Control Unit for Electromagnet Current

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Abstract. The paper deals with the results of research and development of the electromagnet current control unit for the case when only two outputs without specifying the polarity of the source connection may be available from a circuit with a series of DC voltage sources and electromagnet winding. Theoretical results have been verified by modelling in Matlab-Simulink environment as well as by testing the starter of the contactor air switch.

1 Introduction

Today, electronic blocks for optimal control of their responding, holding and switching-out processes are widely used by the world's leading manufacturers of electromagnetic devices (relays, contactors, air- and oil-circuit breakers) [1]. However, they haven't been applied extensively in Russian-manufactured devices. The winding of the electromagnet that drives a moving element of the device is the load of such electronic blocks. Western manufacturers develop a wide range of monolithic integrated circuits (IC) for microprocessor control of the coil current, ranging from control windings for hammers of matrix printers [2] to electromagnet windings for high-power electromagnetic devices [3-8]. There is an extensive literature on the development of the electromagnet current control units [9-15]. However, it is assumed in all these papers that there may be outputs from the winding constant voltage source as well as from the winding itself.

The paper presents the results of the development of the electromagnet current control unit (ECCU) for the case when only two outputs, i.e. terminal outputs of the series circuit, from the open circuit with DC power supply connected in series are available. Moreover, voltage polarity at terminals of the circuit has not been present.

2 Functional scheme of a switching unit

Figure 1 shows ECCU main circuit consisting of three power semiconductor keys with drivers Dr and current sensor (CS). A diode bridge may be switched on at ECCU input to avoid incorrect connection of ECCU to the electromagnet coil. Transistor VT1 is designed to connect the electromagnet coil L to the DC voltage source E when the electromagnetic device is switched on. To quickly reduce current i_L in the winding when the electromagnetic device is switched on, transistor VT1 is locked, but transistor VT2 allowing transferring the

energy accumulated in the coil to capacitor C at capacitor charging intervals t_{ch} is unlocked. To provide discharge of the energy accumulated in the capacitor to resistor R when it is charged up to the threshold voltage $U_{th2} > E$, the capacitor is periodically discharged by repetitive unlocking transistor VT3 for discharging time t_{dis} and locking it for time t_{ch} . To reduce current i_L rather quickly, the average voltage at capacitor U_{Cav} should be higher than supply voltage E by some value.

Fig. 1. A scheme for the high power part of the electromagnet control unit.

3 Calculated ratios

Calculated ratios for the capacitor charging-discharging periodic process could be obtained by the averaging method. True equation written as.

$$C \frac{du_C}{dt} = \begin{cases} i_L, & 0 \leq t \leq t_{ch}, \\ i_L - \frac{u_C}{R}, & 0 \leq t \leq t_{dis}, \end{cases}$$

is integrated for the time $t_{ch} + t_{dis}$, and the following equation could be obtained

$$C \Delta u_C(t_{ch} + t_{dis}) = \int_0^{t_{ch} + t_{dis}} i_L dt - \frac{1}{R} \int_{t_{ch}}^{t_{ch} + t_{dis}} u_C dt, \quad (1)$$

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where $\Delta u_C(t_{ch}+t_{dis})$ is voltage increment u_C for the time $t_{ch}+t_{dis}$.

In our case, $\Delta u_C(t_{ch}+t_{dis})=0$, so equation (1) could be written as follows:

$$i_{Lav} - \frac{1}{R} \frac{t_{dis}}{t_{ch}+t_{dis}} u_{Cav} = 0 \quad (2)$$

where average current i_L and average voltage u_C are

$$i_{Lav} = \frac{1}{t_{ch}+t_{dis}} \int_0^{t_{ch}+t_{dis}} i_L dt, \quad u_{Cav} = \frac{1}{t_{ch}+t_{dis}} \int_0^{t_{ch}+t_{dis}} u_C dt$$

Besides, it is accepted that

$$\int_{t_{ch}}^{t_{ch}+t_{dis}} u_C dt = t_{dis} u_{Cav}$$

Charging time t_{ch} could be determined by the following formula

$$t_{ch} = \frac{C \Delta u_C}{i_{Lav}} \quad (3)$$

where the value $\Delta u_C = U_{th2} - U_{th1}$ may be prescribed, assuming that current change i_L for the time t_{ch} is small.

The value t_{dis} could be expressed through t_{ch} from equation (2) as follows:

$$t_{ch} = \frac{C \Delta u_C}{u_{Cav}/R - i_{Lav}} \quad (4)$$

Fig. 2. Time charts for the process of discharging the energy accumulated in the coil.

Then, the duration of one capacitor charging-discharging cycle could be determined by the following expression:

$$t_{ch} + t_{dis} = \frac{C \Delta u_C u_{Cav}}{R i_{Lav} (u_{Cav}/R - i_{Lav})}. \quad (5)$$

The formula (5) error may increase with reduction of current i_L , since the charging time increases excessively. Figure 3 shows the theoretical calculated dependencies of the capacitor charging and discharging intervals.

Fig. 3. Calculated curve for dependencies of the capacitor charging t_{ch} and discharging t_{dis} intervals on the electromagnet winding current at $C=5\mu F$; $u_{Cav}=300V$; $\Delta u_C=50V$; $R=20 \text{ Ohm}$.

It could be assumed when calculating t_{ch} and t_{dis} intervals that current i_L changes slowly while its value at the interval $t_{ch}+t_{dis}$ is constant being equal to i_{Lav} due to the relatively large time constant $T_L=L/r$. For the same reason, it could be assumed when calculating current change i_L during the process of discharging the energy accumulated in the winding, that current change i_L may not depend on voltage ripples at the capacitor and may be determined by average voltage u_{Cav} which, in our case, remains constant and equal to $u_{Cav} = (U_{th2} + U_{th1})/2$ during periodic charging-discharging process. Then, current drop i_L could be described by the following equation:

$$i_L = \left[i_L(0) + \frac{u_{Cav} - E}{r} \right] e^{-t/T_L} - \frac{u_{Cav} - E}{r} \quad (6)$$

where $i_L(0)$ is current at the beginning of the drop while E is voltage of the source, switched in series with the electromagnet winding.

We assume that energy transfer to the capacitor during a cyclic process may occur up to some low value of $\alpha i_L(0)$, where $\alpha < 1$.

Assuming that $t=t_{drop}$ in Equation (6), we obtain the following:

$$t_{drop} = T_L \ln \frac{u_{Cav} - E + r i_L(0)}{u_{Cav} - E + \alpha r i_L(0)}. \quad (7)$$

The required value of u_{Cav} could be also obtained by setting the value of t_{drop} .

4 Recommendations on calculating the power part of the electromagnet current switching unit

The procedure for calculating the parameters of the power part of the energy discharge circuit at a given maximum switching time of the current t_{drop} may be as follows:

- 1) Set the average voltage at the capacitor u_{Cav} higher than voltage E while around 200÷300V lower than the acceptable voltage value at the main transistor VT1.
- 2) Select a film capacitor with the capacity at which its dimensions are acceptable in terms of its location on the baseplate.
- 3) Set the acceptable voltage ripple range $\Delta u \approx 50V$ at the capacitor. Then, the voltage ripple amplitude at the capacitor would amount to $\Delta u_C \approx \Delta u/2 = 25V$. Check the acceptability of such a variable component for the selected capacitor.
- 4) Determine time t_{drop} of the electromagnet winding current drop down to zero by formula (7).

5 Experimental results

5.1 Modelling of ECCU

Circuit simulation has been carried out in Matlab-Simulink environment with the following initial data: power supply voltage $E=220V$; $U_{th1}=250V$; $U_{th2}=300V$; electromagnet coil inductance $L = 1H$; active electromagnet coil resistance $r=25 \text{ Ohm}$; storage capacitor capacity $C=5\mu F$; storage capacitor resistance $R=50 \text{ Ohm}$. At the beginning of the modeling process, transistor VT1 is switched on, and the electromagnet winding current increases according to the exponential law up to a steady state value. Transistors VT2 and VT3 are switched off. On switching transistor VT1 off and transistor VT2 on, the electromagnet coil current, short-circuited through VT2, may start charging capacitor C (Figure 4). Transistor VT3 through which the electromagnetic energy may be discharged from the electromagnet winding to a ballasting resistor is switched on when the capacitor voltage u_C comes up to the level of $U_{th2}=300V$. When level $U_{th1}=250V$ may be achieved, transistor VT3 may be blocked, and the capacitor recharging process may continue. When the coil current reaches zero, transistor VT2 is switched off while transistor VT3 is switched on to discharge the energy remained in storage capacitor to the ballasting resistor. The selected power circuit parameters along with switching thresholds of the high-power transistor VT3 may allow delaying the process of coil current drop in order to minimize instantaneous power output from the ballasting resistor as well as provide a necessary condition for discharging the capacitor.

Fig. 4. Voltage at the storage capacitor and instantaneous power output at the resistor at $R=50 \text{ Ohm}$, $C=5\mu F$.

5.1 Experimental Verification of ECCU

Tests have been carried out under normal climate conditions using the installation shown in Figure 5. The installation consists of 3.3V, 5V, 12V and 220V DC power supplies, a digital oscilloscope and a magnetic starter of the air switch.

Fig. 5. Experimental installation.

Tests have shown that when the air switch starter of the contactor having inductance of $1H$ and current of $6A$ is switched on to provide the electromagnet winding load and current of $6A$, switching-off may take approximately $50ms$ (Figure 6). Residual voltage at the capacitor may amount to $255V$ with current decrease down to $50mA$ (Figure 7). After switching the control circuit off, the output capacitor is discharged completely in about $500ms$, while it may be discharged down to voltage equal to 10% of the residual voltage in $350ms$.

Fig. 6. Oscillograms of current in the starter electromagnet winding.

Fig. 7. Oscillograms of voltage at capacitor.

6 Conclusion

Thus, fundamental questions concerning the development of the electromagnet current switching unit allowing connecting only two outputs to the circuit consisting of the direct voltage source and the electromagnet winding have been solved in the paper.

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