Jacek KANIEWSKI, Zbigniew FEDYCZAK, Paweł SZCZEŚNIAK

University of Zielona Góra, Faculty of Electrical Engineering, Computer Science and Telecommunication, Institute of Electrical Engineering

doi:10.15199/48.2015.06.02

AC Voltage Transforming Circuits in Power Systems

Abstract. *The paper deals with AC voltage transforming circuits applied in power systems. It includes a general description of AC power systems, single and three-phase AC converters, especially PWM AC line choppers and a description of their implementation in AC transmission or distribution systems.* This includes a description of the topologies, the operation and test results of the voltage sag/swell compensators, quadrature phase shifters, *power flow controllers, static VAr compensators and Interfaces of renewable energy sources.*

Streszczenie*. Artykuł dotyczy układów transformujących napięcia przemienne stosowanych w systemach elektroenergetycznych. Ujęto w nim opis ogólny systemów elektroenergetycznych, jedno- i trójfazowych przekształtników prądu przemiennego, a zwłaszcza impulsowych sterowników prądu przemiennego oraz opis ich implementacji w systemach elektroenergetycznych transmisyjnych i dystrybucyjnych. Obejmują one opis topologii działania oraz wyniki badań kompensatorów załamań/wzrostów napięcia przemiennego, kwadraturowe przesuwników fazowych, szeregowych sterowników mocy czynnej, kompensatorów mocy przesunięcia oraz sprzęgi z odnawialnymi źródłami energii. (****Układy transformowania napięć przemiennych w systemach elektroenergetycznych****).*

Słowa kluczowe: System elektroenergetyczny, Przekształtniki AC/AC, Jakość zasilania.
Keywords: Power System, AC/AC converters, Power Quality.

Introduction

The AC power system is divided into two subsystems: Alternating Current Transmission System (ACTS) and Alternating Current Distribution System (ACDS) (Fig. 1) [1].

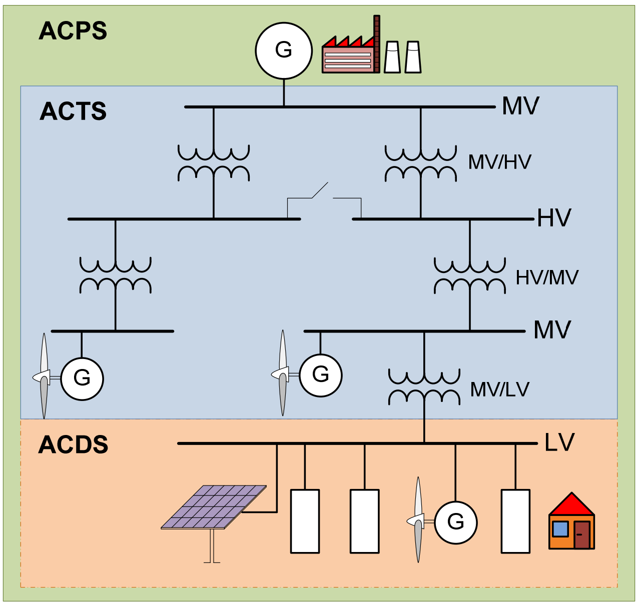

Fig. 1. Simplified structure of AC Power System

The long transmission lines in expanded ACTS are exposed to many different faults caused by adverse weather conditions (e.g., atmospheric discharge, wind, temperature changes), accidents, load changes, etc. The situation is similar in the case of ACDS. Faults are caused in ACDS by rapid load changes, switching effects, heavy start-up of electrical equipment, especially high power drives [2]. These faults generate undesirable effects for the end-user, such as voltage perturbations understood as: voltage variations, voltage unbalance, voltage sags/swells, flicker effect or voltage interruption. Moreover, presently the AC power system is being developed as a decentralized supply from many scattered sources, especially renewable energy sources, e.g., photo voltaic (PV) systems and wind generators [3]. The voltage perturbations and uncontrolled power flow phenomena both in ACTS and ACDS can be caused additionally by turning on and turning off of renewable energy sources connected to the grid, being dependent on the condition of the energy source (wind, sun, water flow, etc.). In the case of AC voltage supply changes, both downward and upward, there is a high risk of damage to devices which are sensitive to voltage perturbations [4, 5]. In the case of big plants and factories, voltage sags and swells may cause very large financial damage [6]. To improve the voltage profile, the reduction of transmission losses, power flow control, etc., devices called Flexible Alternating Current Transmission Systems (FACTS) are used [7]. The case is similar with the low voltage AC distribution system, when Custom Power Devices (CPD) are implemented. Custom Power Devices are defined as power electronic devices installed in power distribution systems to supply sensitive loads ("sensitive users") [8, 9]. In comparison with FACTS devices installed in transmission lines, CPDs are installed in a public or industrial customer network to mitigate a voltage fluctuation, flicker, current harmonics or compensation of reactive power.

The application in the ACPS of power electronic devices (FACTS and CPD) mitigates unwanted detrimental effects in the supply, improves grid asset utilization, reduces transmission losses, improves power system stability and the ability of the power system to provide ancillary services and increases the reliability of the entire power system [10]-[12].

The conventional solution for FACTS devices is based on AC/DC/AC converters with DC energy storage elements (electrolytic capacitors, batteries, etc.). The DC energy storage unit is both susceptible to damage and the most expensive part of the AC/DC/AC converter. In the case of compensation for deep voltage sags or voltage interruptions the DC energy storage system is necessary. However, in many applications the conventional FACTS device (based on an AC/DC/AC converter) may be successfully replaced by a solution based on direct PWM AC/AC converter without DC energy storage.

The main aim of this paper is to present a description of recent results, obtained by the authors in the area of AC voltage transforming circuits without DC energy storage for application in the AC Power System to improve power quality problems.

AC voltage transforming circuits

Due to the nature of coupling used for the transfer of electrical energy the AC voltage transforming circuits (VTC) may be divided into three groups (Fig. 2) [13,15].

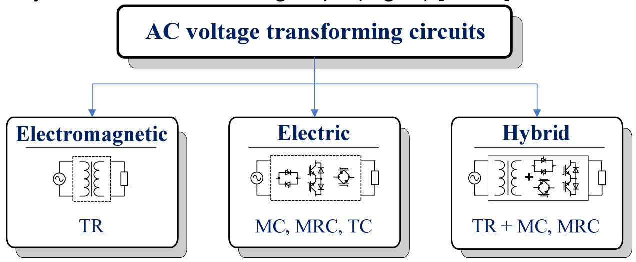

Fig. 2. Types of the AC transforming circuits, TR – transformer, MC – matrix chopper, MRC – matrix-reactance chopper

The most popular group of AC VTC are electromagnetic devices (with electromagnetic coupling) based on conventional transformer (TR) with tap changer [14]. Another group of compensators is based on electric devices (matrix choppers (MC), matrix-reactance choppers (MRC), thyristor controllers (TC)) (with electrical coupling) [15].A third group of AC voltage transforming circuits is based on hybrid solutions (with electromagnetic and electrical coupling), where a conventional electromagnetic transformer TR cooperates with a MC, MRC or TH [13].

"Topologies of the single phase matrix choppers (MC) and matrix-reactance choppers are shown in Fig. 3 [47, 13, 15], whereas the three-phase solutions of these choppers are shown in Fig. 4 and 5 [48, 13, 15].

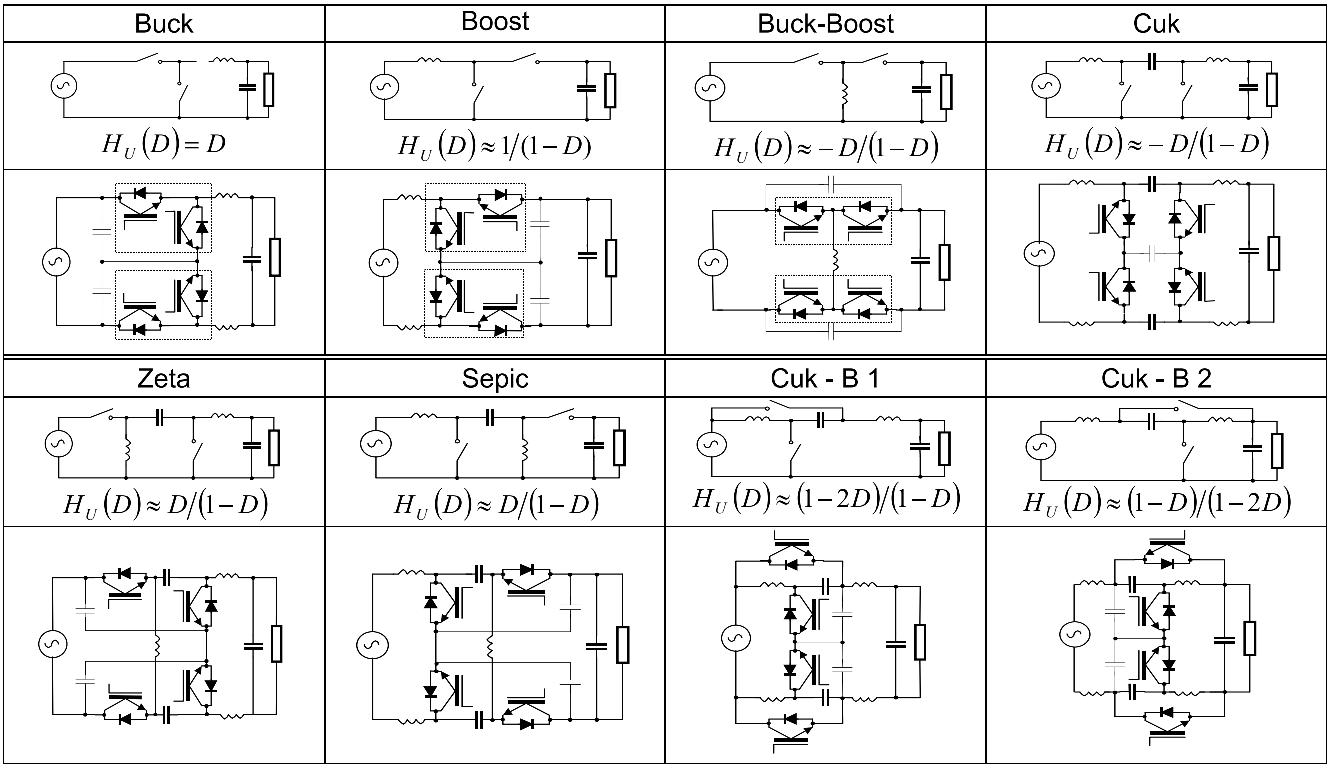

Fig. 3. Topologies of the single-phase MC or MRC

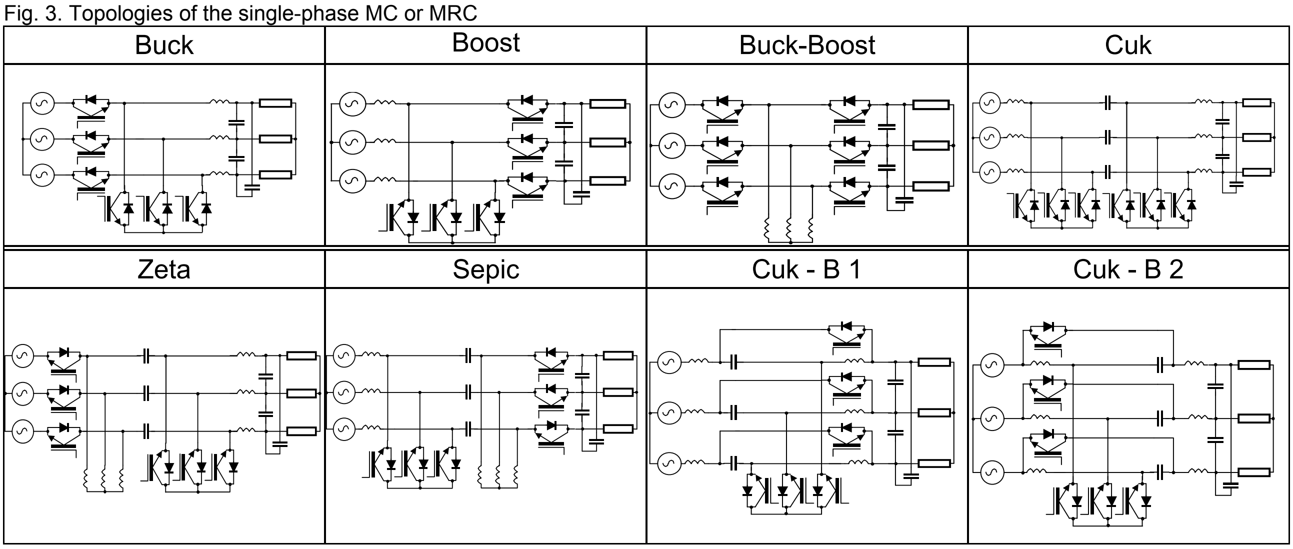

Fig. 4. Topologies of the three-phase MC or MRC

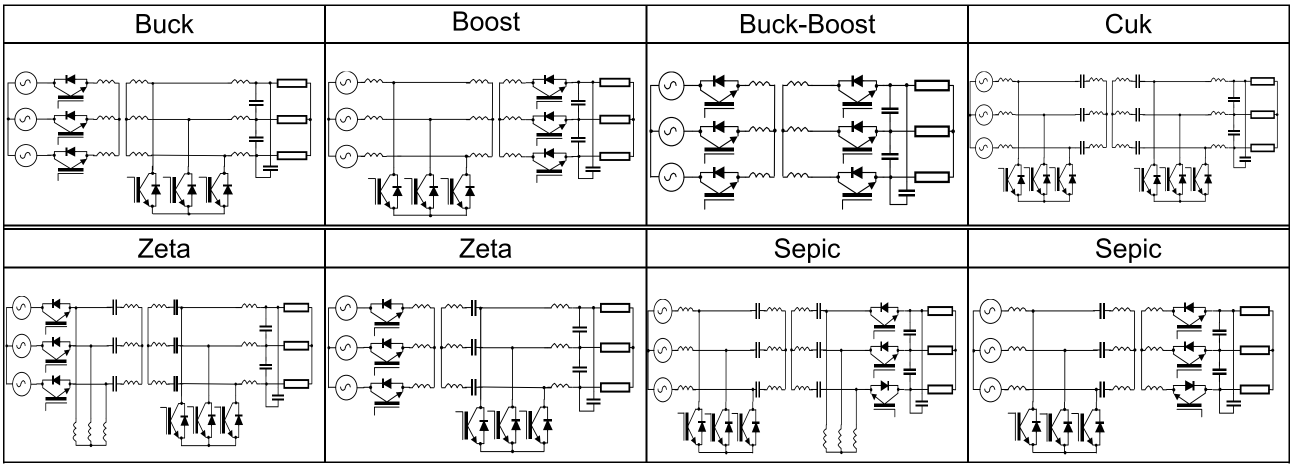

Fig. 5. Topologies of the three-phase isolated MC or MRC

AC voltage converter implementation

The general division of AC voltage transforming circuits implemented in ACPS is shown in Fig. 6.

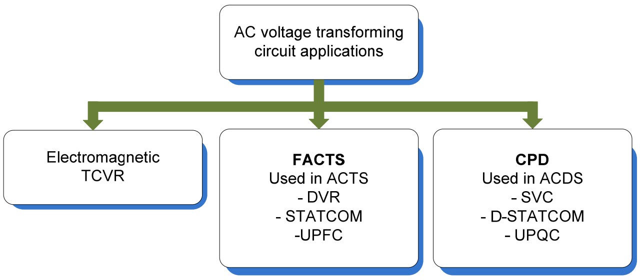

Fig. 6. AC voltage transforming circuits applications

The applications of AC VTC in electromagnetic devices are based on a conventional electromagnetic transformer with tap changers [14]. The electromagnetic AC VTC based on electromechanical or thyristor tap changer solutions usually operate as a Thyristor Controlled Voltage Regulator (TCVR). The TCVR have major defects, such as poor dynamics, step changes and a narrow range of output voltage adjustment [16, 17].

The second-one group of the AC VTC applications there are FACTS devices installed in high and medium voltage AC transmission system (ACTS). They operate in ACTS as a Dynamic Voltage Restorer (DVR) [18, 19], a Static Synchronous Compensator (STATCOM) [7, 20], or a Unified Power Flow Controller (UPFC) [21]. Such FACTS devices as DVR and STATCOM are intended to mitigate voltage disturbances such as voltage sag and swell. The DVR equipped with DC energy storage is also able to compensate voltage interruption. Additionally STATCOM can be implemented as a reactive power compensator. The main difference between both latter devices (DVR and STATCOM) is the method of connection to the grid. The DVR, and any device based on the DVR concept, is series connected to the grid. For voltage compensation DVR injects voltage in series with the line. The STATCOM is shunt connected to the grid. The shunt connected device injects current (capacitive or inductive) into the grid at the point of connection. The Unified Power Flow Controller is intended to control power flow in the AC power grid and usually is series-shunt connected to the grid. Conventional solutions of DVR, STATCOM and UPFC are based on AC/DC/AC converters. However, in the literature there can be found many solutions based on AC/AC converters [22-26], though the devices described in [23-26] operate only in an “in-phase” mode. This means that the voltage phase angle cannot be controlled. In the case of the solution described in [27] it is possible to control simultaneously voltage amplitude and phase. This means that it can be implemented both as voltage compensator and power flow controller.

The last of the above groups AC VTC applications are CPDs installed in low voltage alternating current distribution systems. The CPDs operate in ACDS as Series Voltage Compensators (SVC) based on the DVR concept [8, 9], the Distribution Static Compensator (D-STATCOM) [22], and the Unified Power Quality Conditioner (UPQC) [22]. Destination and principle of operation of SVC and D-STATCOM is similar to that in FACTS devices (DVR and STATCOM). The UPQC devices often fulfil several functions, such as active power filter, voltage conditioner, or power electronic interface between renewable energy sources and the AC power grid.

Voltage sag/swell compensators

For improved voltage parameters in the AC power grid and to protect sensitive loads and alleviate variation, sag/swell or interruption in the supply voltage are corrected by implementing devices called voltage conditioners [27, 28], voltage sag/swell compensators [25, 29, 32], AC voltage sag supporters [24, 30] or AC voltage regulators [31]. The three-phase AC voltage sag/swell compensator based on the hybrid transformer (HT) with buck- boost matrix-reactance chopper (MRC) is described in [32-34] (Fig. 7).

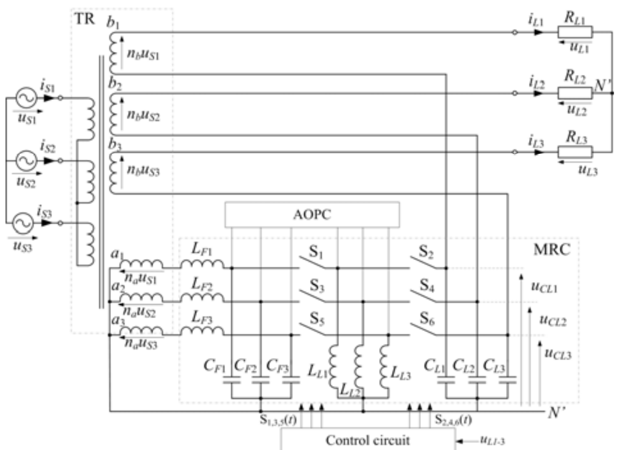

Fig. 7. The AC voltage sag/swell compensator based on HT with buck-boost matrix-reactance chopper; TR – transformer, AOPC – active overvoltage protective circuit

The described HT contains two main units: an electromagnetic transformer (TR) and a buck-boost matrix-reactance chopper (MRC). As shown in Fig. 4, the primary windings are in Y-configuration. The main secondary windings (a_1, a_2, a_3) of the TR also have a Y-configuration and, by input filter *LC*, are connected to a buck-boost MRC. The secondary phase windings (b_1, b_2, b_3) are connected in series with the required phase output connectors of the MRC. The output RMS voltages of the HT (U_{L1}, U_{L2}, U_{L3}) are the sum of the RMS secondary voltages (n_bU_{S1}, n_bU_{S2}, n_bU_{S3}) and the phase RMS output voltages of the MRC (U_{CL1}, U_{CL2}, U_{CL3}). Output voltages of the MRC (U_{CL1}, U_{CL2}, U_{CL3}) are dependent on the pulse duty factor *D* (1) defined as: $D=t_{on}/T_S$ (t_{on} – time-on of switches S_1, S_3, S_5, T_S – switching period).

$$(1) \qquad \left|\underline{H}_U^{TH}\right| = \left|\frac{\underline{U}_L}{\underline{U}_S}\right| = \left|\frac{\underline{U}_{CL} + n_b\underline{U}_S}{\underline{U}_S}\right| \approx \frac{n_a D}{1-D} + n_b .$$

The static characteristics of magnitude, phase of voltage transmittance and input power factor as a function of pulse duty factor *D* are shown in Figs. 8a, 8b and 8c respectively.

As one can see, the output voltage of the presented HT is smaller than the source voltage (H_U<1) for *D*<0.2, approximately equal to the source voltage (H_U=1_ for *D*=0.2 and greater than the source voltage (H_U>1) for *D*>0.2 (Fig. 8a). Because voltage transmittance and input power factor rapidly decreases for *D*>0.75 (Fig. 8a, c), the useful working area is limited from *D*=0 to *D*=0.75.

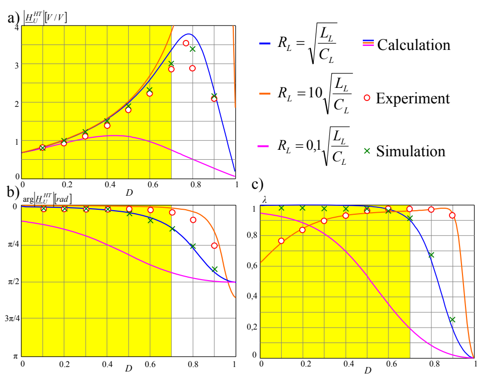

Fig. 8. Static characteristics of HT a) magnitude of voltage transmittance, b) phase of voltage transmittance, c) input power factor

The buck-boost matrix-reactance chopper (Fig. 7) is controlled via a PWM control strategy. A simplified schematic block diagram of the control circuit of the HT is shown in Fig. 9.

The experimental voltage and current time waveforms for various values of duty pulse factor *D* are shown in Fig. 10 and Fig. 11.

The range of change of output voltage is from 0.66U_S (Fig. 10a) to more than 3U_S (Fig. 10c). For *D*>0.75 (Fig. 10d), output voltage U_L is decreasing and source current I_S is much bigger than in the case when the pulse duty factor is less than 0.75, due to resonance phenomena of SMR. The load voltage U_L is kept at the nominal level, during deep voltage sags and swells (Fig. 11).

AC voltage compensators based on the HT can operate also with active load, e.g., interfaces between two voltage sources (Fig. 12) [34].

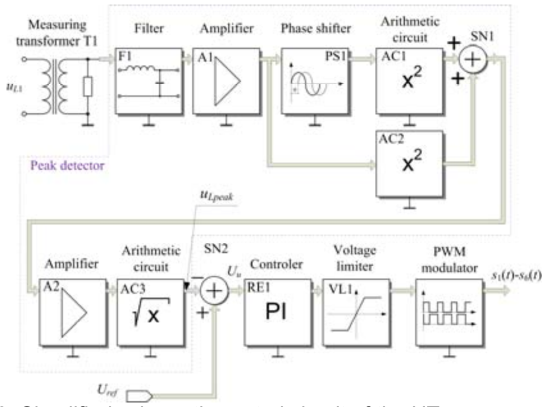

Fig. 9. Simplified schematic control circuit of the HT

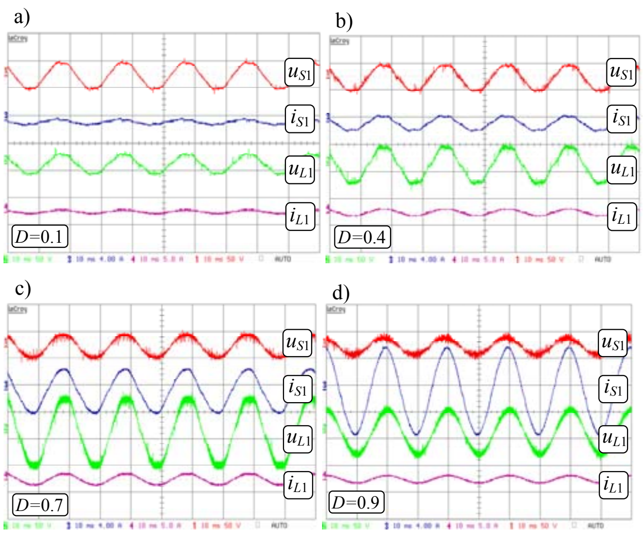

Fig. 10. Experimental source and load voltage and current time waveforms for, a) *D* = 0.1, b) *D* = 0.4, c) *D* =0.7, d) *D* = 0.9

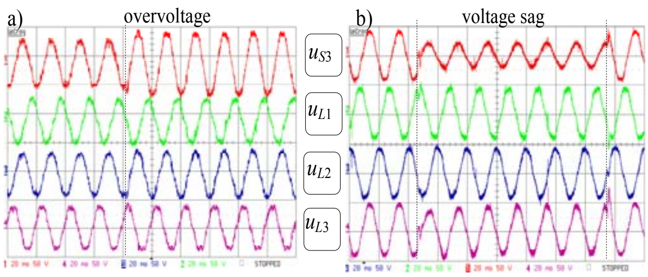

Fig. 11. Experimental voltage time waveforms during, a) 140%U_S overvoltage, b) 55%U_S voltage sag

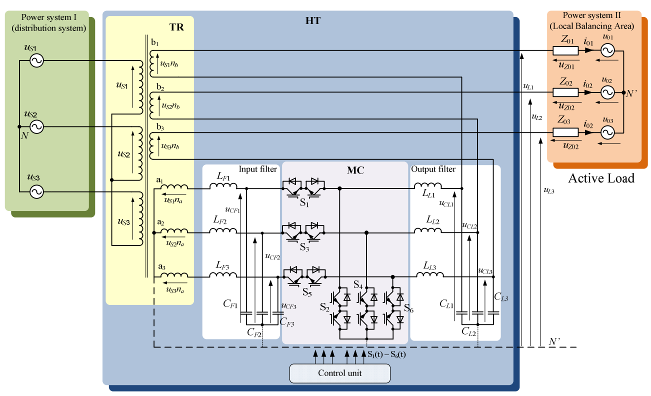

Fig. 12. Three-phase hybrid transformer using matrix chopper with active load

The output voltages of the considered HT are dependent on duty cycle D and can be adjusted flexibly from a value smaller than source voltages to about two times greater than source voltages [34]. The voltages, currents and instantaneous power waveforms for various values of duty cycle D and for a source voltage value equal to load voltage value (U_S=U_0) are shown in Fig. 13.

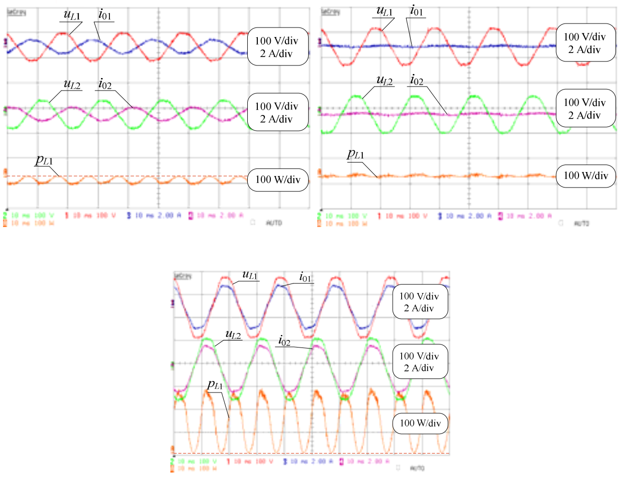

Fig. 13. Experimental waveforms of voltages, currents and power for duty cycle, a) D=0.1, b) D=0.25, c) D=0.9

The instantaneous power can be either positive (Fig. 13c) or negative (Fig. 13a) in value. If the averaged value of instantaneous power p (active power) has a positive value then energy is transferred from source voltage U_S to load voltage U_L, and conversely when p has a negative value.

Both the presented voltage compensators (Figs 7 and 12) operate only "in-phase" mode (without phase control mode). Often, in real conditions, especially in medium and high voltage grids, the control of voltage amplitude only is not enough. Some specific voltage perturbation can generate simultaneous voltage sag and phase jump. In regard to the above these voltage compensators can operate in ACDS as CPDs to protect sensitive loads.

Quadrature phase shifters

The phase control of the AC line voltage is one of the well-known methods for power flow control and for transient stability in the flexible AC transmission systems (FACTS) [7]. In three-phase systems, the line voltages are in quadrature with the phase voltages ($V_{bc} \perp V_a$) and a simple way of obtaining quadrature voltage injections is by means of a Δ:Y shunt transformer connected in series to a series transformer (Fig. 14) [35].

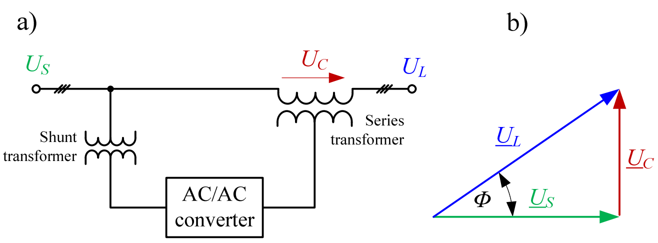

Fig. 14. Classical quadrature-booster phase shifter, a) schematic diagram, b) voltage phasors

The three-phase quadrature phase shifter based on a Hybrid transformer with matrix chopper is described in [36]. In comparison to [35] this solution provides galvanic separation between source and load (Fig. 15).

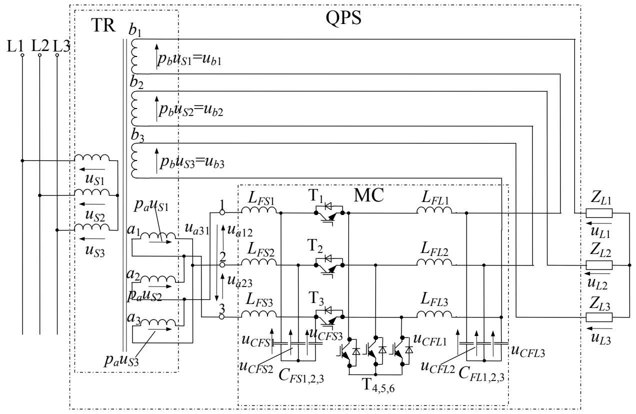

Fig. 15. Three-phase quadrature phase shifter based on hybrid transformer.

As is visible in Fig. 15 the circuit of the considered phase shifter contains two main units. The first one is a conventional transformer (TR) with two secondary windings in each phase (a_1-b_1, a_2-b_2, a_3-b_3). The second one is a three-phase matrix chopper (MC) with 3+3 unidirectional switches. Primary windings are Y-connections. The main secondary windings (a_1, a_2, a_3) of TR have delta-connections (Δ-connections) and are connected with MC. Secondary windings (b_1, b_2, b_3) are connected in series with the required phase output of the MC. The relations between voltage phasors of the presented phase shifter are shown in Fig. 16.

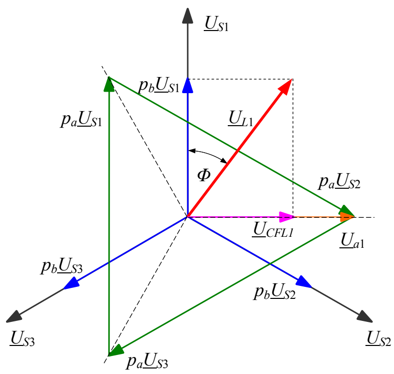
Fig. 16. Exemplary voltage phasors of the presented phase shifter

The phase voltage $\underline{U}_{S1}$ is shifted about π/2 (90^0) in relation to phase voltage U_{CFL1}. The output voltages of the phase shifter ($\underline{U}_{L1}$, $\underline{U}_{L2}$, $\underline{U}_{L3}$) are geometrically the sum of the secondary voltages ($p_b\underline{U}_{S1}$, $p_b\underline{U}_{S2}$, $p_b\underline{U}_{S3}$) and the phase output voltages of the MC ($\underline{U}_{CFL1}$, $\underline{U}_{CFL2}$, $\underline{U}_{CFL3}$).

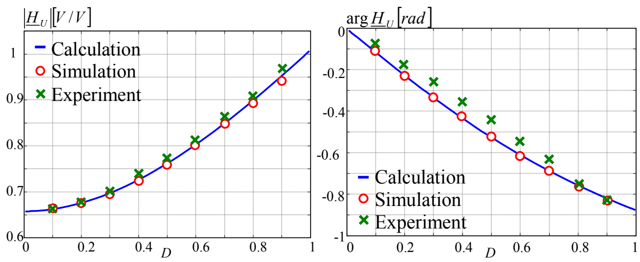

Fig. 17. Static characteristics of, a) magnitude and, b) phase, of the quadrature phase shifter based on HT as a function of pulse duty factor D

Taking into the account voltage transmittance of the used matrix chopper (H_U=D), the idealized voltage transmittance of the quadrature phase shifter (Fig. 15), in complex form, can by described by (2). The static characteristics of the magnitude and phase of the quadrature phase shifter are shown in Fig. 17.

$$(2)\quad \underline{H}_U^{QPS} \cong \frac{\underline{U}_{L1}}{\underline{U}_{S1}} \cong \frac{\frac{-jp_a \underline{U}_{S1}}{\sqrt{3}} D + p_b \underline{U}_{S1}}{\underline{U}_{S1}} \cong \frac{-jp_a}{\sqrt{3}} D + p_b .$$

The range of change of output voltage is from 0.66 u_S to u_S (Fig. 17a). As is visible from Fig. 17b the range of change of phase shift between source and load voltage is from 0 to about $\pi/4$. The experimental time waveforms of load voltage u_L of the phase-shifter (Fig. 15) for various values of pulse duty factor D are shown in Fig. 18.

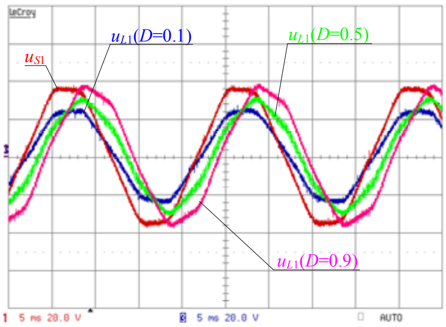

Fig. 18. Exemplary experimental load voltage (u_L) time waveforms of quadrature phase shifter for various value of D

The presented phase-shifter (Fig. 15) gives the possibility to obtain the phase shift between the source and load voltage from 0 to $\pi/4$. This value is enough for potential control of power flow in the AC power grid. The main disadvantage of the presented phase shifter is the wide a range of change of voltage transmittance, which is dependent on pulse duty factor D and which has the ability to shift phase only in one direction. The presented quadrature phase shifter can operates in ACTS as FACTS device.

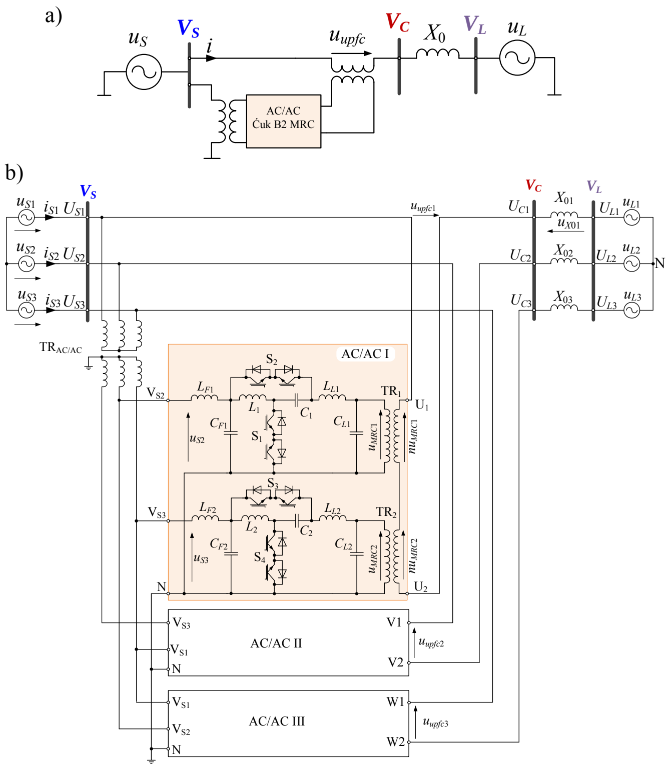

Fig. 19. Power flow controller based on Ćuk B2 matrix-reactance choppers, a) general concept, simplified schematic diagram

Power flow controllers

Power flow controllers with an AC/AC converter (without DC link or DC energy storage) are usually based on matrix converters [37]. The solution of the power flow controller described in [38] is based on ĆukB2 matrix-reactance choppers (MRCs) (Fig. 19).

The presented circuit contains three AC/AC converter modules (AC/AC I, AC/AC II and AC/AC III) (Fig. 19). Each module of the AC/AC converter contains two single phase Ćuk B2 MRCs. The input connections of the converter AC/AC I are connected to the connections of other phases U_{S2} and U_{S3} by transformer $TR_{AC/AC}$, with voltage ratio $n_{TRAC/AC}$. The output connections of converter AC/AC I (U1-U2) are connected in series between source and load. Connected in an analogous way are the other AC/AC converters (AC/AC II and AC/AC I). The voltage transmittance defined for the AC/AC I module of the considered UPFC is given by equation (3).

$$(3)\quad \underline{H}_U^{AC/ACI} = \frac{\underline{U}_{C1}}{\underline{U}_{S1}} = e^{j0} + n_{TRAC/AC} \cdot n \cdot \left(e^{j\frac{-2\pi}{3}} \cdot \left(\frac{(1-2D_1)}{(1-D_1)} \right) + e^{j\frac{2\pi}{3}} \cdot \left(\frac{(1-2D_2)}{(1-D_2)} \right) \right)$$

The diagrams for the voltage phasors of the power flow controller (Fig. 19), illustrating the principle of operation, are shown in Fig .20.

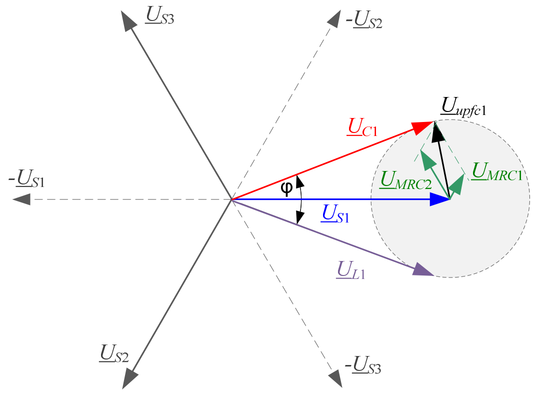

Fig. 20. Exemplary voltage phasor diagram

The output voltage of the power flow controller (Fig. 19) in the first phase ($\underline{U}_{upfc1}$) is constructed from output voltages of MRC1 and MRC2 – $\underline{U}_{MRC1}$ and $\underline{U}_{MRC2}$ respectively (Fig. 20). It is possible to obtain an output voltage $\underline{U}_{upfc1}$ in relation to source voltage $\underline{U}_S$: in phase, in opposite phase or shifted in phase and with various values of amplitude. To show clearly the voltage dependence, in all experimental cases load voltage $\underline{U}_L$ is shifted in phase in relation to source voltage $\underline{U}_S$ by phase angle $\delta \approx 20^0$.

As is shown in Fig. 21ab, the instantaneous power p_{S1} has a negative value (p_{S1}<0). This means that the energy is transferred from the load to the source. As can be seen in Fig. 21b the controlled voltage u_{C1} has the same phase and amplitude as load voltage u_{L1}. Under this condition there is no power flow between source and load ($p_{S1} \approx 0$). In the case shown in Fig. 21c the voltage u_{C1} has the same amplitude and phase as source voltage u_{S1}, but is shifted in phase in relation to load voltage u_L. The voltage u_{C1} precedes in phase voltage u_{L1} by phase angle φ. The instantaneous power p_{S1} has a positive value (p_{S1}>0). Under this condition (Fig. 21c) the energy is transferred from the source to the load.

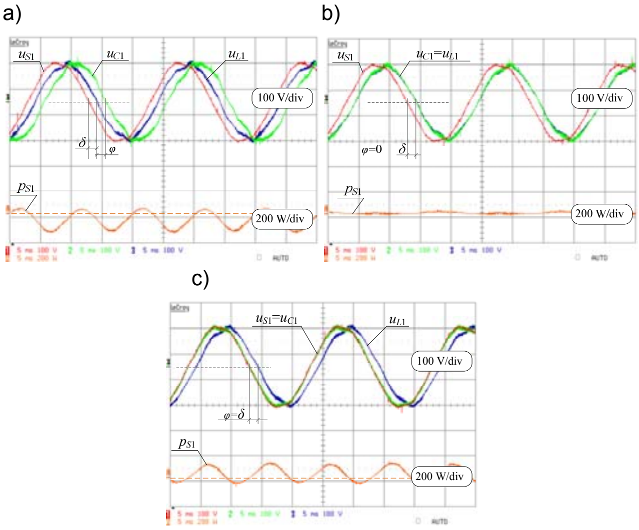

Fig. 21. Experimental voltage waveforms under conditions, a) $U_{S1}=U_{C1}=U_{L1}$, $\varphi < 0$, b) $U_{S1}=U_{C1}=U_{L1}$, $\varphi = 0$, c) $U_{S1}=U_{C1}=U_{L1}$, $\varphi > 0$

The voltage regulator/conditioner based on hybrid transformer (HT) with matrix converter and providing galvanic separation between source and load is described in [39] (Fig. 22). The circuit of the considered solution contains two main units. The first one is a conventional transformer (TR), with two secondary windings in each phase (a_1-b_1, a_2-b_2, a_3-b_3). The second one is a three-phase matrix converter. Primary windings are Y-connections. The secondary windings (a_1, a_2, a_3) have Y-connections and are connected with the MC. Secondary windings (b_1, b_2, b_3) are connected in series with the required phase output of the MC.

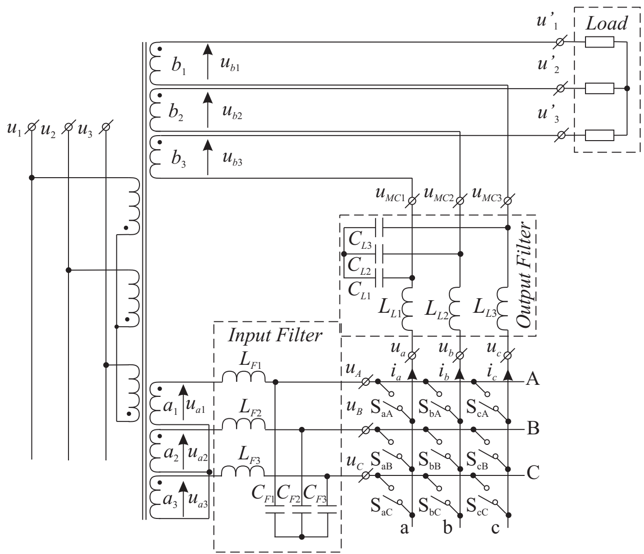

Fig. 22. Voltage regulator/conditioner based on hybrid transformer with matrix converter

The voltage transmittance is dependent on the matrix converter voltage gain q and the setting of the matrix converter output phase shift φ_L. The maximum output voltage is achieved for setting φ_L=0 (matrix output voltages u_{MC1}, u_{MC2}, u_{MC3} have the same phase as a voltages u_{b1}, u_{b2}, u_{b3}).

By control of the matrix converter voltage gain q and the setting of output voltage phase shift φ_L, it is possible to obtain an amplitude of output voltage U'_m equal to the amplitude of source voltage U_m but with phase shift between source and output voltages. The adjustment range of the amplitude and phase shift of the output voltage is shown in Fig. 24. The voltage regulator/conditioner (Fig. 22) can control simultaneously and independently the amplitude and phase of output voltage. These properties allow the implementation of this solution as a power flow controller and voltage sag/swell compensator.

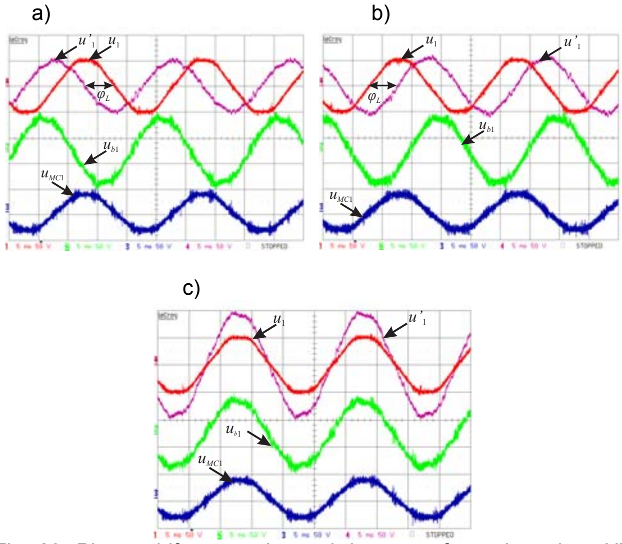

Fig. 23. Phase shifter experimental time waveforms based on HT with MC, a) for φ_L>0 $|u_1|=|u'_1|$, for φ_L <0 $|u_1|=|u'_1|$, for φ_L=0 $|u_1|<|u'_1|$

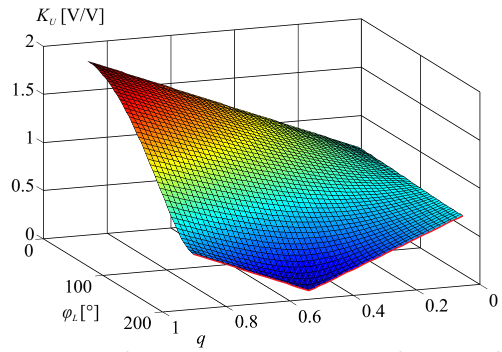

Fig. 24. Phase shifter voltage gain K_U, as a function of setting output voltage phase shift φ_L and matrix converter voltage gain q

The described solutions (Figs. 19 and 22) can operate both in ACTS as facts devices and in ACDS as custom power devices.

Static VAr compensators

The AC/AC converters based on the matrix-reactance chopper (MRC) can operate also as reactive power compensators. The shunt power compensator based on a Ćuk MRC is described in [40] (Fig. 25).

The main part of the SVC (Fig. 25) is the matrix-reactance chopper (MRC), which is used as a PWM controllable variable phase reactance. The MRC is able to generate, absorb or to generate and absorb the reactive power, depending on the pulse duty factor D [40]. The exemplary voltage and current time waveforms of the presented SVC are shown in Fig. 26.

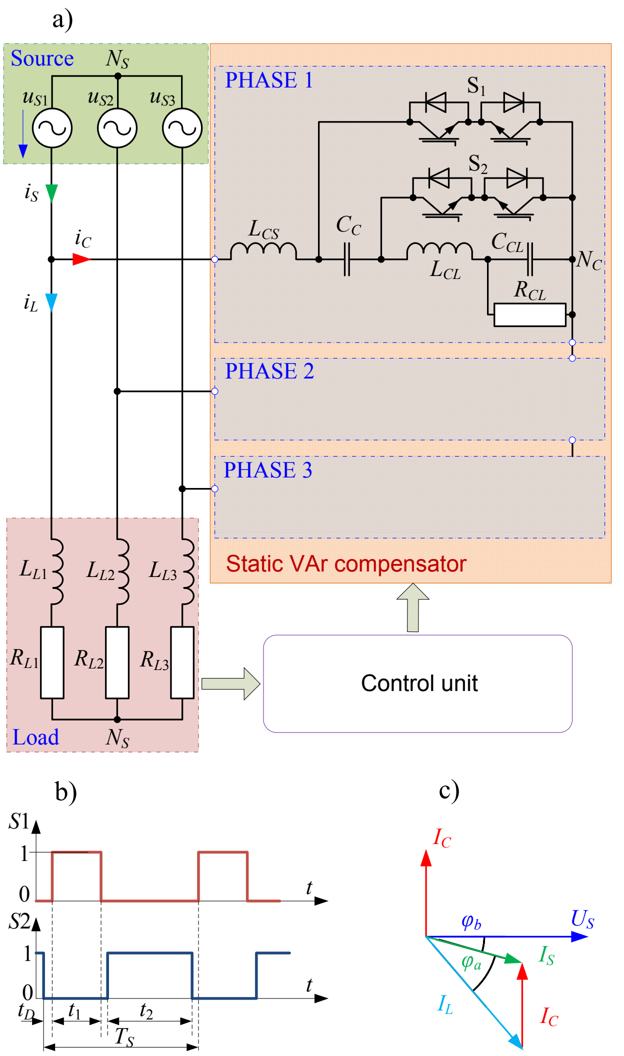

Fig. 25. SVC with matrix-reactance PWM AC line conditioner based on Ćuk converter topology, a) simplify schematic, b) control signals, c) phasors of voltage and current

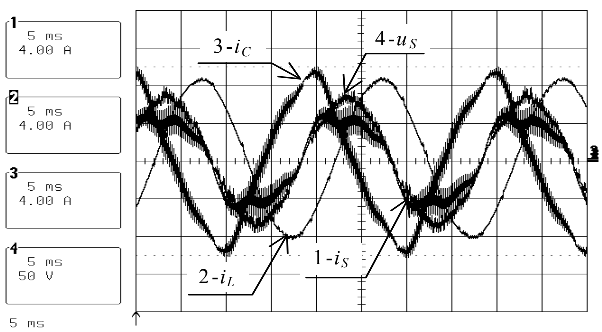

Fig. 26. The voltage and current time waveforms of presented SVC with MRC for *RL* load *D* = 0.76

Interfaces of renewable energy source

It is also possible to integrate two AC systems of different parameters (voltage and frequency) by a power electronic converter without DC energy storage [41]. The most widely known AC-AC power converter is the matrix converter (MC) [42]. The most obvious area for the application of AC-AC converters is in distributed generator systems, in wind installations. Fig. 27 show four possible wind solutions with AC-AC converters without DC-link [43]:

- squirrel cage induction generator (IG) with self-excitation and an AC–AC converter in the main line,
- synchronous generator (SG) with an AC-AC converter in the main line and an AC–DC converter in the exciter circuit,
- permanent magnet synchronous generator (PMSG) and AC–AC converter in main line,
- double feed induction generator (DFIG) with an AC–AC converter in the rotor circuit.

A MC can be used for controlling the active and reactive power independently. Furthermore, a MC is responsible for the quality of the generated power and the grid code requirements. The proposed control strategy used to integrate renewable energy sources is based on synchronous Voltage Oriented Control (VOC) with PI controllers [41, 44-46]. A simplified block diagram of the VOC control with PI controllers and MC is shown in Fig. 28. This control strategy is based on the coordinate transformation between the stationary α-β and the synchronous d-q reference frames. It provides a fast transient response and high static performance due to the internal current control loops. The exemplary time waveforms are show in Fig. 29. In a solution with MC there is no need to increase the generated voltage, because the MC have not a DC-link or freewheeling diodes. The feeding back of energy to the grid with unity power factor is possible even at low levels of generated voltages (Fig. 29b). This is the main advantage of power electronics interface solutions with matrix converter compared with a two stage AC/DC/AC converter [41, 44].

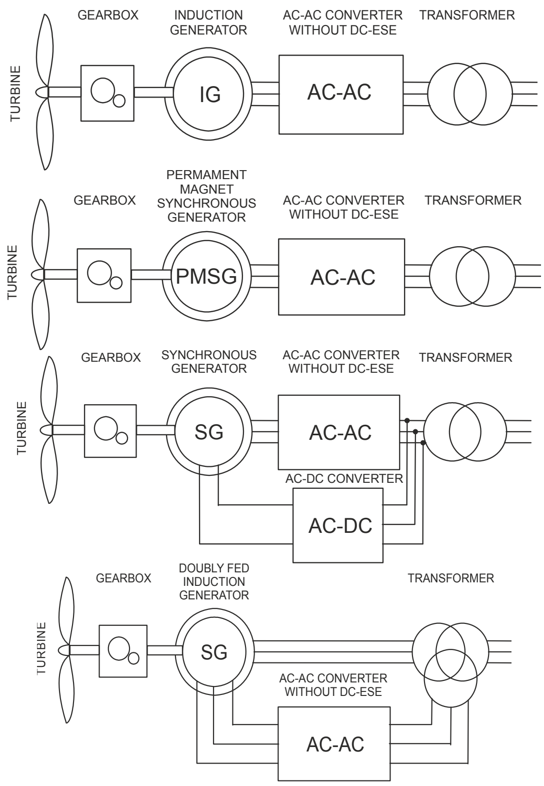

Fig. 27. Basic types of wind turbine generators with AC-AC converters: a) squirrel cage induction generator (IG), b), permanent magnet synchronous generator (PMSG), c) synchronous generator (SG), d) double feed induction generator (DFIG)

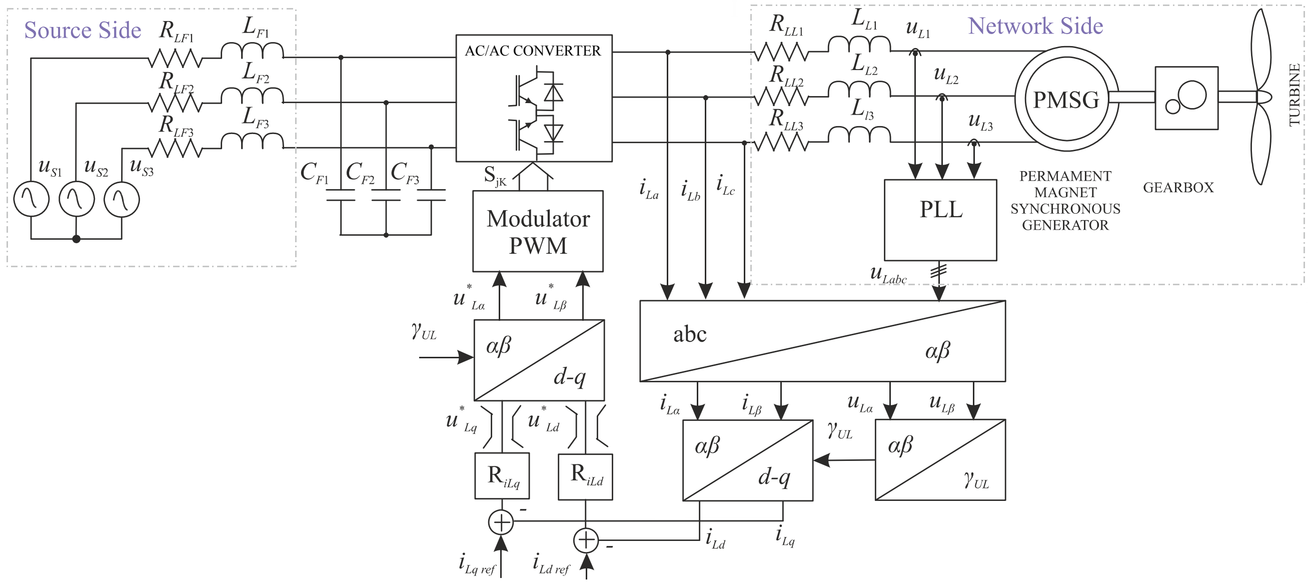

Fig. 28. Control block diagram for a matrix converter interface of two three-phase AC systems

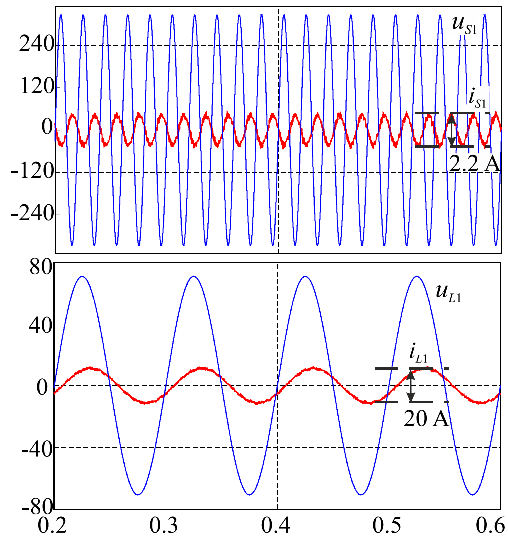

Fig. 29. Energy transfer from network side (wind generator) to source side: a) time waveforms of source current i_{S1} and voltage u_{S1} b) time waveforms of network side current i_{L1} and voltage u_{L1}; System parameters: source voltage u_{S1}=230 V/ 60 Hz, network voltage u_{L1}=50 V/10 Hz

Conclusions

The paper has described the topologies, the operation and test results of voltage sag/swell compensators, quadrature phase shifters, power flow controllers, static VAr compensators and interfaces of renewable energy source applications in power systems. The following devices have been proposed: the three-phase AC voltage sag/swell compensator based on hybrid transformer with buck- boost matrix-reactance chopper, the three-phase quadrature phase shifter based on hybrid transformer, the power flow controller based on Ćuk B2 matrix-reactance choppers, Static VAr compensator with matrix-reactance PWM AC line conditioner based on Ćuk converter topology and an example of the AC/AC interface based on matrix converter. Simulation and experimental test results confirm the usefulness of the presented implementation of the AC/AC converters in power systems.

REFERENCES

[1] Sivanagaraju S., Electric Power Transmission and Distribution, *Pearson Education India*, 2008,.
[2] Milanović J., Hiskansen I., Effect of load dynamics on power system damping, *IEEE Trans. on Power System*, vol. 10, No. 2, pp. 1022–1028, May 1995
[3] Liserre M., Sauter T. and Hung J. Y., Future energy systems: integrating renewable energy sources into the smart power grid through industrial electronics, *IEEE Ind. Electron. Magazine*, vol. 4, pp. 18-37, March 2010
[4] Brumsickle W. E., Schneider R. S., Luckjiff G. A., Divan D. M., McGranaghan M. F., Dynamic Sag Correctors: Cost-Effective Industrial Power Line Conditioning, *IEEE Trans. on Ind. Applications*, vol. 37, Jan./Feb 2001
[5] Bollen, M. and Zang, L., Analysis of voltage tolerance of ac adjustable – speed drives for three phase balanced and unbalanced sags, *IEEE Trans. on Ind. Applications*, vol. 36 No.3, pp. 904-910, May/June 2000
[6] Bhattacharyya S., Cobben S., Consequences of Poor Power Quality – An Overview, in Power Quality, edited by Mr Andreas Eberhard, *InTech,* 362 p., April, 2011
[7] Hingorani N. G., Gyugyi L., Understanding FACTS : Concepts and Technology of Flexible AC Transmission Systems,. *New York: IEEE Press*, 2000
[8] Ghosh A., Ledwich G., Power Quality Enhancement Using Custom Power Devices, *Springer Science+Business Media* New York, 2002
[9] Gupt S., Dixit A., Mishra N., Singh S.P., Custom Power Devices for Power Quality Improvement: A Review, *International Journal of Research in Engineering & Applied Sciences*, Volume 2, Issue 2, February 2012, pp. 1646–1659
[10] Molinas M., The role of power electronics in distributed energy systems, in *Proc. Symposium on Distributed Energy Systems*, Tokyo, Japan, Dec. 2008
[11] Kroposki B., Pink C., DeBlasio R., Thomas H., Simões M., Sen P. K., Benefits of power electronic interfaces for distributed energy systems, *IEEE Trans. Energy Conversion*, vol. 25, no. 3, pp. 901–908, Sept. 2010
[12] Blaabjerg F, Chen Z., Kjaer S. B., Power electronics as efficient interface in dispersed power generation systems, *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1184–1194, Sept. 2004.
[13] Kaniewski J, Analysis and study of properties of the hybrid transformers, Ph.D. dissertation, *University of Zielona Góra Press,* Zielona Góra 2011. (In Polish)
[14] Bashi S.M., Microcontroller-based Fast On-Load Semiconductor Tap Changer for Small Power Transformer, *Journal of Applied Sciences* 5 (6), pp. 999–1003, 2005
[15] Fedyczak Z.: *PWM AC voltage transforming circuits*, University of Zielona Góra Press, Zielona Góra 2003. (In Polish)
[16] Yorino N., Danyoshi M., Kitagawa M., Interaction among multiple controls in tap change under load transformers, *IEEE Trans. on Power System,* vol. 12, pp. 430-436, Feb. 1997
[17] Wu Q., Popović D.H., Hill D.J., Avoiding sustained oscillations in power systems with tap changing transformers, *Elsevier,*

Electrical Power and Energy Systems, No 22, pp 597–605, 2000
[18] Nielsen J. G., Newman M., Nielsen H., Blaabjerg F., Control and testing of a Dynamic Voltage Restorer (DVR) at medium voltage level, *IEEE Trans. on Power Electronics,* vol.19, pp. 806–813, May 2004
[19] Omar R., Rahim N.A., Voltage unbalanced compensation using dynamic voltage restorer based on supercapacitor, *Electrical Power and Energy Systems* 43, 2012, pp. 573–581
[20] Jain A., Joshi K*.,* Behal A., Mohan N*,* Voltage Regulation With STATCOMs: Modeling, Control and Results, *IEEE Transactions on Power Deliver*, Vol. 21, No. 2, pp. 726-735April 2006
[21] Sen K. K., Stacey E. J., UPFC – Unified Power Flow Controller: Theory, Modeling, and Applications, *IEEE Transactions on Power Deliver*, Vol. 13, No. 4, October 1998, pp. 1453-1460
[22] Lee Tzung-Lin, Hu Shang-Hung, Chan Yu-Hung, D-STATCOM With Positive-Sequence Admittance and Negative-Sequence Conductance to Mitigate Voltage Fluctuations in High-Level Penetration of Distributed-Generation Systems, *IEEE Transactions on Industrial Electronics*, Vol. 60, No. 4, April 2013
[23] Benslimante T., Aliouane K., Chetate B., Voltage and Current Disturbances Elimination with Reactive Power Compensation Using Unified Power Quality Conditioner, *in Proc. SPEEDAM 2009*, Taormina , 23-26 May 2006, pp. 780 – 784
[24] Subramanian S., Mishra M. K., Interphase AC-AC topology for voltage sag supporter, *IEEE Tran. on Power Elec*, vol. 25, No. 2, Feb. 2010, pp. 514-518
[25] Babaei E., Kangarlu M. F., Sabahi M., Compensation of voltage disturbances in distribution systems using single-phase dynamic voltage restorer, *Electric Power Systems Research*, 80 (2010), pp. 1413–1420
[26] Babaei E., Kangarlu M. F., Cross-phase voltage sag compensator for three-phase distribution systems, *Electrical Power and Energy Systems* 51 (2013), pp.119–126
[27] Jothibasu S., Mishra M. K., An improved direct AC-AC converter for voltage sag mitigation, *IEEE Trans. on Ind. Electronics*, vol. 62, No. 1, pp. 21-29 January 2015
[28] Lefeuvre E., Meyenard T., Viarouge P., Fast Line Voltage Conditioners using a PWM AC Chopper Topology, *In Proc. EPE*, Graz 2001
[29] Aeoliza E. C., Enjeti N. P., Moran L. A., Montero-Hernandez O. C., Sangsun K., Analysis and Design of a Novel Voltage Sag Compensator for Critical Loads in Electrical Power Distribution Systems, *IEEE Trans. on Ind. Appl.*, vol. 39, no. 4, July/Aug. 2003.
[30] Lee Dong-Myung, Habetler T. G., Harley R. G., Roston J., Keister T., A Voltage Sag Supporter Utilizing a PWM-Switched Autotransformer, *IEEE Trans. on Power Electr.*, vol. 22, no. 2 March 2007.
[31] Ryoo H. J., Kim J.S., Rim G.H., Series Compensated Step-down AC Voltage Regulator using AC Chopper with Transformer, *KIEE International Transactions on Electrical Machinery and Energy Conversion Systems,* vol. 5-B, no. 3, pp. 277-282, 2005
[32] . Kaniewski, Z. Fedyczak, and G. Benysek, AC Voltage Sag/Swell Compensator Based on Three-Phase Hybrid Transformer With Buck- Boost Matrix-Reactance Chopper, *IEEE Trans. Ind. Electron.*, vol.61, no.8, pp. 3835-3846, Aug. 2014.
[33] Kaniewski J., Modeling and analysis of three-phase hybrid transformer using buck-boost MRC, *in Proc. Compatibility and Power Electronics - CPE 2011 7th international conference-workshop*, Tallinn, Estonia, 2011, pp. 202-207
[34] Kaniewski J., Fedyczak Z., Szcześniak P., Three-phase hybrid transformer using matrix-chopper as an interface between two AC voltage sources, *Archives of Electrical Engineering*, vol. 63(2), pp. 197-210 (2014)
[35] Lopez L. A. C., Joos G., Ooi B-T., A PWM quadrature-booster phase shifter for AC power transmission, *IEEE Trans. on Power Electronics*, Vol. 12, No. 1, pp. 138 – 143, Jan. 1997
[36] Kaniewski J., Fedyczak Z., Modelling and Analysis of a Three-Phase Quadrature Phase Shifter with a Hybrid Transformer, *Electrical Review*, No 11, pp. 269-274, 2008
[37] Monteiro J., Fernando Silva J., Pinto S. F., Palma J., Linear and Sliding-Mode Control Design for Matrix Converter-Based Unified Power Flow Controllers, *IEEE Trans. on Power Electronics*, Vol. 29, No. 7, JULY 2014
[38] Kaniewski J., “Three-Phase voltage sag/swell compensator with phase shifter function based on bipolar matrix-reactance chopper,” i*n Proc. of Power Electronics, Electrical Drives, Automation and Motion - SPEEDAM 2014: International Symposium*. Ischia, Włochy, 2014 pp. 631-636
[39] Szcześniak P., Kaniewski J., A voltage regulator/conditioner based on a hybrid transformer with matrix converter, *in Proc. of 40th Annual Conference of the IEEE Industrial Electronics Society - IECON 2014*. Dallas, USA, 2014, pp. 3292-3297
[40] Fedyczak Z., Strzelecki R., Kasperek R., Skórski K.: Three-Phase Self-Commutated Static VAr Compensator Based on Ćuk Converter Topology*, PESC 2000,* Conference Proceedings, Galway, 2000 .- Vol. 1, p. 494-499
[41] Szcześniak P., Matrix Converter Interfaces Two Three-Phase AC Systems as a Component of Smart-Grid, in Proc. of *Power Electronics, Electrical Drives, Automation and Motion - SPEEDAM 2014: International Symposium,* Ischia, Włochy, 2014, pp. 676-681
[42] Szcześniak P, Kaniewski J, Jarnut M, AC-AC power electronic converters without DC energy storage: a review, *Energy Conversion and Management*, 92 (2015) 483-497
[43] Benysek G, Strzelecki R, Modern power-electronics installations in the Polish electrical power network. *Renewable and Sustainable Energy Reviews*, 15 (2011) 236–251.
[44] Blaabjerg F., Teodorescu R., Liserre M., Timbus A.V., Overview of control and grid synchronization for distributed power generation systems, *IEEE Trans. Ind. Electron.*, 53(5), 1398–1409, (2006).
[45] Cichowski A., Banach P., Śleszyński W., Nieznański J.: Comprehensive distortion compensation of grid-connected inverter currents, *40 Annual Conference of the IEEE Industrial Electronics Society IECON 2014*, Dallas, (2014) 1331-1336.
[46] Szcześniak P, Fedyczak Z, Application of the matrix converter to power flow control, *Archives of Electrical Engineering*, 63 (3) (2014) 409–422.
[47] Fedyczak Z., Strzelecki R., Benysek G., Single-phase PWM AC/AC semiconductor transformer topologies and applications, *Conference proc. of 33rd IEEE Power Electronics Specialists Conference - PESC '02,* Cairns, Australia, 2002, Vol. 2, pp. 1048-1053.
[48] Fedyczak Z., Strzelecki R., Sozański K., Review of three-phase PWM AC/AC semiconductor transformer topologies and applications, *Proc. of Power Electronics Electrical Drives Automation & Motion - SPEEDAM 2002*, Ravello, Italy, 2002, pp. B5-19—24.

Authors*: Dr inż. Jacek Kaniewski, University of Zielona Góra, Institute of Electrical Engineering, ul Podgórna 50 65-246 Zielona Góra, E-mail: J.Kaniewski@iee.uz.zgora.pl; dr hab. inż. Zbigniew Fedyczak, prof. UZ, University of Zielona Góra, Institute of Electrical Engineering, ul Podgórna 50 65-246 Zielona Góra, E-mail: Z.Fedyczak@iee.uz.zgora.pl, dr inż. Paweł Szcześniak, University of Zielona Góra, Institute of Electrical Engineering, ul Podgórna 50 65-246 Zielona Góra, E-mail: P.Szczesniak@iee.uz.zgora.pl*

.