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IMPROVEMENT OF ENERGY TRANSFER IN BIDIRECTIONAL PHASE CONVERSION CIRCUITS BY SWITCHED-MODE POSITIVE-SEQUENCE FILTERS

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Abstract. This paper analyzes a new simple and efficient power electronic phase converter for either three- to single-phase or single- to three-phase conversion. The converter is featured by the unity displacement factor, by the use of a single inductive time-invariant energy-storing element and by a simple switched-bridge realization of the positive-sequence power filter. The improvement of the energy transfer achieved is based on an appropriate implementation of the zero-reactive-power operation mode of the energy-storing inductor. Experimental evaluation of the proposed phase converter was carried out in laboratory conditions.

Key words: bidirectional phase converters, three- to single-phase conversion, single- to three-phase conversion, positive-sequence filter.

1. INTRODUCTION

Power phase converters, an important link between power sources and loads, which vary in their phase number, operate to adapt the parameters of the generated electrical energy to the users' needs. Primarily, either three- to single-phase or single- to three-phase conversion is required. At the same time, low-distorted current waveforms and the symmetry of the three-phase currents are essential.

To obtain the unity power factor, the best known balanced phase conversion circuits require a simultaneous use of both inductive and capacitive balancing elements [1–3]. However, as shown in [4], a phase conversion circuit characterized by the unity displacement factor and by the use of the only inductive balancing element can be designed, applying a time-variable inductor plus a time-variable transformer.

This paper analyzes a new efficient and simple bidirectional phase conversion circuit, containing a time-invariant balancing inductor and a switched transformer to form the proper positive-sequence filter (PSF). Such a solution corresponds to the contemporary worldwide trend to replace passive balancing systems by the efficient switch-controlled phase converters and unbalance compensators [5–7].

2. OPERATING PRINCIPLES

Suppose we have a three-phase PSF to provide a symmetrical three-phase system of supply currents i_A, i_B, and i_C in the case of both unsymmetrical supply voltages and loads. Figure 1 shows the examples of the possible connections for three- to single-phase and single- to three-phase conversion.

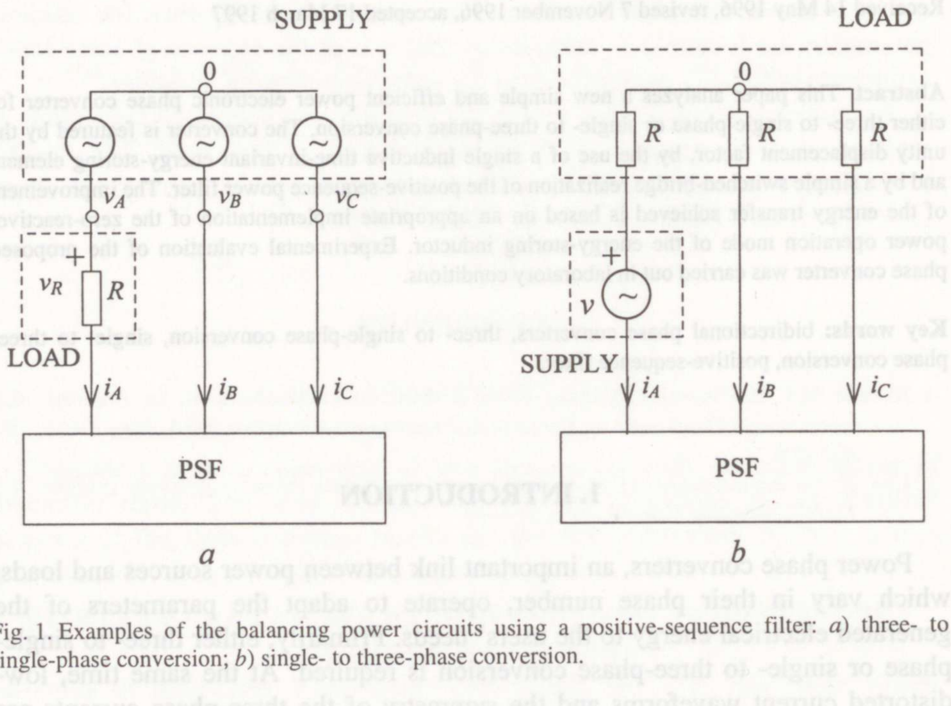

Fig. 1. Examples of the balancing power circuits using a positive-sequence filter: *a*) three- to single-phase conversion; *b*) single- to three-phase conversion.

In an ideal case, a PSF is the loss-less circuit, containing at least one energy-storing element, to provide compensation of the alternating power component in the unsymmetrical load or supply. Such a PSF can be implemented, using a time-variable transformer (TVT) for energy exchange control and an inductor L for energy storage, as proposed in [3]. Figure 2 shows a possible circuit configuration for three- to single-phase conversion corresponding to Fig. 1*a*.

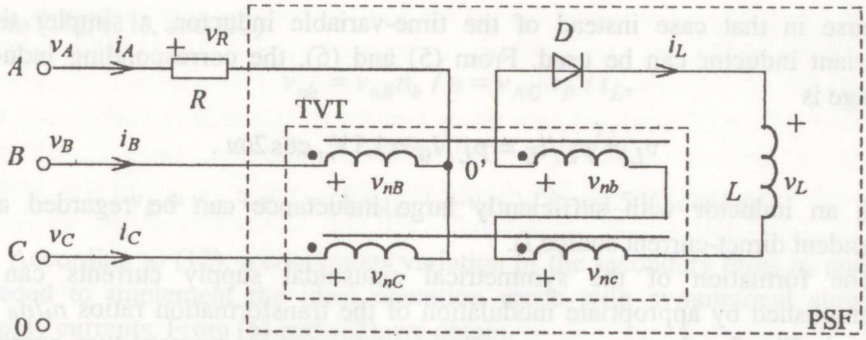

Fig. 2. Three- to single-phase power conversion circuit, using the time-variable transformer and the time-invariant inductor.

Let us consider, first, the case of sinusoidal phase voltages v_A, v_B, v_C and sinusoidal line currents i_A, i_B, i_C with $v_A = V_m\sin\omega t$, $i_A = I_m\sin\omega t$. Owing to the balanced supply, the instantaneous supply power p_1 equals the average supply power P_1, and thus

$$p_1 = v_A i_A + v_B i_B + v_C i_C = 1.5\,V_m I_m = P_1\,. \tag{1}$$

At the same time, the instantaneous load power is

$$p_R = v_R i_A = R i_A^2 = 0.5 R I_m^2 (1-\cos 2\omega t) = P_R + p_{R\sim}\,, \tag{2}$$

where P_R and $p_{R\sim}$ are the average and the alternating component of the instantaneous load power, respectively.

Because of the loss-less PSF, we have $P_1 = P_R$. Therefore, from (1) and (2), we obtain

$$I_m = 3V_m/R\,, \tag{3}$$

$$v_R = R i_A = 3V_m \sin\omega t = V_{Rm}\sin\omega t\,. \tag{4}$$

To provide a balanced operation mode, we must have such a control of the PSF which ensures compensation of the power component $p_{R\sim}$ by the instantaneous inductor power $p_L = v_L i_L$, and therefore,

$$p_L = -p_{R\sim} = 0.5\,V_{Rm} I_m \cos 2\omega t = 1.5\,V_m I_m \cos 2\omega t\,. \tag{5}$$

It can be obtained as the product of various voltage v_L and current i_L pairs. Moreover, to ensure the zero-reactive-power operation mode, the inductor voltage and current must have different harmonic content [4].

To simplify practical realization, it is desirable to choose

$$i_L = i_{A\max} = I_0 = I_m = \text{const}\,, \tag{6}$$

because in that case instead of the time-variable inductor, a simpler time-invariant inductor can be used. From (5) and (6), the corresponding inductor voltage is

$$v_L = p_L / i_L = p_L / I_0 = 1.5 V_m \cos 2\omega t\,. \tag{7}$$

Such an inductor with sufficiently large inductance can be regarded as a dependent direct-current source I_0.

The formation of the symmetrical sinusoidal supply currents can be accomplished by appropriate modulation of the transformation ratios n_b/n_B and n_c/n_C in Fig. 2, where $n_B = n_C = n$ are the time-invariant primary turn numbers, and n_b and n_c are the time-variable secondary turn numbers.

The equations of the ideal two-core transformer in Fig. 2 are

$$i_B n_B = i_B n = i_L n_b\,, \tag{8}$$

$$i_C n_C = i_C n = i_L n_c\,, \tag{9}$$

$$v_{nB} = v_R - v_{AB} = v_{AC}\,, \tag{10}$$

$$v_{nC} = v_R - v_{AC} = v_{AB}\,. \tag{11}$$

Figure 3 shows a phasor diagram with the phasors $\dot{V}_A$, $\dot{V}_B$, $\dot{V}_C$, $\dot{V}_{nB}$, $\dot{V}_{nC}$, and $\dot{V}_R$ of the corresponding fundamental harmonic voltages $v_A, v_B, v_C, v_{nB}, v_{nC}$, and v_R.

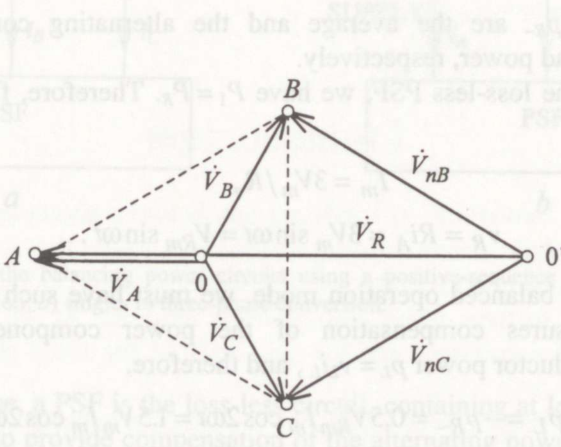

Fig. 3. Phasor diagram for the ideal operation mode with sinusoidal supply currents in the circuit in Fig. 2.

From (8) and (9), we obtain

$$n_b = n i_B / i_L, \quad n_c = n i_C / i_L, \tag{12}$$

from (10), (11), and (12)

$$v_{nb} = v_{nB} n_b / n = v_{AC} i_B / i_L, \tag{13}$$

$$v_{nc} = v_{nC} n_c / n = v_{AB} i_C / i_L, \tag{14}$$

$$v_L = v_{nb} + v_{nc} = (i_B v_{AC} + i_C v_{AB}) / i_L = 1.5\, V_m \cos 2\omega t . \tag{15}$$

According to (12), a continuous variation of the secondary turns n_b and n_c is needed to implement the ideal operation mode with symmetrical sinusoidal supply currents. From (6) and (12), we obtain

$$n_b = i_B n / i_L = n \sin(\omega t - 120^{\circ}), \tag{16}$$

$$n_c = i_C n / i_L = n \sin(\omega t + 120^{\circ}) . \tag{17}$$

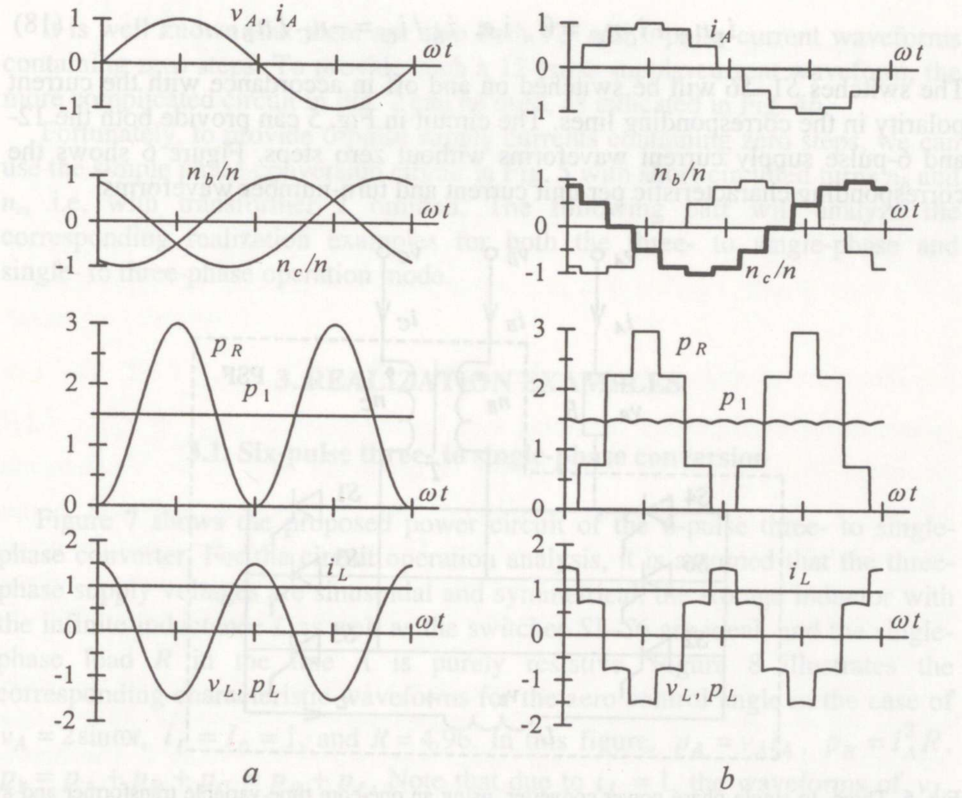

Fig. 4. Characteristic per unit waveforms in the circuit in Fig. 2: *a*) ideal operation mode with sinusoidal supply currents; *b*) 12-pulse operation mode with supply current having the zero step.

The negative value of the turn numbers n_b and n_c indicates that the corresponding winding connection is reversed as compared to that shown in Fig. 2. Figure 4*a* shows the corresponding typical per unit waveforms in the circuit in Fig. 2. In practice, instead of the ideal continuous turn variations (16) and (17), only a stepped turn variation can be implemented that makes the entire cancellation of the unwanted harmonics impossible. Nevertheless, a suitable stepped variation of turns and turn ratios and the corresponding variation in the line current ratios enables one to implement the *m*-pulse balanced operation mode and thus to eliminate the lower harmonics up to $m-1$ in the supply currents. For example, the characteristic per unit waveforms in the circuit in Fig. 2, corresponding to the 12-pulse operation mode, are shown in Fig. 4*b*.

The general phase-conversion circuit in Fig. 2 enables the implementation of balanced operation modes with any pulse number. On the other hand, in the case of the 12- and 6-pulse operation mode, simpler PSF configurations with simpler, and therefore, more efficient energy transfer can be used. For example, Fig. 5 shows a possible three- to single-phase converter containing an one-core TVT *T*, a time-invariant inductor *L*, and a controlled rectifier bridge *S*1–*S*6. In this circuit, for the ideal transformer *T*, the following relationship is valid:

$$i_B n_B + i_C n_C = 0, \text{ i.e. } i_B / i_C = -n_C / n_B. \quad (18)$$

The switches *S*1–*S*6 will be switched on and off in accordance with the current polarity in the corresponding lines. The circuit in Fig. 5 can provide both the 12- and 6-pulse supply current waveforms without zero steps. Figure 6 shows the corresponding characteristic per unit current and turn-number waveforms.

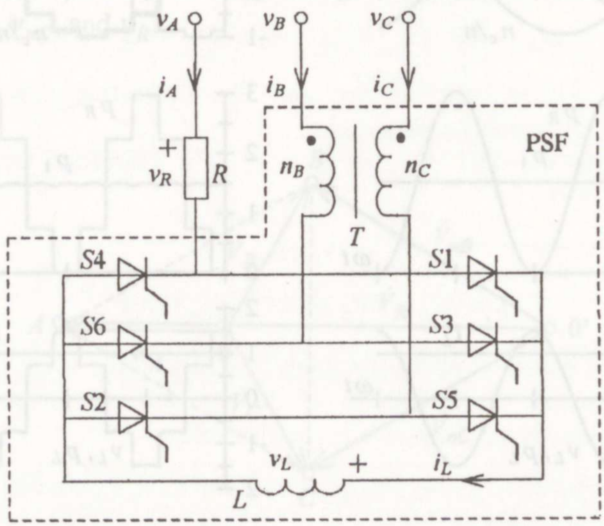

Fig. 5. Three- to single-phase power converter, using an one-core time-variable transformer and a controlled rectifier bridge.

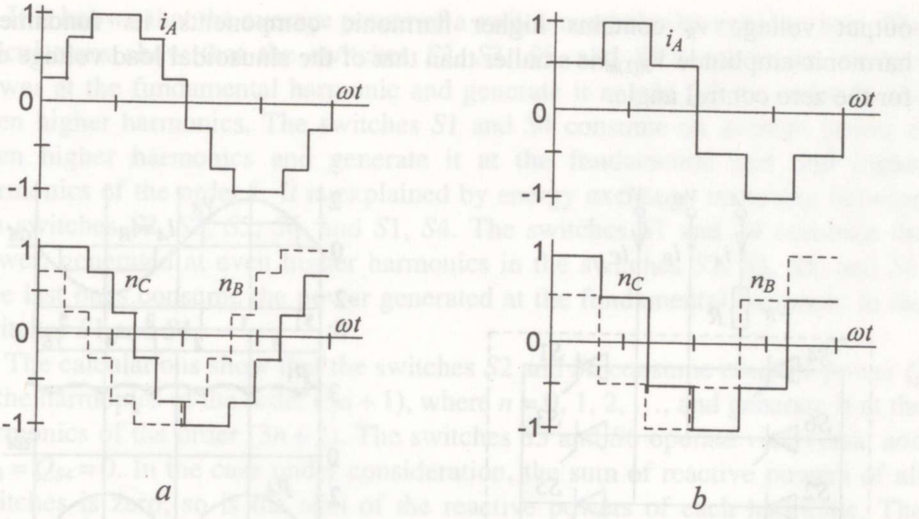

Fig. 6. Characteristic per unit current and turn-number waveforms in the circuit in Fig. 5: *a*) 12-pulse operation mode; *b*) 6-pulse operation mode.

It is well known that there are also both 12- and 6-pulse current waveforms containing zero steps. To provide such a 12-pulse supply-current waveform, the more complicated circuit in Fig. 2 can be used, as indicated in Fig. 4*b*.

Fortunately, to provide 6-pulse supply currents containing zero steps, we can use the simple phase-conversion circuit in Fig. 5 with short-circuited turns n_b and n_c, i.e. with transformer *T* omitted. The following part will analyze the corresponding realization examples for both the three- to single-phase and single- to three-phase operation mode.

3. REALIZATION EXAMPLES

3.1. Six-pulse three- to single-phase conversion

Figure 7 shows the proposed power circuit of the 6-pulse three- to single-phase converter. For the circuit operation analysis, it is assumed that the three-phase supply voltages are sinusoidal and symmetrical, the storage inductor with the infinite inductance *L* as well as the switches *S*1–*S*6 are ideal, and the single-phase load *R* in the line *A* is purely resistive. Figure 8 illustrates the corresponding characteristic waveforms for the zero control angle in the case of $v_A = 2\sin\omega t$, $i_L = I_0 = 1$, and $R = 4.96$. In this figure, $p_A = v_A i_A$, $p_R = i_A^2 R$, $p_1 = p_A + p_B + p_C = p_R + p_L$. Note that due to $i_L = 1$, the waveforms of v_L and $p_L = v_L I_0$ coincide. Since the circuit elements are assumed to be ideal, the input average power P_1 has to be equal to the load power P_R, i.e. $P_1 = P_R$. As the output voltage v_R contains higher harmonic components, its fundamental harmonic amplitude $V_{R(1)m}$ is smaller than that of the sinusoidal load voltage even for the zero control angle.

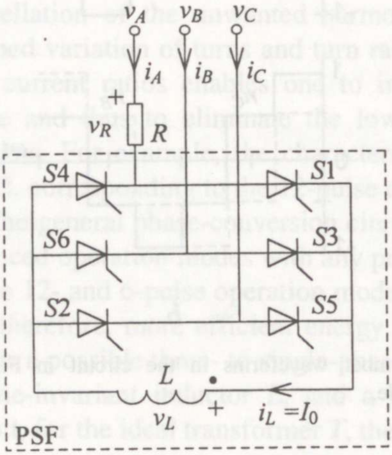

Fig. 7. Power circuit of the proposed 6-pulse three- to single-phase converter.

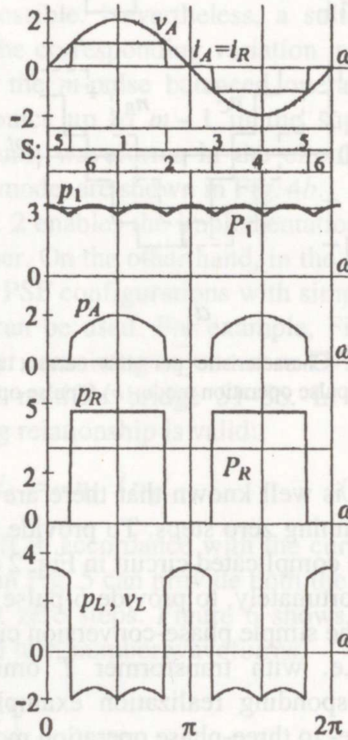

Fig. 8. Voltage, current, and power waveforms in the circuit in Fig. 7.

The input average power can be written: $P_1 = 3V_{Am}V_{R(1)m} / 2R$. The load power at the fundamental harmonic may be expressed as $P_{R(1)} = V_{R(1)m}^2 / 2R$, therefore $P_1 > P_{R(1)}$. The input power is generated only at the fundamental harmonic, the load consumes power at the fundamental and odd higher harmonics of the order $k = 5, 7, 11, 13$, etc. The calculations show that the power at the fundamental harmonic is delivered to the load by the symmetrical three-phase alternating voltage source, the power at the odd higher harmonics – by the switches.

The current and voltage waveforms of the switches contain odd and even higher harmonics. The switches consume average power at the fundamental harmonic and generate it at the odd higher harmonics of the order *k*. The sum of average powers, consumed and generated by all switches, must be equal to zero. The average power generated in the switches at the odd higher harmonics is consumed in the load.

It is known that the average power of a switch must also be equal to zero. The calculations show that the switches $S2$, $S3$, $S5$, and $S6$ consume an average power at the fundamental harmonic and generate it at odd (of the order k) and even higher harmonics. The switches $S1$ and $S4$ consume an average power at even higher harmonics and generate it at the fundamental and odd higher harmonics of the order k. It is explained by energy exchange occurring between the switches $S2$, $S3$, $S5$, $S6$, and $S1$, $S4$. The switches $S1$ and $S4$ consume the power, generated at even higher harmonics in the switches $S2$, $S3$, $S5$, and $S6$. The last ones consume the power generated at the fundamental harmonic in the switches $S1$ and $S4$.

The calculations show that the switches $S2$ and $S5$ consume reactive power Q at the harmonics of the order $(3n+1)$, where $n = 0, 1, 2, \ldots$, and generate it at the harmonics of the order $(3n+2)$. The switches $S3$ and $S6$ operate vice versa, and $Q_{S1} = Q_{S4} = 0$. In the case under consideration, the sum of reactive powers of all switches is zero; so is the sum of the reactive powers of each harmonic. The current of the inductor $i_L = I_0$ contains only a direct-current component, the inductor voltage v_L – only even harmonics, therefore, the reactive power $Q_L = 0$, and only distortion power exists in the inductor.

3.2. Six-pulse single- to three-phase conversion

Figure 9 shows the power circuit of the 6-pulse single- the three-phase converter. For the circuit operation analysis, it is assumed that the symmetrical resistive load is supplied from the single-phase sinusoidal voltage source, the storage inductor with infinite inductance L and the switches $S1$–$S6$ are ideal. Figure 10 illustrates the corresponding characteristic waveforms for the zero control angle for the case $v = -3.63\sin\omega t$, $R_A = R_B = R_C = 1$, and $i_L = I_0 = 1$. It is taken into account that

$$p_{RA} = v_{RA}\, i_A = P_R + p_{RA\sim}\,, \tag{19}$$

$$p_{RABC} = p_{RA} + p_{RB} + p_{RC} = 3P_R + p_{RABC\sim}\,, \tag{20}$$

$$p_L = v_L i_L = v_L I_0\,, \tag{21}$$

$$p_1 = -v i_A = p_{RABC} + p_L = P_1 + p_{1\sim} = 3P_R + p_{1\sim}\,. \tag{22}$$

The calculations show that the switches $S1$ and $S4$ consume an average power at the fundamental harmonic and generate it both at odd (of the order k) and even higher harmonics. The switches $S2$, $S3$, $S5$, and $S6$ consume the power mainly at the second harmonic (generated in the switches $S1$ and $S4$) and generate it mainly at the fundamental and odd higher harmonics of the order k. It means that energy exchange occurs simultaneously between the switches, and the essential harmonics in this process are the fundamental harmonic and the second one. The power generated in the switches at the higher harmonics of the order k is consumed in the three-phase load.

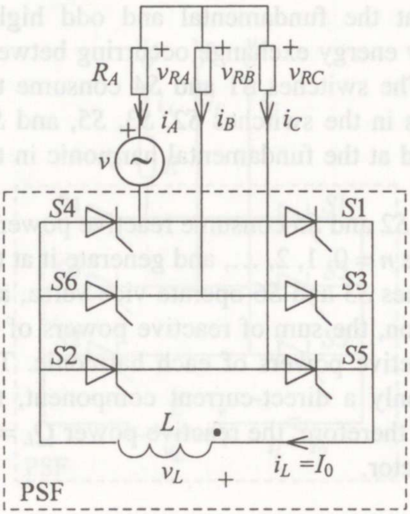

Fig. 9. Power circuit of the proposed 6-pulse single- to three-phase converter.

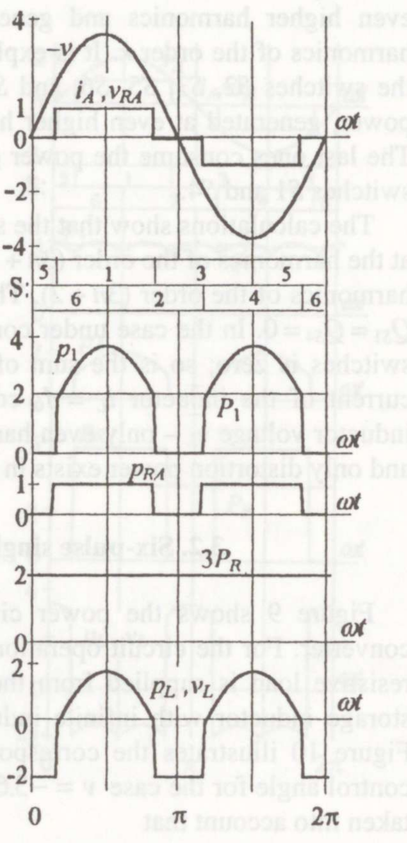

Fig. 10. Voltage, current, and power waveforms in the circuit in Fig. 9.

The calculations show that the switches $S2$ and $S5$ consume reactive power at the harmonics of the order $(3n+2)$ and generate it at the harmonics of the order $(3n+1)$, the switches $S3$ and $S6$ operate vice versa, so that the sum of reactive powers in the circuit is zero. The switches $S1$ and $S4$ are not involved in the process of reactive power exchange, neither is the inductor ($Q_{S1} = Q_{S4} = Q_L = 0$), in which only distortion power exists.

To verify the feasibility of the proposed bidirectional phase converters, the corresponding laboratory prototypes of the 6-pulse converters shown in Figs. 7 and 9 were built and tested. It was verified that the unity-displacement-factor operation mode holds for both the time-invariant and time-variable resistive load. Further investigation is required to determine the performance characteristics in the case of the reactive-resistive load.

4. CONCLUSION

A new simple and efficient power electronic phase converter for the two conversion modes – either three- to single-phase or single- to three-phase power conversion – has been analyzed. It is featured by the unity displacement factor, by the use of the single inductive time-invariant energy-storing element and by the simple switched-bridge realization of the positive-sequence power filter. An improvement of energy transfer is achieved by such a control of the energy flow, which ensures the zero-reactive-power operation mode of the simple balancing inductor.

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KAHESUUNALISTE FAASIMUUNDUSAHELATE ENERGIAÜLEKANDE TÄIUSTAMINE LÜLITI TÜÜPI PÄRIJÄRGNEVUSFILTRITE ABIL

Vello SARV ja Maire OJAVEER

On analüüsitud uut, efektiivset ja lihtsat võimsuselektronfaasimuundurit kolmefaasilise süsteemi muundamiseks ühefaasiliseks või ühefaasilise süsteemi muundamiseks kolmefaasiliseks. Muunduri nihketegur on 1 ning selles on kasutatud ühtainsat statsionaarset induktiivset energiasalvestit ja lihtsat lülitatava sillaga pärijärgnevusfiltrit. Energiaülekande paranemine põhineb energiasalvestuspaispooli reaktiivvõimsusvaba talituse realiseerimisel. Esitatud faasimuundurit on laboris katseliselt kontrollitud.