Investigation of automatic electric drives balancing transformers with lead control angles

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Abstract. Analysis were carried out of power rectifiers’ commutation in balancing transformers at lead control angles, positive effect of shielding angle against surge voltage on the equipment main performance indicators was established, equations and experimental characteristics of this component operation were provided. As a result of theoretical and experimental investigations of the surge protection device operation, a significant positive effect on the quality of switching power rectifiers in the balancing transformer in case of lead control angles was detected. The relationship between the degree of reduction of overvoltage in the input phase voltage of the converter and the capacitance values of the capacitor, the angle of the first switching stage and the lead control angle of the converter were determined. A further study of the unit operation is to establish practically applicable quantitative relations between the specified values.

1. Introduction
Analyses of power rectifiers commutation is one of the main stages of a valve inverter operation because it has significant influence on equipment characteristics as a whole.

Compared with standard thyristor rectifiers with natural commutation in the balancing transformer [1] there is artificial commutation with lead angles of phase control of power rectifiers.

The voltage of the phase that comes into operation with the lead control angle is lower than the voltage of the phase that goes out of operation. In accordance with this, the nature of commutation in the balancing transformer becomes complicated by the high level of overvoltage when the valve is turned off in the phase that comes out of operation. Availability of overvoltage is due to the internal inductance of the supply voltage source (as a rule, a transformer), and their level is enormously higher than its amplitude.

To protect the components of the power circuit and improve quality of commutation, the balancing transformer provides for a node for protection against surge overvoltage. This article addresses the theory of its operation when switching Phase A and B power switches with equations of converter state at each of two stages [2].

Due to the symmetry of the converter circuit, the processes in the anode and cathode half-bridges are identical, therefore, it will be enough to consider its anode half-bridge on switches S1, S3, S5, replacing the cathode half-bridge with a neutral wire (figure1). Capacitor C1, switches S1, S3, S5, S7 and diodes VD1, VD3, VD5, VD7 are to be considered as ideal elements. In accordance with this, we exclude switches currents from the equations. We assume \( L_A = L_B = L_C = L_E \), \( R_A = R_B = R_C = R_E \).
$E_i = 0$, and capacitor capacity as $C1 = C$. The timing of the processes will be carried out for the phase starting operation, relative to the point of natural switching of the phase EMF switching under consideration.

![Figure 1. Scheme of balancing transformer substitution for commutation processes analyses.](image)

2. Operation of node for surge protection device

Assume that the switch S1 of phase A operates in the steady state immediately before the start of the next switching. In this case the switch S7 is open, and in the capacitor C1 there is voltage $u_{C1}^0$, current via capacitor $i_{C1}^0$ is equal to zero, therefore, it does not influence on the circuit operation. The current flow path in the circuit before switching is shown on figure 1 as the solid main line with an arrow.

The following equations are valid in this time interval:

$$i_{A}^{0} = i_{A}^{0},$$

$$R_i^{0} + L_i^{0} \frac{di_{A}^{0}}{dt} + R_o^{0} + L_o^{0} \frac{di_{A}^{0}}{dt} = e_A \cdot F_{A}(\alpha_c)$$

where $F_{A}(\alpha_c)$ – commutation function of the phase A switch S1 with lead control angle $\alpha_c \in \left[0; \frac{\pi}{2}\right]$, in relation to the natural commutation points of phased EMF [3].

During the switch S1 operation time equal to $\lambda = 2\pi/3$ [c’] = 0.02/3 [c], the inductance of the phase A source $L_e$ accumulates magnetic field energy $W_{L_A}^0$ equal to:

$$W_{L_A}^0 = \int_{u_{A}}^{u_{A,0}} i_{A}^{0} dt = \int_{u_{A}}^{u_{A,0}} \frac{di_{A}^{0}}{dt} dt = L_e \left( I_{A,0}^0 (\alpha_c + \lambda) \right)^2 / 2 - \left( I_{A,0}^0 (\alpha_c) \right)^2 / 2 = L_e \left( I_{A,0}^0 (\alpha_c + \lambda) \right)^2 / 2$$

By the end of switch S1 operation, it commutes with the phase B switch S3 in two stages. The first stage begins at the time when the switches S3 and S7 are simultaneously closed. In this case, the switch S1 is turned off, and the phase A current continues to flow through the diode VD1 and the switch S3 (figure 2, dashed main line with an arrow). The capacitor C1 begins to discharge to the load with the current of the phase B entering the operation along the circuit formed by switches S3 and S7 (figure 2, a solid main line with an arrow). The VD7 diode is required for setting the directions of the current flow in the converter during switching and in the switching intervals. At this stage, it is under
the reverse voltage of phase A and, therefore, it is closed. Similarly, the diode VD3 is under the reverse voltage of phase A, so the current through it is also equals to zero [4].

Figure 2. Scheme of balancing transformer substitution at the first stage of switches S1 and S3 commutation.

Equations at the first stage of commutation appears as following:

(I): \[ \begin{align*}
    i_{vD1}^i + i_{C1}^i &= i_{S7}^i, \\
    i_{vD1}^i &= i_A^i, \\
    i_{C1}^i &= i_B^i, \\
    i_{S7}^i &= i_a^i \\
    \Rightarrow i_A^i + i_B^i &= i_a^i,
\end{align*} \] (4)

(I): \[ \begin{align*}
    R_A i_A^i + L_A \frac{di_A^i}{dt} + R_S i_s^i + L_S \frac{di_s^i}{dt} &= e_A \cdot F_{S3}(\alpha_c) \\
\end{align*} \] (5)

(II): \[ \begin{align*}
    R_B i_B^i + L_B \frac{di_B^i}{dt} + R_S i_s^i + L_S \frac{di_s^i}{dt} &= e_B \cdot F_{S3}(\alpha_c) + u_{C1}^i
\end{align*} \] (6)

where \( F_{S3}(\alpha_c) \) is commutation function of phase B switch S3 with lead control angle \( \alpha_c \in \left[0; \frac{\pi}{2}\right] \), in relation to natural commutation point of phased EMF [5, 6].

During the first switching step, which is characterized by duration \( \gamma_i \) of operation of the diode VD1, the inductance \( L_e \) of the source phase A puts into load a portion of the previously \( W_{LA}^i \) stored electromagnetic energy \( W_{LA}^i \) equal to:

\[ W_{LA}^i = \int_{\alpha_c+\lambda}^{\alpha_c+\lambda+\gamma_i} u_A^i i_A^i dt = \int_{\alpha_c+\lambda}^{\alpha_c+\lambda+\gamma_i} L_e \frac{di_A^i}{dt} i_A^i dt = L_e \int_{\alpha_c+\lambda}^{\alpha_c+\lambda+\gamma_i} i_A^i \frac{di_A^i}{dt} dt = L_e \int_{i_A^i}^{i_A^i(\alpha_c+\lambda+\gamma_i)} \left( \frac{I_{mA}(\alpha_c+\lambda+\gamma_i)}{2} \right)^2 - \left( \frac{I_{mA}(\alpha_c+\lambda)}{2} \right)^2 \] (8)
At the end of capacitor discharge by the current of phase B, the second switching stage starts. After discharge to voltage \( u_{C1} \), capacitor C1 becomes free to receive the energy remaining in the inductance of phase A after the first switching step during the diode conductivity period VD1:

\[
W_{LA} = W_{LA}^0 - W_{LA}^i
\]

(9)

For this purpose the S7 switch is disabled. Current of phase B, which has entered into operation, started flowing directly into diode VD7 under voltage, directly into the load (figure 3, dashed main line with an arrow). At the same time, capacitor C1 starts charging with phase A current through diodes VD1 and VD7 (figure 3, solid main line with an arrow).

![Figure 3. Scheme of balancing transformer substitution at the second stage of switches S1 and S3 commutation.](image)

Equations at the second stage of commutation appears as the following:

(I) \( : \)
\[
i_{C1}^2 + i_{S3}^2 = i_{VD7}^2 \Rightarrow i_{C1}^2 = -i_{S3}^2
\]

(10)

\[
R_A i_A^2 + L_e \frac{di_A}{dt} + R_d i_A^2 + L_d \frac{di_A}{dt} = e_A \cdot F_{S3} (\alpha_C - \gamma_L) - u_{C1}^2
\]

(11)

\[
R_B i_B^2 + L_e \frac{di_B}{dt} + R_d i_B^2 + L_d \frac{di_B}{dt} = e_B \cdot F_{S3} (\alpha_C - \gamma_L)
\]

(12)

\[
i_{C1}^L = C \cdot \frac{du_{C1}}{dt}
\]

(13)

After charging the capacitor C1 to the voltage \( u_{C1}^2 \), the phase A current through the diode VD1 becomes zero, whereby the diode is closing. Commutation ends and the next cycle of quasi-steady state occurs [7]. Phase B switch S3 and VD7 diode remain in conductive state (figure 4, solid main line with an arrow).
Equations after commutation:

\[ i_{s3} = i_{vd7} = i_{d} \Rightarrow i_{b} = i_{t}, \]

\[ R_{e}i_{d}^3 + L_{e} \frac{di_{d}^3}{dt} + R_{a}i_{d}^3 + L_{a} \frac{di_{d}^3}{dt} = e_{b} \cdot E_{S3} (\alpha_{c} - \gamma), \]

where \( \gamma = \gamma_{1} + \gamma_{2} \) – duration of the first and second commutation stages.

Thus, in the mode with lead control angles \( \alpha_{c} \) the surge protection device based on capacitor \( C_{1} \) fulfills two important functions [8]:

- separation of the current circuits of the incoming and outgoing phase;
- smooth transfer into the load of the inductance energy of the phase out of operation.

Under conditions of lead control angles, when voltage of phase out of operation is higher than input phase voltage, execution of the first function ensures lack of overvoltage, and the second - reduction of energy losses during switching in inductance of phases of supply network. As a result, the operating conditions of the balancing transformer power switches are improved, the harmonic distortion factor of the network voltage and current is decreasing, and efficiency of the "balancing transformer supply network" system is increasing.

3. Computer simulation of surge protection device

Comparative assessment of switching quality in case of lead control angles of converter during surge protection device operation and without it, was carried out experimentally by the computer simulation method in MATLAB Simulink environment [9]. The lead control angle is \( \alpha_{c} = 45 \) el. degree. Load parameters are \( R_{a} = 1 \) ohm and \( L_{a} = 0,001 \) henry, linear voltage of supply network \( E_{A} = E_{B} = E_{C} = E = 380 \) V (RMS), frequency \( f = 50 \) hz, \( R_{e} = 0,1 \) ohm, \( L_{e} = 0,0001 \) henry. Parameters of converter: \( \gamma_{1} = 3 \) el. degree, surge protection device capacitors capacity was selected experimentally according to the criterion of minimum overvoltage in the network at the specified control angle and the first switching stage and in this case it amounts to \( C_{1} = C_{2} = 10000 \) mfd.

Phase current and voltage curves in the absence of surge protection device are given on figure 5. The Y scale for the current is 200 A/units, for voltage – 200 V/units, along the axis X for time – 5 ms/units.
The total harmonic distortion (THD) of voltage and current of phase A was 171.4% and 35.13%, accordingly, the average value of voltage and load current 290V and 290 A accordingly, efficiency of the system "supply network – balancing transformer" is 93.94%. Switching overvoltage appears as short time surges much higher amplitude than the phase voltage level [10].

Curves of phase current and voltage during operation of surge protection device are shown on figure 6. The Y scale for current is 200 A/D, for voltage - 200 V/D, for time - 10 ms/D. The total harmonic distortion of voltage and current of phase A was 13.18% and 30.1%, accordingly, the average value of voltage and load current are 314.6 V and 314.6 A respectively, efficiency of the system "supply network – balancing transformer is 97.43%. Overvoltage during switching changed into "steps" of small amplitude decreasing at more accurate ratio between capacity values of surge protection device capacitors, control angle of converter $\alpha_c$ and angle of the first stage of switching $\gamma_1$.

4. Conclusion
As a result of theoretical and experimental investigations of the surge protection device operation, a significant positive effect on the quality of switching power rectifiers in the balancing transformer in case of lead control angles was detected. The relationship between the degree of reduction of overvoltage in the input phase voltage of the converter and the capacitance values of the capacitor, the angle of the first switching stage and the lead control angle of the converter were determined. A further study of the unit operation is to establish practically applicable quantitative relations between the specified values.

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