The Control System on the Base of Signal Processing for Power Quality Improvement in Electrotechnical Complexes of Alternative and Renewable Power Sources

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***Abstract*—The paper deals with the problem of creation and developing of effective and perspective control means and methods for correction of voltage and current level and harmonic spectrum by means of active and hybrid correction systems in conditions of distributed generation on the base of renewable and alternative power sources. The main types of active and hybrid correction systems are presented and analyzed. The main existing means and methods of harmonic detection, compensation and signal processing are presented and analyzed. The universal control system structure for active and hybrid correction systems is proposed. The proposed control system structure and algorithm are based on existing theories of harmonic compensation and power decomposition, current physical components, p-q theory and also on modern signal processing methods. The efficiency of proposed algorithm and control system is proved by results of mathematic modeling and computer simulation. The required level of proposed control system redundancy is proved.**

I. Introduction

Nowadays the problem of power quality and electromagnetic compatibility ensuring is actual both for conventional centralized power supply systems and distributed generation systems on the base of alternative and renewable power sources. The main reason of power quality and electromagnetic compatibility decreasing is a wide spread of nonlinear load, which consumes non-sinusoidal current and generates harmonics in power supply system.

The main type of nonlinear load is power frequency converters of different structure and function mode. In case of conventional centralized power supply systems mentioned nonlinear loads are mostly presented as a part of variable frequency drives of process installations. In case of distributed generation systems on the base of alternative and renewable power sources mentioned nonlinear loads can be presented also as a part of variable frequency drives of process installations and as a part of electrical complexes of solar power stations, wind farms and micro turbine installations, which work on following oil gas. For example the electrical complexes of solar power stations include one and more DC/AC or DC/DC power converters for compliance of voltage levels of solar panels and consumers or for conversion of direct current of solar panels to alternative current of power supply system [1, 2]. The similar example is valid also for wind farms and micro turbine installations, which work on following oil gas.

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II. The Existing Devices and Decisions

The main consequences of negative influence of voltage and current harmonics to electrical equipment are the decreasing of rated lifetime, the possibility of resonance modes occurrence, incorrect function of digital relay protection systems, isolation damage [3, 4].

There are a number of the following passive technical devices for voltage and current harmonics elimination:

- Passive filters of different structure.
- Damping reactors.
- Power transformers with special connection of the secondary winding.

One common disadvantage of the mentioned passive technical devices is the limited range of harmonic order for compensation [5, 6].

Also there is a class of active devices, based on voltage source converters and current source converters, intended for harmonic elimination, reactive power compensation, voltage dips and deviations elimination, source and load asymmetrical modes compensation [7]. Among these devices it is necessary to indicate the following:

- Shunt and series active filters.
- Active front end rectifiers.
- STATCOM devices.
- SVC devices.
- Dynamic voltage restorers.

The functional capability of these devices is considerably wider than passive devices, but in some cases even active devices can not give the required result [8, 9]. That is why for such difficult cases the hybrid systems should be used [10].

The hybrid systems can be classified according to the following key factors:

- The way of active and passive part connection to each other.
- The way of hybrid system connection with compensated network.
- The type of power converter in active part.

Also for hybrid systems it is necessary to use more difficult algorithms and methods. The realization of such algorithms and methods should be provided on the base of modern signal processing technologies.

III. The Existing Algorithms and Methods

The most existing algorithms and methods for control of hybrid systems are based on Clark transformations of voltages and currents. Also some numerical methods can be used in existing algorithms such as Fast Fourier Transformation (FFT) and Discrete Fourier Transformation (DFT). The general classification of existing algorithms and methods is presented on Fig.1.

There are some basic functions of active and hybrid correction systems in the area of power quality improvement and electromagnetic compatibility ensuring [11]:

- Voltage and current harmonic elimination.
- Voltage dips and fluctuations compensation.
- Power factor correction.
- Source and consumer unbalance compensation.
- The improvement of energy efficiency of variable speed drives systems.

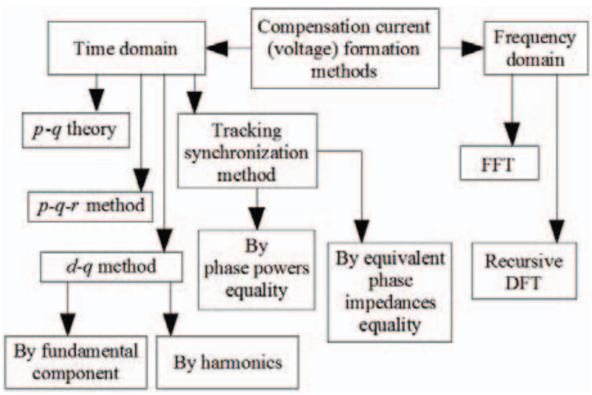

Fig. 1. The general classification of existing algorithms and methods

Most algorithms of current harmonic elimination are based on reference current determination by means of different power theories and methods of orthogonal current decomposition. Nowadays there is a set of theories and methods, which are applied in active and hybrid correction systems control. According to researches results and analysis of recent significant publications the following theories, methods and scientific directions should be indicated for using when developing of effective algorithms [12, 13]:

- Classical theories, developed by C. Budeanu and S. Fryze.
- Current physical components theory, proposed by L. Czarnecki.
- Instantaneous power theory, developed by H. Akagi.

The mentioned three main scientific directions are the basis of different modern theories and methods of power and current components. That’s why they must be considered as theoretical basis for developing new effective control methods and means for active and hybrid correction systems control. However these theories have some disadvantages, let’s consider them.

Theory, proposed by C. Budeany, doesn’t give an exact and applicable in practice equation for calculation of distortion non-active power [14].

Theory, proposed by S. Fryze, doesn’t allow to determine exactly the active current, because the active conductance can vary during a period [15].

Current physical components theory, proposed by L. Czarnecki, is applicable only in three-phase three-wire power systems, for three-phase four-wire power systems this theory isn’t applicable [16].

Instantaneous power theory or *p-q* theory, proposed by H. Akagi, is correct only in the case of balanced linear load. Also in some publications it’s maintained and proved that according to Akagi’s theory the active current isn’t in phase with supply voltage [17]. This fact contradicts to fundamental definition of active current according to classical theory, proposed by Fryze.

IV. Theoretical Basis of Proposed Universal Control System Structure

The universal and flexible system for effective control of active and hybrid correction systems must perform the mentioned in section III base functions for power quality improvement and electromagnetic compatibility ensuring. For realization of each function it’s necessary to create theoretical basis with help of acknowledged methods.

Theoretical basis for voltage and current harmonic elimination is the current physical components theory, proposed by L. Czarnecki. For effective realization of this function it’s necessary to detect two main values: active current magnitude and phase relations of supply voltages for phase synchronization of compensation current or voltage with power supply system [18]. According to current physical components theory the equivalent active conductance G_{eqv} is determined by means of the following formula:

$$G_{eqv} = \frac{P}{U_{rms}^2} \tag{3}$$

In (3) P is an active power, U_{rms} is a RMS value of supply voltage. The results of theoretical researches, mathematical modeling and computer simulation show that the equivalent active conductance for active current magnitude determination should be calculated for the fundamental component, according to the following equation:

$$G_1 = \frac{P_1}{U_1^2} \tag{4}$$

In (4) P_1 and U_1 are the active power and RMS value of supply voltage of fundamental component correspondingly. Then the active current magnitude can I_{a1m} be calculated by means of the following formula:

$$I_{a1m} = \sqrt{2} G_1 U_1 = \sqrt{2}\frac{P_1}{U_1} \tag{5}$$

Instantaneous value of the reference active current $i_{a1}(t)$ can be determined according to the following equation:

$$i_{a1}(t) = G_1 u_1(t) \tag{6}$$

In (6) $u_1(t)$ is the instantaneous value of supply voltage of fundamental component.

A phase synchronization of compensation current or voltage with power supply system is realized by means of the phase locked loop (PLL) system. PLL is well known technology, which has been applied in different electronic power and communication devices [19]. There are several methods of PLL realization, the most effective of them are the following:

- The usage of orthogonal components of input signals by means of Park and Clark transformations.
- The application of additional low-pass filter in case of unbalanced power supply system.
- The usage of state space formalism.

For effective PLL application in active and hybrid correction systems it is reasonable to use Park and Clark transformations of input voltages and currents according to the results of mathematical modeling and computer simulation.

Theoretical basis for unbalance elimination is the method of symmetrical components. According to this method it is necessary to detect the direct sequence components of supply voltages vector by means of the following equations [5]:

$$u_{A1} = \frac{1}{3}\left(u_A + a u_B + a^2 u_c\right),\ u_{B1} = u_{A1} a^2,\ u_{C1} = u_{A1} a \tag{7}$$

In (7) u_A, u_B, u_C are the instantaneous values of supply phase voltages, a is the operator, defined as $a = e^{j2\pi/3}$, u_{A1}, u_{B1}, u_{C1} are the instantaneous values of direct sequence component of supply phase voltages. The equations (7) can be presented in vector form by means of Fortescue transformation [5]:

$$\vec{u_1} = \begin{bmatrix} u_{A1} \\ u_{B1} \\ u_{C1} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} u_{A1} \\ a^2 u_{A1} \\ a u_{A1} \end{bmatrix} \tag{8}$$

Finally the compensation voltage vector for unbalance elimination in conditions of combined functioning of centralized power supply and distributed generation system can be calculated according to the following formula [5]:

$$\overrightarrow{u_{uc}} = \overrightarrow{u_c} - \overrightarrow{u_{c1}} - \overrightarrow{u_d} + \overrightarrow{u_{d1}} \tag{9}$$

In (9) $\overrightarrow{u_{uc}}$ is the compensation voltage vector for unbalance elimination, $\overrightarrow{u_c}$ and $\overrightarrow{u_d}$ are the vectors of centralized power supply and distributed generation voltages correspondingly, $\overrightarrow{u_{c1}}$ and $\overrightarrow{u_{d1}}$ are the vectors of direct sequence component of centralized power supply and distributed generation voltages correspondingly.

Reactive power compensation is based on C. Budeanu and S. Fryze definitions with some corrections and additions. Firstly it is necessary to divide the fundamental component and harmonic reactive powers, then the harmonic active power should be extracted [20]. Also the cross-harmonic non-active power should be determined. Reactive power compensation should be realized firstly on fundamental component frequency, other reactive and non-active components can be eliminated during harmonic compensation.

Fundamental component and harmonic reactive powers Q_1 and Q_h can be determined according to the following equations:

$$Q_1 = U_1 I_1 \sin \varphi_1 \tag{10}$$

$$Q_h = \sum_{n=2}^{\infty} U_n I_n \sin \varphi_n \tag{11}$$

In equations (10) and (11) U_1 and I_1 are the RMS values of supply voltage and consumption current of fundamental component, φ_1 and φ_n are phase angles for fundamental component and harmonic of n order.

Harmonic active power P_h can be calculated by means of the following equation:

$$P_h = \sum_{n=2}^{\infty} U_n I_n \cos \varphi_n \tag{12}$$

Cross-harmonic non-active power components can be calculated according to the following equations:

$$\mathrm{Re}(S_{nm}) = U_m I_n \cos((n-m)\omega t + \psi_{in} - \psi_{um}) \tag{13}$$

$$\mathrm{Im}(S_{nm}) = U_m I_n \sin((m-n)\omega t + \psi_{um} - \psi_{in}) \tag{14}$$

Equation (13) defines the real part of complex cross-harmonic power S_{nm}, equation (14) defines the imaginary part of complex cross-harmonic power S_{nm}, U_m is voltage harmonic of m order, I_n is current harmonic of n order, ψ_{um} is phase angel of U_m, ψ_{in} is phase angel of I_n.

Reactive power compensation on the frequency of fundamental component and harmonic elimination allows to improve total power factor cosφ and power factor of fundamental component $\cos\varphi_1$, which can be determined by means of the following equation:

$$\cos\varphi = \frac{P}{S} \tag{15}$$

$$\cos\varphi_1 = \frac{P_1}{S_1} \tag{16}$$

In (15) and (16) P_1 and S_1 are the active and total powers of the fundamental component correspondingly, P and S are the active and total powers correspondingly, which may include harmonic components, if their compensation is not provided.

Voltage dips and deviations elimination also is based on PLL system and extraction of direct sequence component of supply voltage [21].

V. The Proposed Universal Control System Structure

The proposed universal control system structure for active and hybrid correction systems is presented on Fig.2.

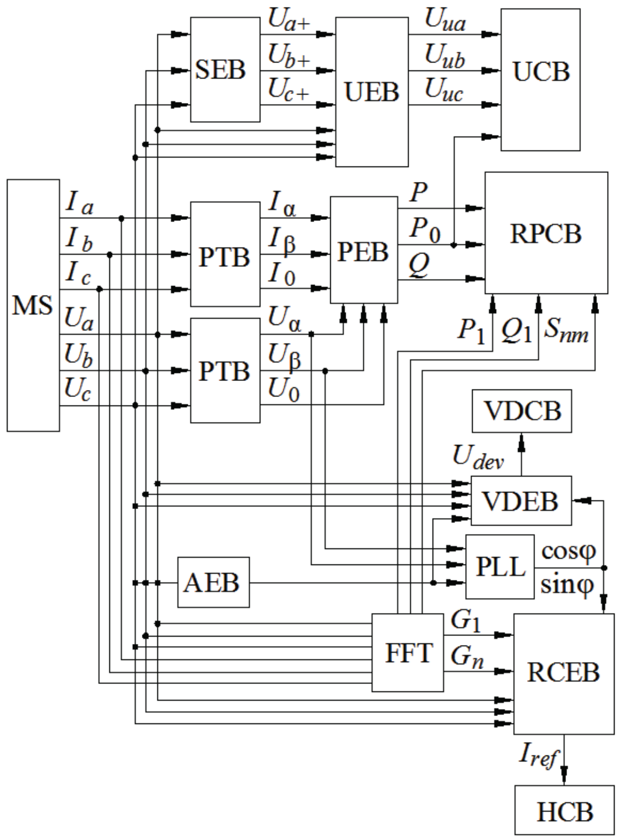

Fig.2. The proposed universal control system structure

The proposed structure includes the following blocks:

- Measurement system (MS).
- Phase transformations block (PTB).
- Sequence extraction block (SEB).
- Amplitude extraction block (AEB).
- Unbalance extraction block (UEB).
- Power extraction block (PEB).
- Fast Fourier transform (FFT).
- Phase locked loop (PLL).
- Voltage deviation extraction block (VDEB).
- Reference current extraction block (RCEB).
- Unbalance compensation block (UCB).
- Reactive power compensation block (RPCB).
- Voltage deviation compensation block (VDCB).
- Harmonic compensation block (HCB).

MS provides measurement information about phase voltages (U_a, U_b, U_c) and currents (I_a, I_b, I_c) of power supply system. PTB is necessary for Clark and Park phase transformations from three phase system abc to αβ0 system (U_α, U_β, U_0, I_α, I_β, I_0). SEB provides the direct sequence component (U_{a+}, U_{b+}, U_{c+}) of supply voltage extraction according to (7) and (8). AEB extracts the amplitude of direct sequence component of supply voltage. UEB separates unbalance components of supply voltage (U_{ua}, U_{ub}, U_{uc}). PEB provides the extraction of active and reactive power (P, Q) and zero sequence component power (P_0) according to instantaneous p-q power theory. FFT is necessary for extraction conductance (G_1), active and reactive power (P_1, Q_1) of fundamental component, conductance (G_n) for n order harmonic. PLL generates unity sine and cosine signals (sinφ, cosφ), which provides phase synchronization of compensation current and voltage with power supply system. VDEB determines the value of voltage deviation or dip and forms proper compensation voltage signal.

Similarly RCEB determines the value of reference current and forms proper compensation current signal. UCB, RPCB, VDCB, HCB provide elimination of unbalance, reactive and non-active power, voltage dips and deviations, harmonics correspondingly. All compensation signals are converted into control pulses for power elements of voltage source and current source inverters by means of hysteresis regulators.

The hardware implementation of proposed system is based on the digital signal processor (DSP), which key parameters are determined by the required level of residual voltage and current harmonics after correction. Also the hysteresis width of hysteresis regulators influences on the CPU clock of DSP.

The required redundancy level of proposed control system may be reached by means of optimization of key parameters calculation sequence. Also in proposed system there is no doubling functions and calculations, which could rise the redundancy level.

VI. Simulation results

For evaluation of efficiency of proposed universal control system the mathematical model of power supply system with nonlinear load and hybrid correction system is developed in MATLAB Simulink software. The parameters of power supply system and nonlinear load are selected according to the results of experimental researches, which were carried out in conditions of oil production enterprises. These parameters are suitable also for other industrial areas, where nonlinear load has wide spread in form of power converters of variable speed drive systems. The hybrid correction system is realized on the base of shunt active filter with voltage source inverter and passive filters, which are tuned to eliminate 5 and 7 harmonic. The control system of hybrid correction system is realized on the base of proposed universal control system structure.

The computer simulation of developed mathematical model was carried out according to the following stages:

- Harmonic elimination simulation.
- Reactive and non-active power compensation simulation.
- Voltage dip and deviations elimination simulation.
- Unbalance compensation simulation.

The results of harmonic elimination simulation are presented in Tab.I, where the voltage and current total harmonic distortion (THD) factors before and after compensation are shown. The values of voltage and current THD factors show the efficiency of proposed control system functioning and power quality factors compliance with requirements of Russian GOST 32144-2013 and International standard IEEE 1459-2010 in power quality and electromagnetic compatibility area.

The results of reactive and non-active power compensation simulation are presented in Tab.II, where the fundamental component (Q_1) and harmonic (Q_n) reactive power and cross-harmonic power (S_{nm}) are shown. Cross-harmonic power is calculated for harmonics before 30 order.

The results of voltage dips and deviations elimination simulation are presented in Tab.III, where the phase supply voltages (U_a, U_b, U_c) are shown.

TABLE I.
THE RESULTS OF HARMONIC ELIMINATION SIMULATION

Simulation mode	Power quality factors	
	Voltage THD, %	*Current THD, %*
Before elimination	17.3	19.6
After elimination	3.77	3.69

TABLE II.
THE RESULTS OF REACTIVE AND NON-ACTIVE POWER COMPENSATION SIMULATION

Simulation mode	Reactive and non-active power		
	Q_1, *kvar*	Q_n, *kvar*	S_{nm}, *kva*
Before compensation	24.5	2.3	1.8
After compensation	8.5	1.2	0.7

TABLE III.
THE RESULTS OF VOLTAGE DIPS AND DEVIATIONS ELIMINATION SIMULATION

Simulation mode	Phase voltages RMS values		
	U_a, *V*	U_b, *V*	U_c, *V*
Before elimination	213.3	213.4	213.4
After elimination	228	227.9	227.3

After this elimination mode the deviations of phase voltages are not exceed ±10 % of rated phase voltage value (220 V), that satisfy the requirements of Russian GOST 32144-2013 and International standard IEEE 1459-2010 in power quality and electromagnetic compatibility area.

The results of unbalance compensation simulation show that negative sequence factor k_2 of phase supply voltages decrease from 12.5 % to 5.9 % and zero sequence factor k_0 of phase supply voltages decrease from 8.4 % to 3.2 %, that also satisfy the requirements of Russian GOST 32144-2013 and International standard IEEE 1459-2010 in power quality and electromagnetic compatibility area. Network voltage (U_c) and current (I_c) waveforms before and after harmonic elimination during computer simulation are presented on Fig.3.

VII. Conclusion

The universal control system structure on the base of signal processing for active and hybrid correction systems is proposed. The mentioned universal control system allows to improve power quality and ensure electromagnetic compatibility in conditions of traditional centralized power supply systems and distributed generation systems on the base of alternative and renewable sources.

The proposed control system is intended for voltage and current harmonic elimination, reactive and non-active power compensation, unbalance correction, voltage dips and deviations compensation.

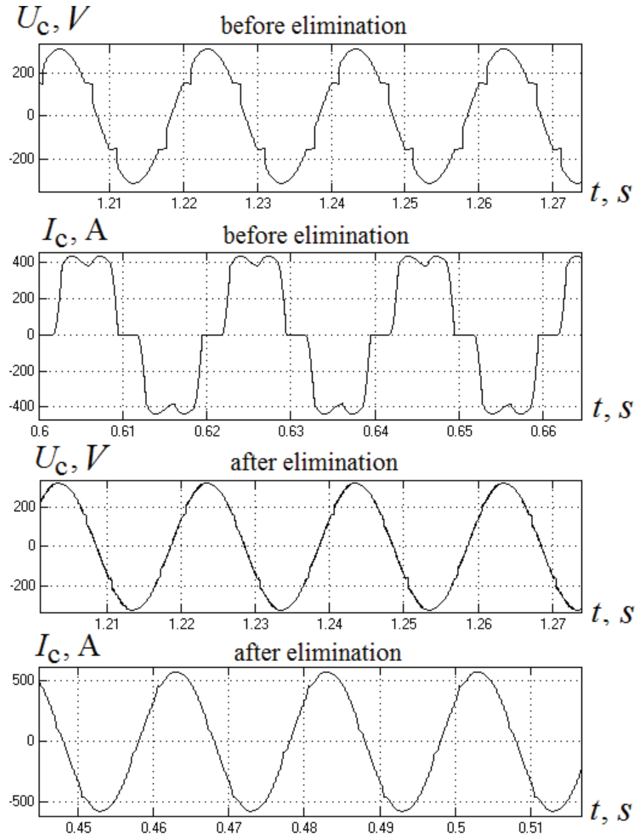

Fig.3. Network voltage and current waveforms before and after harmonic elimination during computer simulation

The mathematical model of power supply system with nonlinear load and active correction system, which equipped with proposed control system, is developed. The results of computer simulation of developed mathematical model show the satisfactory efficiency of proposed universal control system structure. The recommendations for redundancy level improvement of proposed system are presented.

REFERENCES

[1] A. Bose, "Smart transmission grid applications and their supporting infrastructure", *The Consortium for Electric Reliability Technology Solutions (CERTS)*, Oct.2008, pp. 1-18.

[2] A. Sumper, A. Bagini, "*Electrical energy efficiency: technologies and applications"*, Wiley, New York, 2012.

[3] M. Bollen, I. Gu, *"Signal processing of power quality disturbances"*, Wiley, New York, 2006.

[4] B.N. Abramovich, Yu.A. Sychev, V.B. Prokhorova, "The application of modern information technologies for power monitoring and control in conditions of distributed generation", in: *Proceedings of the 16th Conference of the Open Innovations Association (FRUCT 16)*, Oulu (Finland), 27-31 October, 2014, pp. 3-8; doi: 10.1109/FRUCT.2014.7000938.

[5] S.P. Litrán, P. Salmerón, J. Prieto Alejandro Pérez, "Control strategy for an interface to improve the power quality at the connection of AC microgrids", *International Conference on Renewable Energies and Power Quality (ICREPQ'14) Cordoba (Spain)*, Apr.2014, ISSN 2172-038 X, No.12.

[6] B.N. Abramovich, Yu.A. Sychev, V.A. Burchevskly, A.A. Vyrva, R.A. Ulbaev, V.V. Polishuk, "The shunt active filters implementation for power quality increasing in electrical networks of Priobskoye deposit", *Neftyanoe Khozyaistvo - Oil Industry* 6 (June) (2011) 130-132.

[7] A. Patrascu, M. Popescu, "Comparative active current calculation by p-q and CPC theories", *Annals of the University of Craiova, Electrical Engineering series*, No. 35, 2011; ISSN 1842-4805, pp. 25-30.

[8] A. Bitoleanu, M. Popescu, "How can the IRP p-q theory be applied for active filtering under nonsinusoidal voltage operation?", *Przegląd Elektrotechniczny (Electrical Review),* ISSN 0033-2097, R. 87 No. 1/2011, pp. 67-71.

[9] M. Firoozian, H. Mirnezhadi, E. Hadadi, "Active shunt filter for harmonic mitigation in wind turbines generators", *International Journal of Engineering and Innovative Technology (IJEIT)* Vol. 3 Issue 5 (November) (2013) 6-12.

[10] B.N. Abramovich, Y.A. Sychev, D.A. Ustinov, "Intelligent Active-adaptive Power System of Industrial Enterprises", *Proceedings of the 12th Conference of Open Innovation Association FRUCT and Seminar on e-Travel*., Nov.2012. pp. 197-203.

[11] R. H. Lasseter, "Smart Distribution: Coupled Microgrids", *The Consortium for Electric Reliability Technology Solutions (CERTS)*, Jan.2011, pp. 1-8.

[12] P. Tenti, A. Costabeber, P. Mattavelli, "Improving Power Quality and Distribution Efficiency in Micro-Grids by Cooperative Control of Switching Power Interfaces". *In: Proceedings of 2010 International Power Electronics Conference (IPEC-Sapporo 2010)*. Sapporo (Japan), June 2010, pp 472-479, ISBN/ISSN: 978-1-4244-5395-5.

[13] H.K. Morales Paredes, A. Costabeber, P. Tenti, "Application of Conservative Power Theory to Cooperative Control of Distributed Compensators in Smart Grids", *Proceedings of the 10th International School on Nonsinusoidal Currents and Compensation. Lagow (Poland)*, June 2010, pp 126-132, ISBN/ISSN: 978-1-4244-5437-2.

[14] R. Klempka, "Distributed System for Power Quality Improvement", *Electrical Power Quality and Utilisation*, Journal, vol. XIV, No. 2, Feb.2008. pp. 53-68.

[15] Horowitz, S, A. Phadke, B. Renz, "The Future of Power Transmission," *IEEE Power and Energy*, vol.8, no.2, Mar./Apr. 2010, pp. 34-40.

[16] M. Ranjbar, M. A. Masoumand A. Jalilian, "Comparison of compensation strategies for shunt active power filter control in unbalanced three-phase four-wire systems", in: *Proceedings of 22nd Canadian Conference on Electrical and Computer Engineering (CCECE'09)*, May 2009, pp. 1061-1066.

[17] L. S. Czarnecki, "On Some Properties of Instantaneous Active and Reactive Powers*", Electrical Power Quality and Utilisation*, Journal Vol. XVI, No. 1, 2013, pp. 11-17.

[18] L.S. Czarnecki, "On some misinterpretations of the instantaneous reactive power p-q theory", *IEEE Trans. Power Electronics*, vol. 19, no. 3, 2004, pp.828-836.

[19] J. Li, Z. Chen, Z. Shen, P. Mattavelli, J. Liu, D. Boroyevich, "An adaptive dead-time control scheme for high-switching-frequency dual-active-bridge converter" *Applied Power Electronics Conference and Exposition Annual IEEE Conference - APEC*, 5-9 Feb. 2012. pp 1355 – 1361.

[20] N. Golovanov, G. C. Lazaroiu, M. Roscia, D. Zaninelli, "Power quality assessment in small scale renewable energy sources supplying distribution systems", *Energies* 6 (2013) 634-645; doi:10.3390/en6020634.

[21] L. F. C. Monteiro1, J. L. Afonso, J. G. Pinto, E. H. Watanabe, M. Aredes, H. Akagi, "Compensation algorithms based on the p-q and CPC theories for switching compensators in micro-grids", *The 10th Brazilian Power Electronics Conference*, vol. 1149, Sep./Oct.2009, pp. 32-40.