**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, 0C.

**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:

*S2=U2·I2*, VA (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 ***S₂*** for the given magnetic circuit construction, find approximate values of **Bmax**, **δ**, **kwf**, **kst** [1-3, 14-20, 35-38].

* **Bmax** - [T] magnetic induction (Table 1);
* **δ** - [A/mm²] current density (Table 2);
* **kwf** - window fill factor (Table 3);
* **kst** - 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**):

 [sм4]; (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 Bmax, Tl, for S2, 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 S2, 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 kwin for S2, 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 | Kst 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 **Bmax**:

*Ps****t=****ρst Gst* [Wt], (3)

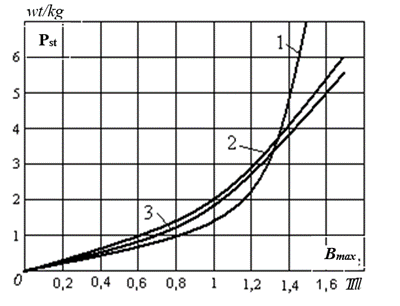
where **ρst** - specific losses (per 1 kg of steel), determined from the curve in Fig.1.

Find the active component of the no-load current using the formula for maximum supply voltage, considering ***Pst*=***Iоа**U1* [Wt]:

 [А], (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 | |
| ƒ=50 | ƒ=400 |
| а | h | c | C | H | B | Sst | *L****st*** | Sst Swa | Vst | Gst | ΣP2 | |
| 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 |

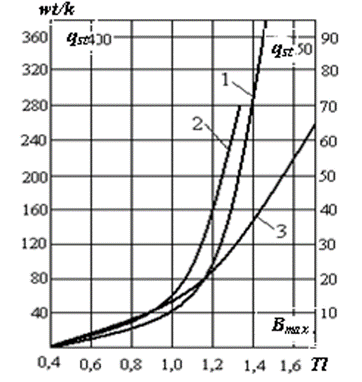


**FIGURE 1.** Specific magnetizing power Specific losses in cores made of transformer steels with a thickness of 0.35 mm at a frequency of 50 Hz. 1 - E42 steel armor cores: 2 - E310 steel core cores: 3 - E310 steel armor cores types of steel armor cores: 1 - E42, 0.35 mm thick, f-50 Hz; 2 - E44, 0.2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

Find the total magnetizing power using the following formula:

*Qst=qst Gst* [VА], (5)

where **qst** - total specific magnetizing power [VA/kg] from curves in Fig.2 [1, 28-34, 39-42].

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**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:

 [VAr] (6)

Find the no-load current value using the formula:

, [А] (7)

Nominal current of the primary winding:

 (8)

where *Р2*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 P2, Wt | | | | | |
| 2-15 | 15-50 | 50-150 | 150-300 | 300-1000 | 1000-2500 |
| 50 | η  соsϕ | 0,5-0,6  0,85-0,90 | 0,6-0,8  0,9; 0,93 | 0,8-0,9  0,93; 0,95 | 0,9-0,93  0,95-0,93 | 0,93-0,95  0,93-0,94 | -  - |

Find the number of turns in windings:

 (9)

 (10)

Here ***E1 = U1(1-ΔU1)****;* ***E2 = U2(1+ΔU2).***

where ΔU1 and ΔU2 - 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 P2, Wt | | | | | |
| 5-15 | 15-50 | 50-150 | 150-300 | 300-1000 | 1000-2500 |
| 50 | Shell type | ΔU1 % ΔU2 % | 20-13  25-18 | 13-6  18-20 | 6–-4,5  10-8 | 4.5-3  8-6 | 3-1  6-2 | –  – |
| Core type | ΔU1 %  ΔU2 % | 18-12  33-17 | 12-5,5  17-9 | 5,5-4  9-6 | 4-3  6-4 | 3-1  4-2 | 1-0,8  2-1,0 |

Using Table 2, find the recommended current density values in windings **δ1**, **δ2** for the selected magnetic circuit configuration [1-3, 21-27, 43-47].

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

, mm2 (11)

 mm2 (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:

 А/mm2;  А/mm2

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

*hD=h1−2hins* , (13)

where **h1 = h - 1** mm - length of the sleeve; **h** - window height; **hins** - end insulation length equal to 1.5÷3 mm.

From Fig.3, select axial laying coefficients **k*l*1** depending on selected winding conductor diameters [48-55].

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

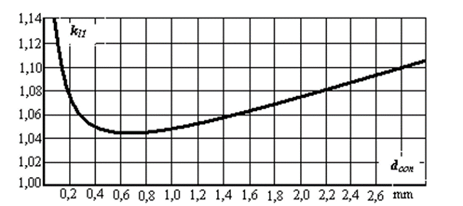
, (14)

 (15)

where **kl1** - 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.

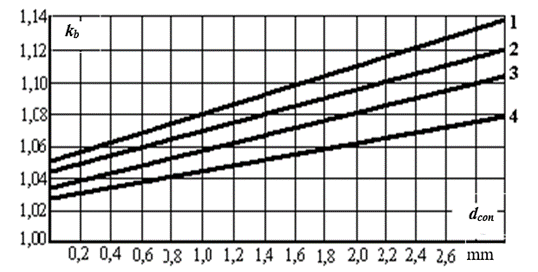
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| nominal copper wire  diameter, mm | Calculated cross-  section, mm² | Mass of 1m Wire,g | DC Resistance,  Ω/m | Maximum Outer Diameter for Different Insulations, 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 **kb=b/a** (applicable only when winding on the sleeve).

Select insulation distances **hins1, hins.bw, hins.ax,** and **hins.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 (**kl2**) and interlayer and interwinding insulation expansion coefficients (**kil** and **kiw**) depending on winding conductor diameters:

Find radial dimensions of each winding using the formula:

**αi = kl2 · N · dins + kil (N-1)hins.mc ,** mm (16)

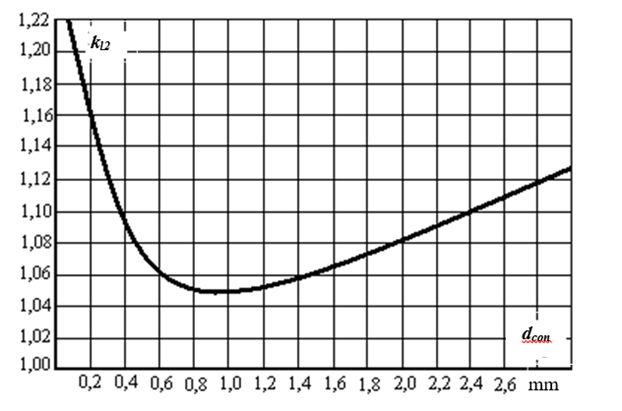
Assume outer insulation winding compaction coefficient values **kr.b**= 1.7÷2.0.

Determine coil radial dimension using the following formula:

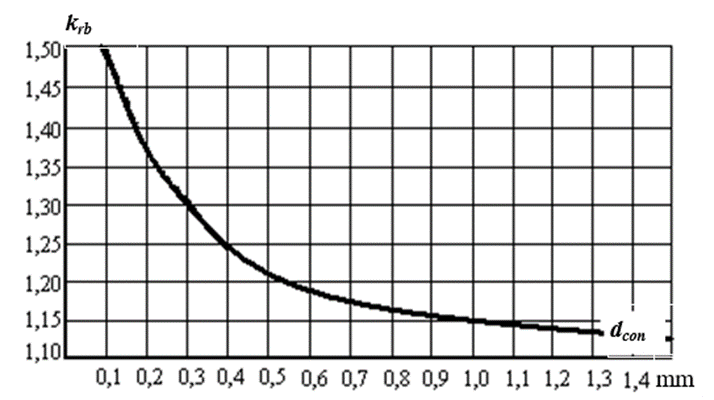
**α = Δgap + (hins.ax + α1 + kiw·h'ins.bw + α2 + kiw·h''ins.bw + kic·hins.out) krb** (17)

where:

* **Δgap** = 0.5 mm - gap between bobbin and core
* **hins.ax** - bobbin thickness including additional insulation over frame
* **α1, α2** - winding radial dimensions, mm
* **h'ins.bw, h''ins.bw**- interwinding insulation thickness, mm
* **hins.out**- outer insulation thickness
* **kic** - interwinding insulation compaction coefficient
* **krb** - 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:

**Pcop = Pcop1 + Pcop2** (18)

**Pcop ≈ m·δ²·Gcop** (19)

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

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| tconductor, °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:

, m. (20)

where , and ; ;

, m. (21)

where  mm.

b) Find copper mass for each winding:

, kg, (22)

where **lav.T** - average turn length, m; **W** - total number of winding turns; **gcopper** - 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 | Rframe | Rcore | Rcore° | Rsteel° |
| °С/Wt | | | |
| EI core 25×40  EI core 32Х40  EI core 32Х50  EI core 32Х64 | 1,7  1,1  0,9  0,8 | 1,0  0,8  0,7  0,7 | 4,0  2,5  2,5  2,5 | 3,1  2,1  1,8  1,5 |

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

, Wt. (23)

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

,°С/Wt, (24)

According to thermal calculation methodology [1], determine heat flow from core to coil *Pc”*using the formula:

, Wt. (25)

If **** value is positive, determine maximum coil temperature rise using the formula:

,°С. (26)

Determine average temperature difference in coil using the formula:

°С. (27)

Determine average volumetric coil temperature rise using the formula:

°С, (28)

;

where **Θ₁** - temperature difference in primary winding, °C

Determine maximum and average conductor temperatures:

*tcon.max=50+* °С; *tcon.av=50+******* °С;

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:

, Ω (29)

at **tconductor** = 105°C, **ρcopper** = 2.35×10⁻² Ω·mm²/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]:

, Ω (30)

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

, Ω (31)

where **g11** and **g22** - average geometric distances of winding cross-sections from their mirror images; **g12** - average geometric distances between winding cross-sections; **ks** - coefficient accounting for steel core influence on leakage inductance; **lavg.coil** - average coil turn length

**g11 ≈ 0.2235(hallowable1 + α₁),** (32)

**g22 ≈ 0.2235(hallowable2 + α₂)**, (33)

**g12 ≈ 0.78d + 0.2235hallowable**, (34)

where

**d = h'ins.mo + (α1 + α₂)/2** (35)

Determine coefficient **ks** accounting for ferromagnetic core influence:

, (36)

, m (37)

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

, % (38)

, % (39)

Transformer efficiency is determined using the formula:

% (40)

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

, % (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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