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HARMONIC DISTORSION SOURCE IDENTIFICATION IN POWER SYSTEMS WITH CAPACITOR BANKS

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Abstract − The deregulation of power market requires methods for the identification of the harmonic distortion source, while the increased presence of power electronics as major harmonic sources raises the level of harmonic distortion present in the electric power systems. Different approaches have been proposed for the identification of the source of harmonic distortion, but if direction of power flow is considered, only the harmonic active power is taken under consideration. In this paper, examples are described and simulations are undertaken to examine what is the actual information conveyed by the both harmonic active and reactive power flow and to find out how the presence of capacitors influence identification schemes.

Keywords: harmonic source identification.

1. INTRODUCTION

The proliferation of power electronics in recent years has increased the level of harmonic distortion in the electric power systems and it raised the number of problems related to harmonic source identification. On the other hand, the deregulation of the electric energy market is requiring methods and instrumentation able to quantify the distortion generated by the customer and many tariffing related issues has been raised.

A great number of contributions [1-10] are dealing with the harmonic source identification problems and different approaches have been adopted. Synchronised and distributed measurements are necessary when using harmonic state estimate techniques to locate the source of harmonic pollution [1]. In [3] the thorough knowledge of the network topology, based on extensive and simultaneous measurements is required to solve a cost allocation problem for power quality mitigation equipment. A single point measurement based index, namely a non-fundamental apparent power defined in [12], has been proposed in [4] for harmonic pollution cost allocation.

A method based on single point measurement of non-fundamental apparent power, created for the estimation of harmonic distortion levels in the system, is relying on the assumption that a customer is completely responsible for the distortion levels at the point of common coupling. More detailed approaches are based on evaluation of the sign of harmonic active power and consequent separation of harmonics currents or powers in two sets; the first harmonic set which is mainly produced by the network and the second one, whose responsibility is on the customer [5-10].

In [6], the index ξ_{slq} is proposed, defined as the ratio P/P_{+1} of the total active power to the fundamental power of positive sequence, while in [7] has been described Harmonic Global Index (HGI), defined as a ratio between quadratic sum of currents with negative harmonic active power (i.e. produced by the customer) and quadratic sum of currents with positive harmonic active power. Both approaches are based on Park transformation [8], which enables the study of three-phase unbalanced and distorted systems in a synthetic and compact way. It has been proven however [9], that indices based on the flow of harmonic active powers can provide unreliable information if they are measured in a single metering section of the network. This problem has been faced in [10] with distributed and synchronised measurements and consequent processing of defined indexes.

Although some drawbacks of harmonic power flow have been reported previously, it was felt that more detailed analysis is needed in order to distinguish those situations where harmonic power flow doesn't identify harmonic polluting load correctly.

In this paper, the analysis of the harmonic distortion and harmonic active power behaviour in the presence of power factor correction capacitors and a single harmonic source is presented first.

Next, the behaviour of harmonic power at the measurement point, as well as behaviour of harmonic angle, has been described in circuits with two current sources.

2. HARMONIC DISTORTION IN THE PRESENCE OF CAPACITOR BANKS

In the next two sections typical situations are analysed in order to demonstrate the influence of the capacitors on the system harmonic distortion. Simple circuit, shown in Fig.1, was taken under consideration, where power system, for harmonic frequency *h*, is modelled as the Norton parallel equivalent circuit with the impedance $\boldsymbol{Z}_S$ and current source $\boldsymbol{I}_o$. In the simulation performed, mainly inductive system impedance where used. Current source $\boldsymbol{I}_o$ is accounting for the background distortion of the system. Load is modelled with the impedance $\boldsymbol{Z}_L$, responsible for the linear part of the

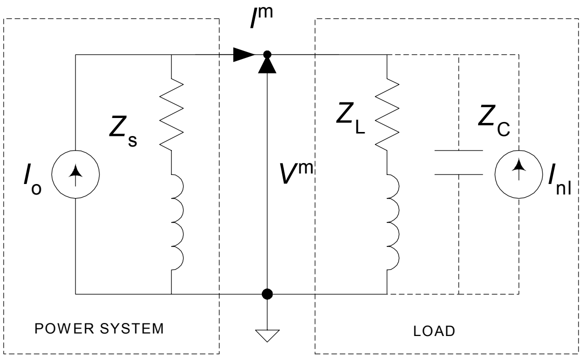

Fig. 1. Electric circuit considered to describe behaviour of the system distortion in the presence of capacitor banks.

load, and with current source $\boldsymbol{I}_{\mathrm{NL}}$, modelling non linear part of the load. In simulations, where effect of the capacitors were considered, capacitor with impedance $\boldsymbol{Z}_{\mathrm{C}}$ where added to the load (compensating completely $\boldsymbol{Z}_{\mathrm{L}}$ at fundamental frequency). Calculations where done using Matlab.

2.1. Power factor correction capacitors in the presence of network voltage distortion

Circuit described in Fig.1, without $\boldsymbol{I}_{\mathrm{NL}}$ and with and without $\boldsymbol{Z}_{\mathrm{C}}$, was taken under consideration in order to show the effects of capacitors on the voltage and current harmonic distortion of the entire system.

In the absence of capacitors, inductive load absorbs distorted current but overall effect is beneficial, i.e. voltage distortion decrease. Connecting capacitor banks, the resonance between the system and the capacitor occurs at harmonic frequency h, given approximately by $\sqrt{Z_{C1}/Z_{S1}}$, where Z_{C1} and Z_{S1} are, respectively, capacitor and system bank impedances modules at fundamental frequency. If h is near a predominant harmonic (typically 5^{th} or 7^{th}), a resonant circuit represents low impedance path for harmonics near h, transforming in this way low voltage distortion in significant current distortion.

For the frequencies different from resonant frequency f_{res} capacitor is still represent a lower impedance path (with respect to the case without capacitor) for the current and, therefore, amplify current distortion. Harmonic voltage is, on the other hand, increased for $f < f_{res}$, while decreased for the frequencies above f_{res}.

In spite of the fact that the capacitors are linear part of the system and as such cannot generate harmonic distortion, care must be taken in identification schemes, when analysing systems with compensating facilities. Capacitors cannot generate harmonic power, but it is clear that they increase current distortion and generally increase total voltage distortion, although, for some frequencies, harmonic voltage can be reduced. On the other hand, being the capacitor passive and linear element, active power is absorbed by the load, and therefore positive, indicating that the load is not distorting the system.

2.2. Power factor correction capacitors in the presence of non linear load

Similar detrimental effect of the capacitors can be seen also in the presence of non linear load (simulated with the current source $\boldsymbol{I}_{\mathrm{NL}}$) connected to the same point of common coupling (PCC). By considering system without background distortion and in the absence of capacitors, harmonic current and voltage are

$$\boldsymbol{I}^{m} = -\boldsymbol{k}_{L}\boldsymbol{I}_{NL} = \frac{\boldsymbol{Z}_{L}}{\boldsymbol{Z}_{S}+\boldsymbol{Z}_{L}}\boldsymbol{I}_{NL}\,, \qquad (1)$$

$$\boldsymbol{V}^{m} = \boldsymbol{Z}_{T}\boldsymbol{I}_{NL} = \frac{\boldsymbol{Z}_{L}\boldsymbol{Z}_{S}}{\boldsymbol{Z}_{L}+\boldsymbol{Z}_{S}}\boldsymbol{I}_{NL}. \qquad (2)$$

In presence of capacitors in (1) and (2), $\boldsymbol{Z}_{\mathrm{L}}$ should be replaced by $\boldsymbol{Z}_{\mathrm{L}}^{\mathrm{C}} = \boldsymbol{Z}_{\mathrm{L}} // \boldsymbol{Z}_{\mathrm{C}}$.

In order to determine the effect of the capacitors on the harmonic distortion, variation of the $\boldsymbol{k}_{\mathrm{L}}$ and $\boldsymbol{Z}_{\mathrm{T}}$, are represented in the Fig.2. It can be observed that capacitor cause an ulterior increase in voltage and current distortion generated by $\boldsymbol{I}_{\mathrm{NL}}$, for frequencies below and around f_{res}, while decrease distortion for the frequencies above f_{res}, i.e. for high frequencies capacitor filters harmonic, and for low frequencies (with respect to f_{res}) distortion is increased.

These considerations have been done by taking in consideration pure capacitance without any parasite or tuning inductance. The latest one is usually added to the capacitor banks in order to limit harmonic currents flowing into capacitors. In this case, the f_{res} is moved closer to the fundamental frequency and high frequency effect is attenuated.

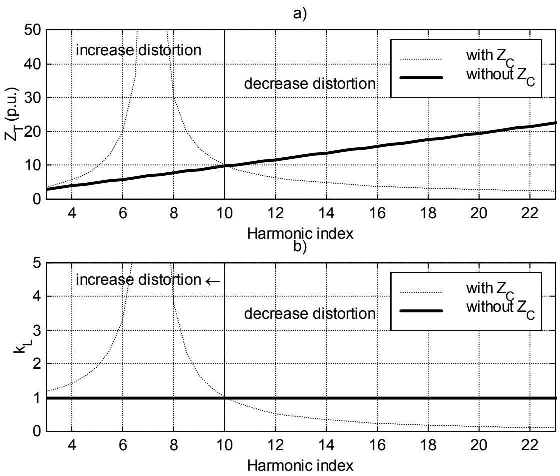

Fig.2 Behaviour of Z_L a) and k_L b) with and without capacitor bank for different harmonic frequency.

3. HARMONIC SOURCE IDENTIFICATION USING HARMONIC POWER FLOW

In this chapter, behaviour of the active and reactive harmonic power, as well as harmonic angle, will be analysed in circuits with one or two harmonic sources, in order to establish relations between these quantities and distorting/non distorting nature of the load connected at PCC.

3.1. Behaviour of harmonic angle, active and reactive power in the systems without capacitors

Circuit of Fig.1 was taken again under consideration in order to clarify if the harmonic power flow can be taken as reliable indicator for harmonic source identification.

It was assumed $Z_{S1} << Z_{L1}$. Influence of considered parameters on the generality of the conclusion will be discussed later in this paper.

Harmonic measurements are usually performed at the PCC. Measured signals are node voltage $\boldsymbol{V}^m$ and net harmonic current $\boldsymbol{I}^m$, defined as:

$$\boldsymbol{I}^m = \boldsymbol{I}_o^m - \boldsymbol{I}_{NL}^m = \frac{\boldsymbol{Z}_S}{\boldsymbol{Z}_S + \boldsymbol{Z}_L}\boldsymbol{I}_o - \frac{\boldsymbol{Z}_L}{\boldsymbol{Z}_S + \boldsymbol{Z}_L}\boldsymbol{I}_{NL} \quad (3)$$

In the diagnostic schemes involving evaluation of harmonic active power sign, active power P^m, defined by $P^m = \mathcal{R}e\{\boldsymbol{V}^m(\boldsymbol{I}^m)^*\}$ is determined, where superscript $()^*$ denotes complex conjugative of the phasors.

In the simply cases, where only one current source exists, the sign of the active power allows to correctly identify the source of the harmonic distortion. When only $\boldsymbol{I}_o$ is present, i.e. in the presence of system distortion and with the linear load, P^m is positive. In the presence of non linear load and without background voltage, P^m is negative, indicating that the distorting load is on the consumer side.

None the less diagnostic scheme under exam starts to fail when both sources are present. The wrong identification of the source of harmonic distortion was evidenced in previous papers [2,9] but explanation of the problem where not evidenced.

In the presence of system distortion and the non linear load, the sign of the harmonic active power depends manly on the phase difference between two current sources ($\Delta\alpha$). The results of the simulations performed with the circuit depicted in Fig.1 are shown in Fig.3, where the phase difference was varied in the range (0^o-360^o).

The results of the simulations shows that the sign of harmonic active power can correctly identify the source of distortion, but only in the presence of one current source. The P^m for the case $I_{NL} = 0$, shown in Fig.3, is positive, as expected. But harmonic active power P^m starts to oscillate and changes the sign, for some values of $\Delta\alpha$, as soon as I_{NL}^m is present and increase above $15\% I_o^m$ (for the circuit considered). When the current I_o^m reaches the order of magnitude of the I_{NL}^m, harmonic active power assumes both positive and negative values and depends strongly on phase difference $\Delta\alpha$ between two current sources. In this case the sign of harmonic active power cannot be taken as the indicator of the I_{NL}^m/I_o^m ratio, as long as $\Delta\alpha$ varies in 0^o-360^o range.

In the cases, where I_{NL}^m is only harmonic source, P^m is negative, as should be expected. But as soon as background distortion is present, P^m becomes strongly influenced by the phase difference $\Delta\alpha$, even in the cases where I_{NL}^m is several orders of magnitude smaller than I_o^m.

Moreover, sign of P^m cannot be correlated with harmonic voltage or current variations, shown in Fig.5a),b).

These results confirm findings reported previously [9], where identification of the harmonic source identification was studied in the presence of two 6-pulse AC/DC phase controlled converters. Similar oscillatory behaviour of the harmonic active power was found when relative firing angles of two converters where varied.

What is the cause for this kind of behaviour of harmonic active power? The cause of the problem can be found in the many factors influencing the system and the lack of the

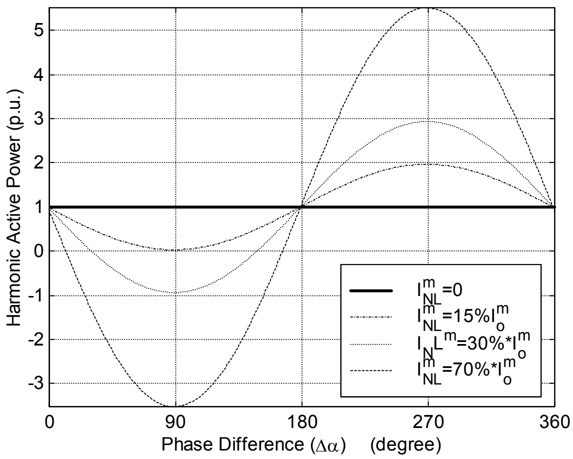

Fig.3. Variation of harmonic active power P^m as a function of phase difference $\Delta\alpha$ between two current sources and with different I_o^m/I_{NL}^m ratios.

possibility to perform complete measurement.

As already stated, P^m is obtained by measuring $\boldsymbol{V}^m$, $\boldsymbol{I}^m$, and by calculating

$$P^m = \Re e\left\{\boldsymbol{V}^m\left(\boldsymbol{I}_o^m - \boldsymbol{I}_{NL}^m\right)^*\right\} = P_o^m - P_{NL}^m + \Delta P; \quad (4)$$

$$\Delta P = \left(R_L|\boldsymbol{k}_o|^2 - R_S|\boldsymbol{k}_L|^2\right)I_o I_{NL}\cos(\Delta\alpha) + \\ -\left(X_L|\boldsymbol{k}_o|^2 + X_S|\boldsymbol{k}_L|^2\right)I_o I_{NL}\sin(\Delta\alpha); \quad (5)$$

$$P_o^m = R_L\,|\boldsymbol{I}_o^m|^2; P_{NL}^m = R_S\,|\boldsymbol{I}_{NL}^m|^2 \quad (6)$$

$$\text{with } \boldsymbol{k}_o = \frac{\boldsymbol{Z}_S}{\boldsymbol{Z}_S + \boldsymbol{Z}_L}; \boldsymbol{k}_L = \frac{\boldsymbol{Z}_L}{\boldsymbol{Z}_S + \boldsymbol{Z}_L}$$

where P_o^m is harmonic active power generated by the source $\boldsymbol{I}_o$ on the load impedance $\boldsymbol{Z}_L$, and P_{NL}^m is harmonic active power generated by the source $\boldsymbol{I}_{NL}$ on the system impedance $\boldsymbol{Z}_S$. The term ΔP is remaining part and, as can be seen, varies with $\Delta\alpha$, depends on the parameters of the network, and on the customer load impedance. From (5) it is clear that term ΔP cannot be considered negligible in a variety of situations, and not only for the particular case considered.

It is evident that the study of harmonic active power alone doesn't provide enough information to identify the source of harmonic distortion in the presence of multiple sources. Does the sign of the reactive powers can help in the identification of the source of the distortion?

The behaviour of measured reactive power $Q^m = Im\{\boldsymbol{V}^m(\boldsymbol{I}^m)^*\}$, calculated as:

$$Q^m = \Im m\left\{\boldsymbol{V}^m\left(\boldsymbol{I}_o^m - \boldsymbol{I}_{NL}^m\right)^*\right\} = Q_o^m - Q_{NL}^m + \Delta Q; \quad (7)$$

$$\Delta Q = \left(X_L|\boldsymbol{k}_o|^2 - X_S|\boldsymbol{k}_L|^2\right)I_o I_{NL}\cos(\Delta\alpha) + \\ + \left(R_S|\boldsymbol{k}_L|^2 + R_L|\boldsymbol{k}_o|^2\right)I_o I_{NL}\sin(\Delta\alpha); \quad (8)$$

$$Q_o^m = X_L\,|\boldsymbol{I}_o^m|^2; Q_{NL}^m = X_S\,|\boldsymbol{I}_{NL}^m|^2 \quad (9)$$

is shown in Fig.4. It can be observed that in the presence of background distortion only, reactive power is inductive, i.e. load absorbs inductive power. In the presence of non linear load only, reactive power assumes negative values, i.e. system absorbs inductive power generated by the load. For the cases where current sources are present, and $\boldsymbol{I}_o^m$ and $\boldsymbol{I}_{NL}^m$ are comparable, Q^m assumes both positive and negative

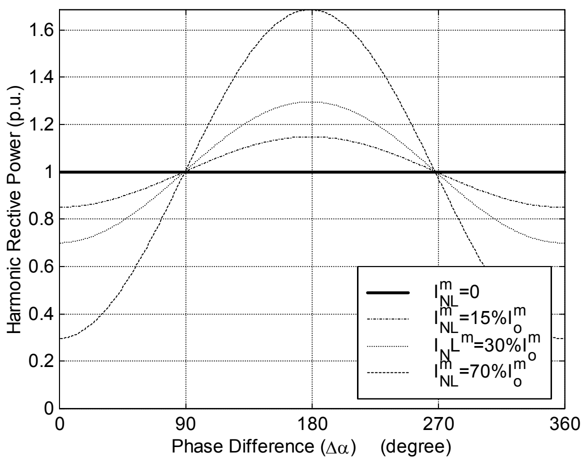

Fig.4. Behaviour of harmonic reactive power Q^m with the phase difference between two current sources and with different I_o/I_{NL} ratios.

values, as Δα varies from 0^o to 360^o. But in this case variations of the Q^m are smaller and the sign of the Q^m is correlated to the variation of the harmonic voltage, shown in Fig. 5.a). In the region where the effect of the non linear load is beneficial to the voltage distortion, Q^m increases, while for the values of Δα where harmonic voltage is increased, harmonic reactive power is decreased.

Having this in mind, harmonic angle $\varphi^m = \varphi_U{}^m - \varphi_I{}^m = arctan(Q^m/P^m)$ convey information related to the effect of the load on the voltage distortion of the system. In particular, it could be stated for particular system considered so far, that:

a) in the presence of background distortion only, measured reactive power will be positive and φ^m will be near 90^o.

b) In the presence of non linear load alone, reactive power will be negative, i.e. system absorbs inductive reactive power; φ^m will be near -90^o.

c) For cases where both distorting sources are present and $\boldsymbol{I}_o{}^m$ is prevailing, reactive power is still positive, and φ^m oscillates around 90^o, but remains positive.

d) When $I_{NL}{}^m$ starts to prevail over $I_o{}^m$, Q^m remains positive and increase, with respect to the case $I_{NL}{}^m=0$, for those values of Δα where $\boldsymbol{I}_{NL}{}^m$ has beneficial effect on harmonic voltage. Measured reactive power will decrease, and eventually become negative, for values of Δα where non linear load has detrimental effect on the voltage distortion; region where Q^m will be negative increases with $\boldsymbol{I}_{NL}{}^m$.

These considerations are suggesting that the sign of φ^m is related to the load effect on the harmonic voltage. In the situations where φ^m is near 90^o, load is mainly linear and inductive or non linear but beneficial to the harmonic voltage distortion. In the opposite case, for φ^m near -90^o, it could be stated that the load is non linear and detrimental to the harmonic voltage distortion.

For the voltage and current distortion levels, shown in Fig. 5.a), b), can be stated following:

a) harmonic voltage is only slightly influenced by the current generated by the non linear load. This is basically due to small system impedance $\boldsymbol{Z}_S$ relative to the load impedance $\boldsymbol{Z}_L$.

b) Measured harmonic current depends strongly on the current generate by the non linear load.

c) Both voltage and current distortion varies with phase difference between two current sources, but in a opposite manner, e.g. for the $\Delta\alpha=180^o$ the effect of the current $\boldsymbol{I}_{NL}$, from the voltage point of view, is beneficial to the system, while the current distortion deteriorates for the same Δα. Opposite behaviour of current and voltage distortion can be observed also for phase difference of 0^o.

These finding may result surprising, but they can be explained immediately by observing that current generating harmonic distortion is $\boldsymbol{I}_o+\boldsymbol{I}_{NL}$, while Fig.5.b) describes behaviour of measured current $\boldsymbol{I}^m$, define by (3).

This put another limit to the separation of the harmonic source as beneficial/detrimental to the system. If the influence of the source to system is considered from voltage distortion point of view, the conclusions can often be in conflict with the results obtained by considering effects on current distortion. It is evident that one non linear load can reduce voltage distortion at the PCC (beneficial to the customer), but, at the same time, it increases current distortion at the same point and at another point of the system (detrimental to the system). It is still open question which approach is to prefer. Harmonic voltage depends on $\boldsymbol{I}_o+\boldsymbol{I}_{NL}$ and indicates the effect of the particular non linear load $\boldsymbol{I}_{NL}$ to the general distortion of the system. Measured current $\boldsymbol{I}^m$ indicate, on the other hand, what is the local effect of the non linear load to the harmonic current.

It must be pointed out that all the simulations described so far where performed assuming mainly inductive system admittance $\boldsymbol{Z}_{S1}$, and $Z_{S1} \ll Z_{L1}$. It is clear that $\boldsymbol{Z}_{S1}$, which can be approximated with the system short circuit impedance at the PCC, is generally much smaller than load impedance. It is also safe to assume that the reactive part of system

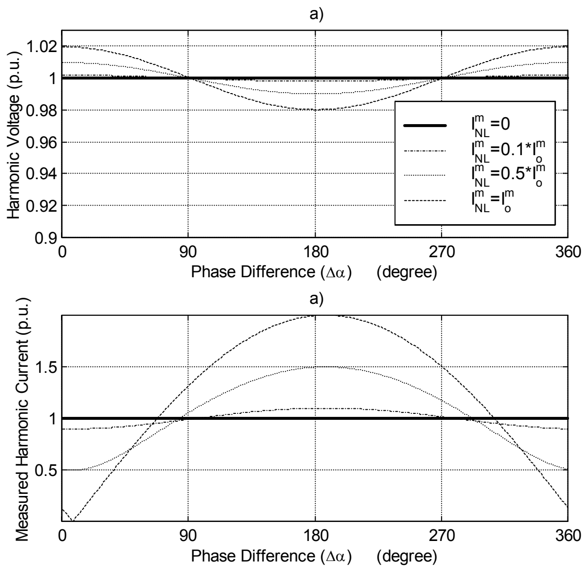

Fig.5. Harmonic voltage (a), and measured harmonic current (b) for different phase difference Δα and for different I_o/I_{NL} ratios.

impedance is dominant over its resistive component. Nevertheless, simulations performed with different values of Z_{S1}/Z_{L1} and generality of the conclusions was verified in a wide range of reasonable values.

Simulations has shown that by decreasing ratio Z_{S1}/Z_{L1} all the comments made are still valid except the fact that the voltage distortion become more influenced by the non linear load, as it should be expected.

3.2. Behaviour of harmonic angle, active and reactive power in the systems with capacitors

What can be said for the cases where capacitors are present in the circuit?

Simulations performed by modifying circuit of Fig.1 by adding in parallel with $\boldsymbol{Z}_L$ capacitor $\boldsymbol{Z}_C$, allows to states the following:

a) harmonic voltage and current variations, due to $\Delta\alpha$, are no more opposite, i.e. both current and voltage distortion decrease for the same $\Delta\alpha$.
b) Reactive power increases significantly with respect to the case with no capacitors. Consequently, harmonic phase φ^m oscillates around -90^o.

Interpreting these results it can be stated that in the presence of capacitors, Q^m is almost always negative, but the voltage is increased for the frequencies below f_{res}, while for higher frequencies voltage is decreased (see Fig.2).

Do the conclusions reached in the section 3.1. remain valid in the presence of capacitors?

In the simulations with ideal capacitors the conclusions are still valid for the frequencies below f_{res}. For the frequencies above f_{res} harmonic voltage is decreased but the harmonic phase remains in the negative range, which is in conflict with the conclusions reached in section 3.1. In the more realistic schemes, where the parasitic or tuning inductance are present, the series impedance will have inductive phase for higher frequencies and will narrow this range of discordance with the conclusions reached in section 3.1. In any case, if precise information is requested, it is necessary to have some notion of impedance frequency behaviour.

4. CONCLUSIONS

In this paper, methods devoted to the identification of the source of harmonic distortion have been investigated. After the brief review of relevant contributions in the field, the influence of capacitors on harmonic distortion of the system has been analysed. Capacitors cannot generate harmonics, but their presence generally amplify both current and voltage total harmonic distortion, although they are passive and linear elements and, as such, absorb harmonic active power.

Next, influence of different parameters on the identification algorithms has been analysed. Simulations have been carried out in order to verify if the harmonic active power sign can be taken as a reliable indicator of the distorting load in various system configurations. The results of the simulations as well as theoretical considerations have shown that harmonic active power depends not only on the active power net flow, but depends also on phase difference between the sources and convey useful information only in the presence of single polluting load.

Although harmonic reactive power depends also on phase difference between two distorting loads, it was shown that the sign of harmonic reactive power is more stable indicator of distorting load and that the harmonic angle is correlated with the effect of the load on the system harmonic voltage. It was also shown that the presence of capacitors in the system alters relation between harmonic phase and harmonic voltage variations for higher frequencies, which highlights the need for information on impedance frequency behaviour.

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