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Modelling of voltage transfer function of the three-phase hybrid transformers with voltage or current source matrix converter

Abstract. *This paper deals with a three-phase power system with hybrid transformer (HT). The HT contains a conventional three-phase transformer with electromagnetic coupling and AC/AC converter integrated with the secondary windings through an electric coupling. The HT uses a three-phase Yy connected transformer with additional secondary windings and three-phase voltage or current source matrix converter (VSMC or CSMC), which give possibility to changing the value and phase shifting of the output phase voltage. The paper gives a description of such power system with passive load, as well as the modelling and comparison of voltage transfer functions for both solutions of the HT. The steady state analysis results of power systems with simplified HT mathematical models are verified by means of the simulation and experimental test results obtained for the power system with HT of about 6 kVA.*

Streszczenie. *Artykuł dotyczy trójfazowego systemu zasilania z transformatorem hybrydowym (TH). TH zawiera konwencjonalny transformator trójfazowy ze sprzężeniem elektromagnetycznym i przekształtnik energoelektroniczny typu AC/AC ze sprzężeniem elektrycznym, zintegrowany z uzwojeniami wtórnymi transformatora. W TH jest stosowany transformator uzwojeniami typu Yy oraz dodatkowymi uzwojeniami i trójfazowym przekształtnikiem matrycowym (PM) napięcia lub prądu, które umożliwiają zmianę przesunięcia fazowego napięcia wyjściowego. W artykule opisano działanie takiego systemu zasilania z obciążeniem pasywnym oraz jego modelowanie i porównanie relacji napięciowych dla dwóch rozwiązań TH (z PM napięcia lub prądu). Wyniki analizy właściwości w stanie ustalonym systemu zasilania z uproszczonymi modelemi matematycznymi są weryfikowane za pomocą badań symulacyjnych i eksperymentalnych systemie zasilania z TH o mocy ok. 6 kVA. (**Modelowanie relacji napięciowych trójfazowego transformatora hybrydowego z przekształtnikiem matrycowym napięcia lub prądu**).*

Słowa kluczowe: Przekształtniki typu AC/AC, Transformator trójfazowy, Przekształtnik matrycowy napięcia lub prądu.
Keywords: AC/AC converter, Three-phase transformer, Voltage or current source matrix converter.

Introduction

It is well known that rapid load changes, switching effects, and atmospheric discharge, generate undesirable effects in the AC power system, such as, voltage sags, interruptions and swell [1]. These effects in Europe are more than 60% of power quality and reliability related problems [2]. In the case of AC supply voltage changes, both downward and upward, there is a high risk of damage to devices which are sensitive to voltage changes, and consequently large financial damages may arise, especially in automotive, pharmaceutical and semiconductor industries [3]–[5]. In the known publications, there are presented various types of AC/AC voltage sag/swell compensators that mitigate the unwanted effects on supply [6]–[32]. These compensators contain: (i) conventional transformer (electromagnetic coupling) with tap changer [6], [7], (ii) AC/AC thyristor controller [8], (iii) PWM matrix choppers (MC) and PWM matrix reactance choppers (MRC) with or without a series addition transformer, [8]-[14], (iv) AC/DC/AC converters as the dynamic voltage controllers (DVR) with DC storage and a series addition transformer [15]– [21]. In addition there are, (v) hybrid transformers (HT) with a conventional transformer (electromagnetic coupling) and MC or MRC (electrical coupling), which have recently been intensively developed [22]–[32]. The HT provides galvanic separation and a wide range of change of voltage transmittance ($0.5 \leq H_U \leq 2$). This is particularly true for HT with buck-boost MRC [29]-[32]. Works on HT are continuously being developed and recently concern HT with voltage source matrix converter (VSMC) that give possibility to favourable change of output voltage phase in the HT [32]. The intention of the authors of this paper is to further develop the concept of HT with matrix converter by introducing current source matrix converter (CSMC) which has somewhat simpler topology with lower numbers of passive components [33].

This paper presents the results of the modelling and analysis of the three-phase HT with three-phase voltage or current source matrix converter (VSMC or CSMC). The next section describes the topology and operation of the presented HT. Following this are sections with HT voltage transfer functions, the simulation and experimental test results for c.a. 6 kVA laboratory model and conclusions.

Hybrid transformers description

Simplified scheme of the analysed HT is shown in Fig. 1, whereas the schemes of the VSMC and CSMC used in the HT are shown in Fig. 2 a) and b).

In general form, output phase voltage is formed as a sum of the phase voltage at the output of the matrix converter (VSMC or CSMC) powered by voltage inducted in secondary winding *a* of the TR and the phase voltage inducted in secondary winding *b* of the TR, as it is described for the supply voltages (1) by expression (2) and as illustrated in Fig. 3.

$$\begin{bmatrix} u_{S1} \\ u_{S2} \\ u_{S3} \end{bmatrix} = \begin{bmatrix} U_m \sin(\omega t + \varphi_S) \\ U_m \sin(\omega t + 2/3\pi + \varphi_S) \\ U_m \sin(\omega t - 2/3\pi + \varphi_S) \end{bmatrix}, \tag{1}$$

$$\begin{bmatrix} u_{L1} \\ u_{L2} \\ u_{L3} \end{bmatrix} = \begin{bmatrix} u_{C1} + n_b u_{S1} \\ u_{C2} + n_b u_{S2} \\ u_{C3} + n_b u_{S3} \end{bmatrix}, \tag{2}$$

where: u_{S1}-u_{S3}, u_{C1}-u_{C3} and u_{L1}-u_{L3} – supply, output of the VSMC or CSMC and output of the HT phase voltage respectively, U_m – maximum voltage, φ_S – initial phase, n_b – number of turns the secondary winding b.

Detailed description of the matrix converter (VSMC or CSMC) output voltages u_{C1}, u_{C2}, u_{C3}, based on expressions (3) and (4), that describing voltage and current relations for VSMC and CSMC respectively, there are presented in [32]–[35].

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} s_{aA} & s_{aB} & s_{aC} \\ s_{bA} & s_{bB} & s_{bC} \\ s_{cA} & s_{cB} & s_{cC} \end{bmatrix} \begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} = \mathbf{T} \begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix}, \tag{3}$$

$$(4)\quad \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} s_{aA} & s_{aB} & s_{aC} \\ s_{bA} & s_{bB} & s_{bC} \\ s_{cA} & s_{cB} & s_{cC} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \mathbf{T} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix},$$

where: $s_{jK} = \begin{cases} 1, & \text{switch } S_{jK} \text{ closed} \\ 0, & \text{switch } S_{jK} \text{ open} \end{cases}$ - switch state function, $j = \{a, b, c\}$, $K = \{A, B, C\}$, $\mathbf{T}$ – instantaneous transfer matrix.

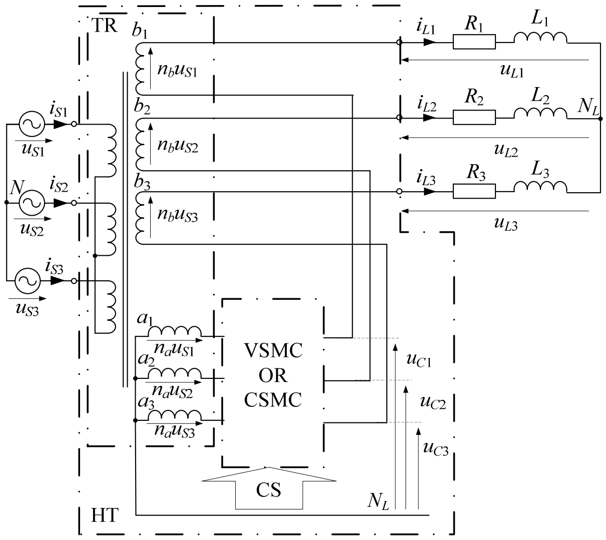

Fig. 1. Simplified diagram of the HT; CS – control signals

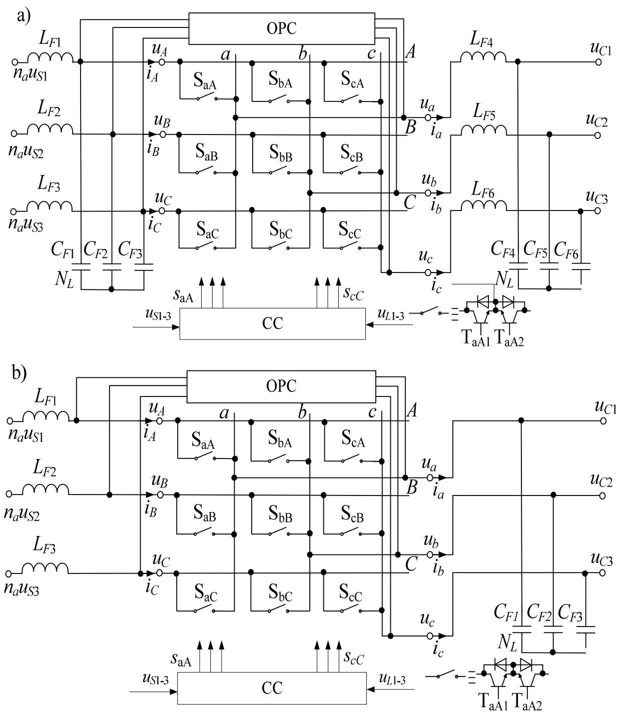

Fig. 2. Diagram of the, a) voltage source matrix converter, b) current source matrix converter; CC – control circuit, OPC – overvoltage protective circuit

Well known control strategies can be used to forming of the voltage or current relations [32] – [35] but simplified approach for TH with VSMC lead to phase voltage relation described by (5) [32], whereas for TH with CSMC can be described by (6).

$$(5)\quad U_O = q_U n_a U_s \cong U_C,$$

$$(6)\quad I_O = q_I I_S,$$

where: U_S, U_O, U_C – RMS values of supply voltage, output voltage of the VSMC without filter and output voltage of the VSMC with filter respectively, q_U – voltage relation coefficient, I_S, I_O – RMS values of supply and output current of the CSMC, q_I – current relation coefficient, n_a – number of turns the secondary winding a.

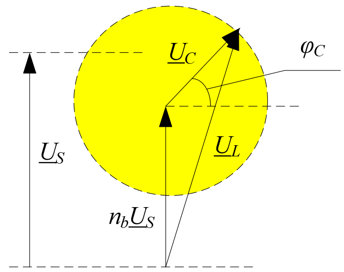

Fig. 3. Illustrative set of HT voltage phasors; φ_C – initial phase of the VS or CSMC

Taking into account (6) for circuit with CSMC we can obtain phase voltage relation as in (7) which after rearranging and assuming that $\omega_S = \omega_O = \omega$ and $\omega^2 L_F C_F >> 1$ has form as in (8).

$$(7)\quad \frac{U_C}{X_{CF}} \cong q_I \frac{n_a U_S}{X_{LF} - X_{CF}},$$

$$(8)\quad U_C \cong q_I n_a U_S \frac{X_{CF}}{X_{LF} - X_{CF}} = q_I n_a U_S \frac{1}{\omega^2 L_F C_F - 1} \cong q_I n_a U_S \left(\frac{\omega_r}{\omega}\right)^2,$$

where: ω_S, ω_O – input and output voltage pulsation of the CSMC, X_{LF}, X_{CF} – input (L_F) and output (C_F) phase reactance of the CSMC, $\omega_r = 1/\sqrt{L_F C_F}$ - resonance pulsation.

Voltage transfer functions

Taking into account time waveforms of output voltages (5), (8) and expression describing a sum of two sinusoid type $A\sin(\omega t + \alpha) + B\sin(\omega t + \delta)$ derived in [36] the phase output voltage expression (2) has form (9) whereas coefficients K_i and N_i are described by (10) and (11) for HT with VSMC and by (12) and (13) for HT with CSMC.

$$(9)\quad \begin{bmatrix} u_{L1} \\ u_{L2} \\ u_{L3} \end{bmatrix} = \begin{bmatrix} \sqrt{K_1^2 + N_1^2}\sin\left[\omega t + \tan^{-1}\left(\frac{N_1}{K_1}\right)\right] \\ \sqrt{K_2^2 + N_2^2}\sin\left[\omega t + \tan^{-1}\left(\frac{N_2}{K_2}\right)\right] \\ \sqrt{K_3^2 + N_3^2}\sin\left[\omega t + \tan^{-1}\left(\frac{N_3}{K_3}\right)\right] \end{bmatrix},$$

$$(10)\quad \begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix} = \begin{bmatrix} q_U n_a U_m \cos(\varphi_S + \varphi_C) + n_b U_m \cos\varphi_S \\ q_U n_a U_m \cos(\varphi_S + 2\pi/3 + \varphi_C) + n_b U_m \cos(\varphi_S + 2\pi/3) \\ q_U n_a U_m \cos(\varphi_S - 2\pi/3 + \varphi_C) + n_b U_m \cos(\varphi_S - 2\pi/3) \end{bmatrix},$$

(11) $$\begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix} = \begin{bmatrix} q_U n_a U_m \sin(\varphi_S + \varphi_C) + n_b U_m \sin\varphi_S \\ q_U n_a U_m \sin(\varphi_S + 2\pi/3 + \varphi_C) + n_b U_m \sin(\varphi_S + 2\pi/3) \\ q_U n_a U_m \sin(\varphi_S - 2\pi/3 + \varphi_C) + n_b U_m \sin(\varphi_S - 2\pi/3) \end{bmatrix},$$

(12) $$\begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix} = \begin{bmatrix} q_I n_a U_m \left(\frac{\omega_r}{\omega}\right)^2 \cos(\varphi_S + \varphi_C) + n_b U_m \cos\varphi_S \\ q_I n_a U_m \left(\frac{\omega_r}{\omega}\right)^2 \cos(\varphi_S + 2\pi/3 + \varphi_C) + n_b U_m \cos(\varphi_S + 2\pi/3) \\ q_I n_a U_m \left(\frac{\omega_r}{\omega}\right)^2 \cos(\varphi_S - 2\pi/3 + \varphi_C) + n_b U_m \cos(\varphi_S - 2\pi/3) \end{bmatrix},$$

(13) $$\begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix} = \begin{bmatrix} q_I n_a U_m \left(\frac{\omega_r}{\omega}\right)^2 \sin(\varphi_S + \varphi_C) + n_b U_m \sin\varphi_S \\ q_I n_a U_m \left(\frac{\omega_r}{\omega}\right)^2 \sin(\varphi_S + 2\pi/3 + \varphi_C) + n_b U_m \sin(\varphi_S + 2\pi/3) \\ q_I n_a U_m \left(\frac{\omega_r}{\omega}\right)^2 \sin(\varphi_S - 2\pi/3 + \varphi_C) + n_b U_m \sin(\varphi_S - 2\pi/3) \end{bmatrix},$$

where: φ_C – initial phase of the VSMC or CSMC output phase voltage,

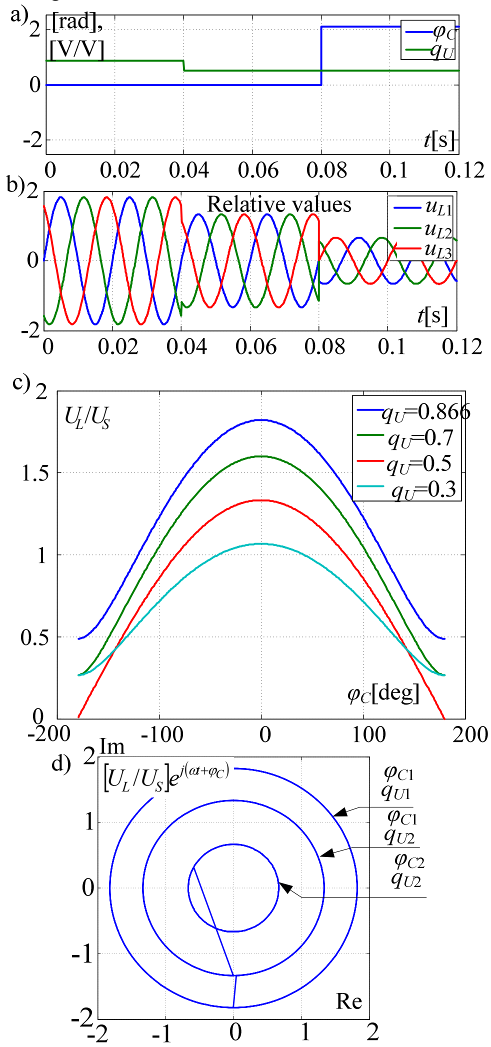

Fig. 4. HT with VSMC, a), b) output phase voltage time waveforms for different q_U (from 0.866 to 0.5) and φ_C (from 0 to $2\pi/3$), c) characteristics of the relative values of the output voltages and d) hodographs of the space vectors of output phase voltages as in b)

Example time waveforms of the HT output phase voltage, characteristics of the relative values and hodographs of space vectors of this voltages described by (14) for HT with VSMC or CSMC for different parameters are shown in Figs. 4 and 5.

(14) $$\underline{X}_L(\omega t) = \frac{2}{3}\left[u_{L1} + \underline{a} u_{L2} + \underline{a}^2 u_{L3}\right].$$

where: $\underline{a}=e^{j2\pi/3}$.

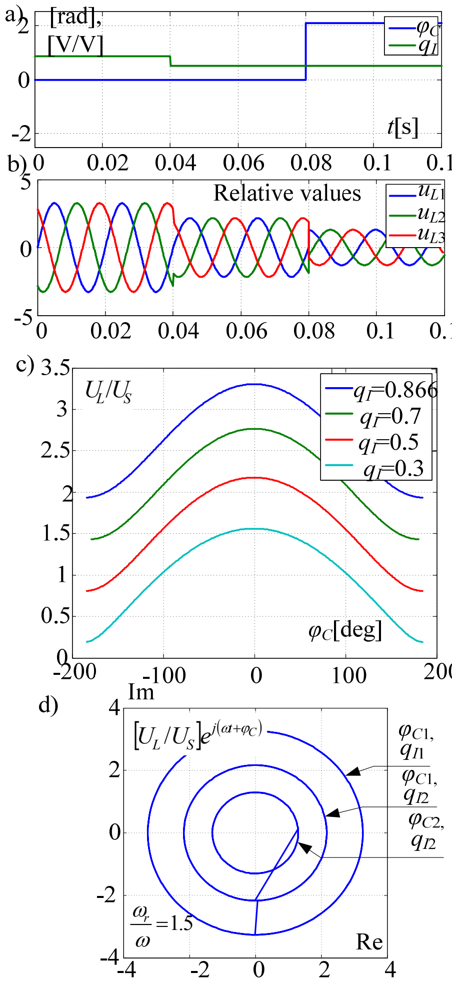

Fig. 5. HT with CSMC, a), b) output phase voltage time waveforms for different q_I , (from 0.866 to 0.5), φ_C (from 0 to $2\pi/3$) and (ω_r/ω) = 1.5, c) characteristics of the relative values of the output voltag es and d) hodographs of the space vectors of output voltages as in b)

From figures Fig. 4 and 5, is visible that for HT with VSMC (Fig. 4), as would be expected, value of the output voltage can be formed both by change of the voltage relation coefficient (q_U) and by change the phase of the VSMC output phase voltage (φ_C). Furthermore, for HT with CSMC, there is still one degree of freedom by means of resonance pulsation ($\omega_r = 1/\sqrt{L_F C_F}$) change. It is important, that this additional degree of freedom for HT with CSMC that allow obtaining the greater output phase voltage that is visible from Fig. 4 and is also visible from Fig 6.

Simulation and experimental test results

The simulation Simulink Matlab circuit model is shown in Fig. 7 whereas description and value of the simulation and experimental circuit parameters there are collected in the Table 1. Example of the simulation time waveforms of the HT output phase voltage, characteristics of the relative values and hodographs of space vectors of this voltages described by for HT with VSMC or CSMC for different parameters are shown in Figs. 8 and 9, whereas example of the experimental test results for HT with VSMC are shown in Fig. 10.

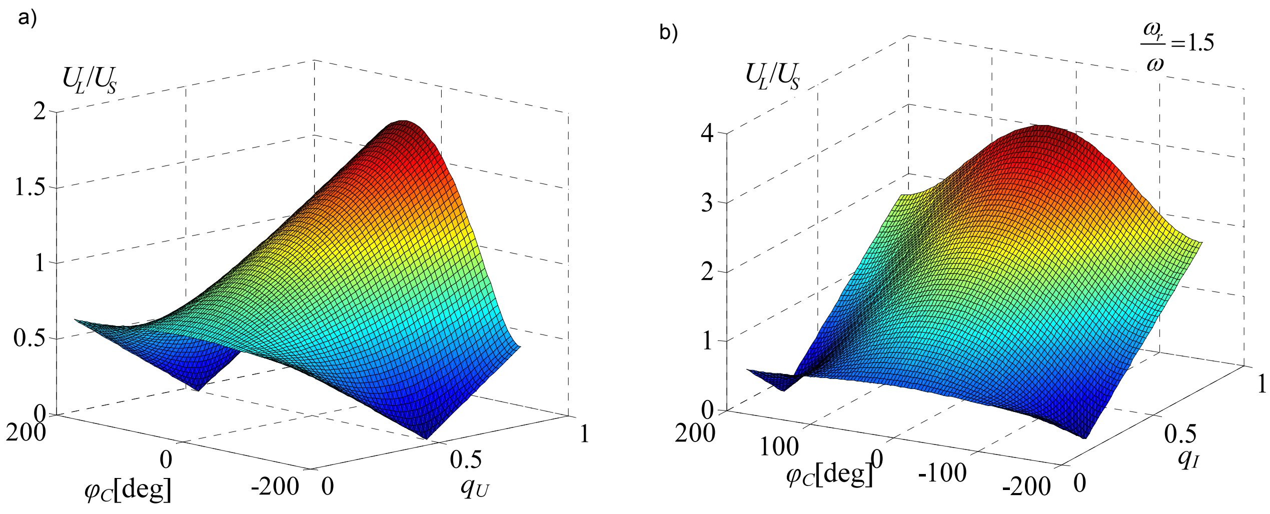

Fig. 6. Voltage relation for HT as a function of the voltage relation coefficient (q_U or q_I) and by change the phase of the MC output phase voltage (φ_C), a) for VSMC, b) for CSMC

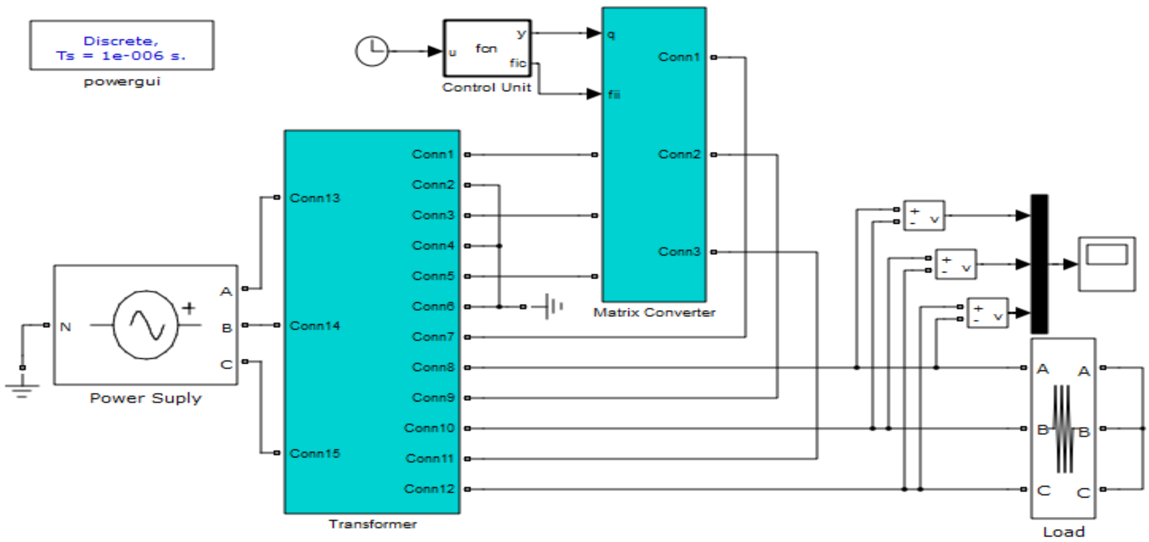

Fig. 7. Simulation circuit model

Table I.Circuit Parameters

Para-meter	Name	Value			unit
		VSMC		CSMC	
		Simulation	Experiment	Simulation	
n_a	Voltage ratio	4/3	4/3	4/3	-
n_b	Voltage ratio	2/3	2/3	2/3	-
L_F	Filter inductance	1	1	15	mH
C_F	Filter capacitance	15	10	30	μF
R_L	Load resistance	20	20	20	Ω
f_S	Switching frequency	5	5	5	kHz
U_S	Supply voltage	230	100	230	V

In general term, the HT simulation tests results, for circuit shown in Fig. 2, shown in figures Fig. 8 and 9 are similar to calculation ones (Fig. 4 –Fig. 6). As it is visible from Fig. 8 the value of the output voltage can be formed both by change of the voltage relation coefficient (q_U) and by change the phase of the VSMC output phase voltage (φ_C) and high compatibility of the calculation and simulation test results is noticeable. For HT with CSMC, greater difference between calculation and simulation test results can be observed, due to the simplifying assumptions adopted for the mathematical model of the CSMC output voltage (8).

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).

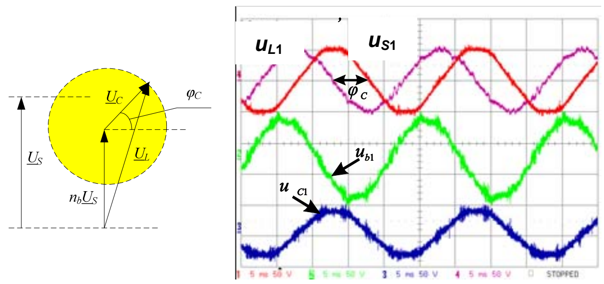

Fig. 10. Experimental time waveforms for HT with CSMC

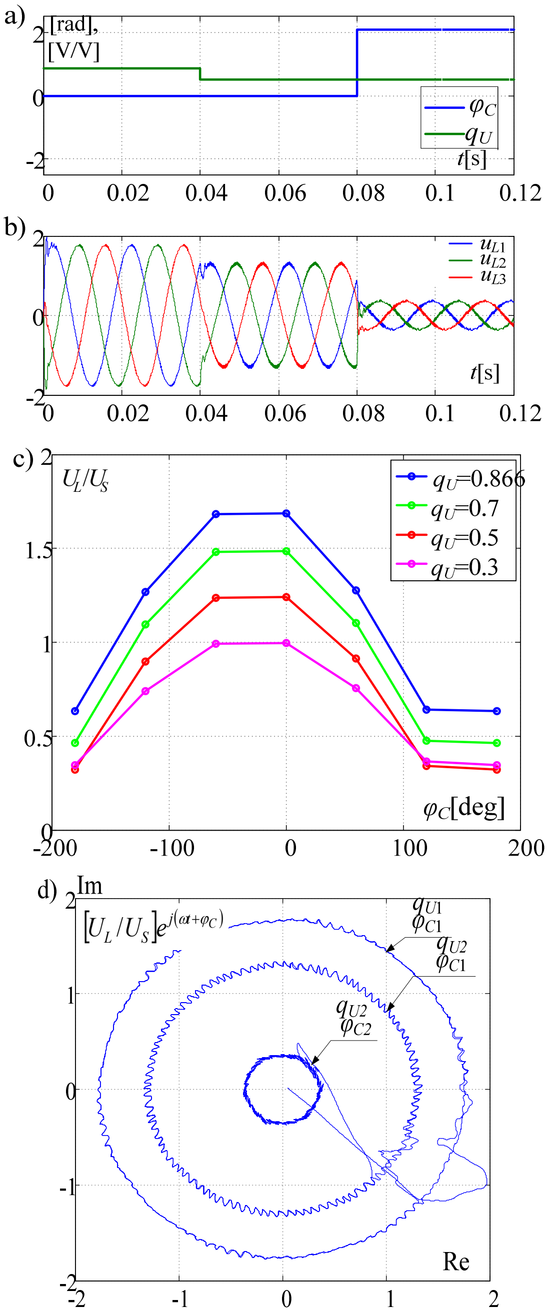

Fig. 8. HT with VSMC, a), b) output phase voltage time waveforms for different q_U (from 0.866 to 0.5) and φ_C (from 0 to $2\pi/3$), c) characteristics of the relative values of the output voltages and d) hodographs of the space vectors of output phase voltages as in b)

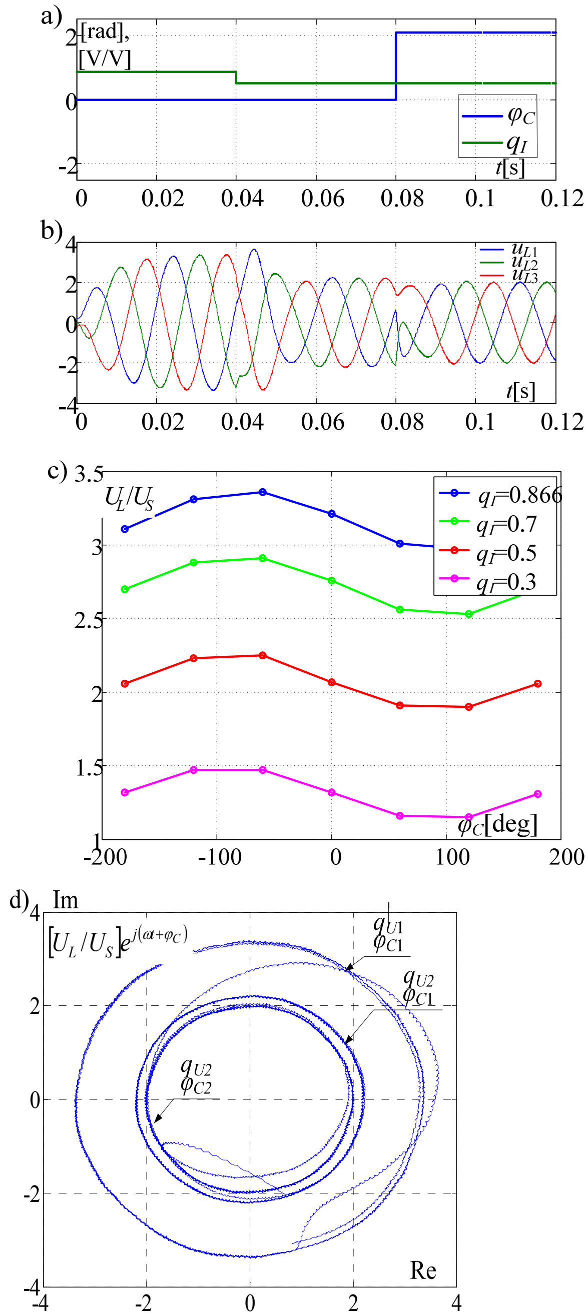

Fig. 9. HT with CSMC, a), b) output phase voltage time waveforms for different q_I, (from 0.866 to 0.5), φ_C (from 0 to $2\pi/3$) and $(\omega_r/\omega) \approx 3$, c) characteristics of the relative values of the output voltages and d) hodographs of the space vectors of output voltages as in b)

Conclusions

In this paper the mathematical models of the voltage transfer function the three-phase hybrid transformer (HT) with voltage or current source matrix (VSMC or CSMC) converter have been presented. In both circuit solutions the phase output voltage amplitude and phase can be changed by means of the VSMC or CSMC voltage or current relation coefficient (q_U) or (q_I) and the phase of the VSMC or CSMC output phase voltage (φ_C) respectively. For HT with CSMC, there is still one degree of freedom by means of the resonance pulsation (ω_r) change. In general term the simulation and experimental test results confirmed the theoretical ones. Further investigations will be focused on developing mathematical models, especially HT with CSMC and experimental implementation of the discussed transformers.

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