

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:

$$i_{ld} = I_{ldm} \sin v, \quad (1)$$

and the load voltage is as follows:

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

where  $\varphi_{ld} = \arctg \frac{\omega L_{ld}}{R_{ld}}$ ,  $Z_{ld}$  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.

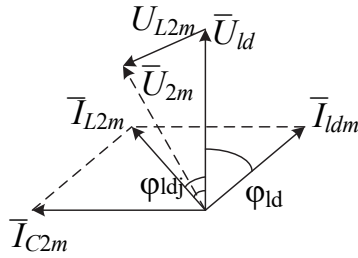


Fig. 2. Phasor diagram for the load junction.

Hence

$$I_{L2m} = I_{ldm} \sqrt{Z_{ld}^2 \omega^2 C_2^2 - 2Z_{ld} \omega C_2 \sin \varphi_{ld} + 1} = I_{ldm} \sqrt{a} \quad (3)$$

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

$$\tan \varphi_{ldj} = \frac{Z_{ld} \omega C_2}{\cos \varphi_{ld}} - \tan \varphi_{ld}, \quad (4)$$

so current  $i_{L2}$  is shifted by angle  $(\varphi_{ld} + \varphi_{ldj})$  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:

$$i_{fM} = D_1 I_{L2m} \sin(v + \varphi_{ld} + \varphi_{ldj}), \quad (5)$$

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  $u_{2M}$  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:

$$u_{2M} = u_{C1} D_1. \quad (6)$$

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

$$\begin{aligned} U_{2Mm} &= I_{ldm} \sqrt{Z_{ld}^2 - 2Z_{ld} \omega L_2 \sqrt{a} \sin \varphi_2 + a \omega^2 L_2^2} = \\ &= \frac{U_{ldm}^b}{Z_{ld}}, \end{aligned} \quad (7)$$

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

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

$$U_{2Mm} = D_1 U_{C1m}, \quad (8)$$

$$U_{ldm} = \frac{Z_{ld} D_1 U_{C1m}}{b} \cong \frac{Z_{ld}}{b} D_1 U_{1m}. \quad (9)$$

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

$$\tan \varphi_3 = \frac{U_{L2m} \cos \varphi_{ldj}}{U_{ldm} - U_{L2m} \sin \varphi_{ldj}}, \quad (10)$$

where  $U_{L2m} = I_{L2m} \omega L_2$ .

Due to the fact that  $U_{L2m}$  usually is much smaller than  $U_{ldm}$ , angle  $\varphi_3$  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  $\varphi_{1dj}$  as well (Fig. 3).

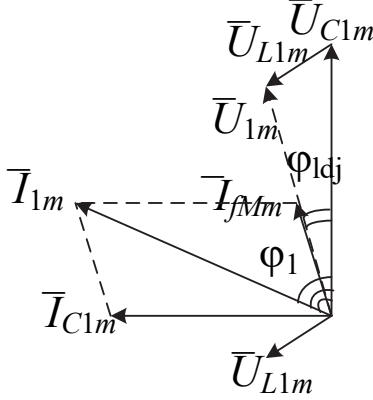


Fig. 3. Phasor diagram for the input filter junction.

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

$$I_{1m} = I_{ldm} \sqrt{\frac{Z_{ld}^2}{D_1^2} \omega^2 C_1^2 + 2Z_{ld} \omega C_1 \sqrt{a} \sin \varphi_{1dj} + D_1^2 a}. \quad (11)$$

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

$$\varphi_{1C} = 90^\circ - \arctg \frac{D_1^2 \sqrt{a} \cos \varphi_{1dj}}{Z_{ld} \omega C_1 + D_1^2 \sqrt{a} \sin \varphi_{1dj}} \quad (12)$$

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

By taking into account that  $U_{C1m} \approx U_{1m}$  (the voltage drop on inductance  $L_1$  is small) and that the active power balance on the input and output is

$$U_{1m} I_{1m} \cos \varphi_1 = I_{ldm}^2 R_{ld}, \quad (13)$$

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  $D_1 T_m$ , where  $T_m$  is the period of modulation  $1/f_m$  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  $U_{ldm} \approx D_1 U_{1m}$ , is as follows:

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

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

$$L_2 = \frac{U_{1m} D_1 (1 - D_1)}{(0.1 \dots 0.2) I_{ldm} f_m}. \quad (15)$$

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:

$$\Delta U_{C2} = \frac{\Delta I_{L2}}{8 C_2 f_m}. \quad (16)$$

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

$$C_2 = \frac{\Delta I_{L2 \max}}{8 \cdot 0.01 U_{1m} f_m}. \quad (17)$$

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:

$$\Delta U_{C1} = \frac{I_{L1m} (1 - D_1)}{C_1 f_m}. \quad (18)$$

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

$$C_1 = \frac{I_{L1m} (1 - D_1)}{0.02 U_{1m} f_m}. \quad (19)$$

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

$$\Delta I_1 = \frac{\Delta U_{C1}}{8 \cdot L_1 f_m}. \quad (20)$$

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

$$L_1 = \frac{\Delta U_{C1 \max}}{8 \cdot 0.01 I_{1m} f_m}. \quad (21)$$

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

	$U_{1dm}, V$	$U_{C1m}$	$I_{ldm}, A$	$\varphi_{1d}, ^\circ$	$\varphi_{2}, ^\circ$	$I_{1m}, A$	$\varphi_1$	$\varphi_3$
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

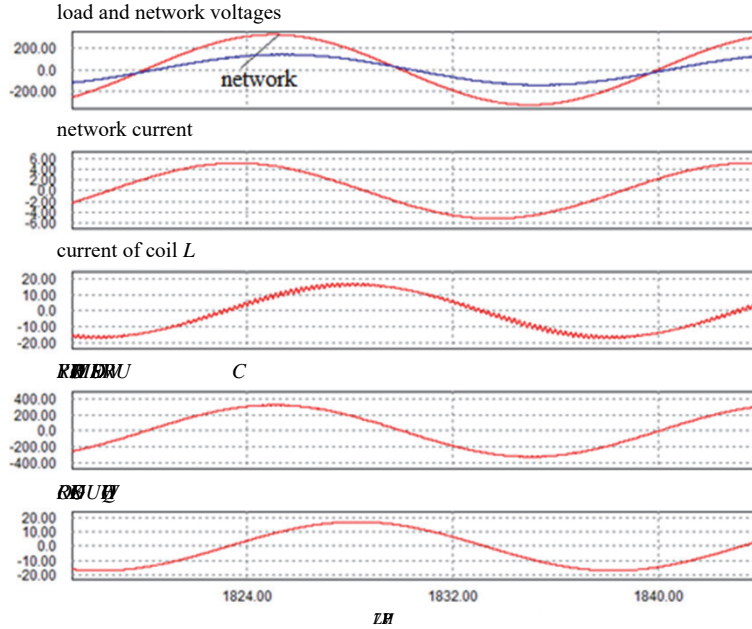


Fig. 4. Simulated diagrams of the currents and voltages of the circuit in buck mode at the assumed parameters.

#### 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

$$i_{L2MB} = (1 - D_3)i_{L2B}, \quad (22)$$

in which  $i_{L2B}$  can be calculated by using expression (3) for the buck mode. The amplitude of the mean current wave is

$$I_{L2mB} = I_{ldmB} \sqrt{a} \quad (23)$$

and the amplitude of the current through coil  $L_2$  is

$$I_{L2m(B)} = I_{fmB} = \frac{I_{ldmB} \sqrt{a}}{(1 - D_3)}. \quad (24)$$

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

$$U_{S3(m)B} = (1 - D_3)U_{ldmB}. \quad (25)$$

To this voltage of the switch, the voltage drop across coil  $L_2$  with amplitude  $I_{L2m(B)}\omega L_2$  is added and the sum of the both yields the voltage of input filter capacitor  $C_1$  with amplitude as follows (Fig. 5):

$$\bar{U}_{C1m} = \bar{U}_{S3(m)B} + \bar{I}_{L2m(B)}\omega L_2; \quad (26)$$

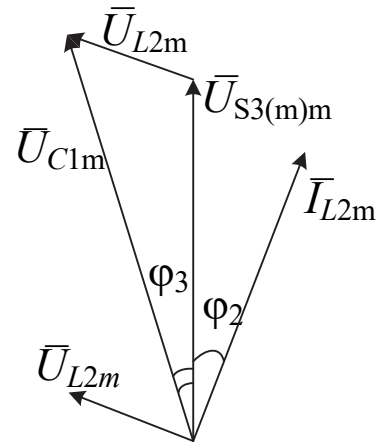


Fig. 5. Vector diagram for the voltage calculation for capacitor  $C_1$ .

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

whence

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

Angle  $\varphi_3$  between the voltages of capacitor  $C_1$  and the load can be calculated as follows:

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

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 the 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

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

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  $\varphi_1 = 63.54^\circ$  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  $\varphi_3$  is close to zero, the voltage of capacitor  $C_1$  can be calculated as follows:

$$U_{C1m} = U_{1m} - I_{1m} \omega L_1. \quad (31)$$

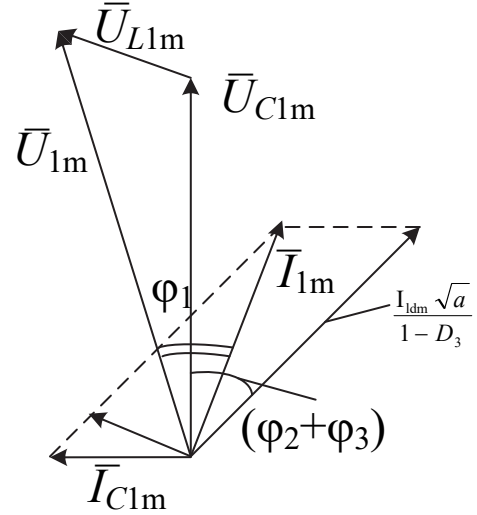


Fig. 6. Vector diagram for the input filter junction.

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

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

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:

$$L_{2B} = \frac{D_3 \max U_{1m}}{0.2 I_{ldmB} f_m}. \quad (33)$$

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

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

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

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

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.

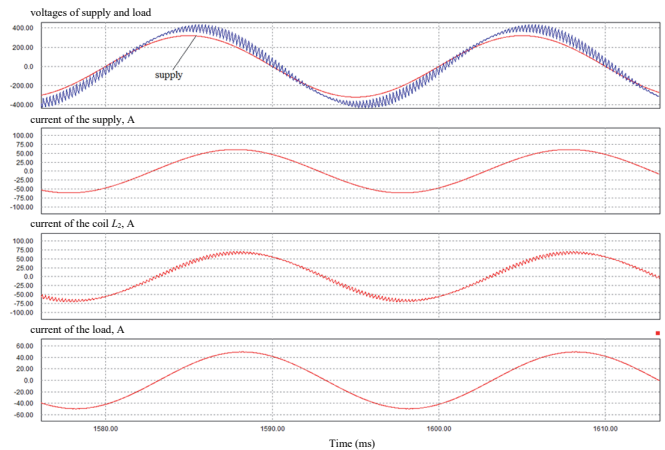


Fig. 7. Comparison of simulated and calculated results for the boost operation case with  $L_1 = 1$  mH,  $L_2 = 1.5$  mH,  $C_1 = 90$   $\mu$ F,  $C_2 = 25$   $\mu$ F.

TABLE II  
COMPARISON OF CALCULATION AND SIMULATION RESULTS IN BOOST MODE

	$U_{Idm}$ , V	$I_{Idm}$ , A	$\varphi_1$ , d	$I_{L2m}$	$\varphi_2$	$I_{1m}$	$\varphi_1$	$\Delta U_{C2}$ max	$\Delta I_{L2}$ max
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.

#### ACKNOWLEDGMENT

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