Proceedings of the Seventh IASTED International Conference
POWER AND ENERGY SYSTEMS
August 29–31, 2007, Palma de Mallorca, Spain
ISBN Hardcopy: 978-0-88986-689-8 / CD: 978-0-88986-690-4

INSTANTANEOUS POWER FLOW DETERMINATION FOR SINGLE-PHASE UPFC

Branislav Dobrucky, Slavomir Drozdy, Michal Pokorny, Rastislav Pavlanin
University of Zilina
Univerzitna 1, 010 26 Zilina
Slovak Republic
dobrucky@fel.uniza.sk

ABSTRACT
The paper deals with the high dynamic properties of single-phase unified power flow conditioner (UPFC). Using a virtual approach and application of orthogonal transform theory the ordinary single-phase system can be transformed into equivalent two-axes system. The new thought is based on the idea that ordinary single-phase quantity can be complemented by virtual fictitious phase so that both of them will create orthogonal system, as is usual in three-phase systems. Application of above-mentioned theory makes it possible to use complex methods of analysis as instantaneous reactive power method. Both, the active and reactive powers can be determined by this way. Practical application of the method is outlined for the case of active and reactive power determination for single-phase power unified power flow controller. The paper presents some examples of the simulation experiments results focused on regulation output voltage of UPFC, in its last part.

KEY WORDS
Power flow analysis, unified power flow conditioner, power active filters, moving average method, instantaneous reactive power theory

1. Introduction - Controlling UPFC

Voltage changes and voltage drops belong in the most important quality parameters of supplying electric energy. With extension of voltage sensitive appliances, industrial processes are exposed to permanent risk of failure, respectively to wrong function of process activity because of voltage drop. Serial active filter has to generate missing voltage for power system voltage drops corrections. It is also possible to control active and reactive power simultaneously with output voltage regulation [3], [6], [7].

Parallel shunt active filter of UPFC can filter and compensate reactive power of basic and higher current harmonics.

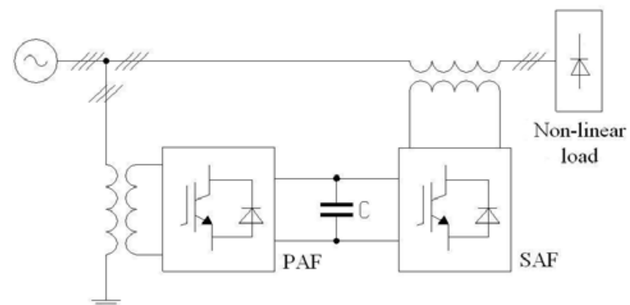


Fig. 1 Basic block scheme of unified power flow controller/conditioner (UPFC)

2. Instantaneous Power Flow Determination

Assume now, for the simplicity, harmonic waveforms of phase-voltage and phase-current

$$u(t) = U.cos(\omega t)\,;\; i(t) = I.cos(\omega t - \varphi) \tag{1a,b}$$

Utilization of instantaneous reactive power method is used in [1], [2] for three-phase systems, and the theory introduced in [4], [5], [8] allows its use for single-phase systems as well

$$\begin{aligned} p_{\alpha\beta} &= u_\alpha . i_\alpha + u_\beta . i_\beta \\ q_{\alpha\beta} &= u_\alpha . i_\beta - u_\beta . i_\alpha \end{aligned} \tag{2a,b}$$

where $p_{\alpha\beta}$ and $q_{\alpha\beta}$ are the instantaneous active and reactive powers of both phases in orthogonal co-ordinates.

Using time-sub-optimal analysis in transformed orthogonal co-ordinates for 4-side symmetry an average value of active power P_{AV} of an original (real) phase is

$$P_{AV} = \frac{P_{\alpha\beta AV}}{2} = \frac{2}{T}\int_0^{T/4}\left(u_\alpha . i_\alpha + u_\beta . i_\beta\right)dt \tag{3}$$

Average values of active power of fictitious phase P_{iAV} and reactive powers of both original Q_{AV} and fictitious Q_{iAV} phases can be determined by similar way.

$$Q_{AV} = \frac{Q_{\alpha\beta AV}}{2} = \frac{2}{T}\int_{0}^{T/4}\left(u_{\alpha}.i_{\beta} - u_{\beta}.i_{\alpha}\right)dt \qquad (4)$$

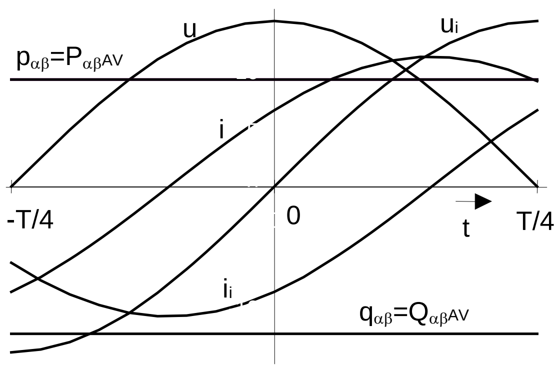


Fig. 2 Time-dependence of instantaneous p□□, q□□ components of the power for harmonic supply and reactive load

3. Instantaneous Phase Shift Determination

Average values of active and reactive powers for harmonic waveforms are equal to constants (Fig. 2), and power factor can be determined by phase shift

$$\varphi = arctg\left(Q_{\alpha\beta AV} / P_{\alpha\beta AV}\right) = arctg\left(q_{\alpha\beta} / p_{\alpha\beta}\right) \qquad (5)$$

It's important that $p_{\alpha\beta}$, $q_{\alpha\beta}$ and φ are in this 'harmonic case' determined **instantaneously**, what is the essential contribution of the introduced method.

In case of non-linear loads the values of instantaneous active and reactive powers are not constant (Fig. 3), due to existence of distortion power caused by current harmonic components. Then the instantaneous active and reactive powers are

$$p_{\alpha\beta} = P_{\alpha\beta AV} + p_{\alpha\beta AC} \text{ , and } q_{\alpha\beta} = Q_{\alpha\beta AV} + q_{\alpha\beta AC} \qquad (6a,b)$$

thus

$$\varphi = arctg(Q_{\alpha\beta AV} / P_{\alpha\beta AV}) \qquad (7)$$

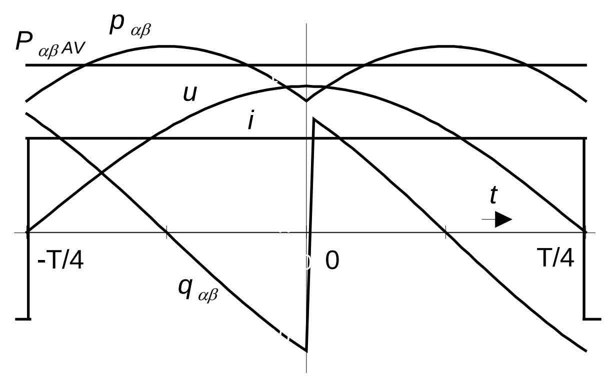


Fig. 3 Time-dependence of instantaneous p□□, q□□ components of the power for non-linear load

Thanks to the orthogonal transform theory for single-phase system described in [4]-[5], it is possible to compute the average values of active and reactive powers for 1/4 of time period. These average values can be calculated continuously for each calculation step (or time instant Δt), using data stored for previous 1/4 of period, and using moving average method [5]

$$P_{av} = \frac{1}{T}\sum p(k) \qquad (8a,b)$$

$$P_{\alpha\beta AV} = \frac{1}{N}\sum_{k=1}^{N-1} p_{\alpha\beta}(k) + (p_{\alpha\beta}(0) + p_{\alpha\beta}(N))/2$$

where k = 0 for time (t - T/4) and k = N for time 0.

4. Control Strategy of UPFC for Output Voltage (with unity power factor)

New control strategy of output voltage has been developed for both compensation of power factor, and regulation of voltage changes. This is based on knowledge of instantaneous phase shift of load current against load voltage (see previous Chap. 3).

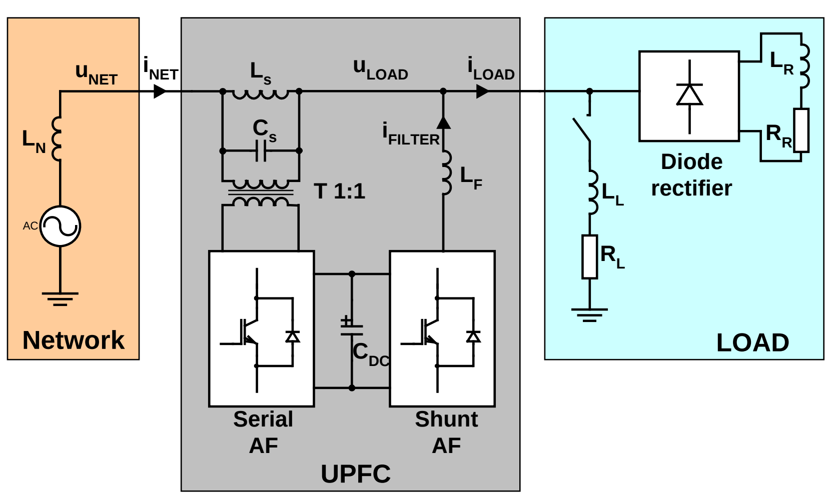


Fig. 4 Block scheme of network, UPFC, and load connecting

Control of shunt active filter of UPFC can be focused now on filtering higher harmonics only, without compensation of fundamental harmonic component, and it can be controlled with very small sampling interval, and switched by rather high frequency (Fig. 5a bellow).

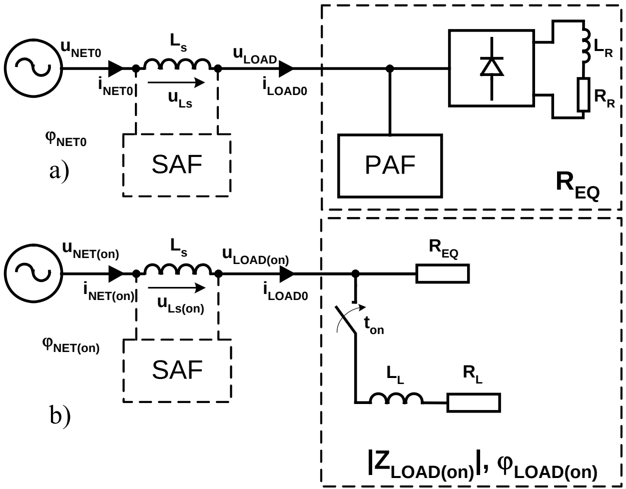


Fig. 5 Detailed connection of filtering PAF (a), and inductive load (b)

Then, there is possibility to rotate vector of series filter voltage by such shift angle, so, the vector of load current will align with vector of network voltage. That means, power factor on input side of UPFC will be equal to one, and reactive power of load will be delivered by series active filter of UPFC.

The operation of PAF is clear from Fig. 6, whereby the inductive load has been switched-on in time equal 0.26 sec.

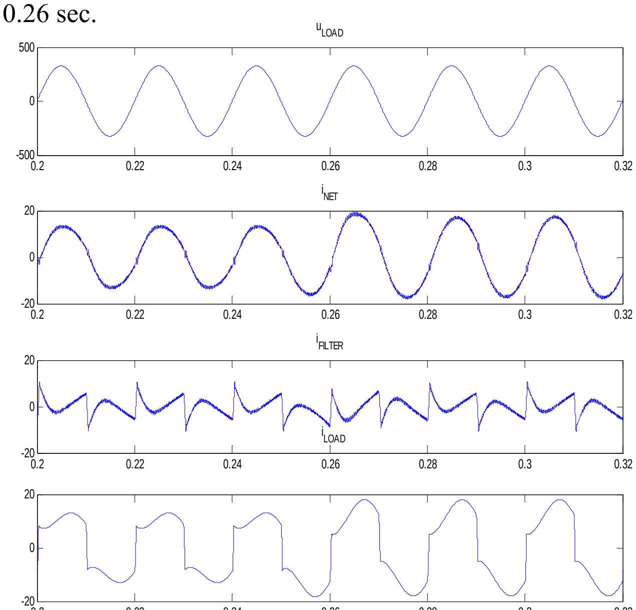


Fig. 6 Time-waveforms of instantaneous u_{LOAD}, i_{NET}, i_{FILTER}, i_{LOAD} quantities

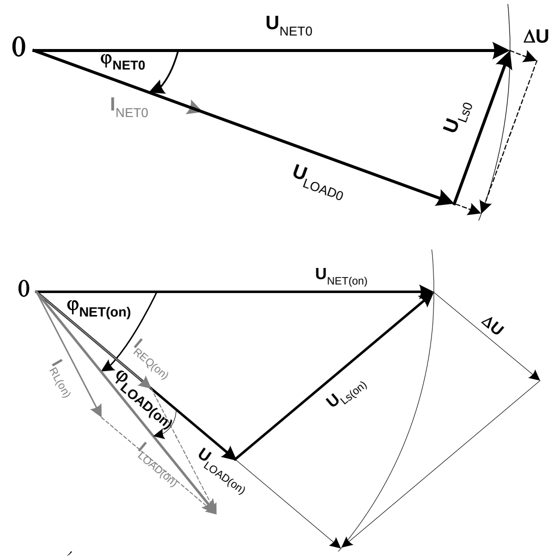


Fig. 7 Phasor diagrams for UPFC voltage without- (a) and with inductive load connecting (b)

Besides, it is also possible to control small changes of active power by such a way that contribution of the series voltage will be in phase with the network voltage. This can be done either with compensation of power factor or without compensation, Fig. 7a,b or 8a,b.

Above mentioned manner of control of output voltage of UPFC can be called **continuous vector voltage control** for compensation both of power factor and voltage load changes. Since the phase shift is determined continuously and instantaneously it is also possible to provide compensation of step changes of voltage (or power factor) very fast, i.e. in the next calculation interval Δt. (see also appendix).

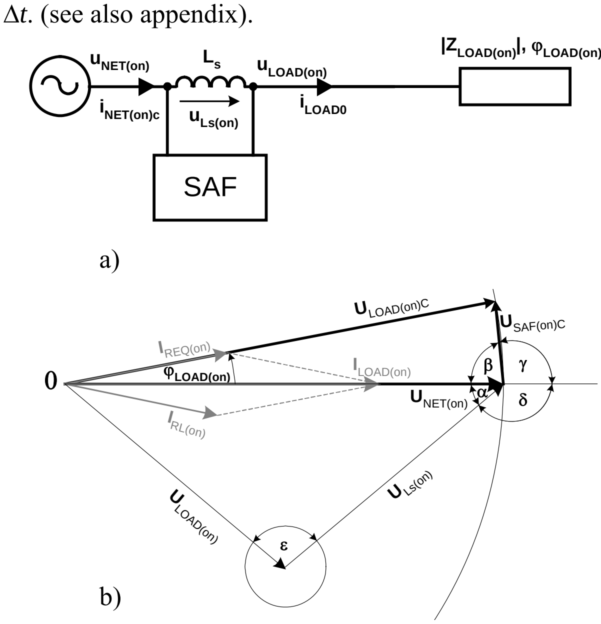


Fig. 8 Scheme for compensation of power factor by SAF (a), and phasor diagram (b)

In case that network voltage is smaller than nominal one, SAF will compensation such a drop voltage, Fig. 9.

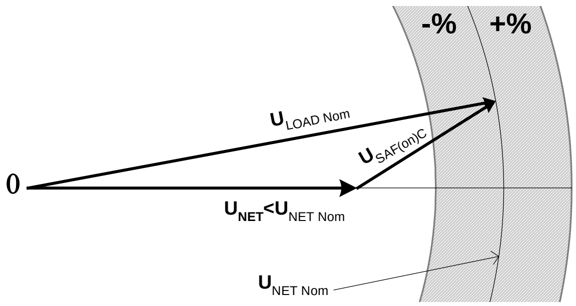


Fig. 9 Compensation when $u_{NET} < u_{NET\ Nom}$

The block scheme of control circuits is shown in next Fig. 10. Both power factors, load- and network, are continuously calculated, and any load or network changes can be respected in next calculation step, almost instantaneously.

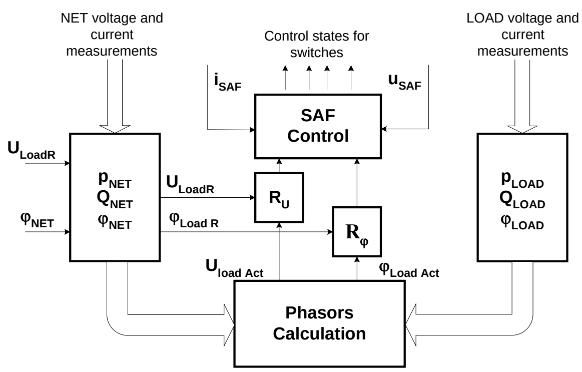


Fig. 10 Block scheme of control circuits

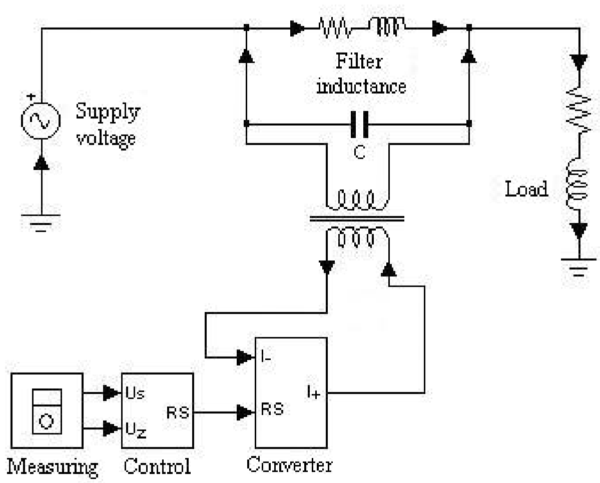


Fig. 11 Scheme of series part of simulated circuit of UPFC

5. Simulation Experiment Results of UPFC

The scheme of series part of simulated circuit of UPFC with continuous vector control of output voltage and power factor compensation is given in Fig. 11.

There are some simulation results in the next Figs. 12a,b,c,d. It has been assumed for all of these simulation experiments that distortion power of the load is to be filtered by shunt active filter of UPFC, and reactive power of the load will be compensated by series filter.

Network and load voltages are shown in Fig. 12a. Load voltage has been increased by 20 %. Detailed time waveform of output voltage of serial active filter is depicted in Fig. 12b (next page).

During these experiment (12a-12d) the power factor of the load has not be compensated.

Current circumstances in serial active filter with sampling frequency f_{SAM} =25 *kHz* and relative hysteresis *h* = ± 3 % are presented in Figs. 12c,d.

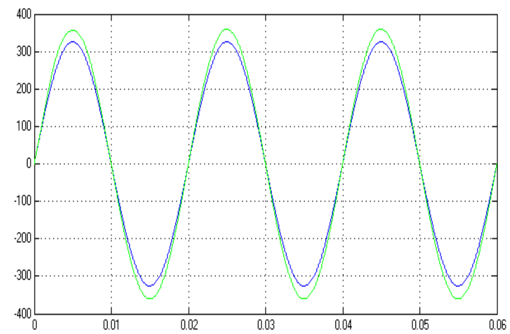


Fig. 12a Network u_{NET} - and output voltage of SAF u_{SAF}

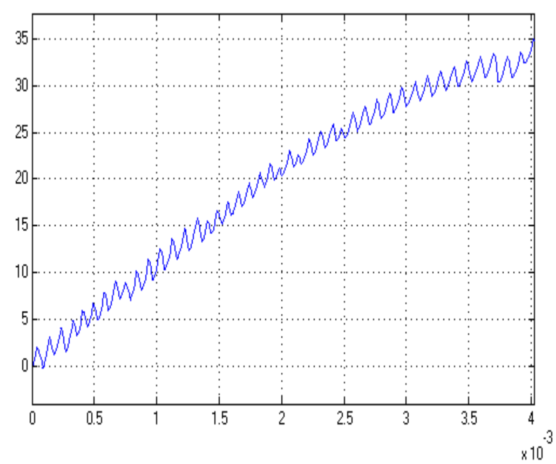


Fig. 12b Detail of output voltage of serial filter

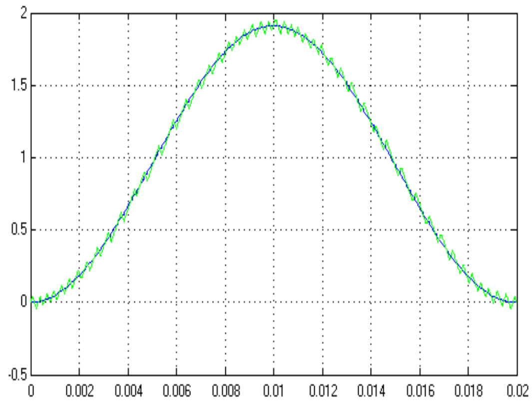


Fig. 12c Reference I_{REF} - and switched currents I_{SW} of serial filter of UPFC, f_{SAMP} = 25 kHz, h = ± 3 %

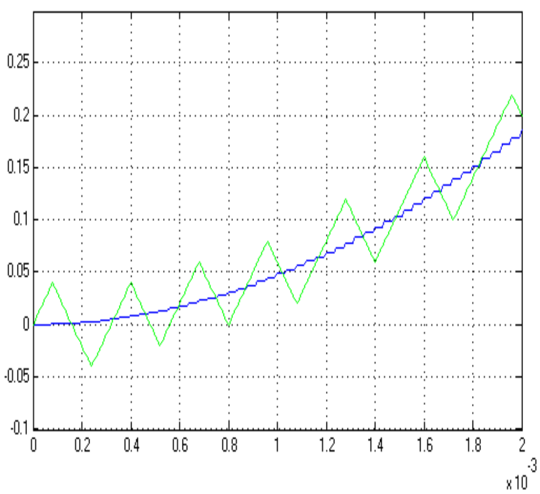
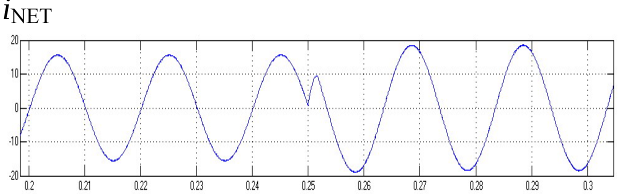


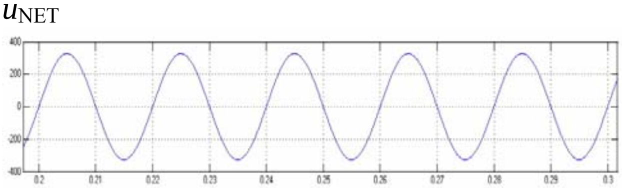
Fig. 12d Details of reference I_{REF} - and switched currents I_{SW} of serial filter of UPFC

The simulation experiment of inductive load switch-on and compensation of load power factor are depicted in Fig. 13.

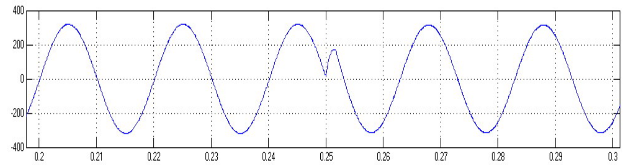
i_{NET}



u_{NET}



u_{LOAD}



u_{SAF}

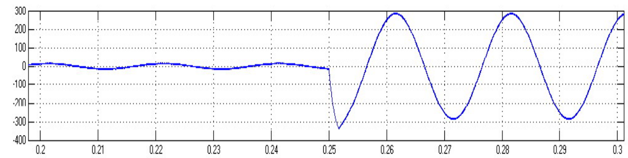


Fig. 13 Time waveforms of i_{NET} , u_{NET} , u_{LOAD} and u_{SAF} during compensation of power factor by SAF

6. Conclusion

A new theory of orthogonal transform for control of single-phase UPFC has been used. This theory makes it possible to use efficient methods of analysis, as time-sub-optimal determination of fundamental harmonic or average- and/or root-mean-square values.

The main advantage of presented theory is to use it forl as instantaneous active and reactive powers determination, and also for phase shift of load current estimation.

The later can then be effectively used for compensation of voltage drops and compensation of load power factor by single-phase UPFC quasi-instantaneously.

The simulation results, given at the end of the paper, show the steady-state operation as well as transient one during inductive load connection. It can be clearly seen from the results that proposed method is suitable.

Acknowledgements

The authors wish to thank for the financial support to Scientific Grant Agency of the Slovak Republic for the VEGA Project No. 1/3086/06, "*Research of the new methods of modelling, control and simulation of mechatronic systems*", and also for APVV Project No.20-051705 "*Intelligent device for giguecycle fatigue test of construction materials which are being used in the field of ultrasonic frequencies*".

References

[1] Akagi H., Kanazawa Y., Nabae A., Generalized theory of the instantaneous reactive power in three-phase circuits. *Proc. of IPEC'83 Conf.*, Tokio (JP), Sept. 1983, pp. 1375-1386

[2] Akagi H., Kanazawa Y., Nabae A., Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components, *IEEE Trans. on IA, Vol. 20*, 1984, No. 3, pp. 625-630

[3] Fujita H., Akagi H.: The Unified Power Quality Conditioner: The Integration of Series- and Shunt Active Filters. *IEEE Trans. On Power Electronics, Vol. 12*, No. 2, March 1998, pp. 315-322
[4] Dobrucky B., Pokorny M., Racek V., Havrila R., A New Method of the Instantaneous Reactive Power Determination for Single-Phase Power Electronic Systems, *Proc. of EPE'99 Conf.*, Lausanne (CH), Sept. 1999, pp. CD-ROM
[5] Dobrucky B., Kim H., Racek V., Roch M., Pokorny M.: Single-Phase Power Active Filter and Compensator Using Instantaneous Reactive Power Method. *Proc. of PCC'02 Int'l. Conf.*, Osaka (JP), Apr. 2002, pp. CD-ROM
[6] Drozdy, S.: *Control of Voltage in Low-Voltage Systems using Active Filters* (Master Thesis, Faculty of Electrical Engineering, University of Zilina, May 2004)
[7] Krajci M.: *Control Design of Power Series Active Filters by Digital Signal Processor* (Master Thesis, Faculty of Electrical Engineering, University of Zilina, May 2006)
[8] Dobrucky B., Pokorny M.: Highest Dynamics- and Ultra Fast Start-Up of Single-Phase PAF Using Virtual Approach, *IREE International Review of Electrical Engineering,* Vol. 3, Aug. 2006. pp. 391-399
[9] Pourbeik P., Bahrman M., John E., Wong W., Modern Countermeasures to Blackouts, *IEEE Power & Energy Magazine*, Sept./Oct. 2006, pp. 37-45

Appendix

Calculation of compensating voltage $u_{SAF(on)C}$:
Assuming $|U_{NET}| = |U_{Load(on)C}|$ (see figure – we get)

$$U_{SAF(on)C} = 2.U_{NET}.sin\,\varphi_{LOAD(on)C} \tag{9}$$

and consequently

$$u_{SAF(on)C} = U_{SAF(on)C}.sin(\omega t + \varphi_{SAF(on)Cu}) \tag{10}$$

where

$$\varphi_{SAF(on)Cu} = \gamma = \frac{\pi - \varphi_{Laod(on)C}}{2} \tag{11}$$

Calculation of compensating current $i_{SAF(on)C}$:

$$i_{SAF(on)C} = \frac{1}{L_s}\int u_{SAF(on)C}\,dt \tag{12}$$

after integration

$$i_{SAF(on)C} = I_{SAF(on)C}.sin(\omega t + \varphi_{SAF(on)Ci}) \tag{13}$$

where

$$I_{SAF(on)C} = \frac{U_{SAF(on)C}}{\omega L_s} \tag{14}$$

and

$$\varphi_{SAF(on)Ci} = \varphi_{SAF(on)Cu} - \frac{\pi}{2} \tag{15}$$