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DAMPING TECHNIQUES OF HARMONIC RESONANCES

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Harmonic resonances may damage equipments and interrupt electric power customers' services. Shutdowns may affect seriously harmonic resonant frequencies and may initiate new resonances in distribution power systems. This paper proposes various techniques for damping harmonic resonances in power systems [1-4]. A series reactor should be connected in series with the shunt power factor correction capacitor, damping resistance across inductor terminals of LC passive filter, increasing the short circuit system power, derating the harmonic generating equipment, and by using hybrid active filters. The hybrid active filters consist of active filter connected in shunt with passive filter. The active filter is characterized by detecting the harmonic current flowing into the passive filter. It is controlled in such a way as to behave as resistor by adjusting certain gain. It is proved that this significantly improves damping of the harmonic resonances, compared with the passive filter when used alone [5-7].

1. INTRODUCTION:

Resonance phenomenon in power systems, including power oscillations, may cause several problems such as voltage distortion, fluctuation and harmonic currents with subsequent instability in the system malfunction of or even damage to electrical equipment and plants.

The resonances can be stimulated not only by fault events and switching transformers, reactors or capacitor banks, but also by operating non-linear loads or power electronic devices, i.e.

- Static VAR compensation ,
- HVDC installations with AC filters,
- Arc furnaces with VAR compensators,
- Uninterruptible power supplies.

Resonances also exist on series-compensated transmission lines, and especially on systems with power factor correction capacitors.

Oscillations due to harmonic generation are nominally eliminated by passive LC filters. Tuned filters and high pass or damped shunt filters offer low impedance for harmonics, limiting harmonic voltages transferred to the network. However, these filters together with the supply impedance cause resonances at other frequencies and therefore, have to be designed carefully. In some cases, resistors are inserted in shunt with the reactor of the filters to damp these resonances. Increasing losses have to be accepted, of course. Another solution is the application of sharply tuned filters which have to achieve constant filter characteristics [5-7].

The efficiency of passive filters depends on the system impedance seen from the point where they are installed. Consequently, passive filter may become expensive depending upon the system impedance and on the required attenuation.
Therefore, severe requirements can lead to the necessity of several filters tuned to different frequencies. Furthermore, filter characteristics have to be matched to changed system conditions to achieve a constant filter performance.

These limitations of passive filters led to the development of a new concept using active filter for damping of resonances together with the other mentioned methods.

2. DAMPING OF HARMONIC RESONANCES:

Harmonic resonances can be damped by either of the following techniques.

2.1 By Using Reactors in Series with the Shunt Power Factor Correction Capacitors:

In order to limit towards the top the variation range of the anti-resonance frequency, a series reactor of inductance (L) should be connected in series with the shunt power factor correction capacitor as shows Fig. (1).

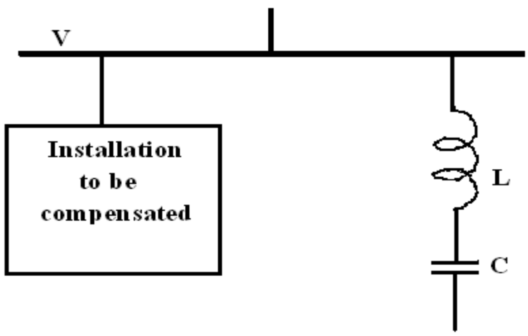

Fig. (1): Shunt capacitor with series reactor to avoid damaging anti-resonances of harmonic sources.

In such a case, there will be a tuning frequency (f_a) of the capacitor (C) with the added series reactor (L), defined by:

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

In order to avoid damaging effects of the coincidence of the anti-resonance frequency (f_{ar}) with the converter chrematistic frequency, f_{ar} should be adjusted so as to be less than the tuning frequency f_a, for all possible expected network elements variations, as shown in Fig. (2)

Therefore that condition can be written as:

$$f_{ar} < f_a \quad (2)$$

This condition is fulfilled by taking (f_{ar}) as inferior to the first characteristic harmonic current generated by the converter. Then the anti-resonance frequency will not be able to coincide with a characteristic harmonic current of the converter.

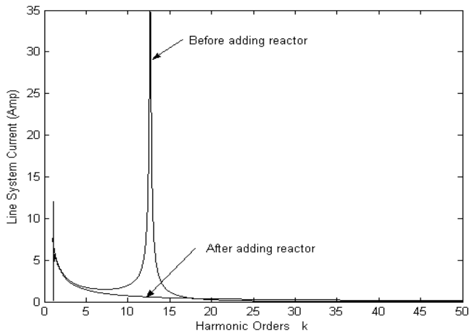

Fig. (2): Damping anti-resonance by adding series reactor with shunt capacitor.

Harmonic resonance is recorded at the 13^{th} order, without the series inductor L. Upon connecting L, the resonance state disappears and no resonance exists. For all frequencies the resonance is damped upon using this 'L'.

2.2 By Using Shunt Resistor with the Reactor of the LC Passive Filter:

When a damped filter is connected to the bus containing a harmonic source in order to prevent its harmonic from penetration to the network is shown in Fig. (3). The resonance and anti-resonance frequencies are identical to those of the resonant type (or the single tuned) filters. However, the damping resistance has the effect of:

- Reducing the anti-resonance: $|Z(\omega_{ar})| << \infty$.
- Making the filter less effective at the tuning range: $|Z(\omega_a)| \neq 0$ (in case of a filter).
- Widening the impedance curve of the damped filter, thus filtering the high frequencies.

The variation of line system current with harmonic orders is shown in Fig. (4).

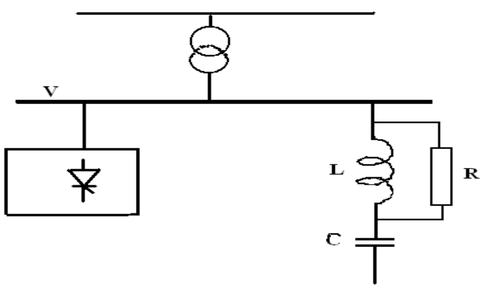

Fig. (3): AC network with harmonic source and damped filter.

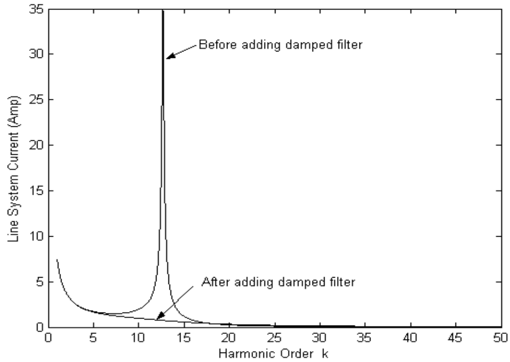

Fig. (4): Damping anti-resonance by adding damped filter.

Harmonic resonance is recorded at the 13th order, without the shunt resistor R. Upon connecting R, the resonance state disappears and no resonance exists. For all frequencies the resonance is damped upon using this 'R'.

2.3 By Increasing the Nodes Short Circuit Levels:

The studied system shown in Fig. (5) consists of a network feeding a static load (R_L+JX_L) through a transmission line. The equivalent system impedance including the line is (R_S+JX_S).

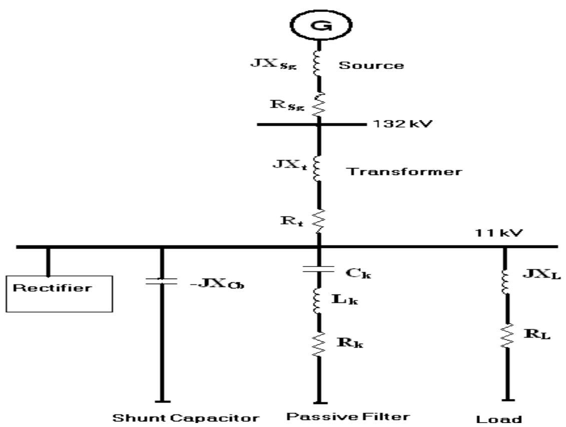

Fig. (5): Studied system configuration.

The step down transformer impedance is (R_t+JX_t). The static load power factor is corrected by shunt capacitor of reactance (-JX_{Cb}) and passive filters of impedance (R_k + $J(X_{lk}$ - X_{ck})) are connected on a common bus. A rectifier load at the point of common connection (PCC) is connected and will be the harmonic source, which generates harmonic order (k).

The power system may cause harmonic propagation as a result of series and/or parallel resonances between the power capacitors and the leakage inductor of the distribution transformer.

The equivalent diagram of the RLC filter, the AC network, the power factor correction capacitor, passive tuned filter and the harmonic source is shown in Fig. (6).

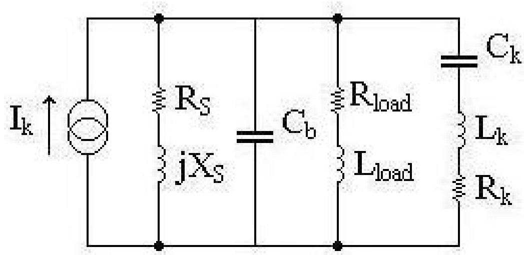

Fig. (6): Equivalent single line diagram of RLC filter, static load, shunt capacitor C_b and harmonic source

The total susceptance with frequency at neglecting the resistances R_S , R_L and R_k is determined by using the following relations, for k^{th} order harmonic:

$$B_k = -\frac{k_{ar}^2 k}{k^2 - k_{ar}^2}\omega C_k - \frac{1}{k\omega L_{esc}} + k\omega C_b \quad (3)$$

After some manual calculations, we obtain:

$$B_k = \frac{\omega^2 C_b L_{esc} k^4 - [k_{ar}^2 \omega^2 L_{esc}(C_5 + C_b) + 1]k^2 + k_{ar}^2}{k\omega L_{esc}(k^2 - k_{ar}^2)} \quad (4)$$

Therefore, there will be a current resonance when:

$$\omega^2 C_b L_{esc} k^4 - \left[k_{ar}^2 \omega^2 L_{esc}(C_k + C_b) + 1\right]k^2 + k_{ar}^2 = 0 \quad (5)$$

Table 1 summarizes the circuit constants in Fig. (2).

Using system data given in Table (1) and with Eq. (5), a voltage resonance occurs with k=13. There are two possible current resonances (k_{ar1} and k_{ar2}), the first at frequency less than 650 HZ, the other at higher frequency as shown in Fig. (7).

Table (1): Circuit Constants

13^{th} tuned passive filter	C_k= 0.083µF, L_k=0.72 H R_k = 72 Ω
System impedance	R_S= 2.27 Ω, X_S=12.1 Ω
Load impedance	R_L= 180 Ω, X_L= 94.25 Ω
Shunt capacitor	C_b= 1.75µF
Base: 3-ph, 800kVA. 11kV, 50 Hz	

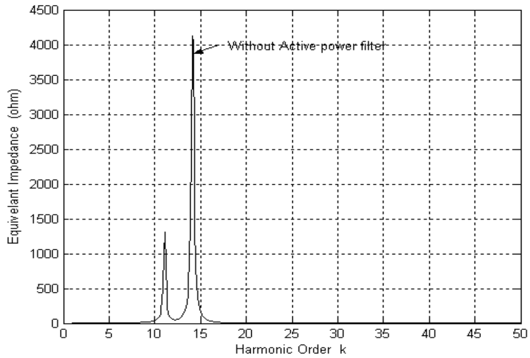

Fig. (7): Equivalent impedance versus harmonic orders for 13th single tuned harmonic filter and shunt capacitor

Fig (8) and Table (2) shows the anti-resonance orders and anti-resonance impedance, upon increased and their amplitudes are decreases with increasing the short circuit system nodes level.

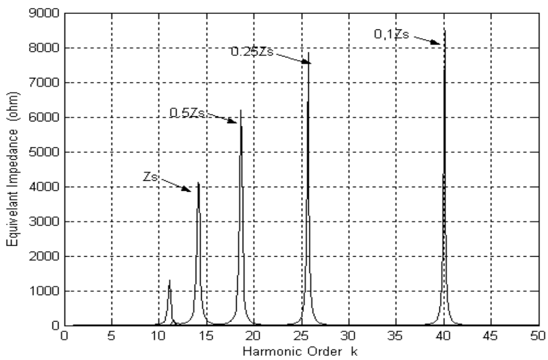

Fig. (8): Equivalent impedance verses harmonic orders for 13th single tuned harmonic filter and shunt capacitors (at various values of system impedance)

Table (2): Anti-resonance orders at different values of system impedance

System Impedance	Anti-resonance orders		Anti-resonance impedance (ohm)
	k_{ar1}	k_{ar2}	
Z_S	11	14	1410, 3730
0.5 Z_S	12	18	180, 5520
0.25 Z_S	-	25	7400
0.1 Z_S	-	39	8670

2.4 By Derating the Harmonic Generating Equipment:

Figure (9) and Table (3) shows the varying of load impedance with harmonic orders and anti-resonance orders occurred.

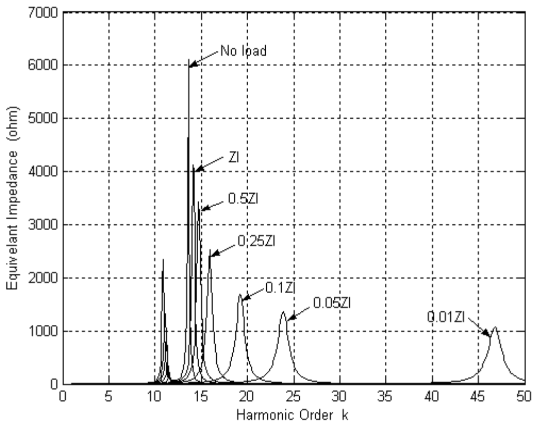

Fig. (9): Equivalent impedance versus harmonic orders for 13th single tuned harmonic filter and shunt capacitors (at various values of load impedance)

Table (3): Anti-resonance orders at different conditions of loading

Load impedance	**Anti-resonance orders**		**Anti-resonance impedance (ohm)**
	k_{ar1}	k_{ar2}	
Z_L	11	14	1410, 3730
0.5 Z_L	12	15	860, 3350
0.25 Z_L	12	16	410, 2400
0.1 Z_L	12	19	120, 1600
No load	11	13	2715, 4780

Slight variations are noticed in the anti-resonant frequencies.

2.5 By Using Hybrid Active Filter:

Active power filters can be used with passive filters improving compensation characteristics of the passive filter, and avoiding the possibility of the generation of series or parallel resonance. The combination of passive and active power filters is by connecting the active filter in shunt with the passive one, as shown in Fig. (10).

The characteristics of this hybrid active power filter give the advantages of passive and active filtering solutions and cover a wide range of power and performance. It can perform the following:

- Filtering on a wide frequency band (damping of harmonic resonance and eliminating harmonics),
- Compensation of reactive power,
- Large capacity for current filtering,
- Good technical-economic solution for "network"

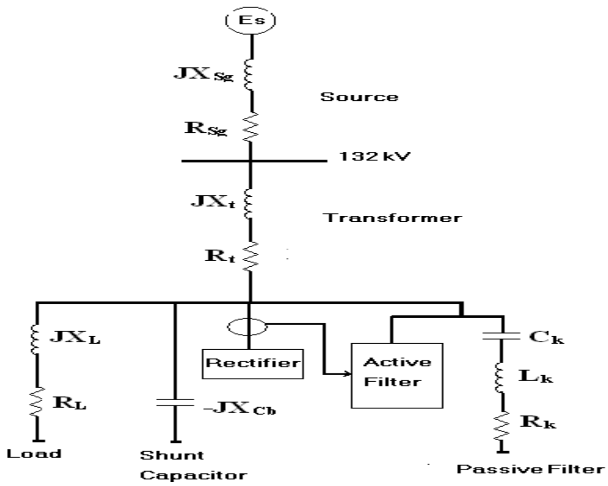

Fig. (10): Single phase circuit diagram of a typical distribution power system with active damping.

Figure (11) present a scheme of a hybrid active filter for damping harmonic resonance, the active filter acts as a pure resistor of R_d (Ω) for the k^{th} harmonic voltage and current.

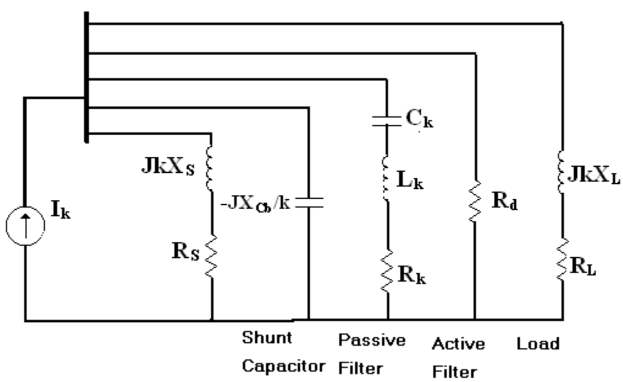

Fig. (11): Hybrid active damping network.

The impedance of the hybrid filter at the k^{th} harmonic frequency, Z_k is given by:

$$Z_{HFk} = \frac{(R_k + J(kX_{Lk} - X_{Ck}/k)(R_d)}{(R_k + R_d) + J(kX_{Lk} - X_{Ck}/k)} \quad (6)$$

The harmonic currents present in the supply current, are given by:

$$I_{HFk} = \frac{I_k(Z_{eq2})}{Z_{eq3}} \quad (7)$$

Where:

$$Z_{eq2} = \frac{Z_S \times Z_L \times Z_{Cb}}{Z_L + Z_{Cb}} \quad (8)$$

$$Z_{eq3} = Z_{eq2} + Z_{HFk} Z_S + \frac{Z_{HFk} \times Z_{Cb} \times Z_L}{Z_L + Z_{Cb}} \quad (9)$$

$$I_k = I_1 / k \quad (10)$$

Where:
R_d : Active filter gain in ohm, which equal to the passive filter resistance R_k.
Z_{HFk} : Hybrid active filter impedance.
k : Harmonic order.
I_1: Fundamental current in amperes.
I_k : Harmonic current at order k.
Assuming that R_d=R_k yields
Harmonic phase voltage at common busbars is:

$$V_{HFk} = I_{kFh} \times Z_{hk} \quad (11)$$

2.5.1. Results and Discussion:

Figure (12) shows the anti-resonance orders of the studied system with static load, shunt capacitors and connected 13th passive filter. Figure (13) shows the anti-resonant orders when studied system is connected with static load, shunt capacitor and hybrid filter.

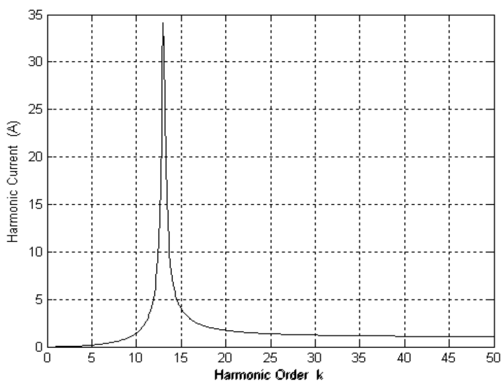

Fig. (12): Harmonic current versus harmonic orders without filtering.

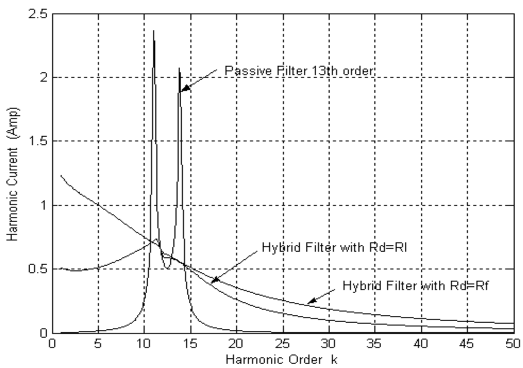

Fig. (13): Harmonic current versus harmonic orders for 13th passive filter and hybrid active filter.

Table (4): Comparative between system without filtering, with passive filter and with hybrid filter

System	**Anti-resonance orders**		**Anti-resonance current (Amp)**
	k_{ar1}	k_{ar2}	
System with static load and shunt capacitors	13	-	34
System with static load, shunt capacitors and 13th passive filter	12	14	2.4, 2.05
System with static load, shunt capacitors and hybrid filter	-	-	-

Table (4) shows comparative results between system without filtering, with passive filter and with hybrid filter. It is shown that using the hybrid proposed filter eliminates totally the harmonic resonances.

3. CONCLUSION:

This paper has proposed several techniques for damping harmonic resonances in distribution power systems. The theoretical analysis developed in this paper has verified the viability and cost-effectiveness of those methods. This paper has led to the following conclusions.

(1) Harmonic resonance can be damped by series reactors with the shunt power factor correction capacitors or by shunt resistors with the inductor of the LC single tuned filters or by increasing the nodes short-circuit level or by derating generators or by using the hybrid active filters.

(2) It is proved that all those methods are effective in harmonic resonance damping, however the generator rating slightly effect resonance damping..

(3) The hybrid filter can reduce the 13^{th} harmonic voltage appearing on the common bus resulting from the passive filter when used alone.
(4) Moreover, the active filter acting as a pure resistor at the 13^{th} harmonic frequency which prevents the passive filter from over current.
(5) The hybrid filter eliminates totally the harmonic resonances when $R_d=R_k$.

REFERENCES:

(1) M.Z. El-Sadek, "Power Systems Power Quality" Muchter Press, Assiut, Egypt, 2004.
(2) M.Z. El-Sadek," Power Systems Harmonics " Muchter Press , Assiut, Egypt, 2007.
(3) M.Z. El-Sadek," Power Systems Harmonic Filters " Muchter Press , Assiut, Egypt, 2007.
(4) Jos Arrillaga, Bruce C. Smith, Nevelle, R. Watson, Alan R.Wood, "Power System Analysis, Book, John &Sons Ltd, England, 1997.
(5) H. Fujita, T. Yamasaki, and H. Akagi, "A hybrid active filter for damping of harmonic resonance in industrial power system" IEEE Trans. Power Electron, vol. 15, no. 2, pp. 215-222, 2000.
(6) D. Detjen, J. Jacobs, R.W. De Doncker, and H.G. Mall, "A new hybrid filter to dampen resonances and compensate harmonic currents in industrial power systems with factor correction equipment", IEEE Trans. Power Electron., vol. 16, no. 6, pp. 821-827, 2001.
(7) P. Jintakosonwit, H. Fujita, H.Akagi, and S. Ogasawara, "Implementation and performance of cooperative control of shunt active filters for harmonic damping throughout a power distribution system", IEEE Trans. Ind. Application, vol. 39, no. 2, pp. 556-564, 2003.

تقنيات إخماد رنين التوافقيات

تقدم هذه الورقة طرق إخماد رنين التوافقيات في الشبكات الكهربية وهى كالتالي:
1- باستخدام ملف على التوالي مع مكثفات تحسين معامل القدرة.
2- باستخدام مقاومة على التوازي مع ملف مرشح التوافقيات.
3- بزيادة معدل قصر نقط الدائرة.
4- تعديل قدرة الأجهزة المولدة للتوافقيات.
5- باستخدام خليط مرشحات التوافقيات النشطة مع مرشحات التوافقيات الهامدة.