Methodology for the Calculation and Selection of Elements of Solid-State Thyristor Voltage Relays

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Abstract. This paper presents a methodology for the calculation and selection of elements required for the development of compact solid-state thyristor voltage relays. The proposed design integrates a highly sensitive input-voltage monitoring system with high-power actuating components capable of switching large load currents. Based on the analysis of existing literature and the outlined calculation procedure, an example of element selection is provided, including the schematic diagram and experimental characteristics of the developed solid-state voltage relay.

INTRODUCTION

Currently, power supply systems of industrial enterprises predominantly employ contact-based switching devices (contactors, relays, starters, circuit breakers, etc.). However, such devices have several significant drawbacks; including arcing at the moment of switching, low electrical and mechanical durability of contacts, high inertia of the system, and others. Replacing these switching devices with solid-state solutions is therefore a highly relevant task, enabling increased reliability, reduced device dimensions, and improved quality of the supply voltage. The objective of the calculation is to determine the required parameters of the elements in the circuit of the developed solid-state thyristor voltage relay (STVR). In selecting semiconductor components, the following factors are considered: maximum transmitted power, rated current, maximum amplitude of the operating voltage, frequency of current pulses, cooling conditions, maximum reverse voltage, and maximum gate current amplitude. The selection of resistances in the thyristor control circuits is performed with regard to the maximum control current values. The capacitance of the control capacitor is determined based on the power of the thyristor control circuit and the required time constant of the circuit [1-5, 25-27, 34-36].

METHODOLOGY FOR CALCULATION AND SELECTION OF ELEMENTS

The calculation and selection of elements for the STVR should reasonably begin with the power thyristor connected in the diagonal of the diode bridge. The following input parameters must be known: rated load power, supply voltage, and frequency. In the power circuit, a single-phase thyristor AC switch configuration is applied, utilizing a diode bridge with the power thyristor connected in its diagonal. In this scheme, the current in the load flows only when the diagonal of the rectifier bridge is short-circuited by the thyristor, and the reverse voltage across the thyristor is zero, since it is always subjected to voltage of the same polarity. The reverse voltage across the diodes of the bridge is equal to the forward operating voltage of the thyristor and is determined by [6-11, 31-33]:

$$U_{rev.}=1{,}41U \qquad (1)$$

Since the thyristor conducts both half-waves of the current consecutively without interruption, the maximum average current through the thyristor equals 0.9 of the RMS load current. The average current through each diode of the bridge is 0.45 of the RMS load current. In the calculation, it may be assumed that the RMS current through the load is equal to the RMS current through the thyristor [12-13].

The thyristor must have a maximum forward voltage rating that exceeds the peak value of the supply voltage $U_{for.max.} \geq U_m$ (the reverse voltage is zero). The maximum forward average current of the thyristor should satisfy $I_{f.max.} \geq 0,637 I_{n.rms.}$ and the permissible surge current should not be less than the RMS load current $I_{n.rms}$. In the proposed STVR circuits, the control signal for the power thyristor is applied from the capacitor plates through the resistance R_{con}. The capacitor voltage U_c equals the maximum value of the secondary transformer winding voltage, or, in the case of the optocoupler scheme, the maximum value of the mains voltage. The resistance R_{con} can be determined by:

$$R_{con} = U_c / I_{g.thy}. \tag{2}$$

where, $I_{g.thy}$. - is the RMS value of the thyristor gate current.

The capacitor parameters are selected based on these values. When choosing the capacitance, the capacitor discharge time across R_{con} must be taken into account. The capacitor should not discharge completely during one full period of the sinusoidal current, i.e., the discharge time constant should satisfy: $\tau = R \cdot C >$ 0,02s. quad f=50 Hz.

In the control system, two low-power thyristors connected in series are selected based on the maximum reverse anode-cathode voltage or the capacitor voltage. In this case, the maximum reverse voltage rating of the thyristor must be chosen with an adequate safety margin [14-16, 28-30].

The resistors in the control circuit of the low-power thyristors are selected based on the gate current requirements. The resistor connected in series with the diode determines the switching time or the relay actuation voltage. Therefore, this resistor is preferably a variable resistor, which allows adjusting the relay triggering voltage (to compensate for thyristor parameter tolerances). The diode type in this circuit is selected according to the gate current of the low-power thyristor. The resistance in the gate circuit of the other thyristor is chosen smaller than that of the resistor in series with the diode, since this thyristor must always remain ready for switching the entire device.

For the design of the input low-power transformer in the STVR control circuit, the starting data are the combined power requirements of the control circuit elements [17-24, 46-47].

The calculation of the control transformer should begin with the selection of the magnetic core, i.e., determination of its configuration and geometric dimensions. The most widely used magnetic core designs include laminated shell-type, tape-wound shell-type, and tape-wound toroidal cores. For low-power applications, ranging from a few watts to several tens of watts, shell-type transformers are the most convenient. They feature a single bobbin with windings and are relatively simple to manufacture [25-27, 56].

CALCULATION OF THE CONTROL CIRCUIT TRANSFORMER

For the calculation of the low-power input transformer of the STVR control circuit, the initial data consist of the combined power consumption of the control circuit elements.

The design procedure should begin with the selection of the magnetic core, i.e., determination of its configuration and geometric dimensions. The most widely used magnetic core types include laminated shell-type, tape-wound shell-type, and tape-wound thyroidal cores. For low-power applications, from a few watts up to several tens of watts, shell-type transformers are the most suitable. They employ a single bobbin for winding's and are relatively simple to manufacture [28-36, 49-51].

The initial simplified input data are:

- primary winding voltage U_1;
- secondary winding voltage U_2;
- secondary winding current I_2.

The power of the secondary winding can be determined as:

$$S_{out} = I_2 \cdot U_2 \tag{3}$$

The dimensions of the magnetic core of the chosen construction can be found using the following expression [1]:

$$S_{cs} \cdot S_{wa} = \frac{0,901 \cdot P_{out}}{B_{max} \cdot J \cdot K_{wf} \cdot K_{st}}, \tag{4}$$

where:

- S_{cs} – cross-sectional area of the magnetic core at the coil position;
- S_{wa} – window area of the magnetic core;
- B_{max} – maximum magnetic flux density;
- J – current density;
- K_{wf} – window filling factor;
- K_{st} – stacking factor of the magnetic core steel.

The values of electromagnetic loadings B and J depend on the output power of the secondary winding. For shell-type cores with output power P_{out}=5-15 Wt, the flux density ranges from 1.1 to 1.3 Tl, while the current density ranges from 3.9 to 23.9 A/mm^2.

The window filling factor K_{wf}=0.22-0.29 for windings made of round enamel-coated wire. The stacking factor K_{st} depends on the thickness of the steel, magnetic core design (laminated or tape-wound), and insulation method of laminations or strips. For the present case, its value lies in the range K_{st}=0.75-0.89 for steel thicknesses of 0.1-0.2 mm. By determining the product S_{cs} S_{wa}, one can select the required linear dimensions of the magnetic core, ensuring that the obtained ratio is not less than the calculated value. The rated current of the primary winding is determined by [37-42, 53]:

$$I_1 = \frac{S_2}{U_1 \cdot \eta \cdot Cos\varphi} \tag{5}$$

where the values of η and cosφ of the transformer depend on the transformer power and can be approximately assumed to be η in the range of 0.6-0.7; $cos\varphi$ in the range of 0.85-0.9 depending on the output power.

The secondary winding current is usually specified. The cross-sectional area of the winding conductor is given by:

$$S_{con} = \frac{I}{J}, \tag{6}$$

and its diameter by:

$$d = 1.13\sqrt{S_{con}} \tag{7}$$

The number of turns in the windings is determined from:

$$W_n = 45 \cdot \frac{U_n \cdot \left(1 - \frac{\Delta U_n}{100}\right)}{B_{max} \cdot S_{st}} \tag{8}$$

where: U_n - winding voltages, ΔU_n- the voltage drop in the windings is within ΔU_1=20÷13; ΔU_2=25÷18 depending on the load capacity [1-4, 43-47].

EXAMPLE OF CALCULATION AND SELECTION OF ELEMENTS

The calculation and selection of the STVR elements were performed in accordance with the proposed methodology and recommendations [48-52].

Initial data:

- Rated load power: S_n=1000VA;
- Supply voltage: U_{mains}=220V;
- Supply frequency: f=50Hz.

Calculation procedure:

1. Based on the rated load power and the rated mains voltage, the load current for an active load is determined:

$$I_n = \frac{S_n}{U_n} = \frac{1000}{220} = 4{,}54\ A$$

2. From the commutated load voltage, the maximum amplitude of the operating voltage applied to the valve is calculated using Eq.(1):

$$U_{max} = \sqrt{2} \cdot 220 = 311{,}127V$$

3. From the obtained results, a thyristor type VT151-500R is selected, designed for medium-power switching applications [53].

Electrical parameters of thyristor VT151-500R:

- Package: SOT-78;
- Off-state voltage: 500 V;
- Gate trigger current (max.): 15 mA;
- On-state current (max.): 12 A.

4. The average current of the diodes forming the bridge is equal to 0.45 of the RMS load current. Since the RMS load current is approximately equal to the RMS thyristor current:

$$I_d = I_t \cdot 0{,}45 = 2{,}043\ A$$

When selecting the diode type, it must be ensured that the bridge diodes protect the circuit from reverse voltage during negative half-cycles of the anode voltage. The maximum permissible reverse voltage of these diodes must satisfy:

$$U_{rev.\max} \geq U_m$$

Where U_m is the mains voltage amplitude. Based on the calculation results, diodes type D246B are selected, with U_{rev}=400V and I_d=5 A [2, 54].

5. The maximum capacitor voltage:

$$U_c = \sqrt{2}U_2 = 1{,}41 \cdot 24 \approx 31 \text{ V},$$

where U_2=24V is the voltage of the transformer secondary winding.

6. The resistance R_3 limiting the gate current of thyristor T_3 is:

$$R_3 = U_c/I_g = 31/0{,}015 = 2066\ \Omega;$$

A resistor of 2.1 kΩ is selected.

7. The capacitor capacitance is determined considering the time constant of the R_3 and C circuit. With τ=0.06s, the required capacitance is: C≈28μF [55].

A DC capacitor rated at 50 V with capacitance 33μF is selected.

8. From the secondary winding voltage of the transformer, two identical low-power thyristors type KU201V are selected.

Elektrical parameters of KU201V [2, 56]:

- Maximum forward/reverse voltage: 50 V;
- Maximum gate current: 100 mA;
- Load current: 2 A.

9. We determine from the control current of the low-power thyristors and the nominal voltage of the secondary winding of the low-power transformer the value of the minimum resistance of the control resistors R. The minimum resistance of the gate resistors is determined as:

$$R_1 = R_2 = U_2 I_{g.\max} / I_{g.\max} = 24/0.1 = 240\ \Omega$$

10. Based on the maximum secondary voltage and the gate current of the low-power thyristor, a diode type D7A is selected, with I_d=30 mA and $U_{rev.max.}$=50 V.

11. For the control transformer, the initial data are:

- Primary voltage: U_1=220 V;
- Secondary voltage: U_2=24 V;
- Maximum load current: I_2=0.3A (according to the control current of the power thyristor).

12. The secondary power is:

$$S_{out} = U_2 \cdot I_2 = 24 \cdot 0.3 = 7.2VA$$

13. The magnetic core dimensions are calculated using Eq. (4).

$$S_{cs} \cdot S_{wa} = \frac{0{,}901 \cdot P_{out}}{B_{\max} \cdot J \cdot K_{wf} \cdot K_{st}} = \frac{0{,}901 \cdot 7{,}2}{1{,}3 \cdot 3{,}7 \cdot 0{,}24 \cdot 0{,}85} = 6{,}6 \text{ sm}^4$$

Assuming: B_{max}=1.3T, J=3.7A/mm^2, K_{wf}=0.24, K_{st}=0.85.

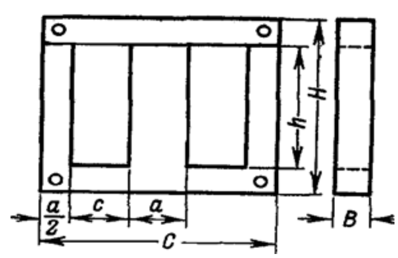

FIGURE 1. Magnetic core

From [1], a core type Ш12×16 (Fig.1), is selected with S_{cs} S_{wa}=6.8 cm^4, $S_{st,ef}$=1.92 cm^2, and G_{st}=0.140 kg.

Core dimensions (mm): a=12, h=30, c=12, C=48, H=42, B=16.

14. The rated primary current is:

$$I_1 = \frac{S_2}{U_1 \cdot \eta \cdot \cos\varphi} = \frac{6{,}6}{220 \cdot 0{,}65 \cdot 0{,}89} = 0{,}051 \text{ [A]},$$

Where the values of η and $cos\varphi$ are dependent on the transformer power and can be approximately taken as η=0.65; $cos\varphi$=0.89.

15. The winding conductor cross-sectional areas:

$$S_1 = \frac{I_1}{J} = \frac{0{,}051}{3{,}7} = 0{,}014 \text{ [mm}^2\text{]}, \qquad S_2 = \frac{I_2}{J} = \frac{0{,}3}{3{,}7} = 0{,}081 \text{ [mm}^2\text{]}$$

16. The conductor diameters:

$$d_1 = 1{,}13 \cdot \sqrt{S_1} = 1{,}13\sqrt{0{,}014} = 0{,}133 \text{ [mm]},$$
$$d_2 = 1{,}13 \cdot \sqrt{S_2} = 1{,}13\sqrt{0{,}081} = 0{,}32 \text{ [mm]}$$

Standard wire diameters of 0.45 mm and 0.69 mm (type PEL) are selected.

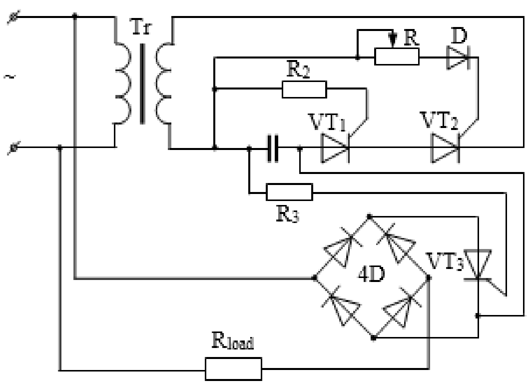

FIGURE 2. The schematic diagram STVR

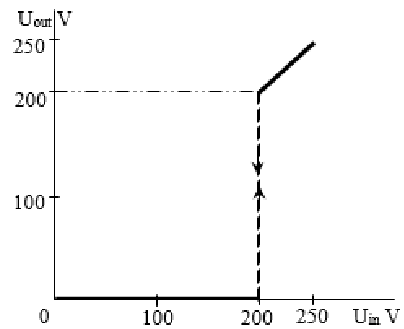

FIGURE 3. The “input–output” characteristic STV

17. The number of turns of the transformer windings is determined from Eq. (8).

$$w_1 = 45 \cdot \frac{U_1 \cdot (1 - \frac{\Delta U_1}{100})}{B_{\text{мах}} \cdot S_{st}} = 45 \cdot \frac{220 \cdot (1 - \frac{18}{100})}{1{,}3 \cdot 1{,}92} = 3252$$

$$w_2 = 45 \cdot \frac{U_2 \cdot (1 - \frac{\Delta U_2}{100})}{B_{мах} \cdot S_{st}} = 45 \cdot \frac{24 \cdot (1 - \frac{23}{100})}{1{,}3 \cdot 1{,}92} = \frac{738}{3{,}12} = 333$$

As a result of the calculation, the following STVR elements were selected:

- Power thyristor: VT_3 type 151-500R
- Bridge diodes: D246B
- Series resistor: R_3=2.1kΩ
- Capacitor: 50 V, 33 μF
- Low-power thyristors: VT_1 and VT_2 type KU201V
- Control diode: D7A
- R_1=3kΩ
- Resistor R_2=5 kΩ.

The schematic diagram of the STVR is shown in Figure 2. The “input-output” characteristic of the fabricated STVR, designed according to the calculation results, is shown in Figure 3 [1-13, 57].

CONCLUSION

Based on the analysis of existing literature on the calculation of elements in contactless switching devices, it has been established that when selecting semiconductor components, resistors, and capacitors, their maximum load operating conditions must be taken into account. The calculation of the input transformer of the thyristor-based solid-state voltage relay (STVR) is most appropriately carried out starting from the determination of the magnetic core dimensions, using specified values of magnetic induction and current density. The selection of thyristors, diodes, and resistors should be made according to rated power, voltage, and calculated current values. The capacitor selection is based on the secondary winding voltage of the input transformer, taking into account the time constant of the R_3-C circuit.

Experimental investigations have demonstrated that the developed alternating-current thyristor-based solid-state voltage relay exhibits high values of reset ratio and multiplicity factor, while ensuring reliable operation under significant nominal switching power.

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