Voltage converter with the controlled energy balance for the electric drive with the pulsation motion mode

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***Abstract* – The article describes the work of the pulse converter with digital control based on the formation of the control actions of maintaining equilibrium of the required and storage power in the energy system for the azimuthal drive of the radar antenna. The algorithm of control power voltage converter and the test results of its operation in various dynamic conditions are presented.**

***Keywords* – pulse converter; energy balance; maximum speed; control synthesis; transient process; the characteristic impedance of the filter.**

It is known that the orientation of the antenna-generated electromagnetic beam can be assigned by rotating the antenna in the desired direction. In this case the antenna scans the surroundings according to the pulsating or harmonic mode in compliance with a predetermined current mode [1].

To get the pulsating motion of the azimuth electric drive of the radar antenna a series production DC motor and special reducer are used [2]. However, the presence of the reduction gear adds an additional coordinate error to determining the direction to the object, degrades the energy performance of the system and significantly reduces the frequency of scanning.

In order to reduce these drawbacks and significantly expand the dynamic range of the operation, you can use the drive, which was built on the basis of a two-phase asynchronous motor (AM), working directly in the mode of periodic motion due to the phase modulation of supply voltage with the interruption of one of them at the times when the electromagnetic torque of AM passes through zero [3]. According to [4], this mode of operation can be achieved, for example, when one of the windings of the motor actuator (excitation winding (EW) is connected directly to a DC voltage source (V_{EW}) and the second control winding (CW) - the source of pulsating voltage (V_{CW}) changing according to the law

$$V_{CW}(t) = V_{m1}\left\{\frac{1}{2} + \frac{1}{2}\sin\Omega t - \frac{2}{\pi}\sum_{k=1}^{\infty}\frac{\cos(2k\Omega t)}{(2k-1)(2k+1)}\right\};$$

$$V_{EW}(t) = V_{m2} \quad ,$$

where V_{m1}, V_{m2} are the amplitudes of the excitation and control voltage windings of AM; Ω - angular frequency of the pulsations of the movable member of the motor.

To generate the necessary voltage on the AM windings it is most appropriate, in terms of efficiency and weight-size parameters, to use pulse voltage converters (PC). The latter are imposed strict requirements to the quality of the output voltage, as this has a major impact on the coordinate precision and power characteristics of the drive.

Analog circuits are traditionally used to operate PC. However, with the increasing requirements to accuracy and versatility the PC analog control system turns cumbersome, multi-element and takes much space on the board. Some tasks, such as machine software interface or the change of the algorithm of the converter are being solved with difficulty. The development of microcontrollers and processors, their capability extension alongside with a constant cost reduction has made it possible to build systems using partial or full digital control techniques.

Typically, the pulse converter includes a power circuit and a control circuit (Fig. 1). To meet modern requirements to the electric drive system for energy parameters is impossible without the organization of complex control algorithms and operating modes of energy sources. If elements of analog elements are used in the control circuit of the power conversion device, implementing complex control law requires significant hardware cost.

It is desirable to organize a pulse converter performance by the pre-set algorithms on the basis of the elements of digital technology making use of built-in programs. A wide variety of microcontrollers and digital signal processors, including the ones that meet the requirements of the spacecraft operation have become available to the developers of electronic equipment of late.

One of the main features of a digital control system is its adaptability, ability to change the nature of the work performed, when required, depending on the external or other factors without changing totally or partially the operation of the managed nodes.

The most common and easily implemented in practice is the algorithm of proportional-integral-derivative (PID) control. One of the alternatives to using the PID controller is the application of the method of the balance of the required and storage power in the energy control convector system [5].

The task of developing control systems with maximum performance is achieved with the help of the Pontryagin's maximum principle [6]. However, the straight-forward application of this principle faces serious difficulties associated with the transformation of the optimal control vector - as a function of the momentum vector into the control vector - as a function of the state or time vector [7]. With regard to the power converter the use of the balance equation between the current value of the internal (stored by the system) energy and its value in the steady state operation allows to simplify the task [7]. In accordance with Hamilton least principle, the control algorithm that provides at least the time integral of the equation of balance, also provides a minimum time of transition.

The described approach can be applied to the power supply for the both windings AD. The article deals with the implementation of this approach with specific reference to the DC voltage motor drive circuit shown in Fig. 1. It comprises an electronic key VT, a diode VD, a choke L, a capacitor C, current sensors UA1 and UA2.

The current value of the LC-filter storage energy is defined as

$$W = \frac{C}{2}V_l^2(t) + \frac{L}{2}\left(i_L(t) - i_l(t)\right)^2 \operatorname{sign}\left(i_L(t) - i_l(t)\right) \quad , \qquad (1)$$

where L, C are the choke inductance and capacitance of the capacitor of the LC-filter; $V_l(t)$ is out voltage; $i_L(t)$ is the choke current; $i_l(t)$ is the load current; sing($i_L(t)$-$i_l(t)$) is a sign of the ripple energy of choke. Let the key switch element (VT) be carried out by changing the sign of the balance between the current value of the storage energy stored by PC continuous part (LC-filter), and the value of the energy in the LC-filter steady state [1]. Then, the transformed equation (1) control law can be written as

$$F_e = \left(V_l^2(t) - V_{ref}^2\right) + \rho^2\left(i_L(t) - i_l(t)\right)^2 \operatorname{sign}\left(i_L(t) - i_н(t)\right);$$
$$F_{drv} = \begin{cases} 1 \text{ if } F_e < 0; \\ 0 \text{ if } F_e > 0, \end{cases} \qquad (2)$$

where $F_e = \frac{2}{C}\left(W - \frac{CV_{ref}^2}{2}\right)$ – is signal proportional to

the current value of the balance between the LC-filter storage energy and the energy (CV^2_{ref} / 2), which is necessary for the LC-filter with an output voltage equal to the specified $V_l = V_{ref}$ and the zero value of capacitor current $i_c(t) = i_L(t) - i_l(t) = 0$;

$\rho = \sqrt{\frac{L}{C}}$ is characteristic impedance LC- filter;

V_{ref} is reference voltage; F_{drv} is the state of VT (with F_{drv}=1 is on, when F_{drv}=0 is off). When the PC is at work, the control system collects the information about the current choke current (i_L), load current (i_l) and load voltage (V_l). In accordance with the equation (2) it calculates the energy balance, and at a time when the energy balance becomes zero F_C produces a control signal for the driver. The driver, in its turn, drives the transistor VT by the signal from F_{drv}.

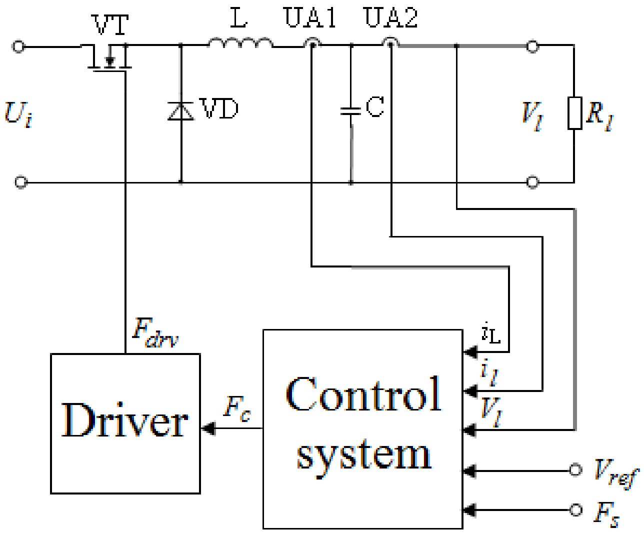

Fig. 1. Diagram of the pulse voltage converter-controlled energy balance

If necessary, the synchronization signal F_S (to limit the switching frequency of power switch, ensure synchronous operation of the PC et al.) is introduced.

Analysis of the influence of the control law (2) on the dynamic processes in the PC held on the mathematical model with the parameters given in Table. 1.

TABLE I. MODEL PARAMETERS

Parameter name	Value
Supply voltage, V_i, V	39.5
Reference voltage V_{ref}, V	28.5
Choke inductance , L, mH	0.15
The capacitance, C, mF	1.65
Scan cycle time, ms	1.75
Load resistance, R_l, Ohm	2.85

For the analysis of the system control unit we calculate the minimum possible duration of the transition process.

So, when the VT with zero initial conditions on the load resistance $R_l \to \infty$ is on, first cutoff should occur at the time tc when F_e=0 and

$$V_{cc} = V_i(1 - \cos(\omega_0 t_{sc}));$$

$$I_{cc} = \frac{V_i}{\rho}\sin(\omega_0 t_{sc});$$

$$t_{sc} = \frac{1}{\omega_0}\operatorname{acos}\left(1 - \frac{\gamma^2}{2}\right),$$

where V_{CC}, I_{CC} are the voltage and current of the LC-filter capacitor when you first turn off the VT;

$\omega_0 = {}^1/_{\sqrt{LC}}$ is natural angular frequency of the LC-filter

V_i is a supply voltage (PC input voltage); $\gamma = V_{ref} / V_i$ is the ratio of the reference voltage to the input PC.

Taking into the account that the interval of the transistor VT is open, the energy that has been accumulated by the LC-filter must ensure the charge of the capacitor C to a predetermined output voltage V_{ref} by the end of the transient moment $t=T_{tp}$, the following equation is valid

$$V_{ref}\cos\left(\omega_0\left(T_{tp}-t_{sc}\right)\right)=V_{cc},$$

from where

$$T_{tp}=t_{sc}+\frac{1}{\omega_0}\arccos\left(\frac{V_{cc}}{V_{ref}}\right).$$

For the PC parameters given in Table 1 you obtain $t_{sc} = 367$ *ms*; V_{CC} = 10.28 *V*; I_{CC} = 88.11 *A*; T_{tp} = 965 *ms*. The transition process has a minimum duration of

because the integral $\int_0^{t_{sc}} F_e(t)dt \rightarrow min$ as on the

interval (0; t_{sc}) the maximum control resources are used ($F_{drv} = 1$), and its duration is minimum. The simulation of the process of incorporating the PC with zero initial conditions controlled by the algorithm (2) showed that the output voltage is set at V_l = 28.500 ± 0.025 *V* and the choke current i_L = 10.0 ± 2.8 A. Thus the duration of the transient exceeds its lowest possible value of less than 1.6% (Fig. 2).

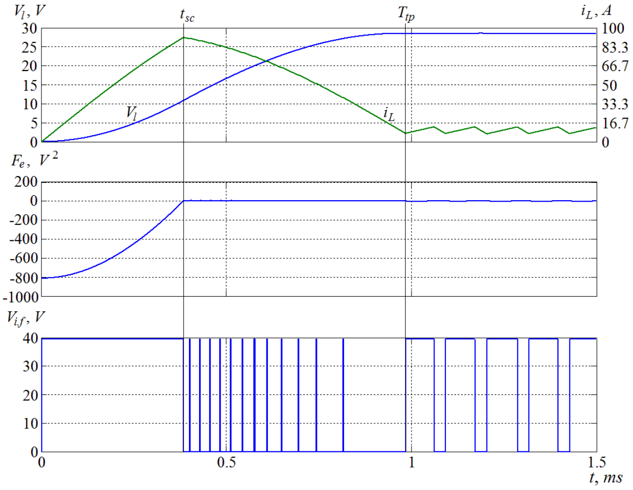

Fig. 2. The transition process when the converter with zero initial conditions

The results of the studies allowed us to estimate the impact of volatility of the LC-filter parameters on the static and dynamic characteristics of the converter.

Fig. 3 shows the process of integrating the PC with zero initial conditions for different values of inductance and capacitance of the filter. It was found that the decrease in value of the capacitors (Fig. 3 a) or increase of the value of the inductance in the circuit (Fig. 3 b) give rise to aperiodic fluctuations in the output voltage at the time of inclusion (overshoot). Increasing the value of capacitance of the capacitor (Fig. 3) leads to a prolongation of the transient process, and decrease of the inductance value (Fig. 3 c) - to the decrease, alongside with increase of the maximum inductor current.

The underestimation of the characteristic impedance of the filter would have the effect of deregulation and re-evaluation - to the prolongation of the transition process.

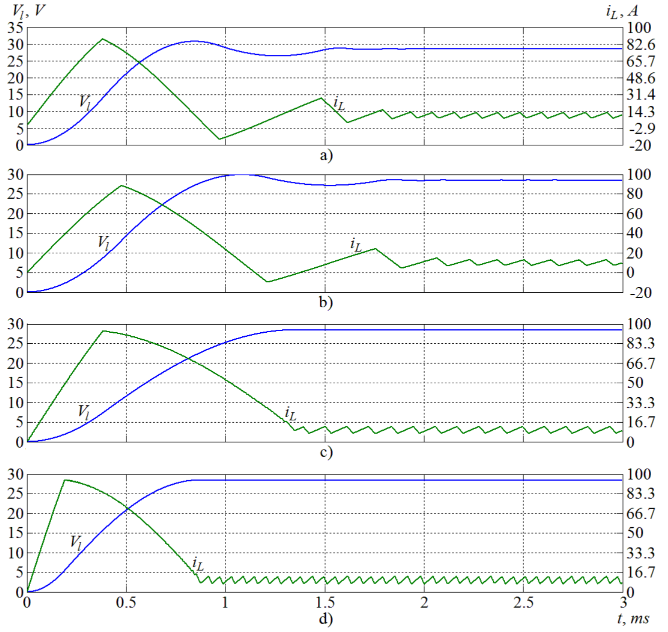

Fig. 3. The transient converter at: a) reducing the capacitor capacitance by 25%; b) increasing the inductance by 25%; c) increasing the capacitor capacitance by 50%; d) reducing the inductance by 50%

To determine the stability of the operating modes of the system, the effect of noise on the supply lines and the load on the output parameters of the PC-controlled energy balance were studied.

Let the input voltage vary in accordance with

$$U_{ii}=U_i+U_{pa}\sin\left(2\pi f_{pa}t\right),$$

where V_{pa} and f_{pa} are the amplitude and frequency of the voltage periodic perturbation on the food chain.

The study has shown that when $V_{pa} \leq 0.2U_i$ and $f_{pa} \leq 10$ kHz and the system remains in the area of regulation, and the disturbance in the power supply circuit is fulfilled with a minimum error of the load voltage not exceeding 0.25% (Fig. 4).

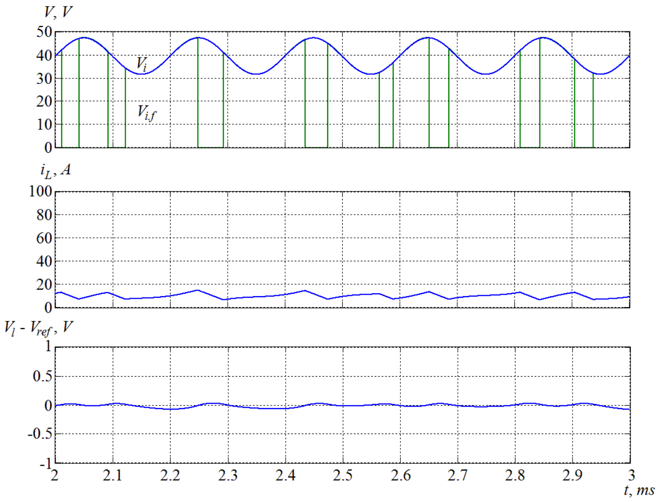

Fig. 4. The effect of sinusoidal interference in the power supply on the output voltage at V_{pa} = 7.9 *V*, f_{pa} = 5 *kHz*

The similarly varying load current of the periodic impact can be written as

$$i_l = I_l + I_{pa}\sin(2\pi f_{pa} t),$$

where I_{pa} and f_{pa} are the amplitude and frequency of periodic influence on the load circuit.

It was found that when at the range of $I_{pa} \leq 0.1 I_l$ and $f_{pa} \leq 10$ *kHz* and the choke current i_L monitors changes in the load current I_l and the system remains in the control zone (Fig. 5).

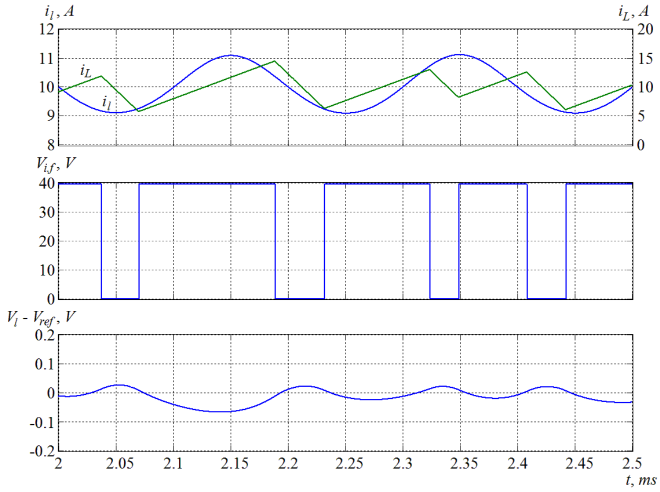

Fig. 5. The impact of changes in the load current on the sinusoidal output voltage at I_{pa} = 1 *A*, f_{pa} = 5 *kHz*

In the case of an abrupt increase of the load current (Fig. 6) the choke current increases with a slope (V_i - V_l) / *L*, at abrupt decrease – decreases with the steepness of V_l / *L*, the transition process at ΔI_l = 8 *A* ends approximately in 0.3 *ms* in the rated current of the output voltage and the choke current ripple.

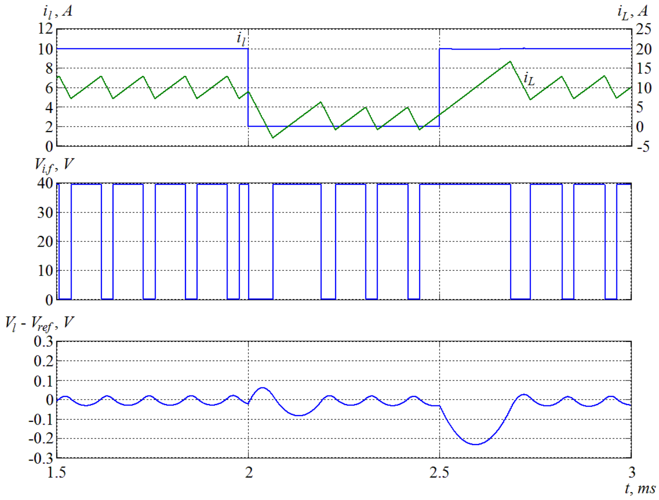

Fig. 6. Sudden decrease or increase of the load converter

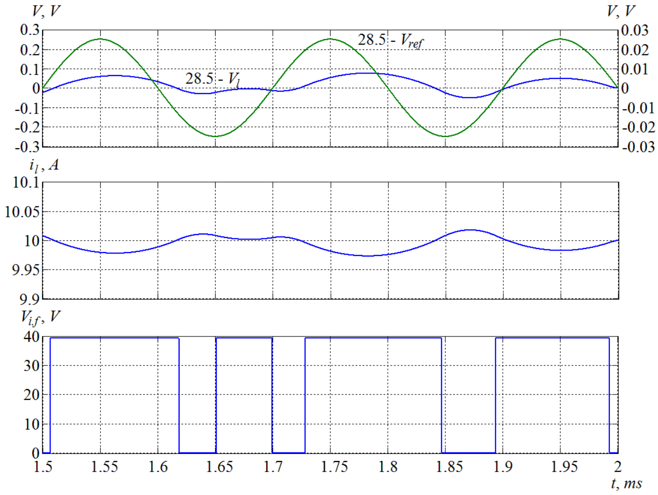

Fig. 7. Operating mode with a cyclic change of the reference voltage

In the experimental studies of the prototype of the converter, the convergence of the obtained results with the results of mathematical modelling was not more than 85%. For the layout of the control system the test board Texas Instruments [8] with a digital signal processor TMS320F28335 was used. In the simulation program, a program part of the control system prototype of the converter is used. To display the graphs use the environment MATLAB [9].

Conclusion

The use of the digital control system in the voltage converter enhances the azimuthal electric radar antenna, makes it possible to change the algorithm of its work without changing the implementation of its circuit.

The balance control of the required and storage energy enables to use the optimal control action with maximum speed, constitutes for the considered voltage converter T_{tp} = 965 ms at startup with zero initial conditions and T_{tp} = 300 ms after a sudden change in load by 80%.

The simulation results show that the underestimation of the characteristic impedance of the filter voltage converter has the effect of deregulation and re-evaluation has the effect of the prolongation of the transition process.

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