve the harmonic distortion, as shown in Figure 4. Fig. 6 shows three typical passive filters [25]. The single-tuned filter is used widely, and it also gives reactive power to improve the power factor. The damped filter has low impedance values at high frequencies. In other words, it has better harmonic filtering performance at higher frequencies.

For the singled-tuned filter, the tuned-point h_0 is

$$h_0 = \frac{1}{2\pi f_b \sqrt{LC}} \tag{4}$$

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

$$h_0 = \frac{1}{2\pi f_b CR} \tag{5}$$

$$m = \frac{L}{R^2 C} \tag{6}$$

where f_b : fundamental frequency

h_0 : characteristic harmonic order

m : damping time constant ratio

The optimal design by using the HDE [16-19] approach is used to determine the parameters of the harmonic filters.

A. Objective Function

$$M = \sum_{i=A}^{C} a_i \times I_{TDD-i} + \sum_{i=A}^{C} b_i \times V_{THD-i} + c \times P_F \tag{7}$$

where P_F is the total filter loss.

B. Constraints

(1) Harmonic Limitation

The harmonic distortions must follow the IEEE Standard 519 [2].

(2) Reactive Power Compensation

The reactive power of each filter must be limited.

$$Q_{Fj}^{\max} > Q_{Fj} > Q_{Fj}^{\min} \tag{8}$$

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

$$Q_F^A = \sum_{j=1}^{m} Q_{Fj}^A \tag{9}$$

(3) 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

$$ah^* \le h_0 \le bh^* \tag{10}$$

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

For the high-pass filters

$$1 < h_0 \le h^* \sqrt{m - m^2}\ , \quad 0 < m < 1 \tag{11}$$

For the C-type filters

$$h_0 < \frac{1}{h^*} \sqrt{m(h^{*2} - 1)[h^{*2} - m(h^{*2} - 1)]}\ , 0 < m < \frac{h^{*2}}{h^{*2} - 1} \tag{12}$$

TABLE II
HARMONIC CURRENT DATA ON PHASE T AND M

		Harmonic distortion (%)									TDD
Order		3	5	7	9	11	13	15	17	19	
VV	phase T	13.85	7.99	3.57	1.19	0.96	0.61	0.30	0.26	0.14	18.07
	phase M	14.05	8.96	3.79	1.31	1.09	0.72	0.35	0.30	0.21	19.01
Scott	phase T	13.76	8.54	3.72	1.13	1.01	0.66	0.24	0.24	0.13	18.24
	phase M	14.08	8.99	4.16	1.33	1.05	0.78	0.33	0.29	0.21	19.07
Le Blanc	phase T	14.08	8.84	3.95	1.29	1.14	0.79	0.36	0.33	0.23	18.77
	phase M	13.99	8.86	4.04	1.27	1.03	0.74	0.30	0.27	0.19	18.88

TABLE III
HARMONIC CURRENT DATA ON 69-KV SIDE OF SPECIALLY CONNECTED TRANSFORMER OF SYSTEM WITHOUT FILTER

		Harmonic current (%)									TDD
Order		3	5	7	9	11	13	15	17	19	
VV	phase A	13.80	7.96	3.56	1.18	0.96	0.60	0.29	0.26	0.14	18.01
	phase B	0.44	8.62	3.60	0.21	1.06	0.61	0.10	0.30	0.14	11.44
	phase C	14.00	8.92	3.77	1.30	1.09	0.71	0.34	0.30	0.21	18.93
Scott	phase A	13.71	8.50	3.71	1.13	1.01	0.66	0.24	0.24	0.13	18.17
	phase B	14.48	8.96	4.26	1.19	1.14	0.72	0.35	0.25	0.21	19.39
	phase C	13.45	8.72	3.81	1.35	0.93	0.77	0.26	0.29	0.19	18.21
Le Blanc	phase A	14.03	8.81	3.94	1.29	1.13	0.78	0.35	0.33	0.23	18.70
	phase B	14.34	9.06	4.16	1.23	1.11	0.75	0.35	0.29	0.21	19.29
	phase C	13.61	8.60	3.85	1.30	1.01	0.76	0.29	0.28	0.19	18.31

TABLE IV
POWERS AND POWER FACTOR ON 69-KV SIDE OF SPECIALLY CONNECTED TRANSFORMER

		Power, without filter			Power factor	
		S (MVA)	P (MW)	Q (MVAR)	Without filter	With filters
VV	Phase A	6.5491	6.4620	1.0647	0.9867	1.0
	Phase B	10.530	8.2645	6.5257	0.7848	1.0
	Phase C	6.0629	2.4744	5.5350	0.4081	1.0
Scott	Phase A	7.477	5.793	4.7174	0.7754	1.0
	Phase B	7.0082	5.5475	4.2825	0.7916	1.0
	Phase C	7.4185	6.0626	4.2754	0.8172	1.0
Le Blanc	Phase A	7.5113	5.8377	4.7266	0.7772	1.0
	Phase B	7.0173	5.5396	4.3075	0.7894	1.0
	Phase C	7.4086	6.0618	4.2503	0.8191	1.0

V. PLANNING RESULTS

The requirement is to improve the power factor of each phase of each specially connected transformer to unity. The power values and power factor values with and without harmonic filters on the 69-kV side of the specially connected transformer are given in TABLE IV. TABLE V, VI, and VII give the design values of filter parameters of VV, Scott, and Le Blanc scheme, respectively. Three filter cases are compared. The filters in each phase of each transformer are different.

TABLES VIII gives the planning results of objective functions and filter losss using the HDE approach, where three filter cases of three transformer schemes are compared. Figure 7 gives the convergence of objective function of three cases of the VV connection scheme with respect to number of generation. Because both the emigrant and accelerated operations are embedded in the HDE, a global optimum and faster convergence are achieved.

TABLE IX, X, and XI show the comparison of harmonic current distortions at the phase B of the 69-kV side of VV, Scott, and Le Blanc scheme, respectively. Without the harmonic filter, the harmonic distortion values are greater than the limitation values. With the filters design by using HDE, the harmonic distortion values are greatly reduced. The case 3 have the best results.

VI. 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. So the filter structure in each phase is also different.

TABLE V
DESIGN OF FILTER PARAMETERS OF VV CONNECTED SCHEME

Cases \ Element		Filter type	R(Ω)	L(mH)	C(uF)	C_1(uF)	Q_F(MVA)	Parameters	
								h_o	m
Case 1	Phase A	3rd C-type	2947.9	244.5	0.31	28.78	0.555	2.91	0.091
		5th single-tuned	-	1988.4	0.15	-	0.282	4.85	-
		7th single-tuned	-	1229.7	0.12	-	0.2277	6.79	-
	Phase B	3rd single-tuned	-	2119.1	0.39	-	0.798	2.91	-
		5th single-tuned	-	322.8	0.93	-	1.737	4.85	-
		7th high-pass	175.7	0.34	2.22	-	3.991	6.79	0.005
	Phase C	3rd C-type	564	46.8	1.62	150.4	2.901	2.91	0.091
		5th single-tuned	-	473.2	0.63	-	1.185	4.85	-
		7th single-tuned	-	193.2	0.79	-	1.449	6.79	-
Case 2	Phase A	3rd single-tuned	-	3063.5	0.27	-	0.543	2.91	-
		5th C-type	2921.6	145.4	0.19	48.4	0.336	4.85	0.091
		7th single-tuned	-	1584.6	0.1	-	0.1857	6.79	-
	Phase B	3rd single-tuned	-	1057.6	0.79	-	1.599	2.91	-
		5th C-type	282.6	14.1	1.94	500.3	3.474	4.85	0.091
		7th single-tuned	-	192.7	0.79	-	1.4527	6.79	-
	Phase C	3rd single-tuned	-	613.4	1.35	-	2.757	2.91	-
		5th C-type	530.3	26.4	1.03	266.6	1.851	4.85	0.091
		7th single-tuned	-	302	0.51	-	0.927	6.79	-
Case 3	Phase A	3rd single-tuned	-	5871.7	0.14	-	0.288	2.91	-
		5th C-type	5949.4	296.1	0.092	23.8	0.165	4.85	0.091
		7th high-pass	729.4	0.91	0.34	-	0.6117	10.67	0.005
	Phase B	3rd single-tuned	-	2119.1	0.39	-	0.798	2.91	-
		5th C-type	370.6	1.8	1.48	3800	2.649	4.85	0.0091
		7th high-pass	159.4	0.22	1.72	-	3.0787	9.7	0.005
	Phase C	3rd single-tuned	-	1167	0.71	-	1.449	2.91	-
		5th C-type	1062.4	52.9	0.51	133.1	0.0924	4.85	0.091
		7th high-pass	172.4	0.26	1.76	-	3.162	8.73	0.005

TABLE VI
DESIGN OF FILTER PARAMETERS OF SCOTT CONNECTED SCHEME

Cases \ Element		Filter type	R(Ω)	L(mH)	C(uF)	C_1(uF)	Q_F(MVA)	Parameters	
								h_o	m
Case 1	Phase A	3rd C-type	655.5	54.4	1.39	129.4	2.496	2.91	0.091
		5th single-tuned	-	512.1	0.58	-	1.095	4.85	-
		7th single-tuned	-	248.6	0.61	-	1.1264	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	244.9	478.3	1.60	-	2.8635	6.79	0.005
	Phase C	3rd C-type	739	61.3	1.23	114.8	2.214	2.91	0.091
		5th single-tuned	-	616.9	0.48	-	0.909	4.85	-
		7th single-tuned	-	243	0.63	-	1.1524	6.79	-
Case 2	Phase A	3rd single-tuned	-	723.6	1.15	-	2.337	2.91	-
		5th C-type	634.1	31.6	0.86	222.9	1.548	4.85	0.091
		7th single-tuned	-	336.4	0.45	-	0.8324	6.79	-
	Phase B	3rd single-tuned	-	756.6	1.10	-	2.235	2.91	-
		5th C-type	708.3	35.3	0.77	199.6	1.386	4.85	0.091
		7th single-tuned	-	423.3	0.36	-	0.6615	6.79	-
	Phase C	3rd single-tuned	-	799.6	1.04	-	2.115	2.91	-
		5th C-type	684.6	34.1	0.80	206.5	1.434	4.85	0.091
		7th single-tuned	-	385.5	0.4	-	0.7264	6.79	-
Case 3	Phase A	3rd single-tuned	-	1878.9	0.44	-	0.9	2.91	-
		5th C-type	1083.5	53.9	0.50	130.5	0.906	4.85	0.091
		7th high-pass	153.3	0.19	1.62	-	2.9114	10.67	0.005
	Phase B	3rd single-tuned	-	1910.8	0.43	-	0.885	2.91	-
		5th C-type	1838.3	9.1	0.30	769.1	0.534	4.85	0.0091
		7th high-pass	171.4	0.23	1.60	-	2.8635	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	192.7	0.29	1.58	-	2.8294	8.73	0.005

TABLE VII
DESIGN OF FILTER PARAMETERS OF LE BLANC CONNECTED SCHEME

Cases		Filter type	R(Ω)	L(mH)	C(uF)	C_1(uF)	Q_F(MVA)	Parameters h_o	Parameters m
Case 1	Phase A	3rd C-type	660.2	54.8	1.38	128.5	2.478	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	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	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

TABLE VIII
OBJECTIVE FUNCTION AND FILTER LOSS

		Without filter	With filter Case 1	With filter Case 2	With filter 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(W)	-	44.37	18.33	5.13

TABLE IX
COMPARISON OF HARMONIC CURRENTS AT PHASE B OF 69-KV SIDE OF VV CONNECTED TRANSFORMER

Harmonic orders	Harmonic distortion (%) Without filter	With filters Case 1	With filters Case 2	With filters Case 3	Limitation (%)
3	0.47	0	0	0.003	3.5
5	9.34	0.5	0.11	0.015	3.5
7	3.90	0.09	0.24	0.009	3.5
9	0.22	0.01	0	0.001	3.5
11	1.15	0.05	0.06	0.005	1.75
13	0.66	0.04	0.07	0.003	1.75
15	0.11	0.01	0.02	0.001	1.75
17	0.32	0.03	0.07	0.002	1.25
19	0.15	0.02	0.03	0.001	1.25
TDDi(%)	12.39	0.52	0.29	0.022	6.89

TABLE X
COMPARISON OF HARMONIC CURRENTS AT PHASE B OF 69-KV SIDE OF SCOTT CONNECTED TRANSFORMER

Harmonic orders	Harmonic distortion (%) Without filter	With filters Case 1	With filters Case 2	With filters Case 3	Limitation (%)
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	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

TABLE XI
COMPARISON OF HARMONIC CURRENTS AT PHASE B OF 69-KV 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	88.8e-3	3.5
5	6.48	0.17	0.02	31.52e-3	3.5
7	2.97	0.08	0.09	25.98e-3	3.5
9	0.88	0.04	0.01	12.31e-3	3.5
11	0.79	0.05	0.01	16.18e-3	1.75
13	0.53	0.04	0.02	14.9e-3	1.75
15	0.25	0.03	0.02	9.21e-3	1.75
17	0.21	0.03	0.02	9.77e-3	1.25
19	0.15	0.03	0.01	8.56e-3	1.25
TDDi(%)	13.78	0.26	0.20	0.13	6.89

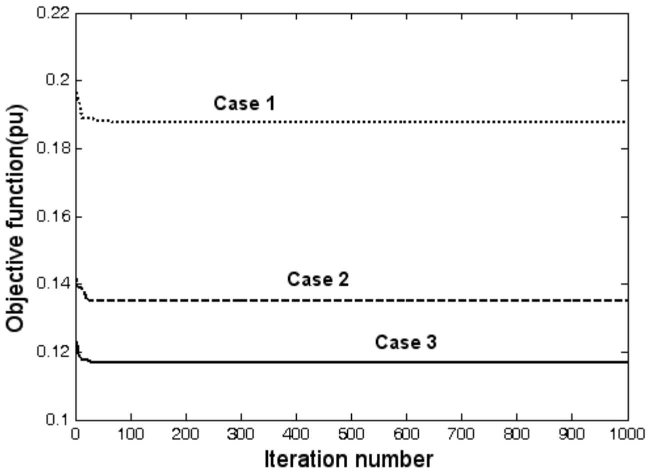

Fig.7. Convergence of objective function of three cases of VV connection scheme with respect to number of generation.

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