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Calculation Methodology for Voltage-Boosting Transformer Voltage Stabilizer

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Calculation Methodology for Voltage-Boosting Transformer Voltage Stabilizer

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Abstract. This paper presents a developed methodology for calculating voltage-boosting transformers for application in the development of contactless voltage stabilizers, where the control of voltage-boosting windings is implemented using contactless voltage relays. The calculation methodology is based on existing literature on transformer design, while addressing the selection of optimal parameters for voltage-boosting transformers in voltage stabilizers, considering the share of installed transformer power relative to the output load power. The paper provides thermal calculation methodology and determination of voltage-boosting transformer parameters.

INTRODUCTION

The main element of the proposed voltage stabilizer circuit is the voltage-boosting transformer. Below is a calculation methodology based on existing literature on transformer design. It is considered that the installed power of the voltage-boosting transformer is within 25÷30% of the output power of the voltage stabilizer [1-3, 21-27].

For calculating the voltage-boosting transformer, the following initial data must be specified [4-7, 33]:

- Supply voltage – U_1;
- Supply frequency – f_{supply};
- Secondary winding voltage – U_2;
- Secondary winding current – I_2;
- Load characteristic;
- Ambient temperature – t_{amb}, ^{0}C.

CALCULATION METHOD

For calculating voltage-boosting transformers with armoured and core-type magnetic circuits for a specified temperature rise, the following calculation procedure is recommended [8-13, 28-32, 34].

Determine the required secondary winding power:

$$S_2 = U_2 \cdot I_2,\ \text{VA} \tag{1}$$

Tables 1 and 2 present the types of magnetic circuit construction that have found the greatest application in manufacturing low-power transformers. From these tables, select the steel grade and thickness of the magnetic circuit plate or tape according to the specified supply frequency. Based on the found value S_2 for the given magnetic circuit construction, find approximate values of B_{max}, δ, k_{wf}, k_{st} [1-3, 14-20, 35-38].

- B_{max} - [T] magnetic induction (Table 1);
- δ - [A/mm²] current density (Table 2);
- k_{wf} - window fill factor (Table 3);
- k_{st} - magnetic circuit fill factor (Table 4);

Using the following formula, find the product of the steel cross-sectional area of the magnetic circuit (S_{st}) and its window area (S_{wa}):

$$S_{cs}S_{wa} \approx \frac{P_2 \cdot 10^2}{2{,}22 f \mathrm{B}_{max}\ \delta\ \mathrm{k}_{wf}\ \mathrm{k}_{st}}\ [\text{sм}^4]; \tag{2}$$

TABLE 1. Types of magnetic circuit designs for selecting steel grades and plate thicknesses for a given frequency

Magnetic Circuit Construction	Core Material and Thickness, mm	supply Frequency, Hz	Magnetic Induction B_{max}, Tl, for S_2, VA					
			5-15	15-50	50-150	150-300	300-1000	1000-2500
Armored (laminated)	E42, Δ=0.35	50	1,1–1,3	1,3	1,3 –1,35	1,35	1,35–1,2	–
Armored (tape)	E310, Δ=0.35	50	1,55	1,65	1,65	1,65	1,65	–
Core-type (tape)	E310, Δ=0.35	50	1,5–1,6	1,6	1,7	1,7	1,7	1,7

TABLE 2. Recommended current density values for the magnetic circuit configuration

Magnetic Circuit Construction	Core Material and Thickness, mm	supply Frequency, Hz	Current Density δ, A/mm², for S_2, VA					
			5-15	15-50	50-150	150-300	300-1000	1000-2500
Armored (laminated)	E42, Δ=0.35	50	3,9–3,0	3,0–2,4	2,4 –2,0	2,0–1,7	1,7–1,4	–
Armored (tape)	E310, Δ=0.35	50	3,8–3,5	3,5–2,7	2,7–2,4	2,4–2,3	2,3–1,8	–
Core-type (tape)	E310, Δ=0.35	50	7–5,2	5,2–3,8	3,8–3,0	3,0–2,4	2,4–1,7	1,7–1,4

TABLE 3. Window Fill Factor by Magnetic Core Construction and Operating Voltage

Magnetic Circuit Construction	Operating voltage, V	Window Fill Factor k_{win} for S_2, VA					
		5–15	15–50	50–150	150–300	300–1000	1000–2500
Armored (laminated)	Up to 10 From 100 to 1000	0,22–0,29 0,19–0,25	0,29–0,30 0,25-0,26	0,3-0,32 0,26-0,27	0,32-0,34 0,27-0,30	0,34-0,38 0,30-0,33	– –
Armored (tape)	Up to 100 From 100 to 1000	0,15-0,27 0,13-0,23	0,27-0,29 0,23-0,26	0.29-0,32 0,26-0,27	0,32-0,34 0,27-0,30	0,34-0,38 0,30-0,33	– –
Core-type (tape)	Up to 100 From 100 to 1000	0,14-0,25 0,12-0,21	0,25-0,28 0,21-0,24	0,28-0,29 0,24-0,25	0,29-0,30 0,25-0,30	0,30-0,35 0,30	0,35 0,30

TABLE 4. Magnetic core filling factor according to magnetic core design

Magnetic Circuit Construction	K_{st} magnetic core filling coefficient for steel thickness, mm				
	0,08	0,1	0,15	0,2	0,35
Core-type, armored (laminated)	–	0,7 (0,75)	–	0,85 (0,89)	0,9 (0,94)
Core-type, armored (tape)	0,87	–	0,9	0,91	0,93

From table 5, extract the necessary data*: a, h, c, C, H, B* [1-3, 21-27, 43].

Steel losses for induction B_{max}:

$$P_{st}=\rho_{st}\ G_{st}\ [\text{Wt}], \tag{3}$$

where ρ_{st} - specific losses (per 1 kg of steel), determined from the curve in Fig.1.

Find the active component of the no-load current using the formula for maximum supply voltage, considering $P_{st}=I_{oa}\,U_1$ [Wt]:

$$I_{oa} = \frac{P_{st}}{U_1}\ \text{[A]}, \tag{4}$$

TABLE 5. Reference values and dimensions of the magnetic circuit

Magnetic Circuit	Dimensions, mm						Reference Values						
							Magnetic circuit cross-section, sm²	The average length of the magnetic circuit, sm	Cross-sectional area of steel x window area sm⁴	Magnetic core volume, sm²	Weight magnetic circuit kg	Approximate transformer capacity	
												f=50	*f*=400
	a	h	c	C	H	B	S_{st}	L_{st}	$S_{st}\,S_{wa}$	V_{st}	G_{st}	ΣP_2	
EI core 25×32	25	62,5	25	100	87,5	32	8	21,3	125	170	1,17	135	730
EI core 25×40						40	10		156	213	1,47	170	810
EI core 25×50						50	12		195	266	1,84	210	990

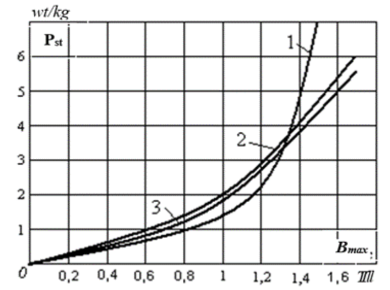

FIGURE 1. Specific magnetizing power Specific losses in cores made of transformer steels with a thickness of 0.35 mm at a frequency of 50 Hz. 1 - E42 steel armor cores: 2 - E310 steel core cores: 3 - E310 steel armor cores types of steel armor cores: 1 - E42, 0.35 mm thick, f-50 Hz; 2 - E44, 0.2 mm thick, 400 Hz; 3 - E340, 0.15 mm thick, f-400 Hz.

Find the total magnetizing power using the following formula:

$$Q_{st}=q_{st}\,G_{st}\ \text{[VA]}, \tag{5}$$

where q_{st} - total specific magnetizing power [VA/kg] from curves in Fig.2 [1, 28-34, 39-42].

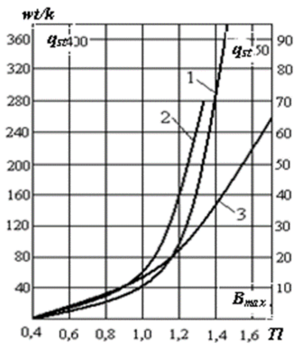

FIGURE 2. Specific magnetizing power for steel armor cores: 1 - E42, 0.35 mm thick, f-50 Hz; 2 - E44, 0.2 mm thick, 400 Hz; 3 - E340, 0.15 mm thick, f-400 Hz

Determine the reactive component of no-load current, knowing that:

$$Q_{st} = I_{or} \cdot U_1 \text{ [VAr]} \quad (6)$$

Find the no-load current value using the formula:

$$I_o = \sqrt{I_{oa}^2 + I_{or}^2}, \text{ [A]} \quad (7)$$

Nominal current of the primary winding:

$$I_1 = \frac{S_1}{U_1} = \frac{P_2}{U_1 \eta Cos\varphi} \quad (8)$$

where P_2 is the power of the secondary winding;

TABLE 6. Efficiency and power factor of the total power of the secondary windings.

Supply Frequency, Hz	Values	Total Secondary Winding Power P_2, Wt					
		2-15	15-50	50-150	150-300	300-1000	1000-2500
50	η	0,5-0,6	0,6-0,8	0,8-0,9	0,9-0,93	0,93-0,95	-
	cosφ	0,85-0,90	0,9; 0,93	0,93; 0,95	0,95-0,93	0,93-0,94	-

Find the number of turns in windings:

$$W_1 = \frac{E_1 \cdot 10^4}{4{,}44 f B_{\max} S_{st.a\kappa t}} \quad (9)$$

$$W_2 = \frac{E_2 \cdot 10^4}{4{,}44 f B_{\max} S_{st.a\kappa t}} \quad (10)$$

Here $E_1 = U_1(1\text{-}\Delta U_1)$; $E_2 = U_2(1+\Delta U_2)$.
where ΔU_1 and ΔU_2 - voltage drops in windings.

TABLE 7. The magnitude of the voltage drop in the total power of the secondary windings

Supply Frequency, Hz	Magnetic Circuit Construction	Values	Total Secondary Winding Power P_2, Wt					
			5-15	15-50	50-150	150-300	300-1000	1000-2500
50	Shell type	ΔU_1 %	20-13	13-6	6–-4,5	4.5-3	3-1	–
		ΔU_2 %	25-18	18-20	10-8	8-6	6-2	–
	Core type	ΔU_1 %	18-12	12-5,5	5,5-4	4-3	3-1	1-0,8
		ΔU_2 %	33-17	17-9	9-6	6-4	4-2	2-1,0

Using Table 2, find the recommended current density values in windings δ_1, δ_2 for the selected magnetic circuit configuration [1-3, 21-27, 43-47].

Determine cross-sections and diameters of winding conductors using the following relationships:

$$S_{con} = \frac{I}{\delta}, \text{ mm}^2 \quad (11)$$

$$d_{con} = \sqrt{\frac{4}{\pi} S_{con}} = 1{,}13\sqrt{S_{con}} \text{ mm}^2 \quad (12)$$

From Table 8, select standard cross-sections and conductor diameters and extract necessary reference data [1].

After selecting standard cross-sections and conductor diameters, find actual current densities in conductors:

$$\delta_1 = \frac{I_1}{S_{con1}} \text{ A/mm}^2; \qquad \delta_2 = \frac{I_2}{S_{con2}} \text{ A/mm}^2$$

The allowable axial length of each winding on the sleeve is determined using the following formula:

$$h_D = h_1 - 2h_{ins}, \quad (13)$$

where h_1 = h - 1 mm - length of the sleeve; h - window height; h_{ins} - end insulation length equal to 1.5÷3 mm.

From Fig.3, select axial laying coefficients k_{l1} depending on selected winding conductor diameters [48-55].

Determine the number of turns per layer and number of layers for each winding:

$$W_{layer} = \frac{h_D}{\kappa_{l1} d_{ins}}, \quad (14)$$

$$N = \frac{W}{W_l} \tag{15}$$

where k_{l1} - axial conductor laying coefficient determined from Fig.5 data; W - total number of winding turns.

TABLE 8. Nominal values and parameters of the copper conductor.

nominal copper wire diameter, mm	Calculated cross-section, mm²	Mass of 1m Wire,g	DC Resistance, Ω/m	Maximum Outer Diameter for Different Insulations, mm,										
				Pel	Pev-1	Pev-2	PEVTL1	PEVTL2	PETV	PELSHO	PELLO	PEPLO , PETLO	PEVLO	PNET-imid
0,90	0,6362	5,66	0,0270	0,99	0,96	0,99	0,96	0,99	0,99	1,05	1,05	1,09	1,07	0,96
0,93	0,6793	6,04	0,0253	0,99	0,99	1,02	0,99	1,02	1,02	1,08	1,08	1,12	1,10	0,99
0,96	0,7238	6,44	0,0238	1,02	1,02	1,05	1,02	1,05	1,05	1,11	1,11	1,15	1,13	1,02
1,00	0,7854	6,98	0,0219	1,07	1,08	1,11	1,08	1,11	1,11	1,16	1,16	1,20	1,19	1,06
1,56	1,9113	17,0	0,0091	1,64	1,64	1,67	1,64	1,67	1,67	1,74	-	-	-	-
2,44	4,676	41,6	0,0037	2,54	2,54	2,57	-	-	2,57	-	-	-	-	-
2,63	5,433	48,3	0.0032	-	-	2,76	-	-	-	-	-	-	-	-
2,83	6,290	55,9	0.0027	-	-	-	-	-	-	-	-	-	-	-
3,05	7,306	65	0,0024	-	-	-	-	-	-	-	-	-	-	-

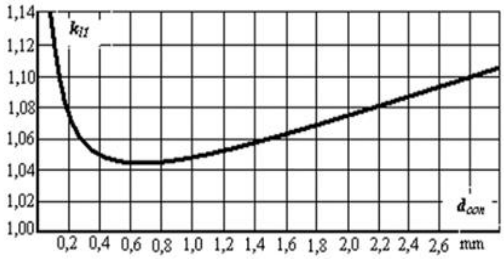

FIGURE 3. Dependence of the laying coefficient in the axial direction on the diameter of the wire

From Fig.4, determine k_b=b/a (applicable only when winding on the sleeve).
Select insulation distances h_{ins1}, $h_{ins.bw}$, $h_{ins.ax}$, and $h_{ins.out}$ using recommendations given in [1, 56-58].

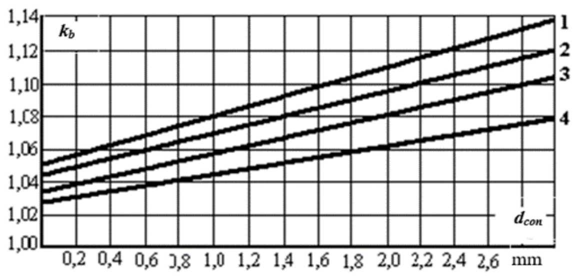

FIGURE 4. Dependence of the bulging coefficient in the radial direction on the diameter of the wire and the sleeve design

From Figs.5-6, determine radial laying coefficients (k_{l2}) and interlayer and interwinding insulation expansion coefficients (k_{il} and k_{iw}) depending on winding conductor diameters:

Find radial dimensions of each winding using the formula:

$$\alpha_i = k_{l2} \cdot N \cdot d_{ins} + k_{il} (N-1) h_{ins.mc}\text{, mm} \tag{16}$$

Assume outer insulation winding compaction coefficient values $k_{r.b} = 1.7 \div 2.0$.

Determine coil radial dimension using the following formula:

$$\alpha = \Delta_{gap} + (h_{ins.ax} + \alpha_1 + k_{iw} \cdot h'_{ins.bw} + \alpha_2 + k_{iw} \cdot h''_{ins.bw} + k_{ic} \cdot h_{ins.out})\, k_{rb} \tag{17}$$

where:

- $\Delta_{gap} = 0.5$ mm - gap between bobbin and core
- $h_{ins.ax}$ - bobbin thickness including additional insulation over frame
- α_1, α_2 - winding radial dimensions, mm
- $h'_{ins.bw}$, $h''_{ins.bw}$ - interwinding insulation thickness, mm
- $h_{ins.out}$ - outer insulation thickness
- k_{ic} - interwinding insulation compaction coefficient
- k_{rb} - radial bulging coefficient

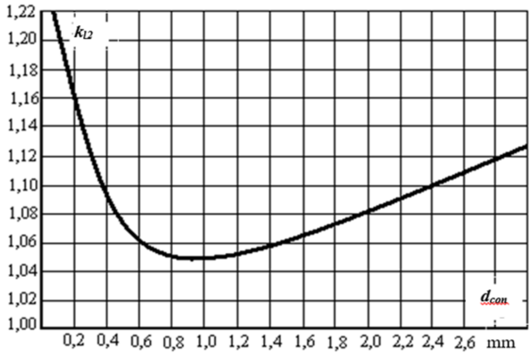

FIGURE 5. Dependence of the coefficient of laying in the radial direction on the diameter of the wire.

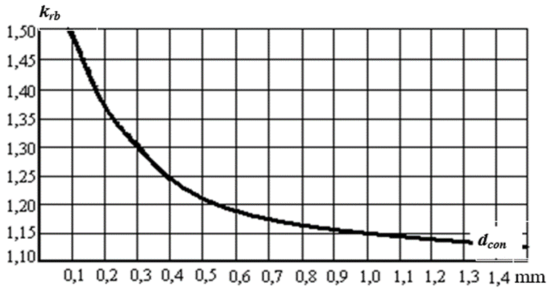

FIGURE 6. Dependence of the coefficient of leakage of the inter-winding insulation on the wire diameter

Determine the gap between coil and core (for armored transformers) or between two coils (for core-type transformers).

Determine total copper losses in windings using formulas and Table 9:

$$P_{cop} = P_{cop1} + P_{cop2} \tag{18}$$

$$P_{cop} \approx m \cdot \delta^2 \cdot G_{cop} \tag{19}$$

TABLE 9. The temperature and length of the conductor for calculating the copper loss of the windings.

$t_{conductor}$, °C	90	105	120	130	155	180	200
m	2,52	2,65	2,76	2,84	3,02	3,23	3,38

a) Find average turn length for each winding using the following formulas:

$$l_{av.T1} = \left[2\left(a_c + b_c\right) + 2\pi r_1\right] \times 10^{-3}\text{, m.} \quad (20)$$

where $a_c = a + 2\Delta_{gap} + 2h_{ins.out}k_{rb}$, and $r_1 = \frac{1}{2}a_1 k_{rb}$; $b_c = b + 2\Delta_{gap} + 2h_{ins.out}k_{rb}$;

$$l_{av.T2} = \left[2\left(a_c + b_c\right) + 2\pi r_2\right] \times 10^{-3}\text{, m.} \quad (21)$$

where $r_2 = (\alpha_1 + h'_{ins.bw}\kappa_{iw} + \frac{1}{2}\alpha_2)\kappa_{rb}$ mm.

b) Find copper mass for each winding:

$$G_c = l_{av.T}\omega g_c \cdot 10^{-3}\text{, kg,} \quad (22)$$

where $l_{av.T}$ - average turn length, m; W - total number of winding turns; g_{copper} - mass of 1m wire, g

THERMAL CALCULATION

Determine thermal resistances from Table 10 data [1, 58-62].

TABLE 10. Thermal resistances according to standard sizes of magnetic circuit's type

Magnetic circuit type	R_{frame}	R_{core}	$R_{core}°$	$R_{steel}°$
	°C/Wt			
EI core 25×40	1,7	1,0	4,0	3,1
EI core 32X40	1,1	0,8	2,5	2,1
EI core 32X50	0,9	0,7	2,5	1,8
EI core 32X64	0,8	0,7	2,5	1,5

Determine coil-to-core heat flow using the formula:

$$P'_c = \frac{\left(R_c + R_c^0 + R_s^0 + R_G\right)P_c - R_s^0 P_{ST}}{2\left(R_c + R_c^0 + R_s^0 + R_G\right)}\text{, Wt.} \quad (23)$$

Determine coil thermal resistance from maximum heated area to bobbin using the following formula:

$$x = \frac{-P'_c\left(R_c + R_c^0 + R_s^0 + R_G\right) - R_s^0 P_{ST} + P_c\left(P_c + R_c^0\right)}{P_c}\text{,°C/Wt,} \quad (24)$$

According to thermal calculation methodology [1], determine heat flow from core to coil P_c'' using the formula:

$$P''_c = \frac{P_c\left(R_c + R_c^0\right) - R_s^0 P_{ST}}{\left(R_c + R_c^0 + R_s^0 + R_G\right)}\text{, Wt.} \quad (25)$$

If P''_c value is positive, determine maximum coil temperature rise using the formula:

$$\Theta_{max} = (P_c - P''_c)\left(R_c + R_c^0\right)\text{,°C.} \quad (26)$$

Determine average temperature difference in coil using the formula:

$$\Theta_c = (P_c - P''_c)R_c\ \text{°C.} \quad (27)$$

Determine average volumetric coil temperature rise using the formula:

$$\Theta_{av} = \Theta_{max} - \Theta_1\ \text{°C,} \quad (28)$$

$$\Theta_1 = 0{,}5 \cdot \Theta_c = 0{,}25(P_c - P'_c)P_c;$$

where Θ_1 - temperature difference in primary winding, °C

Determine maximum and average conductor temperatures:

$t_{con.max} = 50 + \Theta_{max}$ °C; $t_{con.av} = 50 + \Theta_{av}$ °C;

If the maximum allowable temperature does not exceed the permissible temperature based on the calculation, the wire grades adopted in the calculation can be used in this transformer.

Determine active winding resistances using the formula:

$$r = \frac{\rho l_{av.T}\omega}{S_{con}}\text{, }\Omega \quad (29)$$

at $t_{conductor}$ = 105°C, $\rho_{copper} = 2.35\times10^{-2}\ \Omega\cdot mm^2/m$

DETERMINATION OF VOLTAGE-BOOSTING TRANSFORMER PARAMETERS

Determine total active resistances of transformer winding pairs referred to primary winding using the relationship [1-3, 21-27, 57-65]:

$$r_{tr} = r_1 + r_2' = r_1 + r_2\left(\frac{\omega_1}{\omega_2}\right)^2, \ \Omega \tag{30}$$

Determine leakage reactance's of transformer winding pairs using the formula:

$$x_{tr} = 4\pi \cdot 10^{-9} f\omega^2 l_{av.T} \ln\left(k_s \frac{g_{12}^2}{g_{11}g_{22}}\right), \Omega \tag{31}$$

where g_{11} and g_{22} - average geometric distances of winding cross-sections from their mirror images; g_{12} - average geometric distances between winding cross-sections; k_s - coefficient accounting for steel core influence on leakage inductance; $l_{avg.coil}$ - average coil turn length

$$g_{11} \approx 0.2235(h_{allowable1} + \alpha_1), \tag{32}$$

$$g_{22} \approx 0.2235(h_{allowable2} + \alpha_2), \tag{33}$$

$$g_{12} \approx 0.78d + 0.2235_{hallowable}, \tag{34}$$

where

$$d = h'_{ins.mo} + (\alpha_1 + \alpha_2)/2 \tag{35}$$

Determine coefficient k_s accounting for ferromagnetic core influence:

$$\kappa_s = \frac{[0{,}2235h_D + 0{,}78(2e+d)]^2}{[0{,}2235h_D + 1{,}56e][0{,}2235 + 1{,}56(e+d)]}, \tag{36}$$

$$l_{av.T} = 2\left[a_c + b_c + \pi\left(\alpha_1 + \frac{1}{2}h_{in.win}\right)\right] \times 10^{-3}, \text{ m} \tag{37}$$

Determine absolute and relative values of active and reactive voltage drop components in windings:

$$\Delta U_a = \frac{r_{tr} \cdot I_1}{U_1} \times 100, \% \tag{38}$$

$$\Delta U_r = \frac{x_{tr} \cdot I_1}{U_1} \times 100, \% \tag{39}$$

Transformer efficiency is determined using the formula:

$$\eta = \frac{P_2}{P_2 + P_{st} + P_c} \times 100\% \tag{40}$$

Total voltage drop in transformer can be approximately found through winding voltage drops:

$$\Delta U \approx U_a Cos\varphi_2 + U_r Sin\varphi_2 + \frac{(U_r Cos\varphi_2 - U_a Sin\varphi_2)^2}{200}, \% \tag{41}$$

Based on voltage-boosting transformer calculation results, prepare winding specification and testing data table.

CONCLUSION

Thus, based on analysis of existing literature materials, a calculation methodology for voltage-boosting transformer voltage stabilizers has been developed and proposed. Selection of optimal VBT voltage stabilizer parameters is performed considering the share of installed transformer power relative to output load power. Based on the developed methodology, a computer program for calculating voltage-boosting voltage stabilizers has been compiled. Test results of the manufactured voltage-boosting voltage stabilizer prototype showed that the proposed methodology is sufficiently accurate and acceptable for practical use.

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