Digital contour of linear control in the pulse voltage stabilizer

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Abstract. This paper provides an analysis of the operation of the pulse voltage stabilizer with a digital control contour, which uses a linear dependence between power switch opening pulse duration and the output voltage deviation from the nominal one. The influence of the errors, caused by digital data representation, on the control loop output impulse duration was evaluated. The conditions that minimize the influence of these errors on the stabilizer operation are revealed.

1. Introduction

Nowadays, the sources of stabilized voltage are being used almost everywhere. When constructing such sources, developers prefer the pulse voltage stabilizers since, compared to linear stabilizers, they have indisputable and very significant advantages - this is a high efficiency, and, as a result, low heat generation, as well as low weight and small overall dimensions [1,2]. The applying of the digital control contour, instead of the analog one, in the pulse stabilizers eliminates the temperature and time drift of parameters, which is typical for analog circuits and is being a modern subject of study [3-5].

2. Analytical study

The model of the pulse voltage stabilizer contains some power nodes - a key, an inductance coil, a diode, a key control device and a reference voltage source [6, 7].

The key control device aimed to generate a key-opening pulse, which duration depends on the deviation of a measured output voltage from the reference voltage

\[ T_{pu} = F(U_{cur}, U_{et}), \quad 0 \leq T_{pu} \leq T_p, \]  

where \( T_{pu} \) – key-opening pulse duration, \( U_{cur} \) – measured output voltage, \( U_{et} \) – reference voltage, \( T_p \) – duration of the period of work (trigger) of the stabilizer.

Essentially, \( F(U_{cur}, U_{et}) \) maps the \( U_{cur} \) range to \( T_{pu} \) range:

\[ [U_{cur}^{min}, U_{cur}^{max}] \Rightarrow [T_{pu}^{min}, T_{pu}^{max}], \]  

where \( U_{cur}^{min}, U_{cur}^{max} \) – minimum and maximum \( U_{cur} \) values, \( T_{pu}^{min}, T_{pu}^{max} \) – minimum and maximum \( T_{pu} \) values.

The linear function of control can be used in the simplest case [6-9],

\[ T_{pu} = T_0 + C (U_{et} - U_{cur}). \]
where \( T_0 \) and \( C \) – some constants.

In general, the constant \( T_0 \) can be defined as the value of \( T_{\text{pul}} \), in which \( U_{\text{et}} \) is equal to \( U_{\text{cur}} \) (the required voltage is present at the stabilizer output). If we take into account the possibility of changing the load current in the range \( I_{\text{min}} \div I_{\text{max}} \), so \( T_0 \) is \( T_{\text{pul}} \), in the case of an average load current equal to \( (I_{\text{min}} + I_{\text{max}}) / 2 \), \( U_{\text{et}} = U_{\text{cur}} \), then

\[
T_0 = \frac{(T_{\text{pul}}^{\text{min}} + T_{\text{pul}}^{\text{max}})}{2},
\]

and, in the limiting case, when \( T_{\text{pul}}^{\text{min}} = 0, \ T_{\text{pul}}^{\text{max}} = T_p \),

\[
T_0 = T_p / 2.
\]

The constant \( C \) determines the stabilizer sensitivity to \( U_{\text{cur}} \) variation:

\[
dT_{\text{pul}} = -C \ dU_{\text{cur}},
\]

where \( dT_{\text{pul}} \) – pulse duration increment, \( dU_{\text{cur}} \) – output voltage increment, and, at the same time, this constant is the scale of displaying the \( U_{\text{cur}} \) range to the \( T_{\text{pul}} \) range, so, different ratios of the ranges of \( U_{\text{cur}} \) and \( T_{\text{pul}} \) can be observed, as well as unused portions of these ranges, as shown in figure 1.

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**Figure 1.** The ratio of the ranges \( U_{\text{cur}} \) and \( T_{\text{pul}} \).

In the case of using an analog control contour, voltages and durations are continuous, and, in the operating range, \( T_{\text{pul}} \) can be exactly calculated according to (3) for any combination of the values in the right side of the formula.

When organizing a control device in the digital form (figure 2), a transition to discrete values, which have a limited number of values, occurs.

**Figure 2.** Digital control contour.

In the figure above, ADC is an analog-to-digital converter, DC is a digital calculator, CNT is a clock counter, CMP is a comparator, and \( \tau \) is clock pulses. As can be seen in the figure, \( U_{\text{cur}} \) is the subject of analog-to-digital conversion, which leads to a deviation of the measured value from the true value by an amount of the \( \Delta U \) error, which, in turn, depends on the analog-to-digital converter (ADC) bit depth. \( U_{\text{et}} \) is converted to a constant from the set of the values, which being used to represent \( U_{\text{cur}} \), and also contains the \( \Delta U \) error.

Figure 2 shows that \( T_{\text{pul}} \) in a digital circuit is being formed by counting clock pulses, and is actually being replaced by the nearest multiple value of the clock pulse period, which leads to the \( \Delta T \) error, which depends on the duration of the clock pulse period, so, \( T_0 \) turns into a constant from the set of the values from the \( T_{\text{pul}} \) representation, and also contains the \( \Delta T \) error.

Taking into account the discreteness of the values in the digital control contour, the control dependence (3) turns into

\[
T_{\text{pul}} = T_0 + C (U_{\text{et}} - U_{\text{cur}} + 2 \Delta U) + 2 \Delta T,
\]
then the total error of the $T_{pul}$ formation is estimated as

$$\Delta = 2 \ C \ \Delta U + 2 \ \Delta T.$$  

(8)

The expression set out above shows, that the constant C began to influence not only the sensitivity of the stabilizer, but also the error of $T_{pul}$ formation - with its decrease, the error produced by the analog-to-digital conversion decreases.

For an ideal ADC, the error depends on the ratio of the measured voltage range (scale) and the digit capacity of the resulting code.

$$\Delta_{adc} = \pm \frac{S_{\text{max}} - S_{\text{min}}}{2^{n+1}},$$

(9)

where $S_{\text{max}}$ – maximum measured ADC voltage, $S_{\text{min}}$ – minimum measured ADC voltage, $n$ – bit width ADC.

To ensure correct display (2) under the condition of the minimum $\Delta U$ error, it is necessary to match the ADC scale and the operating $U_{\text{cur}}$ range

$$S_{\text{max}} = U_{\text{cur}}^{\text{max}}, \ S_{\text{min}} = U_{\text{cur}}^{\text{min}},$$

(10)

so, $\Delta U$ is estimated as

$$\Delta U = \pm \frac{U_{\text{cur}}^{\text{max}} - U_{\text{cur}}^{\text{min}}}{2^{n+1}}.$$  

(11)

The $\Delta T$ error, in accordance with (4, 5), is estimated as

$$\Delta T = \pm \frac{T_p}{2 \ N},$$

(12)

where $N$ – the number of cycles in the period of the stabilizer.

Since $U_{\text{cur}}$ takes one of the possible $2^n$ values in the discrete version, and $T_{pul}$ turns into the number of ticks, then, to minimize the $\Delta T$ error, it is necessary to have

$$N \geq 2^n, \ \ (N - 2^n) / 2 = 0,$$

(13)

because, in this case, all $2^n$ values of $U_{\text{cur}}$ can be accurately mapped to the corresponding number of the $T_{pul}$ clock cycles symmetrically with respect to the $T_o$. If this condition is met, $\Delta T$ goes to zero, and (8) turns into

$$\Delta = 2 \ C \ \Delta U.$$  

(14)

The C constant becomes the ratio of the ADC quanta number and the duration of the stabilizer period of operation in cycles in the discrete version

$$C = \frac{2^n}{N},$$

(15)

and therefore, in order to comply with condition (13), it should not exceed one, and, according to (15), the selection of the stabilizer sensitivity should be done by changing the number of ticks in the period of operation $T_p$ in accordance with (13).

### 3. Experimental results

The correctness of the proposed behavior model of the pulse voltage stabilizer with a digital control contour, which uses the linear dependence (7), was tested on a model sample, described in [10,11], based on ATxmega128A1 microcontroller with a 32 MHz clock frequency and an ADC MAX1308 with $n = 12$ and $\pm 1$ quantum error. Figure 3 shows oscillograms of the current flowing through the load in a static mode (constant load resistance) at the different values of the stabilizer sensitivity.
Figure 3. Waveforms of current through the load in static mode.

The oscillograms in the lower part shows the control pulses of the stabilizer power key, in the middle part the current through the load. These oscillograms confirm the regularities presented in the model: at \( C = 4 \) a small oscillatory process is observed, which decreases with decreasing \( C \) and is practically absent at \( C = 0.25 \). On the other hand, a sufficiently large similarity between the oscillograms given above suggest that the model sample for the experiment contains ADC with a small error, that has little influence on the stabilizer operation, and this effect needs additional study.

On the same prototype, the stabilizer was tested under conditions of a fourfold abrupt change in load resistance every sixteen periods of stabilizer operation (key control pulses). Waveforms of the current flowing through the load in this mode are shown in figure 4.
Figure 4. Oscillograms of current flowing through a varying load.

The oscillograms in the lower part show the switching pulses of the stabilizer load, in the middle part - the current through the load. These oscillograms show that an increase in the C constant negatively affects the stabilizer operation, especially in areas with a low load, since they contain self-oscillations, which are decreasing with decreasing C, and practically absent at C = 0.25. The duration of transient processes (response time with the load changes) is small, but there is a small surge of the current, which appears when the mode reaches with the maximum load, and disappears with decreasing C.

4. Conclusion.
Conducted research presents an analytical model of the digital control contour of a pulse voltage stabilizer. The proposed model provides opportunities for improving the stabilizer operation by reducing the effect of errors in analog-to-digital conversion in the output voltage measuring circuit and in the transition to a discrete representation of the pulse duration for controlling the stabilizer power key in a whole number of cycles.

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