2000 IEEE PES Summer Meeting, Seattle, USA

An Overview of Methods of Harmonic Suppression in Distribution Systems

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Abstract: Economic benefits from using power electronics equipment are much more visible than losses caused by harmonics produced by this equipment. Consequently, we enter the New Millenium with sources of harmonic distortion more and more distributed over distribution systems. We have to confess that we are much more effective in generating harmonics than in their elimination. This situation should not propagate into the Next Century. A more effective method of harmonic suppression is needed.

Harmonics in distribution systems can be suppressed with reactive devices, switching compensators and hybrid devices built of reactive devices and a switching compensator. Selection of a method of harmonic suppression, best suited to particular conditions, requires that advantages, disadvantages and limitations of these devices, which exhibit a very broad range of properties, are well comprehended.

The paper compiles and discusses general properties of various methods of reducing harmonic distortion. Such methods and devices are compared from the point of view of their effectiveness and related issues in various field situations. The paper also investigates some possibilities of new approach to harmonic suppression. In particular, the concept of *a harmonic blocking compensator* and *a fixed-POLE resonant harmonic filter* is presented.

Keywords: Harmonic filters, compensators,

I. INTRODUCTION

Due to a rapid increase in use of switched and non-linear equipment, harmonics now become omnipresent in distribution systems. This is because customers' benefits from using such devices seem to be much more tangible than the harmful effects caused by harmonics generated by these devices. Moreover, these harmful effects are usually distributed over the entire system, while the benefits are distinctively located on the customers' side.

Limitation of waveform distortion on distribution systems is handled on a few different levels, namely:

- Regulations.
- Development of equipment with a low level of the supply current distortion.
- System structure reconfiguration.
- Installation of equipment for harmonic suppression.

The subject of this paper is confined to situations where the regulatory requirements cannot be fulfilled without installation of equipment for reducing harmonic distortion. Such equipment could be classified as

(i) Reactive harmonic suppressors (RHSs)
(ii) Switching compensators (SCs).
(iii) Hybrid devices built of RHS and SC.

Reactive harmonic suppressors enable reduction of harmonics by a modification of the frequency properties of the system. Resonant harmonic filters (RHFs) are the most common reactive harmonic suppressors [2, 5, 7, 8, 9, 13, 16, 18, 19, 20, 22]. This group also includes band-pass filters, (BPF) and harmonic blocking compensators (HBC) [6].

Switching compensators [1, 3, 10], built of fast switching power semiconductors, reduce harmonic distortion in the distribution system by injection of a current (or voltage) that compensates the waveform distortion. Switching compensators are commonly known as *active harmonic filters*, but they are not active but passive devices nor are they filters in the common meanings of the word. The term *power conditioners* is used sometimes for such compensators but this is a very vague name. Power conditioning has a number of different meanings.

Hybrid devices for harmonic suppression are built to overcome [3, 14, 15] some technical limitations of switching compensators using reactive harmonic suppressors in order to increase the power ratings of SCs and reduce their cost.

Reactive harmonic suppressors are often seen now as out of date devices to be retrofitted by switching compensators or hybrid devices. Indeed, resonant harmonic filters, due to their resonance with the reactance of the supply source, may disturb the distribution system and have low effectiveness. On the other hand, switching compensators develop rapidly, and with the progress in power semiconductor technology, their power ratings will increase and their cost will decline. Their complexity may create a psychological barrier for implementations now, but with an increasing reliability, this barrier will disappear. In spite of this, reactance devices for harmonic suppression prevail in distribution systems presently and for an unforeseen future the reactive harmonic suppressors and switching compensators will coexist. Especially, that in some situations RHFs are very effective and there is still a space for the further development of reactive devices for harmonic suppression.

The choice of a device for harmonic suppression, best suited to particular field conditions, is not only a technical issue but also an economical one. Comparative studies are crucial for the proper choice of such a device. Unfortunately, most publications on various devices for harmonic suppression are confined to design or to properties of particular devices or methods. Comparative studies on them are generally not available. A shortage of such studies may contribute to wrong decisions respective the choice of a method of harmonic suppression and, therefore, contributes to higher costs. The intention of this paper is to initiate a discussion on advantages, disadvantages and limitations of various methods of harmonic suppression.

As the name suggests, reactive harmonic suppressors are devices built of inductors and capacitors, though sometime resistors also have to be included. Usually these are the resonant harmonic filters, but sometimes other devices, that cannot be classified as resonant filters, serve as harmonic suppressors. Even a capacitor commonly installed for the power factor improvement may be considered as such a suppressor.

Reactive harmonic suppressors fulfill their task by modification of the frequency properties of the system. Because of that, RHSs, unlike other power equipment such as transformers or motors and also switching compensators, cannot be treated and analyzed as separate devices. Properties of the distribution system where such a RHS is installed are main factors that affect the properties and effectiveness of this RHS. This is particularly visible in the case of resonant harmonic filters. A RHF creates a low impedance path not only for the load generated current harmonics, but also for the distribution system originated harmonics, which increases their contents in the supply current. Moreover, because of the filter resonance with the distribution system reactance, the effectiveness of such filters is strongly affected by reconfigurations in the distribution system that affect this reactance, and by the voltage and current harmonic spectra. These nasty properties of RHSs make the switching compensators so attractive.

On the other hand, the RHSs have a number advantages over the switching compensators. First of all, they are simple, built of components of a well established technology, cost and reliability. RHSs are insensitive to disturbances and to electromagnetic interference. RHSs are inexpensive, not limited as to power ratings and do not have special maintaining requirements. In a distribution system with a very low voltage distortion and with a single, high power harmonics generating load such as, for example, high power rectifiers, a RHF could be a very effective, cheap and reliable harmonic suppressor. Consequently, the RHSs should be kept as an important and attractive alternative to switching compensators.

II. REACTIVE HARMONIC SUPPRESSORS

There are a number of ways that might elevate the attractiveness of RHSs. They could be arranged as follows.

(i) Resonant harmonic filters should be better matched to properties of the distribution system where they are installed than the presently available filters. This means, that they should not be designed as separate devices, but as devices designed in such a way that the frequency properties of the distribution system and its voltage and harmonic spectra are taken into account during the design process. Moreover, optimization procedures should be included into the design process of such matched filters.

(ii) Even optimized RHFs could be effective devices for harmonic suppression only up to some level of the voltage and current minor harmonics. These relative levels of minor harmonics are different for the distribution voltage and for the load current. Moreover, these levels depend on the short circuit power at the bus where the filter is installed and the voltage and current spectra. Therefore, guidelines that would enable the filter designer to identify conditions for a satisfactory filter performance should be developed.

(iii) The power customers should be aware that, unlike other power equipment, a resonant harmonic filter taken "off a shelf" might not be an effective device for harmonic suppression. Before a filter is selected, the system where it is to be installed has to be identified with respect to its internal impedance and voltage and current harmonic spectra. These are the main data that enable the drawing of conclusions regarding the filter performance. The filter cannot be properly selected without these data.

(iv) In the conditions where even a matched RHF is not sufficiently effective, a choice of a reactive harmonic suppressor other than a RHF might be considered.

The class of RHSs is broader than the class of only RHFs. The effectiveness of harmonic suppression can be elevated in some cases by only a small modification of the basic RHF structure. It has to be changed entirely in other cases. There are a few possibilities for improving the effectiveness of harmonic suppression, namely.

(i) It is enough in some cases to add band-pass (BP) branches to the standard RHF structure to improve its frequency characteristics.

(ii) A line inductor can be added to the filter. It reduces the effect of changes in the distribution system reactance on the filter performance. Changes of this reactance shift the harmful resonances of the RHF and make its performance unpredictable. A line inductor makes it possible to design a filter with the harmful resonances (POLEs of the filter) at fixed frequencies, chosen at the designer's discretion, as far as possible from harmonic frequencies. Such filters are referred to as *fixed POLE RHFs* [17].

(iii) The line inductor can be replaced by a LC series filter, tuned to the fundamental harmonic frequency. This makes it possible to increase the line reactance for higher order harmonics and to reduce at the same time the voltage drop for the fundamental harmonic. Such a line LC filter increases attenuation of the higher order harmonics to such a degree, that the shunt resonant harmonic filter can be replaced by a single shunt capacitor. This substantially reduces the device complexity and reduces the number of harmful resonances to a single one. Such a RHS is referred to as *a harmonic blocking compensator* [*HBC*] [6].

(iv) Reactive harmonic suppressors are usually considered to be devices with fixed properties. However, the recent developments in signal processing and in power electronics makes the conversion of RHSs into adaptable devices possible. Static semiconductor switches can be used to keep a RHS matched to the system. Also, harmonic distortion caused by the filter could be limited by a non-linearity [4]. Even energy dissipated in a RHS could be recovered. However, this converts a RHS into a hybrid device, but in a different meaning than explained in the introduction. Switching could be used to elevate the effectiveness of a RHS, rather than using a RHS for increasing the power ratings of a switching compensator.

Apart from the first approach, (i), which could be considered as well established, the next two, (ii) and (iii), are under development now. The last one, (iv), is essentially still an uncharted area. In spite of some disadvantages, the approaches (ii) and (iii) enable us to overcome some limitations of the common resonant harmonic filters.

III. FIXED POLE RHFs

A common resonant harmonic filter has a relatively high admittance Y_x for the distribution voltage harmonics, that means, the admittance as shown in Fig. 1, as compared to this admittance for the fundamental harmonic. Consequently, the distribution voltage harmonics may strongly contribute to the supply current distortion and degrade the filter effectiveness. As an example, the plot of the magnitude of this admittance for a four branch filter, as shown in Fig. 1, tuned to the 5th, 7th, 11th and the 13th order harmonics, is shown in Fig. 2.

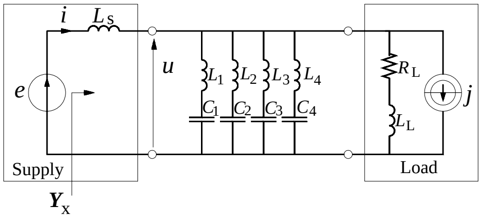

Fig. 1. Equivalent circuit of a distribution system with a harmonics generating load and a resonant harmonic filter

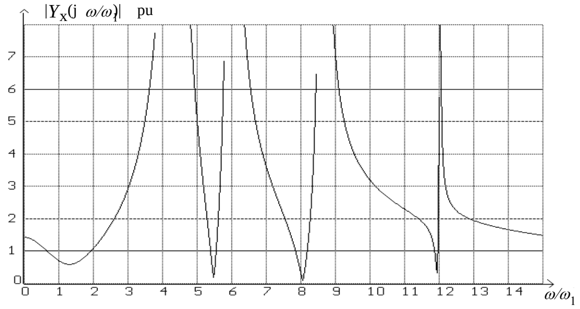

Fig. 2. Magnitude of admittance $Y_x(j\omega)$

It demonstrates that the magnitude of this admittance can be several times higher for some harmonics than for the fundamental. The RHF has, moreover, a few resonances (filter POLEs) with the distribution system reactance and their frequencies could be in a close vicinity of harmonic frequencies. These resonances can amplify both the supply current harmonics and the bus voltage harmonics as compared to these harmonics in the load current and in the distribution system voltage. This harmonic amplification can be expressed in terms of transmittances

$$A(j\omega) = \frac{U(j\omega)}{E(j\omega)}, \qquad B(j\omega) = \frac{I(j\omega)}{J(j\omega)}, \tag{1}$$

where symbols $U(j\omega)$, $E(j\omega)$, $I(j\omega)$, $J(j\omega)$, denote frequency spectra of the bus voltage, u, distribution voltage, e, the supply current, i, and the load generated harmonic current j, respectively. These transmittances have the same numerical values for RHFs. The level $|A| = |B| = 1$ separates the band of harmonic attenuation from the band of harmonic amplification. The plot of the magnitude of these transmittances is shown in Fig. 3. It shows that harmful resonant frequencies (POLEs) can be in a close vicinity of harmonic frequencies and are not predictable during the filter design process. Moreover, POLE frequencies change with system reconfigurations that affect the distribution system reactance.

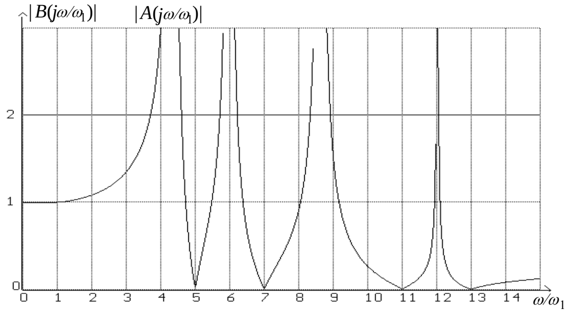

Fig. 3. Magnitude of transmittance $A(j\omega)$ and $B(j\omega)$

The line inductance, L_0, connected as shown in Fig. 4, makes it possible to design the filter in such a way that its POLEs can be chosen at the designer's discretion, and in particular, could be equidistant from the neighboring harmonic frequencies, as shown in Fig. 5. Therefore, such filters are referred to as fixed POLE RHFs. The fixed POLE filters may have the admittance $Y_x(j\omega)$ for harmonic frequencies substantially reduced as compared to common RHFs and consequen-

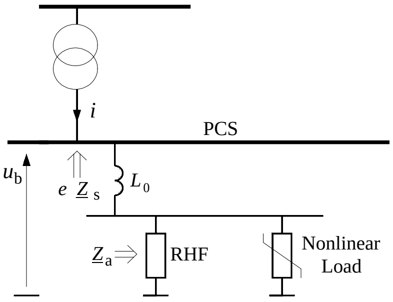

Fig. 4. Distribution system with a fixed POLEs RHF.

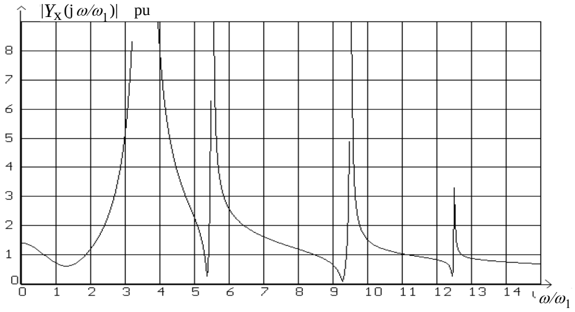

Fig. 5. Magnitude of admittance $Y_x(j\omega)$ of a fixed POLE RHF

tly, substantially reduce the supply current harmonics caused by the distribution voltage distortion. The plot of the magnitude of transmittances $A(j\omega)$ and $B(j\omega)$, drawn in Fig. 6, shows that fixed POLE filters can reduce substantially the harmonic amplification as compared to the common RHFs. Moreover, the line inductance makes the filter performance much less dependent on reconfigu-rations in the distribution system. Consequently, fixed POLEs filters can be installed in systems with much higher distortion of the distribution voltage. They are much more effective and their performance is more predictable than the performance of common resonant harmonic filters.

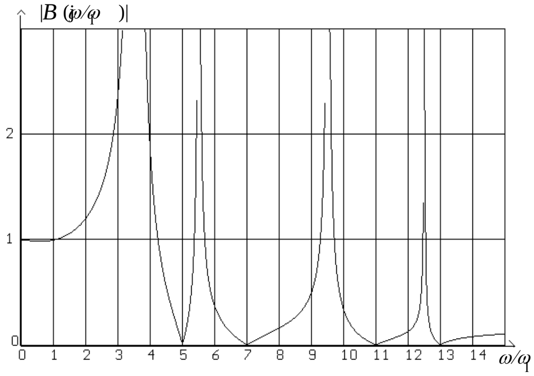

Fig. 6. Magnitude of transmittance $A(j\omega)$ and $B(j\omega)$ of a fixed POLE RHF

The main disadvantage of the fixed POLEs RHFs is the voltage drop on the line inductor. Because of it, the load supply looses its stiffness. The reduction in the voltage stiffness is proportional to the ratio of the line inductance, L_0, to the equivalent inductance, L_S, of the distribution system. An increase in the effectiveness of harmonic suppression may be in some cases more important than the reduction of stiffness. If the stiffness cannot be reduced, a voltage regulator, installed along with the filter, would enable it to be preserved.

VI. HARMONIC BLOCKING COMPENSATORS

Resonant harmonic filters have a resonance with the distribution system inductance below each tuning frequency. Thus their number is equal to the number of the filter branches. With the increase in the harmonic spectrum density, the needed RHF becomes more and more complex or some harmonics are amplified. This could be avoided if the filter is replaced by a capacitor and the line inductor has a sufficiently high inductance. To reduce the voltage drop for the fundamental harmonic, the inductor could be connected in series with a capacitor, as shown in Fig. 7, and the branch should be tuned to the fundamental frequency. The L_bC_b branch can be connected directly into the supply line or through a current transformer. The obtained device can have very high line impedance for high order voltage harmonics and very low shunt impedance for the load current harmonics. Consequently, it can provide very effective separation of the load current and the distribution voltage harmonics. It is referred to, therefore, as a *harmonic blocking compensator.* This structure is similar to an electromagnetic interference (EMI) filter, only the shunt capacitor has to provide reactive power for the load compensation.

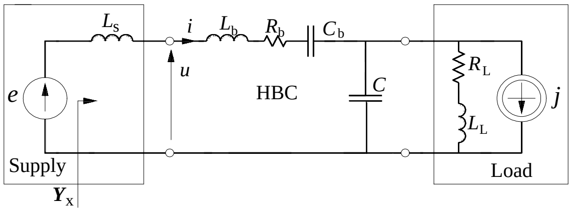

Fig. 7. Equivalent circuit of the distribution system and harmonics generating load with HBC

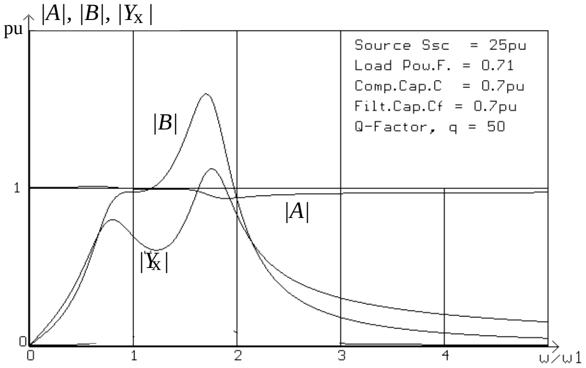

Fig. 8. Plot of magnitude of admittance $Y_x(j\omega)$ and transmittances $A(j\omega)$ and $B(j\omega)$ for harmonic blocking compensator

The magnitude of admittance $Y_x(j\omega)$, and transmittances $A(j\omega)$ and $B(j\omega)$ of a HBC is plotted in Fig. 8. It shows that the HBC eliminates the phenomenon of harmonic amplification and has very low admittance for the supply voltage harmonics. Its efficiency is low only for the 2nd order harmonic.

Similarly as in the case of fixed POLE filters, the presence of the line resonant circuit is the main disadvantage of such compensators especially, that the line inductor should have a higher value than the inductor of a comparable fixed POLE filter. Moreover, it has to be tuned to the fundamental frequency. Not only is the supply stiffness reduced, but also the system is sensitive to the line filter de-tuning. Therefore, before the excellent harmonic suppression properties of HBCs could be exploited, some technical problems have to be solved.

V. SWITCHING COMPENSATORS

Switching compensators, commonly known as active harmonic filters, active power filters or power conditioners, reduce harmonic distortion by sensing harmonics in the load supply currents and next generating and injecting them into the supply lines with the opposite sign, thus compensating these harmonics. There is not sufficient space in this paper for a detailed characterization of these devices, but only for a very concise description. Reference [10] is an excellent source on switching compensator classification and properties.

Compensating currents produced by a switching compensator are shaped by fast switching of power transistors of a pulse width modulating (PWM) inverter. A DC voltage, needed for the PWM inverter operation, is provided by an energy storage device, usually a capacitor. The storage device is charged from the same supply lines where the harmonic currents are compensated. Thus, although switching compensators have to contain an energy storage device, they do not transfer energy to the supply and consequently, such compensators, commonly referred to as "active harmonic filters", are indeed passive, but not active devices. Moreover, current harmonics are not reduced in a filtering process, but by their compensation. Therefore, "active harmonic filters" should not be classified as filters but as compensators.

Switching compensators have a number advantages over the reactive harmonic suppressors. First of all, they are universal devices in the sense that they can reduce not only the supply current harmonics, but also the reactive, unbalanced and scattered currents. Unlike the RHFs, they do not reduce only some selected current harmonics, but all of them. Moreover, they can reduce some non-periodic components of the supply current. At the same time, they do not cause harmful resonances with the distribution systems and they do not cause harmonic amplification. Consequently, unlike the performance of resonant harmonic filters, the switching compensator performance is not dependent on the distribution system properties. At last, by the very nature of their operation, switching compensators are adaptive devices, while reactive harmonic suppressors are rather fixed parameter devices, not easy for converting them into adaptive ones.

Because of all these features, switching compensators will oust reactive harmonic suppressors, at least in some situations, similarly as the digital instrumentation and measurement systems expulse the analog ones, although they will coexist for a long time.

Switching compensators have of course some drawbacks. Some of them are inherent for the switching and digital technology while others are related to the state of the switching compensator development. This is a relatively new technology, practically less than only one decade old. There is still a lot of related research and very often the switching compensators are built only as single prototypes and their technology is not yet well established. Therefore, a number of features of switching compensators, considered as drawbacks, such as their cost, limited power rating or complexity will disappear with the progress in their technology and with a change from the development to a mass production.

An unfavorable but inseparable feature of switching compensator is the necessity of fast switching of high value currents in the power circuit of the compensator. This results in a high frequency noise that may cause an electromagnetic interference (EMI) in the electrical environment of the compensator. With an increase in power rating of SCs, this noise and electromagnetic interference would also increase. This feature is particularly unfavorable, since the number of computer-like equipment that is sensitive to the high frequency noise also increases.

VI. HYBRID COMPENSATORS

A few main limitations of switching compensators, respective available power rating and cost can be overcome with a hybrid compensator [3, 15], built of a switching compensator and a reactive compensator or resonant harmonic filter.

The idea is simple. The load current contains a number of harmful components of a different physical nature. Compensation of some of them does not require a switching compensator, but only a reactive compensator. Since the current components that can be compensated by a reactive compensator are usually the dominating current components, their reduction by such a device substantially reduces the power rating of the PWM inverter of the switching compensator. This reduces at the same time the switching noise and electromagnetic interference, since in such a case the transistor switched currents have a much lower value.

If i denotes the vector of the load line currents, namely

$$i\,(t) \,=\, \begin{bmatrix} i_{\mathrm{R}}(t) \\ i_{\mathrm{S}}(t) \\ i_{\mathrm{T}}(t) \end{bmatrix} \,=\, i\;, \tag{2}$$

then, it can be decomposed into four components

$$i \;=\; i_{1\mathrm{a}} + i_{1\mathrm{r}} + i_{1\mathrm{u}} + i_{\mathrm{h}}\,, \tag{3}$$

where $i_{1\mathrm{a}}$, $i_{1\mathrm{r}}$ and $i_{1\mathrm{u}}$ denote the load active, reactive and unbalanced components of the load current fundamental harmonic and i_{h} denotes a harmonic current. All these current components are mutually orthogonal [21], so that their RMS values $||\, i_{\mathrm{x}}.||$ satisfy the relationship

$$||i||^2 \,=\, ||i_{1\mathrm{a}}||^2 + ||i_{1\mathrm{r}}||^2 + ||i_{1\mathrm{u}}||^2 + ||i_{\mathrm{h}}||^2\,, \tag{4}$$

Usually the RMS value of the reactive and unbalanced currents, $||\, i_{1\mathrm{r}}.||$ and $||\, i_{1\mathrm{u}}.||$ are the dominating components of the load current RMS value and can be compensated without a switching compensator. It can be done by a reactive compensator. Harmonic current i_{h} can be compensated by a harmonic filter, but resonances with the distribution system would occur in such a case. Reducing this current with a switching compensator enables the avoidance of these resonances. If the $i_{1\mathrm{r}}$ and $i_{1\mathrm{u}}$ are compensated by a reactive compensator, the switching compensator needed for the harmonic current i_{h} compensation may have a much lower power rating.

The reactive compensator can be built as a fixed parameter compensator or as an adaptive device. In the first case, a part of the reactive and unbalanced currents of variable loads has to be compensated by the switching compensator. Consequently, its power rating cannot be reduced to the degree possible when the reactive compensator is adaptive.

VII. INSTRUMENTATION

Reduction of harmonic distortion creates particular needs with respect to instrumentation and measurement. In the case of resonant harmonic filters, they cannot be optimized [22] with respect to their effectiveness without detailed data on the distribution system impedance and harmonic spectra of voltages and currents. While spectrum analyzers are common devices now, measurement of the distribution system parameters for harmonic frequencies is not [11,12] a trivial problem. The development of methods and instrumentation for such measurement would contribute to better matching resonant harmonic filters to distribution system parameters. In the case of reduction of harmonics by means of switching compensators instrumentation for identification of the distribution system parameters is not so crucial as in the case of resonant harmonic filters. It may be that only the effects of high frequency noise should be monitored.

VIII.CONCLUSIONS

Economic benefits from using power electronics equipment are much more visible than losses caused by harmonics produced by this equipment. Consequently, we enter the New Millenium with sources of harmonic distortion more and more distributed over distribution systems. We have to confess that we are much more effective in generating harmonics than in their elimination. This situation should not propagate into the Next Century. Effective methods of harmonic suppression are needed.

A quest for effective methods of harmonic suppression may go into the existing technology to improve it. This quest may look for new methods as well. Also, education on the properties of distribution systems with harmonics, on a proper implementation of various methods of their suppression and on instrumentation and measurement for that purpose may contribute substantially to reduction of harmonic distortion in distribution systems.

Resonant harmonic filters, the most common devices for reducing harmonic distortion, increasingly more often compete with switching compensators. The old technology competes with the new one. This old technology still has a capacity for a further development, while switching compensators do not occur to be an absolute and economic remedy for harmonic distortion. Moreover, the interaction of resonant harmonic filters with the distribution system plays a key role in the filter effectiveness, but it seems that this interaction is often not fully comprehended.

REFERENCES

[1] L. Gyugyi and E.C. Strycula, “Active AC power filters,” Conf. Rec., IEEE IAS, 1976, pp. 529-535.

[2] P.W. Hammond, “A harmonic filter installation to reduce voltage distortion from static power converters,” IEEE Trans. on Ind. Appl., Vol. 24, No. 1, Jan./Feb. 1988, pp.53-58.

[3] F.Z.Peng, H. Akagi, A Nabae, “A new approach to harmonic compensattion in power systems,” IEEE paper No. 88CH2585-0/88/0000-0874.

[4] M. Loggini, G.C. Montanari, E. Tironi, D. Zaninelli, “Design of nonlinear resistor for filter performance improvement,” Proc. of the IEEE IAS Annual Meeting, San Diego, 1989.

[5] M.M. Cameron, “Trends in power factor corrections with harmonic filtering,” IEEE Trans. on Ind. Appl., Vol. 29, No. 1, Jan./Feb., 1993, pp. 60-65.

[6] L.S. Czarnecki, “Harmonic blocking compensator: an alternative for improving power quality,” Proc. of the 6th International Conference on Harmonics in Power Systems, ICHPS - VI, pp. 283-288, Bologna, Italy, 1994.

[7] D. Ruthman, “Low voltage harmonic filter considerations for three phase industrial systems,” 1994 IEEE PES Winter Meeting, New York, 1994.

[8] W.E. Reid, K.A. Puskarich. “Harmonic filter application criteria,” 1994 IEEE PES Winter Meeting, New York, 1994.

[9] L.S. Czarnecki, “Effect of minor harmonics on the performance of resonant harmonic filters in distribution systems,” Proc. IEE, Electr. Pow. Appl., Vol. 144, No. 5, July/August 1995, pp. 349-356.

[10] H. Akagi, “New trends in active filters for power conditioning,” IEEE Trans. on Ind. Appl., Vol. 32, No. 6, Nov./Dec. 1996, pp. 1312-1322.

[11] L.S. Czarnecki, Z. Staroszczyk, “On-line measurement of equivalent parameters for harmonic frequencies of a power distribution system and load,” IEEE Trans. on Instr. Measur., Vol. 45, No. 2, April 1996, pp. 467-472.

[12] L.S. Czarnecki, Z. Staroszczyk, “Dynamic on-line measurement of equivalent parameters of three-phase systems for harmonic frequencies,” Europ. Trans. on Electrical Power, ETEP, Vol. 6, No. 5, Sept./Oct. 1996, pp. 329-335.

[13] J.K. Phipps, “A transfer function approach to harmonic filter design,” IEEE Industry Appl. Magazine, March/April 1997, pp. 68-82.

[14] P. Mattevelli and P. Tenti, “Design aspects of hybrid compensation systems,” Europ. Trans. on Electrical Power,” ETEP, Vol. 8, No. 5, Sept./Oct. 1998, pp. 375-381.

[15] L.S. Czarnecki, G. Chen, Z. Staroszczyk, “Application of running quantities for control of adaptive hybrid compensator,” *Europ. Trans. on Electr. Power, ETEP,* Vol. 6, No. 5, Sept./Oct. 1996 pp. 337-344.

[16] C.-J. Wu, J.-C. Chiang, S.-S. Jen, C.-J. Liao, J.-S. Jang and T.-Y. Guo, “Investigation and mitigation of harmonic ampli-fication problems caused by single-tuned filters,” IEEE Trans. on Power Delivery, Vol. 13, No. 3, July 1998, pp. 800-806.

[17] L.S. Czarnecki, “Common and fixed-poles resonant harmonic filters, Europ. Trans. on Electrical Power,” ETEP, Vol. 8, No. 5, Sept./Oct. 1998, pp. 345-351.

[18] Kun-Ping Lin, Ming-Hoon Lin, Tung-Pin Lin, “An advanced computer code for single tuned harmonic filter design,” IEEE Trans. on Ind. Appl., Vol. 34, No. 4, July/Aug. 1998, pp. 640-648.

[19] W. Mielczarski, W.B. Lawrance and J. Szczepanik, “Field test of a filter to reduce harmonic currents in a three phase fluo-resent lamp system,” IEEE Trans. on Pow. Del., Vol. 14, No.3, July 1999, pp.1002-1007.

[20] K.F. Granaghan, R.D. Mueller, “Design harmonic filters for adjustable-speed drives to comply with IEEE-519 harmonic limits,” IEEE Trans. on Ind. Appl., Vol. 35, No. 2, March/April. 1999, pp. 312-318.

[21] L.S. Czarnecki, “Harmonics and power phenomena,” Wiley Encyclopedia of Electrical and Electronics Engineering, John Wiley & Sons, Inc., Supplement 1, 2000, pp. 195-218.

[22] L.S. Czarnecki, H. Ginn, “Effectiveness of resonant hararmonic filters and its improvement,” Proc. 2000 1EEE PES Summer Meeting, Seattle, 20000.

BIOGRAPHY

Leszek S. Czarnecki (SM’84, F’96) received the M.Sc. and Ph.D. degrees in electrical engineering and Habil. Ph.D. degree from the Silesian Technical University, Poland, in 1963, 1969 and 1984, respectively, where he was employed as an Assistant Professor. Beginning in 1984 he worked for two years at the Power Engineering Section, Division of Electrical Engineering, National Research Council of Canada as a Research Officer. In 1987 he joined the Electrical Engineering Dept. at Zielona Gora Technical University, Poland. In 1989 Dr. Czarnecki joined the Electrical and Computer Engineering Dept. of Louisiana State University, Baton Rouge, where he is a Professor of Electrical Engineering now. For developing a power theory of three-phase nonsinusoidal unbalanced systems and methods of compensation of such systems he was elected to the grade of Fellow IEEE in 1996. His research interests include network analysis and synthesis, power phenomena in nonsinusoidal systems, compensation and supply quality improvement in such systems.

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