Transformerless Boost AC/DC Converter with the Front-end Active Filter

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Abstract- The paper proposes a transformerless boost AC/DC converter with the front-end active filter. Constant output voltage, which considerably exceeds the amplitude of the input AC voltage, upon the absence of the consumption of the reactive power from the grid was achieved by such combination. The algorithm of the calculation of elements and the control system is described. The paper describes the efficiency of this control system that is ensured by the assigned static and dynamic parameters. The overload ability of this converter is described in separate.

I. INTRODUCTION

AC/DC converters are most claimed among the secondary power supply. The power sources of personal computers, communication and other equipment supplied from the AC current mains determines the broad class of the switch-mode power supply (SMPS). The field of application of the boost AC/DC converters is more specific and it is, as a rule, determined by the necessity for high constant voltage. Such equipment can include electron-beam valves, lasers, X-ray equipment installations of metallization and spraying, ionic implantation. Also, the converters can be used for control in the case of a wind turbine with unstable voltage parameters.

Powerful power converters are used in the power-supply systems of electric engines. Conventional solutions of the boost AC/DC converters, as a rule, consist of a transformer, rectifier and a power factor corrector (PFC) [1]-[7]. The block scheme of this converter is shown in Fig. 1a.

![Diagram of a conventional boost AC/DC converter with a transformer](image1)

Operation of the converter is based on an increase of the amplitude of supply voltage by using a transformer with subsequent rectification. To ensure the power factor close to 1 PFC is used. Also, a transformerless solution is possible, in which PFC is used with a boost converter (Fig. 1b).

Such schemes are easily adaptable, since they have a sufficiently simple structure and a system of control. At the same time, they have drawbacks. Transformerless schemes have limitations in the amplitude of the output voltage, and also to the high-frequency components of the input current. Embedded PFC ensures the power factor close to 1, but does not ensure the absence of the high-frequency components of the reactive power. The presence of the reactive power of the higher harmonics leads to the power losses and to the distortions of the line voltage form, and failure of other equipment connected to the network.

Existence of the transformer determines the essential overall sizes of similar sources. Taking into account today’s reductions in the prices of semiconductor components and growth in the price of copper and magnetic components on the one hand, and increased requirements for the quality of the consumed electric power on the other hand, as the secondary power supply sources, it is possible to design the schematic of an AC/DC converter with the active filter at the front-end and the boost converter at the output stage. Active filters allow for compensation of a wide spectrum of the load current by means of control [7]-[14]. There is no transformer in this solution (Fig. 2). The overall sizes of the choke of the active filter do not considerably exceed the overall sizes of the PFC filter.

Appearance of powerful high speed transistors makes such schemes feasible, and problems of calculation and analysis of the processes in such systems become topical.

In this paper a transformerless boost AC/DC converter with the front-end active filter is described. A similar combination will solve the problem of obtaining constant output voltage, which considerably exceeds the amplitude of the input AC voltage, in case the consumption of reactive power from the main is absent. The algorithm of the calculation of elements and the control system, which ensures the assigned quality of the output voltage and the energy consuming from the main, is proposed.

II. CONTROL SYSTEM STRUCTURE

Fig. 2 presents the structure of the converter.

![Diagram of a transformerless boost AC/DC converter](image2)
The active filter is a front-end cascade that consists of the choke $L_S$, transistors $S_1$, $S_2$, and capacitors $C_1$, $C_2$. Further, the boost converter is realized with the help of the energy storage choke $L_b$, the power switch $S_3$ and the diode $V_D$. Capacitor $C_3$ performs the role of the filter, which is necessary to decrease the pulsations in the load. To realize the control system a current-sensing device (to track the form of the input current) and two sensors of voltages are required: the value of the voltage of active filter capacities and the output voltage. The control system is shown in Fig. 3.

The control algorithm is divided into two independent blocks. The top channel forms control signals of the transistors of the active filter. The control algorithm is built according to the vector method of control. The input values of the regulator enter the instantaneous value of voltage across the capacitors ($U_{C1}$, $U_{C2}$) and the reference voltage $U_{C_{\text{ref}}}$, equal to the sum of the necessary values of voltage $U_{C1}$ and $U_{C2}$. In order to skip pulsations of voltage across capacitors, only constant components of voltages $U_{C1}$ and $U_{C2}$ are used. Further error on the voltage will be given to the integrator whose output determines the amplitude of the reference current. The form of the reference current is determined by the supply voltage, as a result, the current is in-phase to the voltage. The nonlinear element of the type “saturation” is used for limiting the amplitude of the current. Further reference current will be given to the controller of the commutation of power switches. The unit of the commutation of power switches is built according to the method of vector control of power switches. Fig. 4 shows the scheme of the controller.

Thus, PWM is realized that provides the constant value of the converter output voltage with the presence of the disturbing actions both on the supply side and on the load.

### III. CALCULATION OF ELEMENTS

Parameter determination of reactive elements is the primary task in the design of this converter. The procedure of parameter determination of the input active filter is similar to that described in [17]. In this case it is necessary to determine the value of inductance, capacities and the frequency of the commutation of power switches. In element selection it is necessary to consider the fact that the rate of change in the current is limited by the choke and it may not exceed the reference value of the current $i_{S_{\text{ref}}}$.

Consider $U_C = \text{const}$ and taking into account the following equations:

$$ U_L = \frac{L}{L} \frac{d}{dt} = U_S + U_C , \quad (1) $$

$$ U_L = U_C + U_{SM} \sin \omega t , \quad (2) $$
\[ L \cdot \frac{di_S(t)}{dt} = L \cdot \omega \cdot I_{SM} \cdot \cos \omega t. \]  
\hspace{1cm} (3)

we obtain:

\[ L_{MAX} = \frac{U_C + U_{SM}}{\omega \cdot I_{SM}}. \]  
\hspace{1cm} (4)

Expression (4) determines the maximum value of inductance that supports sinusoidal input current. With a smaller value of inductance it will increase the speed of the growth of mean current and the corresponding high-frequency component. Let us determine the amplitude of mean current from the balance of power:

\[ P_S = \frac{U_{SM} \cdot I_{SM}}{2} = U_{OUT} \cdot I_{OUT}. \]  
\hspace{1cm} (5)

As a result we obtain:

\[ L_{MAX} = \frac{\left( U_C + U_{SM} \right) \cdot U_{SM}}{\omega \cdot 2 U_{OUT} \cdot I_{OUT}}. \]  
\hspace{1cm} (6)

In the selection of the clock frequency it is necessary to consider the maximum permissible deviation of the current.

\[ f_{\min} = \frac{2 \cdot U_{SM}}{\Delta I_{\text{max}} \cdot L}. \]  
\hspace{1cm} (7)

There is no existing united procedure with the calculation of processes in the boost converter, such as its transfer function [14]. Approximation makes it possible to estimate the gain factor of the converter:

\[ K_U = \frac{1}{1 - D}, \]  
\hspace{1cm} (8)

where D is a duration factor that determines the duration of the open switch. Based on this in the nominal rating \( D = 0.5, \) \( K_U = 2. \)

The main task is reduced to the selection of the energy storage choke and the frequency of commutation. In the nominal rating the processes of accumulation and energy dissipation in the choke appear symmetrically. The energy transferred to the load during the operating cycle of the switch is equal to the energy separated in the load:

\[ \frac{2}{L} \int_0^T \frac{U_C^2}{L} dt = \int_0^{U_{OUT}} \int_0^{I_{OUT}} dt. \]  
\hspace{1cm} (9)

From where:

\[ L = \frac{U_C^2 \cdot D^2 \cdot T}{U_{OUT} \cdot I_{OUT}}. \]  
\hspace{1cm} (10)

It is evident that the value of inductance is directly proportional to the commutating period of the switch. The quicker they move the control system and the switch, the lower the rating and the overall sizes of the choke are. This value corresponds to the nominal rating, when the current through the choke is close to the continuous mode. In this case there is no reserve of regulation according to the power in the load. Due to the decrease of the value of the energy storage choke and the automatic decrease of the duration factor it is possible to increase the range of the regulation of the converter and its overload ability. Therefore the value of inductance should be selected lower than the calculated one. No strict ways for choosing the capacity exist. They are energy storage elements in this scheme. The values of capacitors are chosen from flicker voltage demands.

**IV. SIMULATION RESULTS**

MATLAB medium was used for simulation. The simulation parameters accepted are provided in Table 1.

**TABLE I**

<table>
<thead>
<tr>
<th>Accepted Simulation Parameters</th>
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<tbody>
<tr>
<td>Network parameters</td>
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<tr>
<td>Load parameters</td>
</tr>
<tr>
<td>Control system parameters</td>
</tr>
<tr>
<td>Converter accepted parameters</td>
</tr>
<tr>
<td>( \omega = 2 \pi \cdot 60 \text{ Hz} )</td>
</tr>
<tr>
<td>( U_S = 110 \text{ V} )</td>
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Fig. 5 shows the timetables of the converter work. The diagrams of one cycle of the converter are shown separately (Fig. 6).

Fig. 5. The transitional characteristic of the converter.
At the moment of time 0.2 s the control system of the active filter, which supports the establishment of the preset voltage across capacitors, is turned on. At the moment of time 0.5 s the control system of the boost converter is turned on. It is evident from the graphs that despite the fact that the preset voltage in the load is achieved sufficiently rapidly, being completely steady, the process can be counted on the expiration. Long transit time is specified on the coefficients of the regulator that were selected to avoid significant overregulation and the oscillating process. The amplitude of the mains current is shown in Fig. 5.

It is evident from Fig. 6 that the input current is sinusoidal, the total harmonic distortion (THD) is about 1.7%. In this case the pulsations in the load do not exceed 1%.

To analyze the overload ability of the system diagrams both for idling and for exceeding the nominal load are given in Figs. 8 and 9, respectively.

From Fig. 8 it is evident that the voltage on the output sufficiently rapidly attains the nominal value. In this case the currents through the energy storage choke and the input active filter exist only in the initial stage at the moment of the charge of capacities.

Fig. 6. Steady-state regime of the converter.

Fig. 7 shows the current through the energy storage choke and the signals in the control system. As can be seen from the figures, the duration rate is about 0.3. As a result, the current through the energy storage choke does not reach the maximum value. It provides an overload ability of the system.

Fig. 9 shows the transient process with the current in the load slightly exceeding the nominal value. As can be seen from the diagram, the process of establishing the output value of the voltage occurs quicker than in the case of the nominal load (Fig. 7). It is evident that the duration of the state of the open power switch increased slightly, reaching about 0.35.

It should be noted that with a further increase of the current in the load, which considerably exceeds the nominal value, the system loses its stability, and the current through the energy storage choke becomes continuous.
V. CONCLUSIONS

This paper proposes a transformerless boost AC/DC converter with the front-end active filter, as the secondary electric power supply source. The control system that ensures sinusoidal input current (THD ≤2%) and constant voltage on the output (Kp ≤1%) is built. By the help of the simulation, based on the example of the power converter of 600 W, the efficiency of this control system that ensures the assigned static and dynamic parameters is shown. The overload ability of this converter is described in separate. This control system can be easily realized on any signal processor or FPGA. It should also be noted that the stability problem not examined in detail in this work, was solved by the selection of gain factors of regulators from the results of the simulation. The complexity of the evaluation of the stability of similar systems is determined by the absence of mathematical apparatus for their description. Stability problem requires further study and can be solved by the control algorithms on the basis of the artificial intellect.

REFERENCES


