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STABILITY REGION OF DC-DC CONVERTER UNDER ENERGY SOURCE AND PARAMETER VARIATIONS

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Goals and objectives

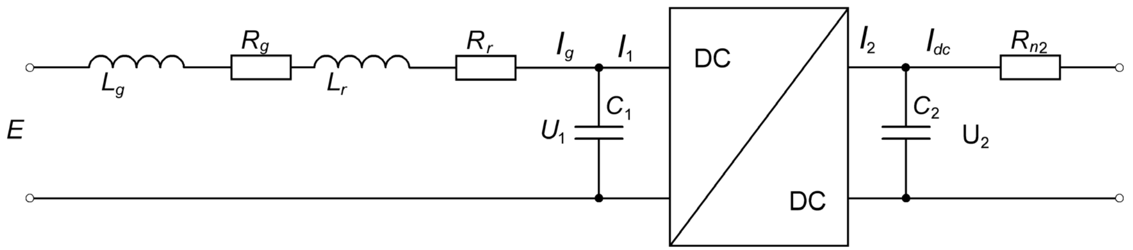
Objective: To analyze the stability of a DC-DC converter using an active-inductive energy source (electric machine)

Tasks:

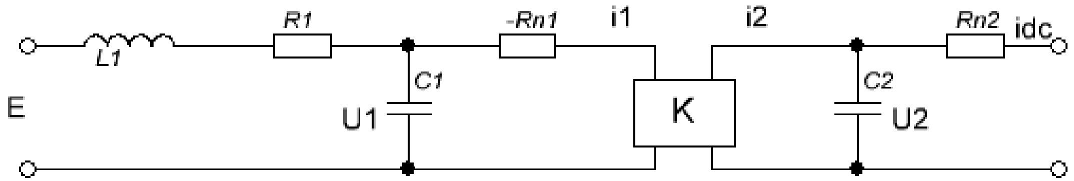
1. Obtaining the structure and description of the power supply system of an autonomous consumer
2. Synthesis of mathematical description
3. Stability analysis

Structure and description of the autonomous consumer power supply system

Subject:



The considered part of the system:



Mathematical description:

$$
\begin{cases}
E = (R_g + R_r)I_g + (L_g + L_r)pI_g + U_1 = R_1 I_g + L_1 p I_g + U_1, \\
U_1 = \dfrac{1}{C_1 p}(I_g - I_1) \rightarrow I_g = C_1 p U_1 + I_1, \\
U_1 = \dfrac{U_1^2}{-P_n} I_1 = -R_{n1} I_1, \\
\dfrac{I_1}{I_2} = K, \\
U_2 = \dfrac{1}{C_2 p}(I_2 - I_{dc}) \rightarrow I_2 = C_2 p U_2 + I_{dc}, \\
U_2 = \dfrac{U_2^2}{P_n} I_{dc} = R_{n2} I_{dc}.
\end{cases}
$$

Assumption and linearization

Bringing to one side of the converter:

Voltage:

$$\frac{U_2}{U_1} = K \rightarrow U_2 = KU_1$$

Load:

$$R_{n2} = \frac{U_2^2}{P_n} = \frac{(KU_1)^2}{P_n} = K^2\frac{U_1^2}{P_n} = K^2 R_{n1}$$

Capacitor capacity:

$$C_2 = aC_1$$

Small-signal linearization model:

$$p\begin{bmatrix} i_{\Delta g} \\ i_{\Delta 1} \\ i_{\Delta dc} \end{bmatrix} = \begin{bmatrix} -\frac{R_1}{L_1} & \frac{R_{n1}}{L_1} & 0 \\ -\frac{1}{C_1 R_{n1}} & \frac{1}{C_1 R_{n1}} & 0 \\ 0 & \frac{1}{K^3 a C_1 R_{n1}} & -\frac{1}{K^2 a C_1 R_{n1}} \end{bmatrix} \times \begin{bmatrix} i_{\Delta g} \\ i_{\Delta 1} \\ i_{\Delta dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} E_\Delta \\ 0 \\ 0 \end{bmatrix}$$

Transfer function and stability analysis:

Transfer function:

$$W_g(s) = \frac{i_{\Delta dc}(s)}{E_\Delta(s)} = \frac{1}{T_3 s^3 + T_2 s^2 + T_1 s + T_0},$$

Constant transfer function:

$$T_3 = -aL_1 C_1^2 K^3 R_{n1}^2$$

$$T_2 = aK^3 C_1 R_{n1} L_1 - aK^3 C_1^2 R_1 R_{n1}^2 - KL_1 C_1 R_{n1}$$

$$T_1 = KL_1 - KC_1 R_1 R_{n1} + aK^3 R_1 C_1 R_{n1} - aK^3 C_1 R_{n1}^2$$

$$T_0 = K(R_1 - R_{n1})$$

The determinant of Rauss-Hurwitz:

$$a_0 = T_2 T_1 - T_0 T_3 = f(a, K, R_{n1}) > 0$$

$$f(a, K, R_{n1}) =$$
$$= C_1^2 R_1 (a^2 K^6 R_{n1}^4) + C_1^3 R_1^2 (aK^4 R_{n1}^3) - C_1^3 R_1^2 (a^2 K^6 R_{n1}^3) -$$
$$- C_1^2 L_1 (a^2 K^6 R_{n1}^3) + C_1^2 (a^2 K^4 R_{n1}^3) - C_1^2 L_1 (aK^4 R_n^3) +$$
$$+ C_1 L_1^2 (aK^4 R_{n1}^2) - C_1^2 L_1 R_1 (aK^4 R_{n1}^2) - C_1^2 L_1 R_1 (aK^4 R_{n1}^2) +$$
$$+ C_1^2 L_1 R_1 (K^2 R_{n1}^2) + C_1^2 L_1 R_1 (aK^6 R_{n1}^2) - C_1^2 L_1 R_1 (aK^4 R_{n1}^2) +$$
$$+ C_1^2 L_1 R_1 (aK^4 R_{n1}^2) - C_1 L_1^2 (K^2 R_{n1})$$

Stability analysis and simplification of surface analysis

The function of the surface of four changes:

$$a_0 = T_2T_1 - T_0T_3 = f(a, K, R_{n1}) > 0$$

Transition to the projection of a four-dimensional projection on a three-dimensional space:

$$a_0 = f(a, K, R_{n1}) = \begin{cases} a_0 = f\big(K(a), R_{n1}(a)\big) \\ a_0 = f\big(a(K), R_{n1}(K)\big) \\ a_0 = f\big(a(R_{n1}), K(R_{n1})\big) \end{cases}$$

Transition to the projection of a three-dimensional projection on a two-dimensional space:

$$a_0 = f(a, K, R_{n1}) = 0 = \begin{cases} a_0 = f\big(K(a), R_{n1}(a)\big) = 0 \\ a_0 = f\big(a(K), R_{n1}(K)\big) = 0 \\ a_0 = f\big(a(R_{n1}), K(R_{n1})\big) = 0 \end{cases} = \begin{cases} a_0 = f_{a=\mathrm{var}}(K) = 0 \\ a_0 = f_{a=\mathrm{var}}(R_{n1}) = 0 \\ a_0 = f_{K=\mathrm{var}}(a) = 0 \\ a_0 = f_{K=\mathrm{var}}(R_{n1}) = 0 \\ a_0 = f_{R_{n1}=\mathrm{var}}(a) = 0 \\ a_0 = f_{R_{n1}=\mathrm{var}}(K) = 0 \end{cases}$$

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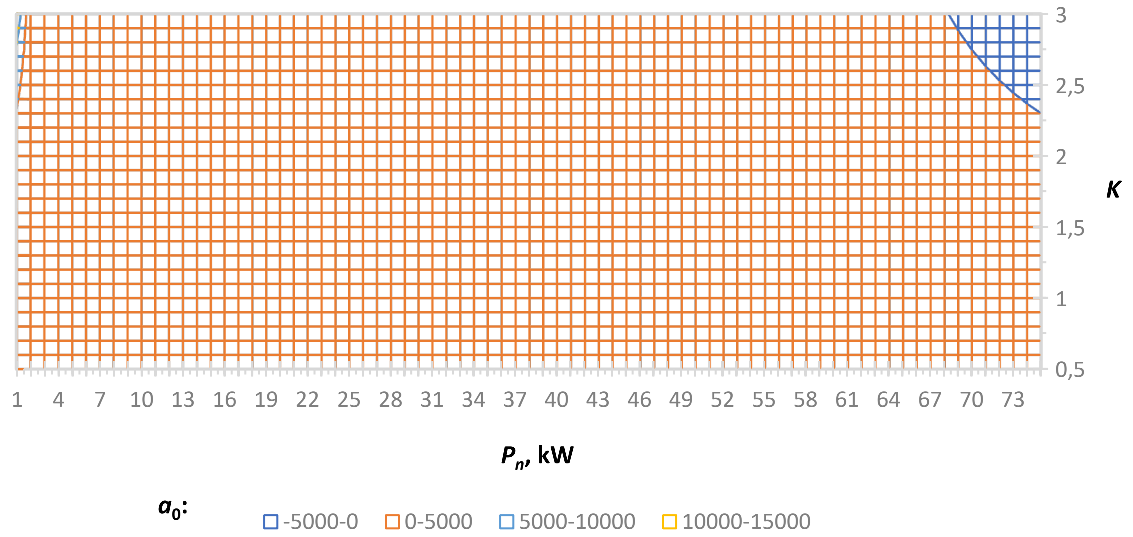
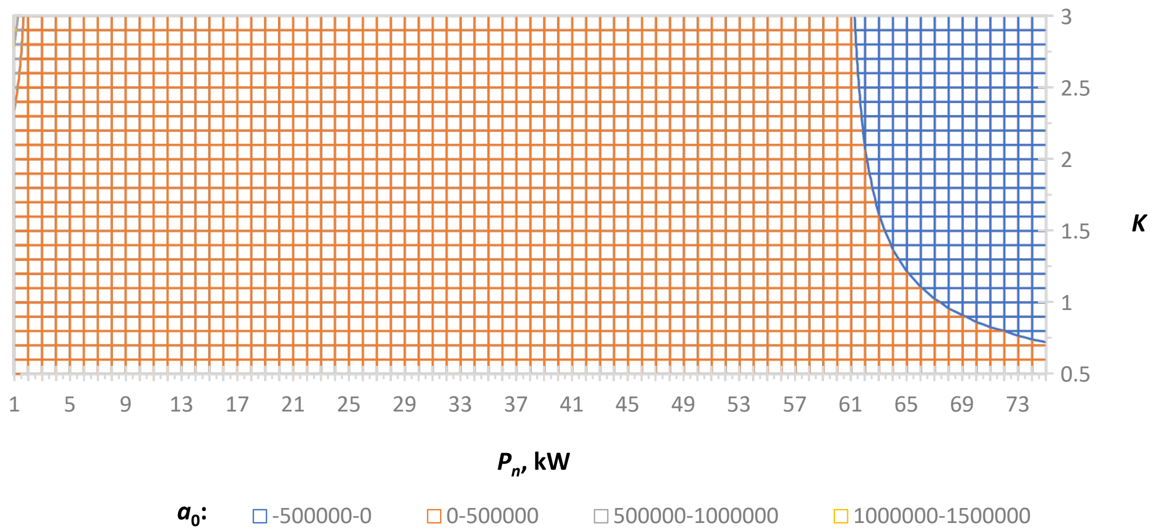


Surface $a_0 = f(K, P_n)$, for $a = 1$



Surface $a_0 = f(K, P_n)$, for $a = 10$

Conclusion:

With an increase in the ratio of the output capacitance to the input, the instability zone increases

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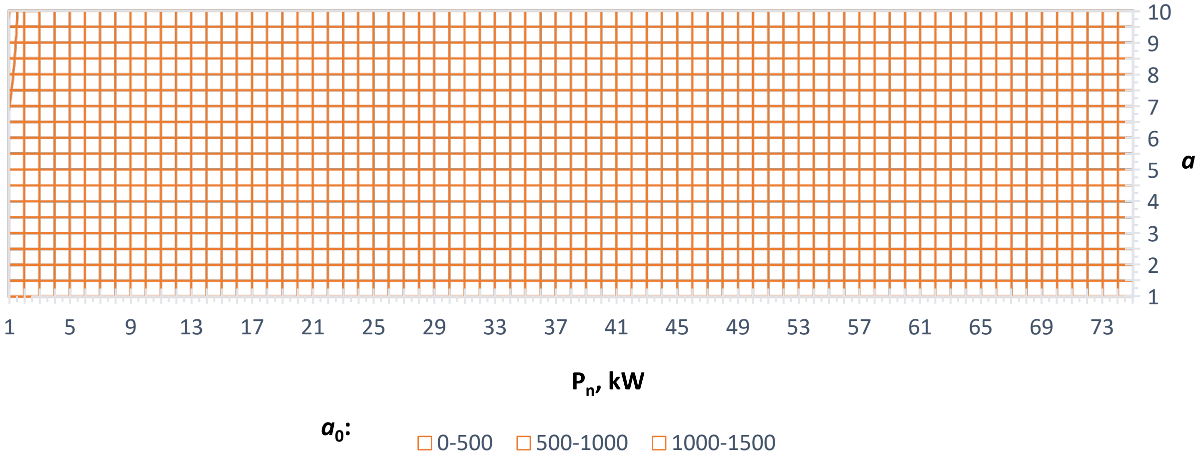
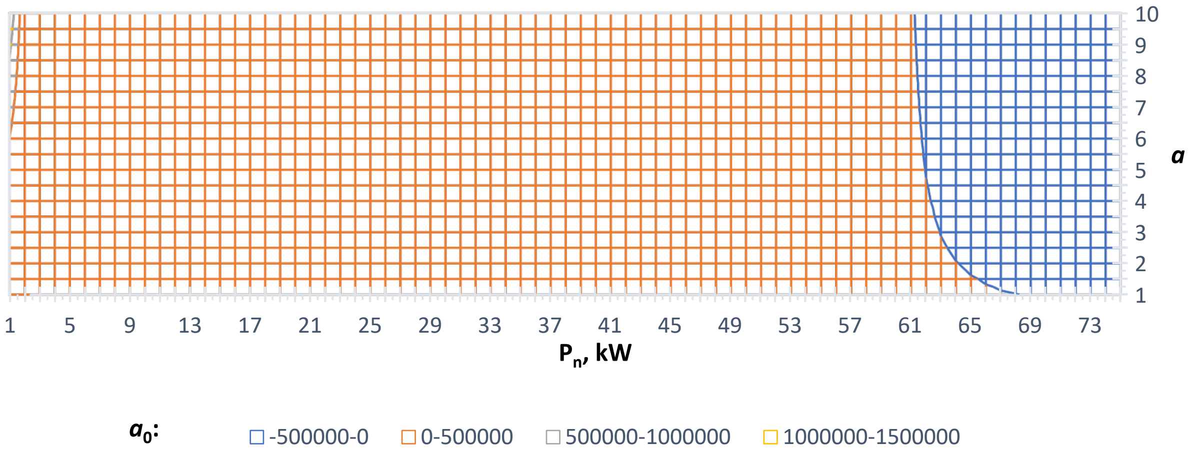


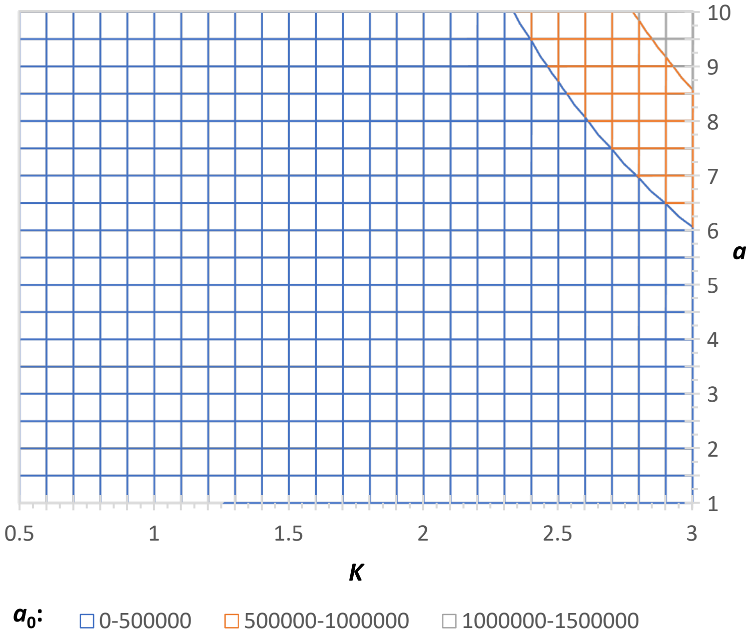
Surface a_0=$f(a, P_n)$, for K = 0.5



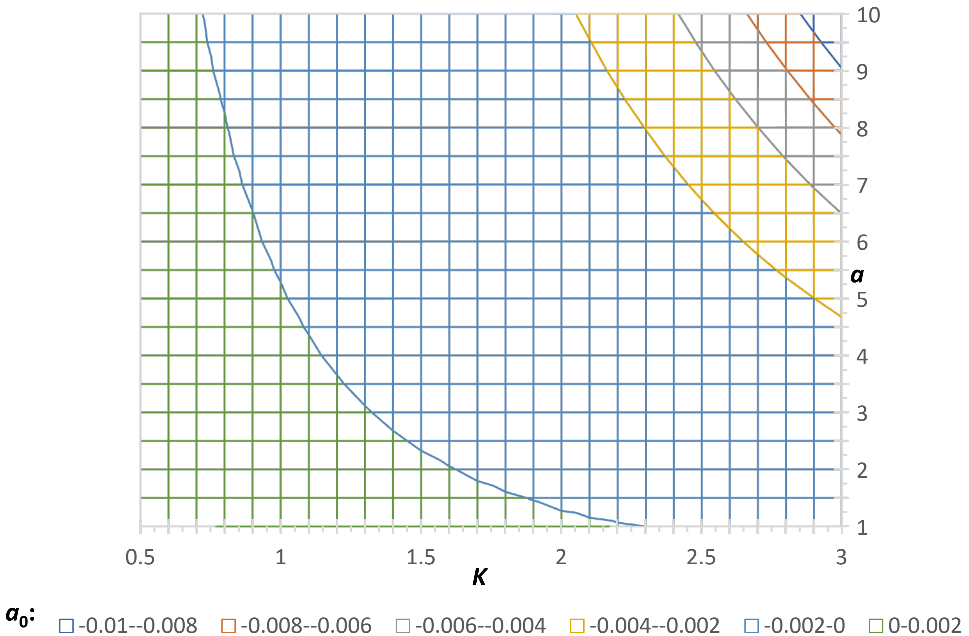
Surface a_0=$f(a, P_n)$, for a = 3

Conclusion:

The transformation coefficient increases, the instability zone increases



Surface $a_0=f(a, K)$, for P_n = 1 kW



Surface $a_0=f(a, K)$, for P_n = 75 kW

Conclusion:

With an increase in power consumption, the instability zone increases

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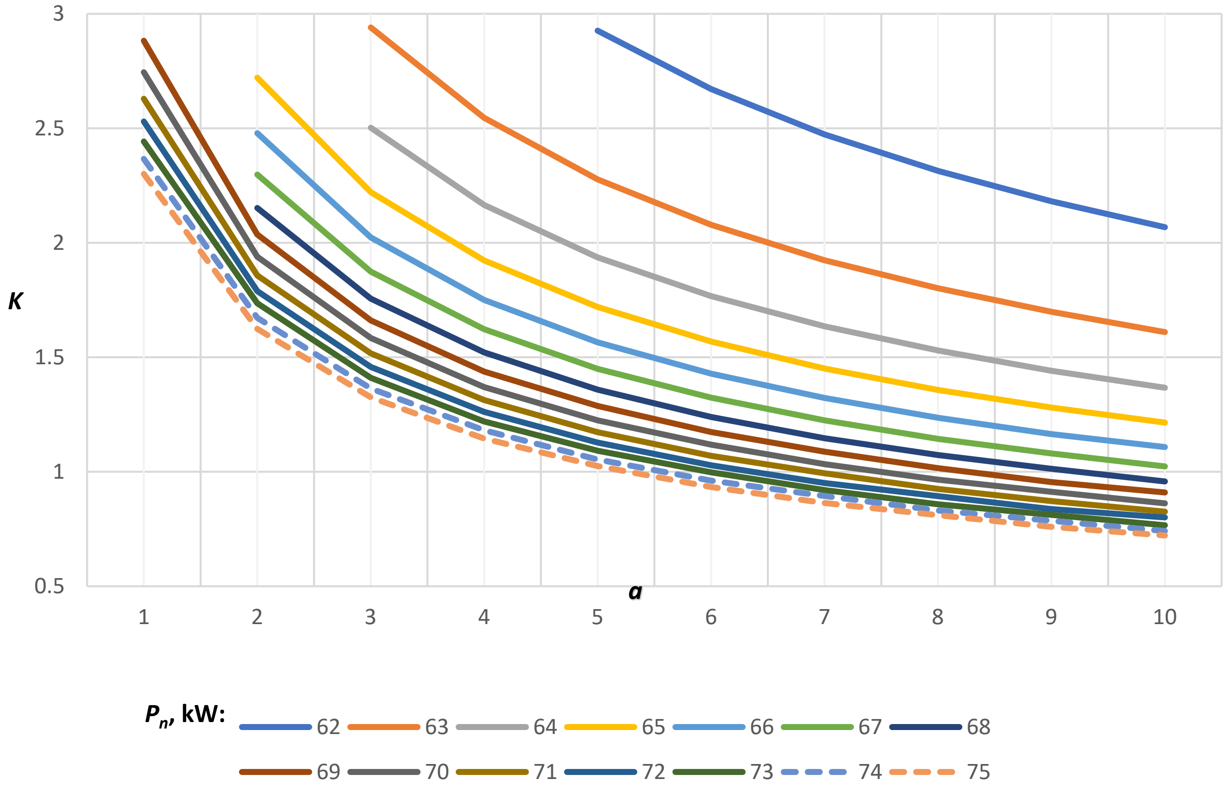
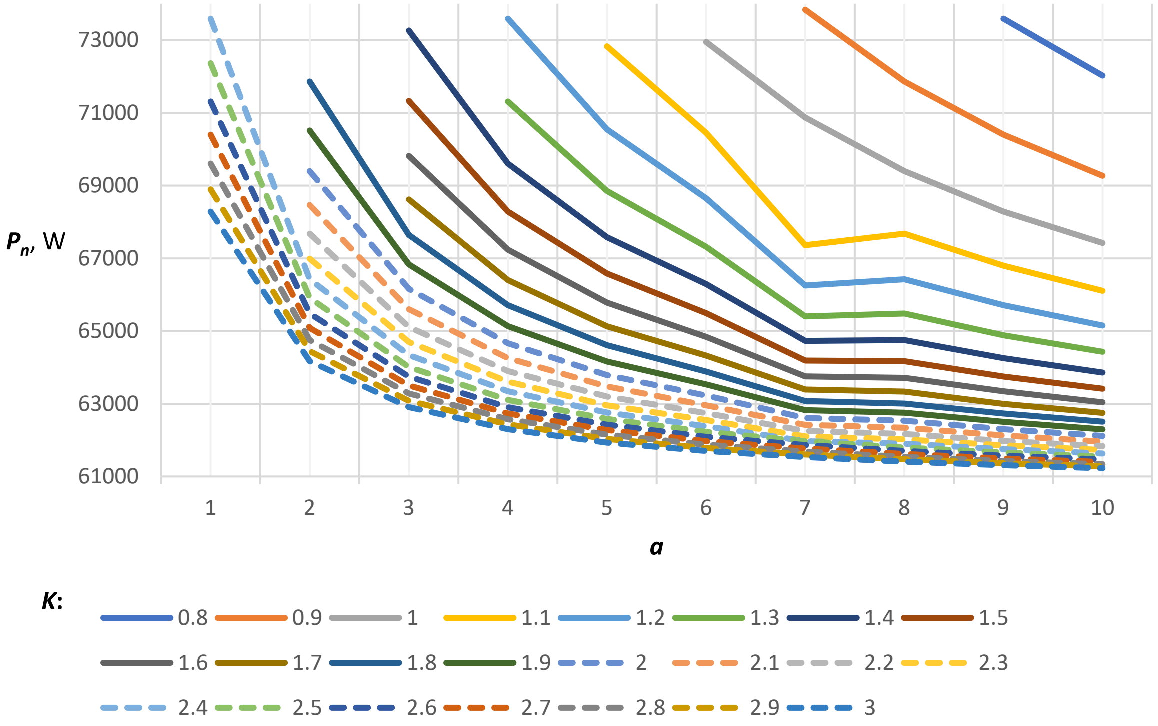
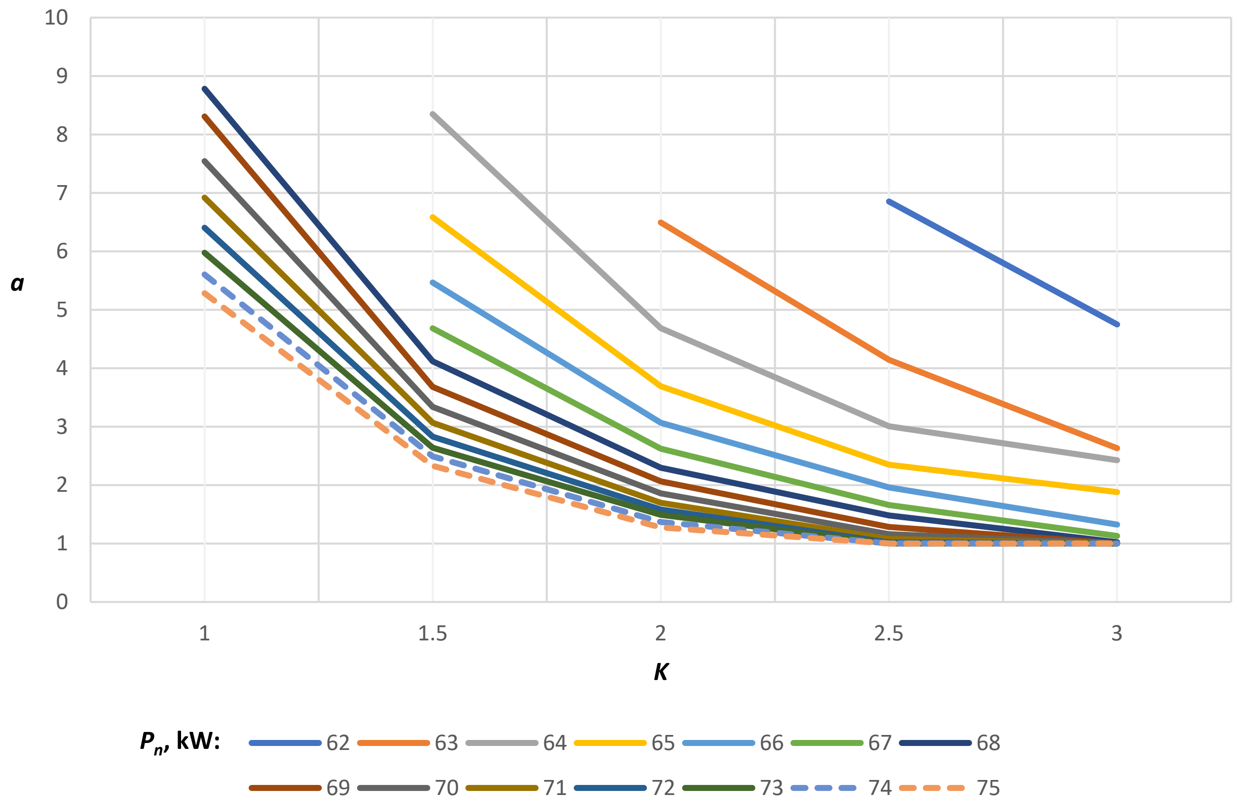


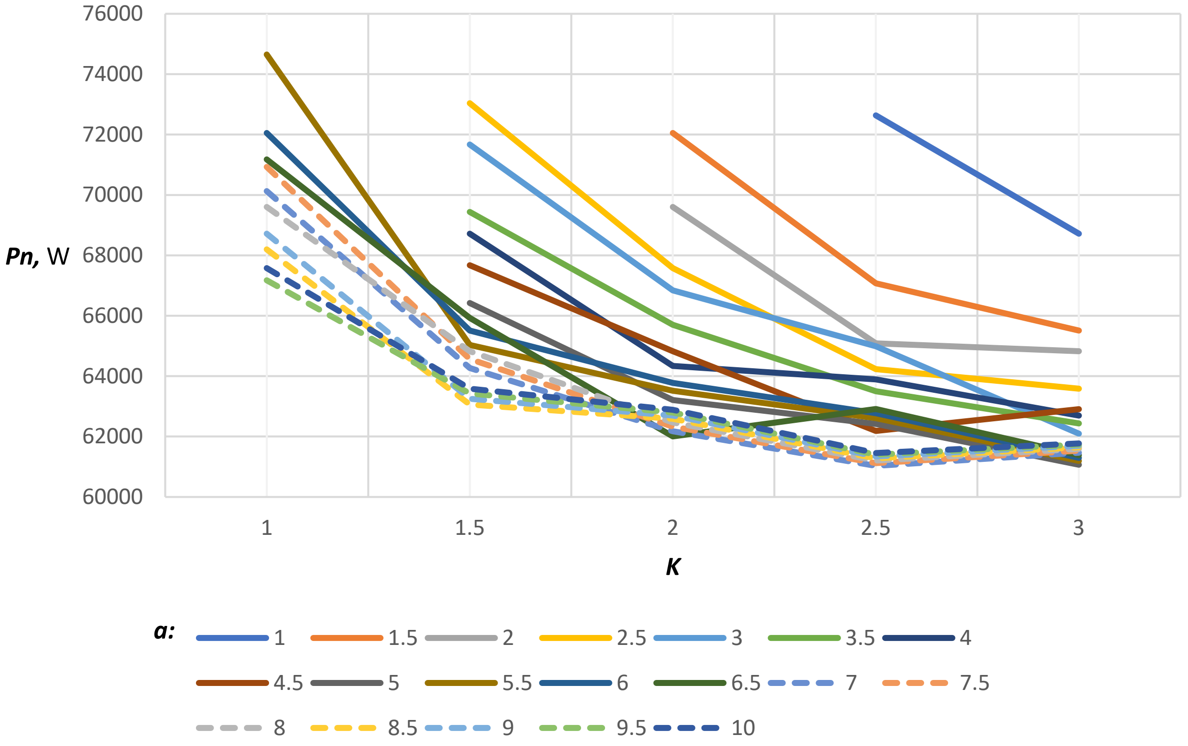
System stability limit’s function $a_0=f_{a=\text{var}}(K)$, for P_n = const



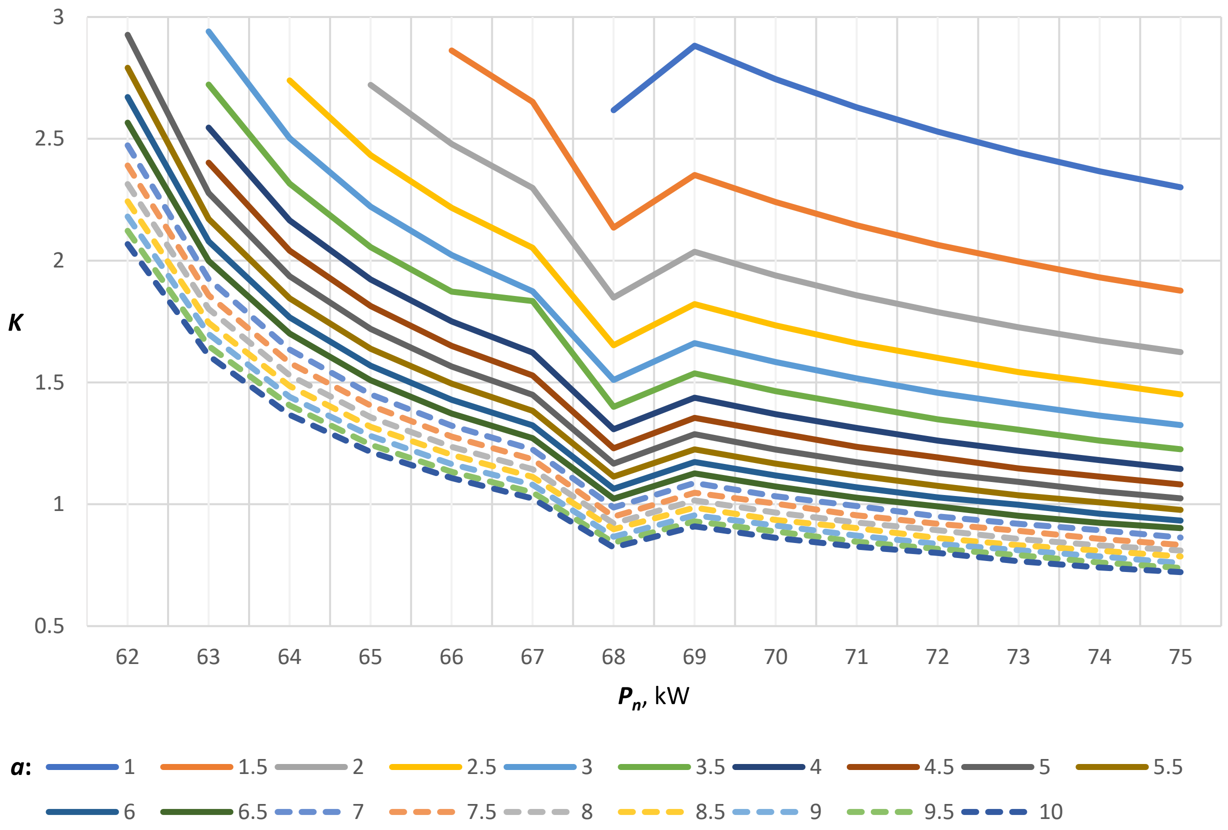
System stability limit’s function $a_0=f_{a=\text{var}}(P)$, for K = const



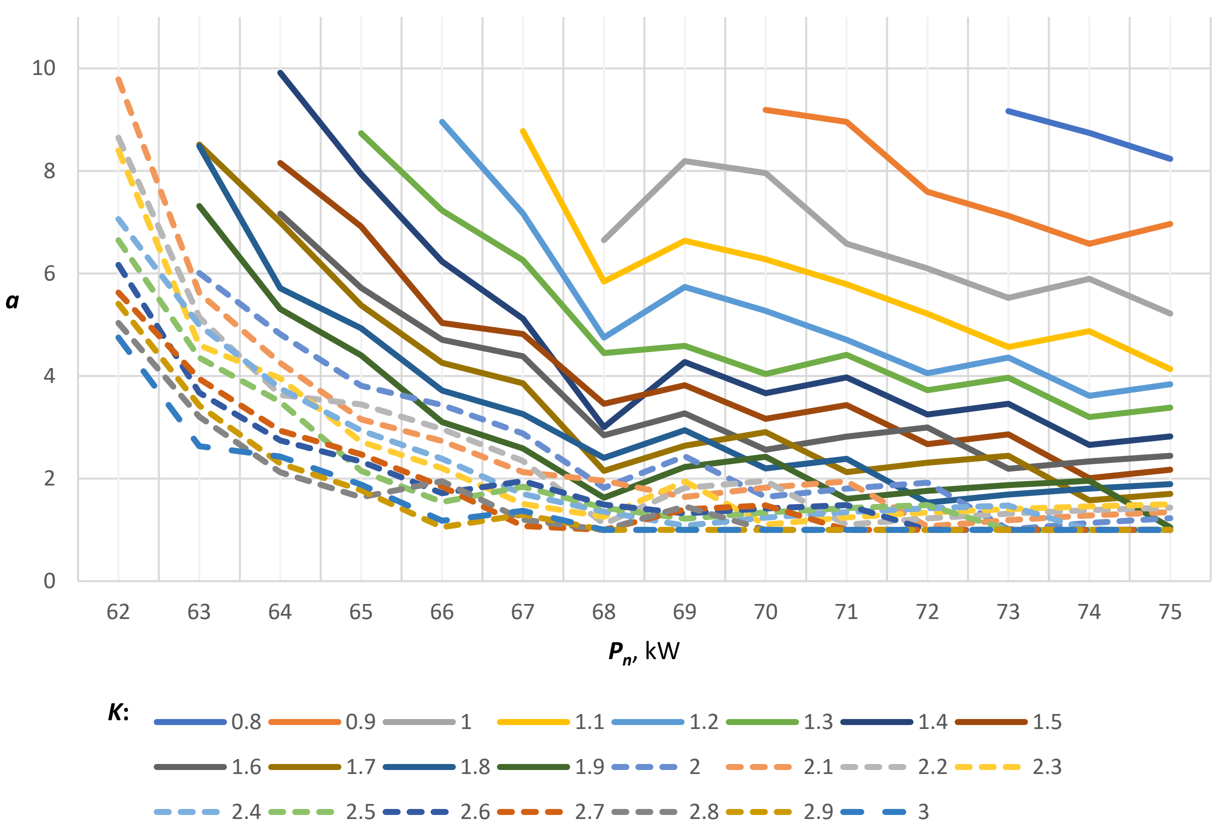
System stability limit's function $a_0 = f_{a=\mathrm{var}}(a)$, for P_n = const



System stability limit's function $a_0 = f_{a=\mathrm{var}}(P)$, for a = const



System stability limit's function $a_0=f_{a=\text{var}}(K)$, for a = const



System stability limit's function $a_0=f_{a=\text{var}}(P)$, for K = const

Conclusion

1. The mathematical description of the DC voltage converter "lower – upper" side of the converter is determined, in which the "lower" side is a synchronous generator, rectifier and input filter.

2. The dependence determining the stability conditions of the system is obtained not only on the power consumption, but also on the parameters of the converter, such as the values of the input and output capacitance, the transformation coefficient and the parameters of the energy source.

3. The boundaries of the stability of the system are obtained and analyzed.

According to the results of the study, it can be seen that the curve K = f(Pn) for a known fixed value of a was the most convenient for the synthesis of the correction device. Based on this curve, a nonlinear regulator can be developed. This regulator will have to limit the energy transfer coefficient K between the primary and secondary windings of the DC-to-DC converter in order to ensure stable operation of the system.