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Investigation of the AC/AC Buck-Boost Converter

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Abstract **– This paper reviews the possibility of implementing a buck-boost AC/AC converter with a changeable configuration, which ensures quasi-sinusoidal characteristics of source and load current. Load is made up of active and inductive components, with a parallel-connected smoothing capacitor whereas at the input stage a current-smoothing LC input filter is applied. The process is controlled by four bidirectional semiconductor switches, from which two are active in each of the operation modes. An explanation of electromagnetic processes in both of the operating modes is given, in order to show how the mathematical description of the circuit functionality is acquired. Computer simulation results are introduced as well, providing a comparison of calculated and simulated parameters at both the buck and boost operation cases.**

Keywords **– Bidirectional semiconductor switch, capacitors, coils, commutation, duty ratio, filters, ripples, position.**

I. Introduction

Traditionally, AC voltage control has been effected by using transformers; in addition, more frequently, semiconductor-controlled tap transformers have been used. The biggest drawback of such systems is the high rated power and the large size of the transformers. Lessening of the previously stated drawbacks for the case of limited change of output voltage by 15 % to 20 % from the input value along with decrease of the transformer power rating and size can be done by using an autotransformer that has a step voltage controlling mode or a uniformly controllable voltage regulation mode [11], [12]. Both modes are implemented by using semiconductor switches. However, even such systems cannot fully cancel out all the drawbacks of transformer systems.

Transformer-less solutions based on semiconductor switches could solve some of the previously stated problems. Since in conventional tap-changing transformer systems the output voltage has to be increased and decreased, the controlling scenario also has to be the same in a transformer-less system and a bidirectional power flow has to be ensured as well. One solution could be the implementation of a buck-boost (BB) AC system, which can be constructed based on DC BB converter schemes and operating principles [8]–[10]. However, the switches applied must have bidirectional conductivity properties; besides, commutation problems arise as well.

For AC conversion needs, application of a traditional BB DC system with an inverted output voltage is proposed [4]–[7]. Especially interesting is the circuit presented in [4], where instead of one operating coil, two are applied, thus enabling of the ZCS of the switch. However, the problem persists related to distinct polarities of the input and output voltages. Therefore, more and more attention is paid to application of more complex systems which allow obtaining harmonized polarity of both voltages. Especially interesting is the proposed application of a system with a BB-controlled AC/AC converter transformer with its secondary winding in series or in parallel to a load [3]. Such application can be very efficient at a relatively small range of load voltage regulation. Anyway, the main disadvantage of such a system is related to the application of a transformer. Therefore, more attention is paid to the DC BB system with harmonized input and output voltages.

From all known DC buck-boost circuits, the most appropriate ones for AC control seem the SEPIC circuit and the circuit presented in [8], both of which have the same harmonized polarity of input and output signals [8]. By evaluating the requirements regarding AC voltage control, the circuit shown in Fig. 1 seems the most appropriate one and such a system is used in the major part of all the range of papers devoted to the investigation and development of this kind of AC/AC conversion devices [1]–[3]. The papers mostly describe conversion principles for variations of the possible diagrams, applying simplified expressions for voltage gain, simulation of processes, results of experimental investigations. However, for proper evaluation of the systems, it is necessary to conduct a deeper investigation of electromagnetic processes, which allows obtaining expressions for versatile calculation of parameters. The target of this paper is to provide a comprehensive analysis of the processes in the most frequently used transformer-less AC/AC BB converter system presented in Fig. 1.

II. Proposed Circuit

For the circuit to work, it is necessary to use four bidirectional conductivity semiconductor switches S1, S2, S3, S4 (Fig. 1.). At a constant **on** position of S4 and a constant **off** position of S3, the remaining two switches S1 and S2 make the circuit work in buck mode. At a constant **on** position of S1 and a constant **off** position of S2, switches S3 and S4 ensure the functioning of the circuit in boost operation mode. It has to be noted that both sides – input and output – must be supplied with LC filters in order to smooth a current [13], [14].

If, instead of load, another AC voltage source is connected, with a source voltage amplitude higher than the input one and with the same frequency, and even with a small phase shift between both voltages, then, by using switches S4 and S3 at a constant **on** position of S1 and a constant **off** position of S2, reverse buck mode operation can be ensured with power flow from the output source to the input AC grid.

In the case when the AC voltage source connected to the load side has a lower voltage than the input voltage of the AC grid, by commutating switches S1 and S2 at constant states of S4 (**on**) and S3 (**off**) reverse boost mode operation can be ensured.

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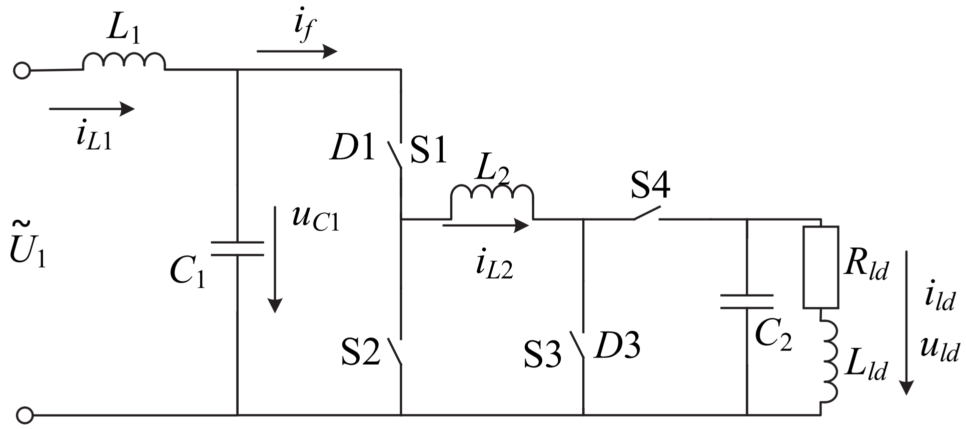

Fig. 1. Proposed circuit.

III. Mathematical Description of Buck Mode

Let us assume that the current of the load (consisting of a resistor and an inductance) is sinusoidal:

$$i_{\mathrm{ld}} = I_{\mathrm{ldm}} \sin v, \tag{1}$$

and the load voltage is as follows:

$$u_{\mathrm{ld}} = I_{\mathrm{ldm}} Z_{\mathrm{ld}} \sin(v + \varphi_{\mathrm{ld}}), \tag{2}$$

where $\varphi_{\mathrm{ld}} = \mathrm{arctg}\frac{\omega L_{\mathrm{ld}}}{R_{\mathrm{ld}}}$, Z_{ld} is the impedance of the L, R load.

The amplitude of the current flowing through inductance L_2 can be evaluated on the basis of the phasor diagram shown in Fig. 2.

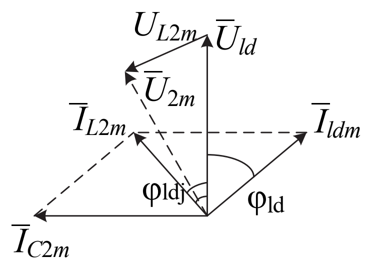

Fig. 2. Phasor diagram for the load junction.

Hence

$$I_{L2\mathrm{m}} = I_{\mathrm{ldm}}\sqrt{Z_{\mathrm{ld}}^2 \omega^2 C_2^2 - 2Z_{\mathrm{ld}}\omega C_2 \sin\varphi_{\mathrm{ld}} + 1} = I_{\mathrm{ldm}}\sqrt{a} \tag{3}$$

The phase shift angle of the current of inductance L_2 against load voltage can also be evaluated from the phasor diagram:

$$\mathrm{Tan}\,\varphi_{\mathrm{ldj}} = \frac{Z_{\mathrm{ld}}\omega C_2}{\cos\varphi_{\mathrm{ld}}} - \tan\varphi_{\mathrm{ld}}, \tag{4}$$

so current i_{L2} is shifted by angle $(\varphi_{\mathrm{ld}} + \varphi_{\mathrm{ldj}})$ with respect to the load current.

Current i_{f}, which is consumed from the input smoothing filter L_1, C_1, equals either zero (S1 is **off**) or i_{L2} and the mean wave of i_{f} formed by modulation can be expressed as follows:

$$i_{\mathrm{fM}} = D_1 I_{L2\mathrm{m}} \sin(v + \varphi_{\mathrm{ld}} + \varphi_{\mathrm{ldj}}), \tag{5}$$

where D_1 is the duty ratio applied for switch S1.

The voltage drop caused by current i_{L2} is u_{L2} and together with the load voltage it makes up the mean wave voltage $u_{2\mathrm{M}}$ of point 2 (Fig. 1), which is also modulated with switches S1 and S2. Mean wave voltage is developed by modulating the voltage of capacitor C_1 and can be expressed as follows:

$$u_{2\mathrm{M}} = u_{C1} D_1. \tag{6}$$

The amplitude of $u_{2\mathrm{M}}$ can also be expressed from the phasor diagram in Fig. 2:

$$U_{2\mathrm{Mm}} = I_{\mathrm{ldm}}\sqrt{Z_{\mathrm{ld}}^2 - 2Z_{\mathrm{ld}}\omega L_2\sqrt{a}\sin\varphi_2 + a\omega^2 L_2^2} = \frac{U_{\mathrm{ldm}}^b}{Z_{\mathrm{ld}}}, \tag{7}$$

where $a = Z_{\mathrm{ld}}^2\omega^2 C_2^2 - 2Z_{\mathrm{ld}}\omega C_2 \sin\varphi_{\mathrm{ld}} + 1$.

The voltage of input filter capacitor C_1 is in phase to the mean voltage wave $u_{2\mathrm{M}}$ and

$$U_{2\mathrm{Mm}} = D_1 U_{C1\mathrm{m}}, \tag{8}$$

$$U_{\mathrm{ldm}} = \frac{Z_{\mathrm{ld}} D_1 U_{C1\mathrm{m}}}{b} \cong \frac{Z_{\mathrm{ld}}}{b} D_1 U_{1\mathrm{m}}. \tag{9}$$

The phase shift angle of $u_{2\mathrm{M}}$ with respect to the load voltage can be expressed as follows:

$$\tan\varphi_3 = \frac{U_{L2\mathrm{m}}\cos\varphi_{\mathrm{ldj}}}{U_{\mathrm{ldm}} - U_{L2\mathrm{m}}\sin\varphi_{\mathrm{ldj}}}, \tag{10}$$

where $U_{L2\mathrm{m}} = I_{L2\mathrm{m}}\omega L_2$.

Due to the fact that $U_{L2\mathrm{m}}$ usually is much smaller than U_{ldm}, angle φ_3 is very small, which results in the phase of the load voltage being almost equal to the phase of the voltage of filter capacitor C_1.

Besides, the phase shift of the filter current i_{fM} consumed from the input with respect to the voltage of filter capacitor C_1 is φ_{ldj} as well (Fig. 3.).

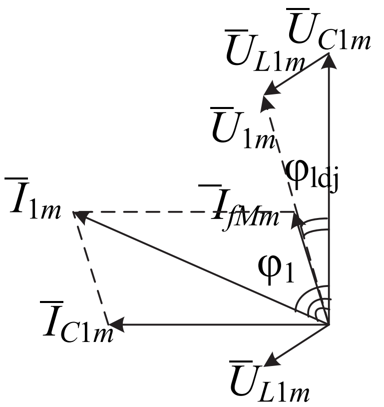

Fig. 3. Phasor diagram for the input filter junction.

From the phasor diagram in Fig. 3 it is possible to express the amplitude of source current i_1:

$$I_{1\mathrm{m}} = I_{\mathrm{ldm}}\sqrt{\frac{Z_{\mathrm{ld}}^2}{D_1^2}\omega^2 C_1^2 + 2Z_{\mathrm{ld}}\omega C_1\sqrt{a}\sin\varphi_{\mathrm{ldj}} + D_1^2 a}. \tag{11}$$

The phase shift angle of i_1 with respect to the voltage of capacitor C_1 can be expressed as follows:

$$\varphi_{1C} = 90^{\circ} - \operatorname{arctg}\frac{D_1^2\sqrt{a}\cos\varphi_{\mathrm{ldj}}}{Z_{\mathrm{ld}}\omega C_1 + D_1^2\sqrt{a}\sin\varphi_{\mathrm{ldj}}} \tag{12}$$

and roughly $\varphi_{1C} \approx \varphi_1$, so it follows that φ_{1C} is the phase shift angle between supply voltage U_1 and I_1.

By taking into account that $U_{C1\mathrm{m}} \approx U_{1\mathrm{m}}$ (the voltage drop on inductance L_1 is small) and that the active power balance on the input and output is

$$U_{1\mathrm{m}} I_{1\mathrm{m}} \cos\varphi_1 = I_{\mathrm{ldm}}^2 R_{\mathrm{ld}}, \tag{13}$$

it can be concluded that description of the circuit parameters greatly depends on the values of the circuit elements.

To ensure that current i_{L2} is as close to sinusoidal as possible, the value of the inductance of L_2 has to be sufficiently high. The increase of instant current i_{L2} is initiated by the voltage across L_2 during the **on** position of S1 over time interval $D_1 T_{\mathrm{m}}$, where T_{m} is the period of modulation $1/f_{\mathrm{m}}$ and f_{m} stands for the frequency of modulation (usually in kHz). The full change range of current i_{L2} during one period of modulation, approximately assuming that $U_{\mathrm{ldm}} \approx D_1 U_{1\mathrm{m}}$, is as follows:

$$\Delta I_{L2} = \frac{(U_{1\mathrm{m}} - U_{\mathrm{ldm}})D_1}{L_2 f_{\mathrm{m}}} = \frac{U_{1\mathrm{m}} D_1 (1 - D_1)}{L_2 f_{\mathrm{m}}}. \tag{14}$$

Assuming that $\Delta I_{L2} \approx (0.1 \ldots 0.2) I_{\mathrm{ldm}}$, the inductance of L_2 must be

$$L_2 = \frac{U_{1\mathrm{m}} D_1 (1 - D_1)}{(0.1 \ldots 0.2) I_{\mathrm{ldm}} f_{\mathrm{m}}}. \tag{15}$$

The pulsations of the current of inductance L_2 during one interval of modulation are absorbed by capacitor C_2. The change of the instant values of voltage across C_2 during one period of modulation can be described as follows:

$$\Delta U_{C2} = \frac{\Delta I_{L2}}{8 C_2 f_{\mathrm{m}}}. \tag{16}$$

Assuming that $\Delta U_{C2} \approx 0.01 U_{1\mathrm{m}}$, the desired value of C_2 can be expressed as follows:

$$C_2 = \frac{\Delta I_{L2\max}}{8 \cdot 0.01 U_{1\mathrm{m}} f_{\mathrm{m}}}. \tag{17}$$

In a similar way, the parameters of input filter $L_1 C_1$ can be determined.

If it is assumed that an instant increase of voltage across C_1 during the interval of modulation takes place due to current i_1 passing through coil in **off** state interval of S1, then the voltage ripple range can be expressed as follows:

$$\Delta U_{C1} = \frac{I_{L1\mathrm{m}}(1 - D_1)}{C_1 f_{\mathrm{m}}}. \tag{18}$$

Assuming that $\Delta U_{C1} \approx 0.02 U_{1\mathrm{m}}$, the required capacity of capacitor C_1 can be expressed as follows:

$$C_1 = \frac{I_{L1\mathrm{m}}(1 - D_1)}{0.02 U_{1\mathrm{m}} f_{\mathrm{m}}}. \tag{19}$$

Oscillations of u_{C1} during the interval of modulation are causing an increase in the oscillations of current i_1:

$$\Delta I_1 = \frac{\Delta U_{C1}}{8 \cdot L_1 f_{\mathrm{m}}}. \tag{20}$$

Assuming that $\Delta I_1 \approx 0.01 I_{1\mathrm{m}}$, the desired inductance of inductor L_1 is

$$L_1 = \frac{\Delta U_{C1\max}}{8 \cdot 0.01 I_{1\mathrm{m}} f_{\mathrm{m}}}. \tag{21}$$

If $U_{1\mathrm{m}} = 320\ \mathrm{V}$, $D_1 = 0.5$, load $R_{\mathrm{ld}} = 5\ \Omega$ and $L_{\mathrm{ld}} = 20\ \mathrm{mH}$, $\omega = 314$, then the amplitude of the load current can roughly be expressed as $I_{\mathrm{ldm}} = {D_1 U_{1\mathrm{m}}}/{Z_{\mathrm{ld}}} = {160}/{8.02} = 19.93\ \mathrm{A}$. If the frequency of modulation is $f_{\mathrm{m}} = 5\ \mathrm{kHz}$, then the parameters of the required inductor and capacitor of the load junction are $L_2 = 5.35\ \mathrm{mH}, C_2 = 25\ \mu\mathrm{F}$. If $D_1 = 0.5$ and it is assumed that $I_{1\mathrm{m}} \approx 0.3 I_{\mathrm{ldm}} = 6\ \mathrm{A}$, then capacitance $C_1 = 90\ \mu\mathrm{F}$ and inductance $L_1 = 2.8\ \mathrm{mH}$. These calculations provide a very rough evaluation of the load voltage level; the actual value is less than assumed here.

Using the assumed parameters of the reactive elements, the normal calculations of the circuit operation parameters were conducted with the single assumption that the amplitudes of the voltages of the load and capacitor C_1 are equal. The results of the calculations are presented in Table I.

A comparison between the calculated and simulated parameters of the circuit in the buck case with $D_1 = 0.5$, $L_1 = 2.8$ mH, $L_2 = 5.35$ mH, $C_1 = 90$ μF, $C_2 = 25$ μF is conducted as well and Fig. 4 presents the diagrams of current and voltage waves simulated at the assumed parameters.

TABLE I.
COMPARISON OF CALCULATION AND SIMULATION RESULTS IN BUCK MODE AT $D_1 = 0.5$

	U_{ldm}, V	$U_{C1\mathrm{m}}$	I_{ldm}, A	φ_{ld}, °	φ_2, °	$I_{1\mathrm{m}}$, A	φ_1	φ_3
calculation	140	320	17.45	51.47	−49.1	5.94	36.77	6.6
simulation	140	322	17.31	50.4	−54	5.2	25.2	5.04

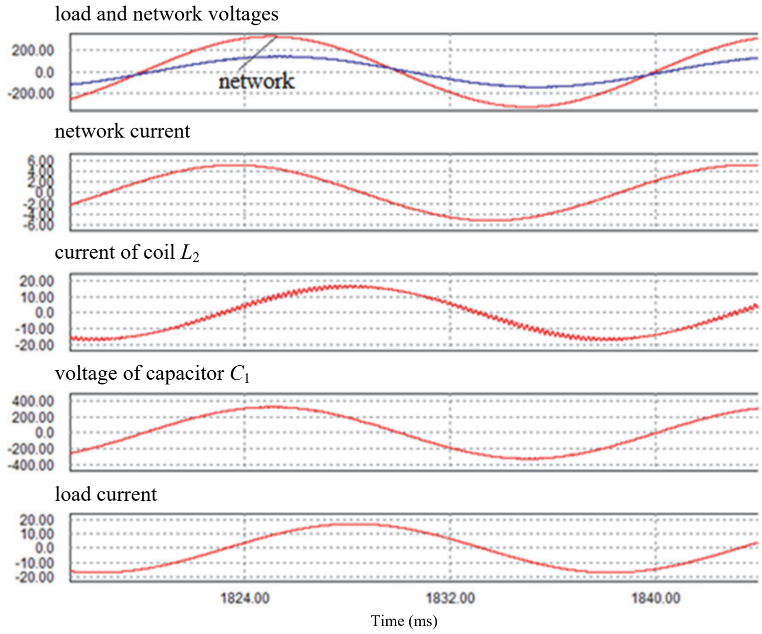

Fig. 4. Simulated diagrams of the currents and voltages of the circuit in buck mode at the assumed parameters.

IV. BOOST OPERATION MODE

In this case, the main operating switches are S3 and S4 and switch S1 is continuously on. In such way, if switch S3 is turned on in interval D_3T_{m}, the voltage of capacitor C_1 is applied, providing storage of electromagnetic energy in the coil. When switch S3 is off and switch S4 is on, the stored energy is transmitted to the load junction. In such way, the pulse-mode current of coil L_2 passes through switch S4 to the load junction, forming mean current wave

$$i_{L2\mathrm{MB}} = (1 - D_3) i_{L2\mathrm{B}}, \qquad (22)$$

in which $i_{L2\mathrm{B}}$ can be calculated by using expression (3) for the buck mode. The amplitude of the mean current wave is

$$I_{L2\mathrm{mB}} = I_{\mathrm{ldmB}} \sqrt{a} \qquad (23)$$

and the amplitude of the current through coil L_2 is

$$I_{L2\mathrm{m(B)}} = I_{\mathrm{fmB}} = \frac{I_{\mathrm{ldmB}} \sqrt{a}}{(1 - D_3)}. \qquad (24)$$

The phase shift of this current in respect to the load voltage can be calculated by using expression (4) for calculation of the shift for buck-mode operation. Alternately switching on switches S3/S4, across S3 a mean wave of voltage by the load voltage pattern is formed and its amplitude is

$$U_{\mathrm{S3(m)mB}} = (1 - D_3) U_{\mathrm{ldmB}}. \qquad (25)$$

To this voltage of the switch, the voltage drop across coil L_2 with amplitude $I_{L2\mathrm{m(B)}} \omega L_2$ is added and the sum of the both yields the voltage of input filter capacitor C_1 with amplitude as follows (Fig. 5):

$$\bar{U}_{C1\mathrm{m}} = \bar{U}_{\mathrm{S3(m)mB}} + \bar{I}_{L2\mathrm{m(B)}} \omega L_2; \qquad (26)$$

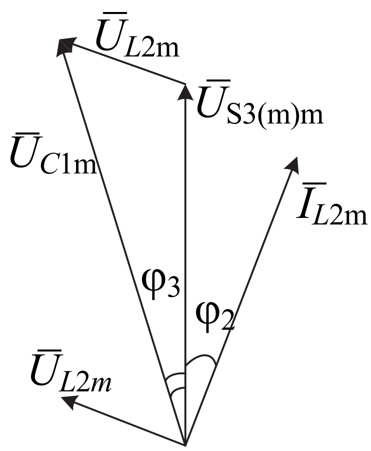

Fig. 5. Vector diagram for the voltage calculation for capacitor C_1.

$$U_{C1m}^2 = (U_{S3(m)mB} - U_{L2m(B)} \sin\varphi_2)^2 + U_{L2m(B)}^2 \cos^2\varphi_2, \tag{27}$$

whence

$$U_{ldm(B)} = \frac{z_{ld} U_{C1m}}{\sqrt{(1-D_3)^2 z_{ld}^2 - 2 z_{ld} \omega L_2 \sqrt{a} \sin\varphi_2 + a\omega^2 L_2^2 / (1-D_3)^2}}. \tag{28}$$

Angle φ_3 between the voltages of capacitor C_1 and the load can be calculated as follows:

$$\varphi_3 = \operatorname{arctg} \frac{\sqrt{a}\omega L_2 \cos\varphi_2}{(1-D_3)^2 z_{ld}^2 - \sqrt{a}\omega L_2 \sin\varphi_2}. \tag{29}$$

And as shown by the calculations, it is small enough to assume that both voltages U_{C1m} and $U_{S3(m)m}$ coincide in phase.

As is shown by the calculations conducted, the increase level of the load voltage with regard to the supply voltage depends not only on the value of duty ratio D_3 but to a large extent on parameters L_1, L_2 of the coils. Thus, with $D_3 = 0.3$ and with the parameters of the elements assumed before, the increase of the load voltage in respect to capacitor C_1 is only 7 % instead of 42 %, which it should be in the DC system case. To provide a higher rate of load voltage increase, it is necessary to use coils with an inductance smaller than was accepted for the buck case, which has to be considered from the point of view of the possible formation of current ripples.

The angle between he voltage of capacitor C_1 and the current consumed from the input filter, i_{fB}, is $(\varphi_3 + \varphi_2) \approx \varphi_2$. Application of this angle enables calculation of the current of the AC source from the vector diagram in Fig. 5. From the diagram, it follows that

$$I_{1m} = \sqrt{U_{C1m}^2 \omega^2 C_1^2 - 2U_{C1m}\omega C_1 \frac{I_{ldm}\sqrt{a}}{1-D_3} \sin(\varphi_2 + \varphi_3) + \frac{I_{ldm}^2 a}{(1-D_3)^2}}. \tag{30}$$

Performing the calculation at $D_3 = 0.3$ and at the parameters assumed before as well as assuming that $U_{C1m} = 320$ V, the amplitude of the supply current is $I_{1mB} = 63.95$ A and the load voltage is 342.5 V, which yields a load current $I_{ldmB} = 42.7$ A. The shift angle of the supply current with regard to the supply voltage can be found from the equality condition of the active powers at the input and at the load and this angle is $\varphi_1 = 63.54°$ at a lagging type of current.

Actually U_{C1m} in this case is less than the amplitude of supply voltage U_{1m}, especially if it is considered that the currents of both coils essentially increase as compared to the buck case and these currents are creating rather large voltage drops across both coils. Considering that angle φ_3 is close to zero, the voltage of capacitor C_1 can be calculated as follows:

$$U_{C1m} = U_{1m} - I_{1m}\omega L_1. \tag{31}$$

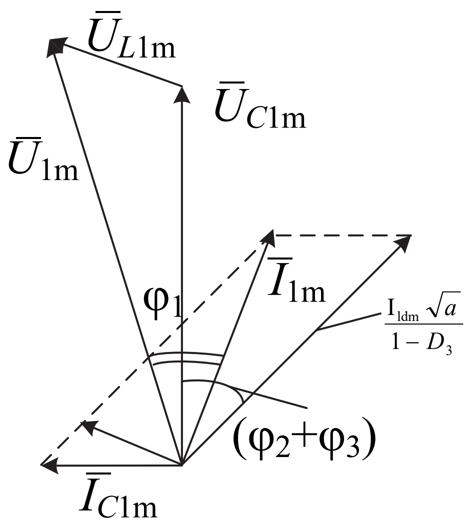

Fig. 6. Vector diagram for the input filter junction.

Such an increased voltage drop across the coils restricts the possibility to obtain increased voltages of load with regard to the input voltage. Therefore, the values of both coils L_1 and L_2 have to be decreased with regard to those assumed for the buck case.

Consideration of the operation modes shows that the heaviest operation modes influence coil L_2, which in pulse mode must pick up the voltage of capacitor C_1, which induces rippling of current i_{L2} in range

$$\Delta I_{L2B} = \frac{D_3 U_{C1m}}{L_2 f_m}. \tag{32}$$

If the ripple range is accepted as $\Delta I_{L2mB} = 0.2 I_{ldmB}$ and it is also accepted that $U_{C1m} \approx U_{1m}$, then in the boost case it is necessary to apply a coil with an inductance as follows:

$$L_{2B} = \frac{D_{3\max} U_{1m}}{0.2 I_{ldmB} f_m}. \tag{33}$$

Further, the difference between the current of coil L_2 and the current of the load in the time interval $(1 - D_3)T_m$ has to be absorbed by the capacity of capacitor C_2, which has to provide the necessary voltage rippling range

$$\Delta U_{C2B} = \frac{(I_{L2B} - I_{ldmB})(1-D_3)}{C_2 f_m} = \frac{I_{ldmB} D_3}{C_2 f_m}. \tag{34}$$

Hence, the capacity of C_2 at the admissible ripple range $\Delta U_{C2B} = 0.05 U_{ldm}$ can be found as follows:

$$C_{2B} = \frac{D_3}{0.05 z_{ld} f_m}. \tag{35}$$

As a result of the calculation, it can be stated that the capacitance of C_2 for boost operation can be 2 to 3 times higher than for the buck case whereas the inductance of coil L_2 should be decreased about 2 to 3 times to reach the value calculated before. That is, instead of a L_2 inductance of 5.35 mH, this value can be decreased to 1.5 mH for both cases; besides, the quality of the load current should be good in both operation cases.

As regards the coil of the input filter, its inductance L_1 can also be decreased in the same range, i.e. its inductance for the considered case should be assumed as 1 mH. At such lowered values of inductance of both coils at boost operation and at a duty ratio of $D_3 = 0.3$, the voltage of the load can be increased up to about 400 V.

Fig. 7 presents the waves of the supply and load voltages as well as the ones for the supply current, the current of the coil L_2 and the load current. The main parameters for the case with duty ratio $D_3 = 0.3$ are presented in Table II, which also presents the results of the calculations conducted by applying the obtained relationships.

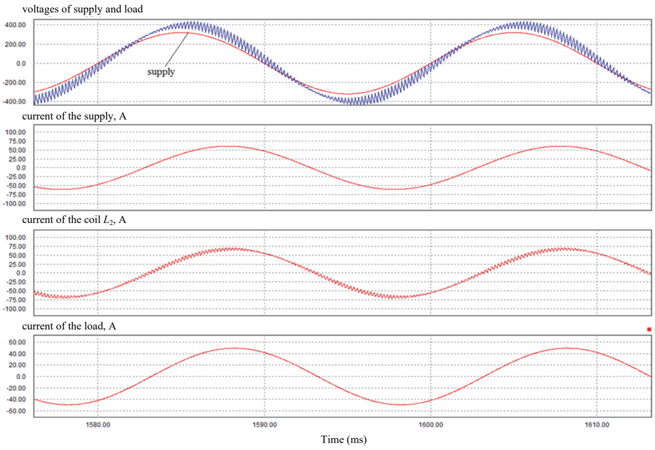

Fig. 7. Comparison of simulated and calculated results for the boost operation case with $L_1 = 1$ mH, $L_2 = 1.5$ mH, $C_1 = 90$ μF, $C_2 = 25$ μF.

TABLE II
COMPARISON OF CALCULATION AND SIMULATION RESULTS IN BOOST MODE

	U_{ldm}, V	I_{ldm}, A	φ_{ld},	I_{L2m}	φ_2	I_{1m}	φ_1	ΔU_{C2max}	ΔI_{L2max}
simulated	400	50	49	70	−15	60	−49.3	100	10
calculated	414	51.6	50	70.5	−12.2	72.3	−54.8	112	12.8

As can be seen, the simulation and calculation results match rather well; besides, it has to be noted that in the calculations, voltage U_{C1m} was assumed to be equal to U_{1m}, although in reality the former is a little less.

V. CONCLUSION

1. The diagram of the proposed buck-boost converter provides proper regulation of AC load from AC supply voltage.
2. The main calculation method for the AC/AC conversion system must be based on the application of vector calculation methods, which allow obtaining simplified expressions, which anyway match the experimental results sufficiently well.
3. Operating in the buck case, from the input *LC* filter a pulse-mode current is consumed whereas in the boost case, continuous current and pulse-mode current is applied to the load circuit bypassed with a capacitor.
4. For proper operation of the system, it is very essential to correctly choose the inductance of both coils in the supply and modulation circuit and to keep them as low as possible, which does not restrict the boost operation efficiency.

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