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PERFORMANCE OF A VOLTAGE STEP-UP/STEP-DOWN TRANSFORMERLESS DC/DC CONVERTER: ANALYTICAL MODEL

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The authors present an analytical model for a voltage step-up/step-down DC/DC converter without transformers. The proposed topology is a combination of classic buck and boost converters in one single circuit but with differing operational principles. The converter is developed for a wind power autonomous supply system equipped with a hydrogen electrolytic tank and a fuel cell for energy stabilization. The main power source of the hydrogen-based autonomous supply system is energized by a synchronous generator operating on permanent magnets and equipped with a diode bridge. The input voltage of the converter in this case varies in the range 0–700 V, while its output DC voltage must be 540 V according to the demand of other parts of the system. To maintain the rated voltage, a special electrical load regulation is introduced. The calculations of the converter, the generator (equipped with a diode bridge) as element of the power system supply joint, and the load replaced by resistance are verified with PSIM software.

Key words: *buck-boost converters, transformerless converter, synchronous generator, wind energy, industrial application*.

NOMENCLATURE

U_1 – the voltage across the terminals of generator;
U_{ld} – the voltage of load;
E – the EMF of the generator;
n – the speed of rotor in rpm;
I_d – the current at the output of diode bridge;
m_2 – the number of pulsations;
X_L – the resistance caused by inductive impedance of the generator`s windings;
k_1 – a coefficient showing relationship between EMF and rpm;
k_2 – a coefficient showing voltage drop caused by the inductivity of stator windings according to the stator current frequency and equivalent resistance of DC voltage source;
i_2 – the instantaneous value of the inductor L2 current;
I_{2max} – the maximum value of current i_2 during a duty cycle;
D_1 – the duty ratio of TR1 for the step-down mode;
D_{1b} – the duty ratio of TR1 for the step-down mode in the boundary case;
D_2 – the duty ratio of TR2 for the step-up mode;
D_{2b} – the duty ratio of TR2 for step-up mode in the boundary case;
R – the resistance of load;

f – the switching frequency of the converter;
L_1 – the inductance of inductor L1;
L_2 – the inductance of inductor L2.

1. INTRODUCTION

A wind power generator operates with variable speed; therefore, its output voltage is also variable. At the same time, to synchronize its output power with grids or to use such a generator for energy supply it should have a constant voltage level at the output. For this purpose a special conversion device should be developed.

In this work, a buck-boost converter was chosen because the wind power system is equipped with a hydrogen electrolytic tank and a fuel cell with the rated voltage of 540 V, while the generator's output DC voltage varies from zero to 700 V. The purpose of the tank and the cell is to stabilize the system's output power by parcelling out hydrogen in the time of strong wind and low electrical power demand and using the chemical energy stored in hydrogen in the time of low wind speed.

The proposed converter circuit is based on a step-up DC converter with a commutating LC-filter [1]. While the existing DC–DC converter topologies (see, e.g. [2, 3]) have a large number of elements and transformers [3], complicated control system, etc., which raise the costs of energy produced by the system and its reliability, the new topology has a smaller number of elements and no transformers. The circuit constructed in the proposed way has simpler design, lower cost, no additional losses caused by the non-rated modes of transformer, no changes in the polarity direction, *etc.*.

2. GENERATOR AS A SYSTEM'S ELEMENT

The proposed circuit contains a three-phase AC generator with a built-in diode bridge rectifier, all its other links being conductive and converting DC voltage. To simplify the analytical calculations, the generator can be considered as a DC-voltage source with the internal resistance proportional to the instantaneous angular speed of the generator. The voltage at the terminals of the generator can be expressed as

$$U_1 = E - I_d \left(R_{ekv} + \frac{m_2 X_L}{2\pi} \right). \tag{1}$$

Replacing the generator voltage and inductive resistance in Eq. (1) we obtain:

$$U_1 = k_1 n - I_d \left(R_{ekv} + k_2 n \right) = 3.28n - I_d \left(6.6 - 0.05363n \right). \tag{2}$$

The coefficients and resistances are measured and calculated using the analytical approach.

The equivalent voltage-current characteristics of a generator equipped with a diode bridge (calculated using Eq. (2)) are shown in Fig. 1 for different speed values.

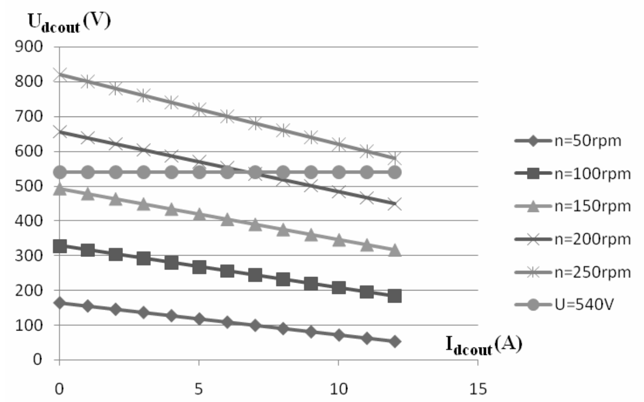

Fig. 1. The output voltage of a generator equipped with a diode bridge *vs*. load current (equivalent circuit).

From the diagram it follows that the generator voltage is not equal to the rated one of the system's DC-bus (540 V) and should be adjusted. For proper performance of the system, the generator should be equipped with a step-up/step-down DC voltage converter.

3. OPERATIONAL PRINCIPLES AND MODES OF THE PROPOSED SCHEME

The scheme proposed for voltage boosting is shown in Fig. 2*A*. According to it, semiconductor switch TR1 is in the conduction mode all the time, transistor switch TR2 operates in the PWM mode, TR3 transistor driving signal is opposite to the TR2 one. During the duty cycle, TR2 is in the saturated mode and TR3 is off, which means that TR1 and TR2 are in the conduction short-through mode as there is only one element, inductor L1, connected in series and storing energy. As D1 diode is not letting the voltage of load be short-circuited, current i_2 initially is flowing through TR2, capacitor C2 is discharged at load resistance R (Fig. 2*B*). In the second phase (Fig. 2*C*) TR2 is turned off and TR3 is at on-state to let the current of TR1 flow easily through D1 by connecting capacitor C1; as the capacitor C1 is connected to load, U_{ld} grows, while C2 and L2 are smoothing the pulsations. Inductance L2 (being highly important for the scheme's operation) could be low, as its main purpose is to operate in the buck mode.

If the proposed scheme is operated in the buck mode when TR2 is permanently turned off, TR1 is working in the pulse-width modulation (PWM) mode, chopping the input voltage from the output. TR3 is in the conduction mode permanently and, as follows, L1 and C1 are working just as devices for filtration of the input voltage and current ripples. We therefore can assume that $U_{C1} = U_1$ and calculate the processes without further discussion.

As in the case of a classic buck converter, the input voltage during the duty cycle is connected to load, and the current starts to rise at the load R junction through inductor L2 and diode D1. The current is increasing while TR1 is closed. During the switch TR1 off-state, the energy stored in L2 is discharging through the diode anti-parallel to transistor TR2, and the current of inductor L2 falls down to minimum. As said above, the TR2 switch is permanently in the off-state.

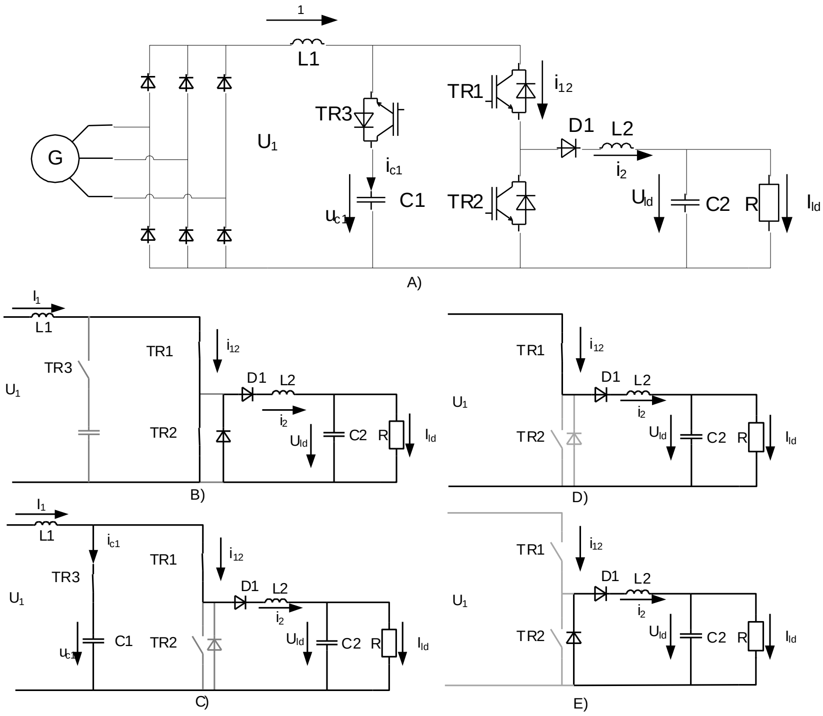

Fig. 2. Circuit diagram for proposed converter (*A*); operational scheme in the voltage boost (*B* and *C*) and buck (*D* and *E*) modes.

While TR1 is in the conduction position and TR2 – in the turn-off one, the output voltage across the load is close to an ideal boost value [4]:

$$U_B = \frac{U_1}{1-D_2}. \tag{3}$$

This leads to current i_2 increase (if starting from $i_2 = 0$) until it reaches the maximum value:

$$I_{2\max} = \frac{(U_B - U_{ld})(1-D_2)}{L_2 f}. \tag{4}$$

After the assumption that switching and reactive elements have no losses [5], the relationship between input/output voltages and currents will be:

$$U_{ld} I_{ld} = U_1 I_d. \tag{5}$$

When TR2 is turned on in the duty cycle, current i_2 is decreasing to zero under the influence of U_{ld} according to the equation [5]:

$$L_2 \frac{di_2}{dt} = -U_{ld} \tag{6}$$

If the scheme is operated in the discontinuous current mode (the necessity of this mode for the circuit performance is proved below) of inductor L2, di_2 could be replaced by $-I_{2\max}$, and dt – by current discharge time (see diagrams in Fig. 3); therefore, for the boundary case (when i_2 reaches zero at the very end of a duty cycle) we can derive the following equation:

$$t_2 = \frac{L_2 I_{2m}}{U_{ld}} = D_2 T \qquad (7)$$

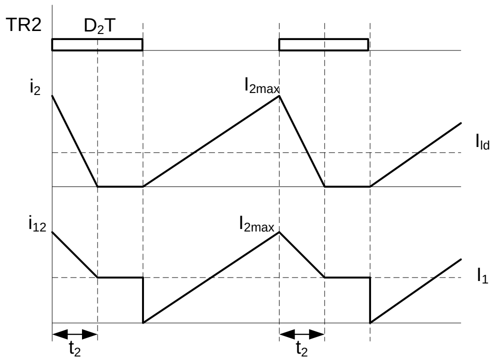

Fig. 3. Diagrams of currents i_2 and i_{12}.

While in the boundary case

$$I_{2\max} = \frac{(U_B - U_{ld})(1 - D_{2b})}{L_2 f}, \qquad (8)$$

the mean value of i_2 in the boundary case is equal to the mean value of load current:

$$I_{ld} = \frac{I_{2\max}}{2} = \frac{U_{ld}}{R}. \qquad (9)$$

In the boundary case at current i_2 constantly passing through diode D1 the mean voltage across TR2 is equal to the load one; taking into account that the average voltage of L1 is zero, the load voltage will be equal to voltage U_1. Therefore, combination of expressions (8) and (9) can be written as

$$\frac{I_{2\max} R}{2} = U_1 = \frac{(U_b - U_{ld})(1 - D_{2b})R}{2L_2 f} \qquad (10)$$

and from this last equation the relationship of parameters in the boundary operation case for current i_2 is derived:

$$D_{2b} = \frac{2L_2 f}{R}. \qquad (11)$$

At $2L_2f/R < D_{2b}$ a discontinuous operation takes place, and only in this case U_{ld} can be higher than U_1. This means that the scheme works normally only in the discontinuous mode, when current i_2 reaches zero value at turned-on TR2 before the end of a D_2T long duty cycle.

For the discontinuous operation mode the load voltage is:

$$U_{ld} = \frac{I_{2\max} R}{2}(1 - D_2 + t_2 f) \tag{12}$$

If the equations for t_2 and $I_{2\max}$ ((5) and (2), respectively) are combined, the load voltage will be expressed as

$$U_{ld} = 0.5\frac{(U_B - U_{ld})(1 - D_2)}{L_2 f} R\left[1 - D_2 + \frac{(U_B - U_{ld})(1 - D_2)}{U_{ld}}\right] =$$

$$= \frac{R(U_B - U_{ld})(1 - D_2)}{2L_2 f} \times \left[\frac{U_{ld} - U_{ld}D_2 + U_B - U_{ld} - U_B D_2 + U_{ld} D_2}{U_{ld}}\right] =$$

$$= \frac{R(U_B - U_{ld})(1 - D_2)}{2L_2 f}\frac{U_b(1 - D_2)}{U_{ld}} \; . \tag{13}$$

This expression is convertible to the quadratic equation:

$$\frac{2U_{ld}^2 L_2 f}{R} = \left(U_b^2 - U_b U_{ld}\right)(1 - D_2)^2 = U_b^2 (1 - D_2)^2 - U_b U_{ld} (1 - D_2)^2 \, . \tag{14}$$

If all members of Eq. (14) are shifted to the left and multiplied by $\frac{R}{2L_2 f}$, we will have:

$$U_{ld}^2 + U_{ld}\frac{U_1 R(1 - D_2)}{2L_2 f} - \frac{U_1^2 R}{2L_2 f} = 0 \tag{15}$$

As the buck-boost input and output voltage polarity is the same, the root of the quadratic equation is positive, and the relationship between U_{ld} and U_1 can be written as

$$U_{ld} = U_1 \frac{\sqrt{R^2(1 - D_2)^2 + 8L_2 fR} - R(1 - D_2)}{4L_2 f} \, . \tag{16}$$

As follows from the equation, R, L_2 and f values are important for the voltage conversion. As power of generator is limited, the load requires regulation to achieve a system's proper workability at low wind speed. The load is to be regulated by the equation:

$$R = \frac{U_{nom}^2}{U_1 I_1} = \frac{540^2}{U_1 I_1} \, . \tag{17}$$

In this case the boundary duty ratio can be presented as

$$D_{2b} = \frac{2 f L_2}{R} = \frac{2 f L_2 I_1}{U_1} \, . \tag{18}$$

Characteristics of the system consisting of a generator, a proposed converter and the load regulated according to Eq. (15) at different speeds and a constant maximum generator current of 10 A are shown in Fig. 4.

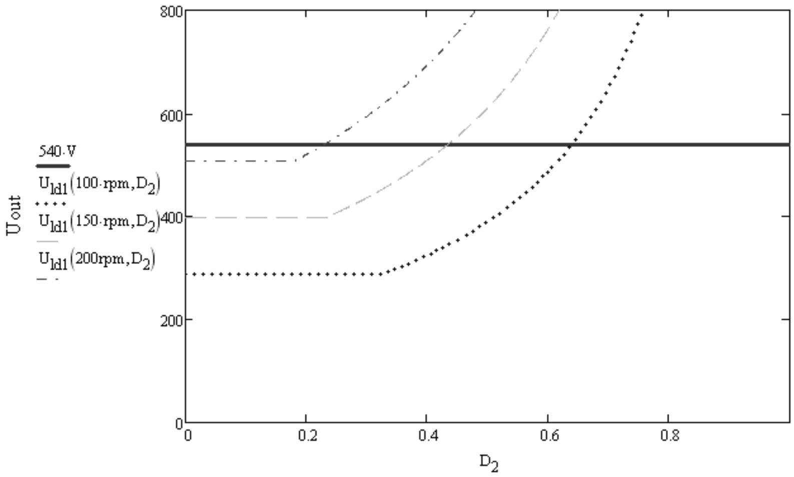

Fig. 4. Voltage step-up mode of the circuit with a generator as element of the system (rotational speed 150rpm, 200rpm, 250 rpm and output current 10 A).

As follows from Fig. 4, the circuit is not stepping-up the output voltage in the continuous current conduction mode – i.e. at low generator speed the voltage is to be stepped-up at high duty ratio values above boundary.

4. VOLTAGE BUCK MODE

The scheme is operable both in continuous and discontinuous current conduction modes of the inductor L2 current in the voltage step-down regime. In the ideal continuous case the load voltage is [5]:

$$U_{ld} = U_{in} D_1 . \quad (19)$$

In the discontinuous mode the current through L2 is increasing from 0 to the maximum:

$$I_{2\max} = \frac{(U_{in} - U_{ld}) D_1}{L_2 f} . \quad (20)$$

The current decreasing time [5] is the same as in the discontinuous case of the voltage step-up mode. The load current is:

$$I_{ld} = \frac{I_{2\max}}{2} (D_1 + t_2 f) . \quad (21)$$

From this it follows that

$$U_{ld} = \frac{I_{2\max} R}{2} (D_1 + t_2 f) =$$

$$= \frac{R(U_{in} - U_{ld}) D_1}{2 L_2 f} \left(D_1 + \frac{f L_2 (U_{in} - U_{ld}) D_1}{U_{ld} L_2 f} \right) . \quad (22)$$

After simplification, this expression can be reduced to the quadratic equation:

$$U_{ld}^2 + U_{ld}\frac{U_{in}D_1^2R}{2fL_2} - \frac{U_{in}^2D_1^2R}{2fL_2} = 0 \qquad (23)$$

with the root:

$$U_{ld} = -\frac{U_{in}D_1^2R}{4fL_2} + \sqrt{\frac{U_{in}^2D_1^4R^2}{8f^2L_2^2} + \frac{U_{in}D_1^2R}{2fL_2}} = \frac{U_{in}D_1^2R}{4fL_2}\left(\sqrt{1+\frac{8fL_2}{D_1^2R}} - 1\right). \qquad (24)$$

For the boundary current case we will have:

$$I_{ld} = \frac{I_{2\max}}{2} = \frac{(U_{in} - U_{ld})D_{1b}}{2L_2f}. \qquad (25)$$

The boundary duty ratio D_{1b} can be obtained through the minimum current conduction mode inductivity (ref. [4] and Eq. (16)):

$$L_{2CCM} = \frac{D_{1b}(U_{in} - U_{ld})R}{2fU_{ld}} = \frac{(1-D_{1b})R}{2f}. \qquad (26)$$

This means that in the boundary case the duty cycle is:

$$D_{1b} = 1 - \frac{2fL_{2CCM}}{R}. \qquad (27)$$

The load voltage in this case will be:

$$U_{ldb} = \frac{R(U_{in} - U_{ldb})D_{1b}}{2L_2f} = \frac{U_{in}D_{1b}R}{2fL_2 + D_{1b}R}. \qquad (28)$$

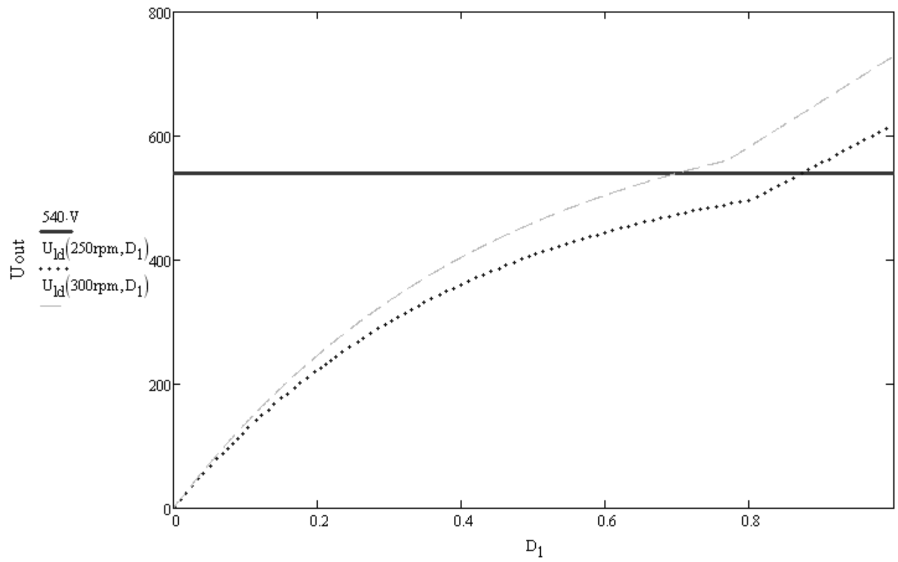

Fig. 5. Voltage step-down mode for the circuit with a generator with rotational speed 250 rpm, 300 rpm and current 10 A.

When the current value is higher than that given by Eq. (25), the buck converter works in the continuous conduction mode. The current-voltage relationships in this case are:

$$U_{ld} = U_1 . D_1 = I_{ld} . R, \tag{29}$$

$$I_{ld} = \frac{U_1 D_1}{R}. \tag{30}$$

Analytic characteristics of the proposed system with load regulation by Eq. (15) are displayed in Fig. 5, where the line of rated output voltage level (540 V) could be seen.

When the duty ratio value is higher than expressed in Eq. (27), the converter works in the continuous conduction mode of voltage step-down mode. The current and voltage values for this case are calculated by Eqs. (12) and (13), respectively.

5. SIMULATION OF THE SCHEME

The analytical calculations are checked by the PSIM software (see Table 1) to make sure that the scheme is working in the same way as calculated above before the circuit implementation in hardware. The parameters of the model are: L_1 = 10 mH, C_1 = 2000 μF, L_2 = 1.155 mH, C_2 = 2000 μF, f = 4 kHz, and E = 492 V, which corresponds to the speed of 150 rpm for the boost mode and the load resistance is adjusted according to Eq. (17). Comparative results of analytical approach and simulation model are shown in Table 1. The analytical results are given for the output current of generator equal to 10A and the output voltage of converter obtained by Eq. (24).

Table 1

The analytical and simulation results for the converter voltage step-up mode

D_2	R, Ω	U_{ld}, V	
		analytic	simulation
0.3	37.85	361.65	360.3
0.4	51.52	421.93	420.9
0.5	74.19	506.31	504.2
0.6	115.91	632.89	628.9

As follows from the table, the calculation results are close to those of simulation. The time dependences for transistor TR2 gate signal, i_2 current and output voltage can be seen in Fig. 6 and compared with the diagrams shown in Fig. 3 for current and transistor on- and off-states. The output voltage of the scheme is in this case ~540 V, the load resistance is 84 **Ω**, and the duty ratio is D_2 = 0.53.

The comparison of analytical and simulation results for the converter voltage step-down mode of operation is given in Table 2. The calculations have been done for the resistance of 58.38 **Ω** (resistance of the load able to consume 5 kW at the voltage of 540 V), because at reaching the voltage of the generator corresponding to the buck mode its output power becomes equal to or higher than 5 kW (the rated consumption power of the system's remaining parts), but there is no power limitation in the buck mode as opposed to the case of voltage step-up one. The input voltage is higher as the calculated values are for the speed of 300 rpm. Other parameters of the circuit are the same.

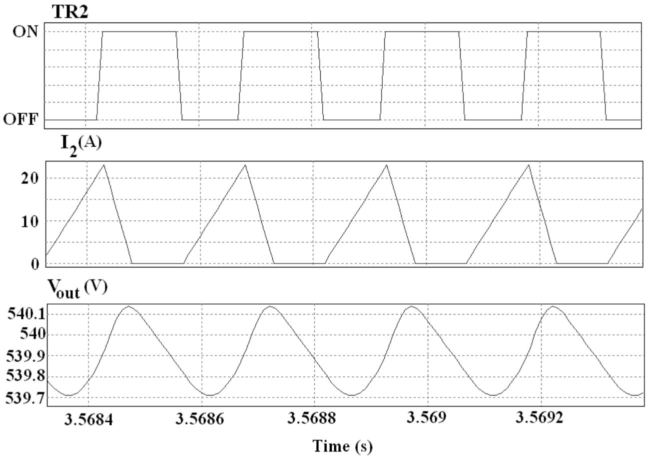

Fig. 6. Simulation results for the voltage step-up mode of converter operation.

Table 2

Comparison of analytical and simulation results for converter voltage step-down mode

D_2	R (Ω)	U_{ld} ,V	
		analytic	simulation
0.4	58.38	452	452.5
0.5	58.38	506	506
0.6	58.38	548	547.1
0.7	58.38	580	580

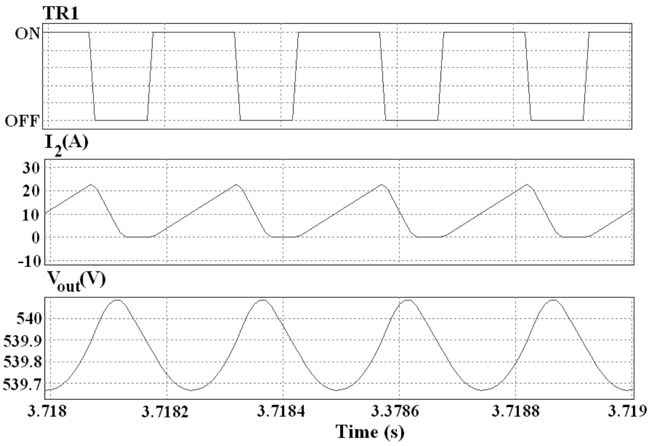

Fig. 7. Simulation results for the voltage step-down mode.

As follows from the table, the calculations are correct. Figure 7 is a screen-shot of transistor TR1 signal, current i_2 and output voltage U_{ld} for simulation of the scheme in the buck mode.

The diagrams of current i_2 in Fig. 7 are given for the discontinuous mode.

6. CONCLUSIONS

The conclusions based on the comparison of the analytical and simulation results for the DC–DC voltage converter are as follows.

The working scheme of the proposed converter is very close to that for a classical buck-and-boost converter, but it allows obtaining the same voltage polarity as for the source. The voltage boost mode is possible only at the discontinuous mode of the load joint inductance current; its value, the converter operation frequency and the load resistance strongly affect the voltage conversion ratio. The load resistance of converter should be adjusted corresponding to the minimum input voltage and the accepted maximum duty ratio. The paper contains output characteristics of converter obtained by analytic calculations and verified by simulation software. This way of calculations sets primary significance to the choice of load joint inductance, while the input inductance is less important. Introducing an adjustable load makes it possible to achieve the rated voltage level at a lower generator speed. The paper contains comprehensive materials on the expected output characteristics of the system.

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SPRIEGUMA PAAUGSTINOŠA–PAZEMINOŠA BEZTRANSFORMATORA PĀRVEIDOTĀJA DARBĪBAS PĒTĪŠANA: ANALĪTISKAIS MODELIS

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K o p s a v i l k u m s

Tradicionālām līdzstrāvas–līdzstrāvas pārveidotāju topoloģijām piemīt vairāki trūkumi, kuri nav vēlami vēja enerģijas sistēmai ar ūdeņraža stabilizāciju, kura tiek izstrādāta projekta ietvaros. Lai tie neietekmētu sistēmas izveidi un izmaksas tika piedāvāta līdzstrāvas paaugstinoša–pazeminoša beztransformatora pārveidotāja shēma. Aprakstīta sistēma ir klasisko Noost un Buck pārveidotāju kombinācija. Piedāvātai shēmu topoloģijai ir sekojošas priekšrocības: samazināts pusvadītāju elementu skaits, shēmā netiek izmantots trasnformators, pārveidotāja ieejas un izejas spriegumu polaritātes sakrīt. Raksts satur detalizētu pārveidotāja matemātisko aprakstu un formulas, kas ļauj aprēķināt svarīgākās vērtības pārveidotāja izveidei. Sistēmas matemātiskais apraksts arī satur formulas, kas attiecas uz ģeneratora izejas raksturlīknēm, kuras ir pielietojamas izejas sprieguma vērtības aprēķinam, uzskatot ģeneratoru ar pārveidotāju kā vienotu sprieguma avotu, jo ģeneratora vijumu aktīvā un reaktīvā pretestība ietekmē pārveidotāja ieejas strāvu un spriegumu. Izejas sprieguma vērtības tiek salīdzinātas ar galīgo elementu metodi, simulējot shēmas darbību PSIM programmatūras vidē.

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