DISTRIBUTION TRANSFORMER MATHEMATICAL MODEL FOR POWER LOSSES MINIMIZATION

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Abstract: In this paper, the significance of minimizing power losses is presented, which is an essential part of each distribution transformer. It is given a description of the mathematical model of the distribution transformer which enables us to obtain information that gives a clear idea of the energy losses in the distribution transformer. A comparison was made with respect to the original transformer, from which energy efficiency improvement can be clearly seen. In this paper the optimized mathematical model for improved energy efficiency design of distribution transformer is presented. The fundamentals of the optimization and calculation are input values, diagrams and parameters obtained from project design catalogue and laboratory test protocol from the manufacturer. This new and unique mathematical model is developed using equation describing the relation between all transformer parameters. For the purpose of best optimization approach, the direct global iterative algorithm technique is used. Based on this method, expressed mathematical model for loss minimization and mathematical equations presented in this paper, the optimal solution is achieved. The new prototype distribution transformer is designed and manufactured. The laboratory test proved the enhanced energy efficiency.

Key words: Distribution transformer, losses minimization, efficiency.

1. INTRODUCTION

With global installed capacity of 45GVA in 2016 [1] transformers are major components in any power system. They are used to transmit and distribute electricity efficiently and reliably. Since their first inception in 1900 the global installed capacity is rising and the expectations are that this tendency will continue until 2050. Together with the rise in global transformer capacity, the annual demand to power them is growing. Energy consumption during their service life is huge, having in mind that transformers operate 24 hours/day, 365 days per year and

have very long lifetimes. Transformers are very efficient devices, with efficiency in the range of 95 to 99. However, transmission and distribution grid losses representing the biggest amount in electricity system. The Joule effect accounts for losses about 2.5% in transmission lines, while the losses in transformers range between 1 % and 2% [2].Saving of just 1 % on the electrical energy produced by a power plant of 1000 megawatts means transmitting 10MW more to consumers, which is far from negligible. At the same time, 10MWh electrical energy reduction is equivalent to 7 metric tons of CO_2 reduction [3].

Transformer design optimization is gaining interest in the last decades. Different optimization techniques are used for this purpose. In [4], for cost efficiency optimization of transformer design, the authors consider nonlinear programming approach for defining objective function and constraint function. The artificial Intelligence (AI) technique such as genetic algorithm and adaptive genetic algorithm is frequently applied for power transformer design [5-11]. In [12] the optimum design is based on minimum number of parameters, "Design Three - Methodology" for selecting input intervals of the variables. The effectiveness of the Bacterial Foraging Algorithm for optimum design of transformer is explained in [4] and is verified on two sample transformers. The aim of this paper is to develop a mathematical methodology for transformer efficiency enhancement. The proposed methodology and the mathematical model evaluated in this paper use enhanced number of variables. In the first part of the paper, the proposed methodology for transformer power losses minimization that uses direct Global Iterative Algorithms Global Search-GS (fmincon) [7] is explained. The second part of the paper deals with the verification of the proposed methodology done over a real transformer. The derived results are verified with measurements and calculations done over a transformer prototype constructed with the parameters derived with the proposed mathematical model. Using nine variables in this paper, more accurate [4,6] constraints and design parameters are obtained.

In this paper the optimized mathematical model for improved energy efficiency design of distribution transformer is presented. The power transformer Type 50-24 is from leading manufactures company Rade Koncar in Skopje with following rated values: $S_n=50$ *kVA*, $U_1/U_2=20$-*10/0,4 kV*, $I_1/I_2=1,444$-*2,888/72,16 A*, $u_{k\%}=4$ *%, f=50 Hz, Yz_n5*. The fundamentals of the optimization and calculation are input values, diagrams and parameters obtained from Project design catalogue and laboratory test protocol from the manufacturer. This unique mathematical model is developed using equation describing the relation between all transformer parameters. For the purpose of best optimization approach, the direct global iterative algorithm technique is used. Based on this method, expressed mathematical model for loss minimization and mathematical equations presented in this paper, the optimal solution is achieved. The new prototype distribution transformer is designed and manufactured. The laboratory test proved the enhanced energy efficiency.

2. METHODOLOGY

2.1. Direct global iterative algorithms Global Search – GS (fmincon)

For minimization of an arbitrary continuous nonlinear function at given constraints *fmincon* function in MATLAB environment is applied. This function is used to solve optimization problems, when minimizing the given target function. The procedure is defined as below:

min f (x)

while the following constraints should be satisfied:

$c(x) \leq 0$

$ceq(x) = 0$

$A \cdot x \leq b$

$Aeq \cdot x = beq$

$lb < x < ub$

In general, *fmincon* function calls as follows:

[x, fval, exitflag] = fmincon (fun,x0,A,b,Aeq,beq,lb,ub,nonlcon,options,p1,p2, ...)

where:

fun - a function that is minimized (the objective function), that receives a parameter vector **x**, while returns a scalar f which is equal to the value of the objective function calculated by the given values of the variables, previously set up in the respective vector **x**;

x0 –vector of the variables at starting point;

A, Aeq - matrices of the left side constraints;

B, beq - vectors of the right side of the constraints;

lb - vector of the lower bounds of the variables;

ub - vector of the upper bounds of the variables;

nonlcon - function that computes non-linear inequality (2) and equality (3) constraints. The function receives as an input parameter vector **x**, and returns two vectors **c** and **ceq**, for non-linear inequalities and non-linear equalities, respectively;

options - vector which defines the options that we want to run the function *fmincon* in determining the minimum of the function *fun*; they are defined using the command *optimset*;

p1, p2, ... - vectors or matrices that define parameters specific to the calculation of the function *fun*.

As a result, the function *fmincon* returns variables *x*, *fval*, *exitflag, that* have the following meaning:

x_i – are the optimal values of the variables;

fval – objective function value, calculated by the optimal values of variables;

exitflag – a variable that signals what is the outcome of the problem solution.

2.2. Mathematical model

2.2.1. Development of mathematical model for losses minimization

The mathematical model of the transformer is developed on the basis of equations associated with all the variables of the transformer. The total losses of the transformer are set as target function in the optimization process. The optimization objective is to find an optimal solution where the total losses will be minimized, while keeping the same rated data as in the initial transformer that is the object of optimization. The following prerequisites have been defined:

1. The active parts of the optimized transformer design are going to be made from the same material as the initial transformer. In this way it is avoided to reduce the total losses by using better quality materials, i.e. the materials with lower specific copper and iron losses.

2. The weight of the active parts, iron and copper, should not exceed the corresponding value of the initial transformer. With this prerequisite, the active parts mass of the optimized transformer should be preferably smaller, or at least equal to the initial transformer. This limitation avoids reduction of the losses, by increasing the masses, i.e. decreasing the electric current and magnetic flux density.

3. The cross-sections of the wire of high voltage (HV) and low voltage (LV) windings are subject to standardization.

4. The short-circuit voltage should remain in the prescribed limits by $\pm 10\%$ of the rated value.

5. Transformer tank should keep the same dimensions as those of the initial transformer.

2.2.2. Definition of the model variables

A particular contribution is the development of an original and accurate mathematical model of the transformer, by which the total losses are expressed through a number of selected variables. The optimization is accomplished by minimizing the objective function – the total transformer losses, by nine variables x_1–x_9 with prescribed bounds of their change. The selected variables represent the geometrical dimensions of the transformer and electric and magnetic quantities. Thus, the target function of optimization is presented in the following form:

$$P_\gamma = \text{Total loss} = f\,[x_1 \ x_2 \ x_3 \ x_4 \ x_5 \ x_6 \ x_7 \ x_8 \ x_9]$$

The selected variables of optimization, and their bounds are the following:

$x_1 = B_m$ (1,65 - 1,75) - maximum value of the limb magnetic flux density (T);

$x_2 = \lambda$ (2,0 - 2,5) - limb height and its diameter ratio (/);

$x_3 = q_1$ [2,54; 2,87; 3,27; 3,64]$\cdot 10^6$- current density of the high voltage winding (HVW) (A/m^2), consistent with standardized wire cross sections;

$x_4 = q_2$ [2,48; 2,49; 2,58; 2,63; 2,66; 2,68; 2,72; 2,8; 2,83; 2,86; 2,99; 3 01, 3.12, 3.19, 3.26, 3.3, 3.42, 3.44, 3.5]$\cdot 10^6$ - current density of the low voltage winding (LVW) (A/m^2), consistent with the standardized wire cross sections;

$x_5 = \gamma$ (0,14 - 0,22) – no-load losses and load losses ratio (/);

$x_6 = \upsilon_2$ (0,01 - 0,02) - distance between LVW and yoke (m);

$x_7 = k$ (0,004 - 0,006) - distance between limb and LVW (m);

$x_8 = \upsilon_1$ (0,02 - 0,03) - distance between HVW and yoke (m);

$x_9 = \xi$ (0,007 - 0,015) - distance between LVW and HVW (m);

The selected bounds for particular variables obey the following approximations:

1. For variable x_1 bounds are assumed to be close to the saturation point of the magnetization curve;

2. The chosen values for variable x_2 allow the new design to fit in the typical rated transformer tank;

3. Variables x_3 and x_4 are vectors with estimated values for the variables matching the bars cross section standards;

4. For variable x_5 the bounds are chosen in a way to comply with the Standard EN 50464-1, for open circuit and short circuit losses respectively;

5. For variables x_6 to x_9, the bounds are selected according to the technical rules for safety distances related to the selected voltage level.

2.2.3. Mathematical model: additional derived constraints included

The constants of the mathematical model are derived from the initial transformer declared rated data:

$k_1 = S_n = 50$ (kVA) – rated apparent power

$k_2 = U_{1n} = 20$ (kV) – rated voltage of HVW

$k_3 = U_{2n} = 0,4$ (kV) – rated voltage of LVW

$k_4 = f_n = 50$ (Hz) – rated frequency

$k_5 = m = 3$ (phases) – number of phases

k_6 (Yz$_n$5) – winding connection

According to the sub-functions defined in the mathematical model, scripts have been made in MATLAB. Using the scripts optimization of the the target- or transformer total losses function is obtained.

The following program codes are defined:

1.Specific core losses Γ_{Fe} (zelezo.m)

```
function z = zelezo(x)
z = 5.4477*x(1)^3-21.821*x(1)^2+30.693*x(1)-14.084;
```

2. Specific cooper losses Γ_{Cu} (bakar.m)

```
function z = bakar(x)
z = (0.605*(x(3)+x(4))^2)/1000000000000;
```

3. Current densityq_{sr} (gustina.m)
```
function z = gustina(x)
z = (x(3)+x(4))/2;
```

4. Limb height and limb diameter ratio C (odnos.m)
```
function z = odnos(x)
z = 0.0032*x(2)^2-0.0506*x(2)+0.4878;
```

5. Limb cross section$S$ (presek.m)
```
function z = presek(x)
z=32.83*odnos(x)*sqrt((bakar(x)*x(5))/(gustina(x)*x(1)*zelezo
(x)));
```

6. Diameter of the circle circumscribing the magnetic core$d$ (dijametar.m)
```
function z = dijametar(x)
z = 1.202*sqrt(presek(x));
```

7. Size of first magnetic core stepa_1 (stepenica.m)
```
function z = stepenica(x)
z = 1.13*sqrt(presek(x));
```

8. EMF in one turne_{nav} (navivka.m)
```
function z = navivka(x)
z = 215.34*x(1)*presek(x);
```

9. LVW number of turns per phaseW_2 (namotka2.m)
```
function z = namotka2(x)
z = 1.238/(x(1)*presek(x));
```

10. HVW number of turns per phaseW_1 (namotka1.m)
```
function z = namotka1(x)
z = 53.6/(x(1)*presek(x));
```

11. Limb heighth_s (stolb.m)
```
function z = stolb(x)
z = 1.202*x(2)*sqrt(presek(x));
```

12. Amper-turns density$A$ (amprenavivki.m)
```
function z = ampernavivki(x)
z = (60.03*namotka2(x))/(x(2)*sqrt(presek(x)));
```

13. Winding area cross sectionS_{np} (povrsinanavpro.m)
```
function z = povrsinanavpro(x)
z = 1650/(x(1)*presek(x)*(x(3)+x(4)));
```

14. Width of the winding areab_{np} (sirinanavpro.m)
```
function z = sirinanavpro(x)
z = 1372.7/(x(1)*presek(x)^1.5*(x(3)+x(4))*x(2));
```

15. Distance between two successive back to back limbs$g$ (sosednistolba.m)
```
function z = sosednistolba(x)
z=2745.4/(x(1)*presek(x)^1.5*(x(3)+x(4))*x(2))+0.072*sqrt(pre
sek(x));
```

16. Yoke length$f$ (jarem.m)
```
function z = jarem(x)
```

```
z=5490.8/(x(1)*presek(x)^1.5*(x(3)+x(4))*x(2))+3.534*sqrt(pre
sek(x));
```

17.Magnetic core mass m_{Fe} (masazelezo.m)
```
function z = masazelezo(x)
z = 7420.5*presek(x)*(2*jarem(x)+3*stolb(x));
```

18.Magnetic core power losses P_{Fe} (zagubizelezo.m)
```
function z = zagubizelezo(x)
z = zelezo(x)*masazelezo(x);
```

19. LVW heighth$_{n2}$ (visina2.m)
```
function z = visina2(x)
z = stolb(x)-2*x(6);
```

20. Total width of LVWa (sirina2.m)
```
function z = sirina2(x)
z = (131.2*namotka2(x))/(x(4)*visina2(x));
```

21. LVW one turn average length l_2 (dolzinanav2.m)
```
function z = dolzinanav2(x)
z = 3.14*(dijametar(x)+2*x(7)+sirina2(x));
```

22. LVW total lengthl$_{2VK}$ (vkupdolzina2.m)
```
function z = vkupdolzina2(x)
z = namotka2(x)*dolzinanav2(x)+1.05;
```

23. LVW mass m_{Cu2} (masabakar2.m)
```
function z = masabakar2(x)
z = (1926672*vkupdolzina2(x))/x(4);
```

24. LVW Ohm resistance per phase for temperature of 75°C r_2 (otpor2.m)
```
function z = otpor2(x)
z = (2.993*x(4)*vkupdolzina2(x))/10000000000;
```

25. LVW load losses for temperature of 75°C P_{Cu2} (zagubibakar2.m)
```
function z = zagubibakar2(x)
z = 15621.2*otpor2(x);
```

26.HVW heighth$_{n1}$ (visina1.m)
```
function z = visina1(x)
z = stolb(x)-2*x(8);
```

27. Total width of HVWb (sirina1.m)
```
function z = sirina1(x)
z = (4.304*namotka1(x))/(x(3)*visina1(x));
```

28. Distance between two successive phasese (megjurastojanie.m)
```
function z = megjurastojanie(x)
z = 2*(sirinanavpro(x)-(x(7)+sirina2(x)+x(9)+sirina1(x)));
```

29. HVW one turn average length l_1 (dolzinanav1.m)
```
function z = dolzinanav1(x)
z=3.14*(dijametar(x)+2*x(7)+2*sirina2(x)+2*x(9)+sirina1(x));
```

30. HVW total length l_{1VK} (vkupdolzina1.m)
```
function z = vkupdolzina1(x)
z = namotka1(x)*dolzinanav1(x);
```

31. HVW mass m_{Cu1} (masabakar1.m)
```
function z = masabakar1(x)
z = (40454.5*vkupdolzina1(x))/x(3);
```

32. HVW Ohm resistance per phase for temperature of 75°C r_1 (otpor1.m)
```
function z = otpor1(x)
z = (143.45*x(3)*vkupdolzina1(x))/10000000000;
```

33. HVW load losses for temperature of 75°C P_{Cu1} (zagubibakar1.m)
```
function z = zagubibakar1(x)
z = 6.247*otpor1(x);
```

34. Cooper total mass m_{Cu} (masabakar.m)
```
function z = masabakar(x)
z = masabakar1(x)+masabakar2(x);
```

35. Total load losses for temperature of 75°C P_{Cu} (zagubibakar.m)
```
function z = zagubibakar(x)
z = zagubibakar1(x)+zagubibakar2(x);
```

36. Phase winding width Π_ξ (srednasirina.m)
```
function z = srednasirina(x)
z = 3.14*(dijametar(x)+2*x(7)+2*sirina2(x)+x(9));
```

37. Short circuit reactance from the HVW side X_{k1} (reaktansa1.m)
```
function z = reaktansa1(x)
z=((790*srednasirina(x)*namotka1(x)^2)/(1000000*(visina1(x)+v
isina2(x))))*(x(9)+(sirina2(x)+sirina1(x))/3);
```

38. Active component of short circuit voltage $u_{ka\%}$ (naponkvaktiven.m)
```
function z = naponkvaktiven(x)
z = (2.12*zagubibakar(x))/1000;
```

39. Reactive component of short circuit voltage $u_{k\sigma\%}$ (naponkvreaktiven.m)
```
function z = naponkvreaktiven(x)
z = 0.0125*reaktansa1(x);
```

40. Short circuit voltage $u_{k\%}$ (naponkv.m)
```
function z = naponkv(x)
z = sqrt((naponkvaktiven(x))^2+(naponkvreaktiven(x))^2);
```

41. Active part of no-load current I_{0a1} (strujapoaktivna.m)
```
function z = strujapoaktivna(x)
z = zagubizelezo(x)/34641;
```

42. Magnetic field function H_m (magnetnopole.m)
```
function z = magnetnopole(x)
z = 46303*x(1)^3-226143*x(1)^2+368433*x(1)-200170;
```

43. Function of yoke length l_{jar} (dolzinajarem.m)
```
function z = dolzinajarem(x)
z = sosednistolba(x)+2*stepenica(x);
```

44. MMFF$_m$ (magnetennapon.m)
```
function z = magnetennapon(x)
z = m-nopole(x)*(stolb(x)+(2*dolzinajarem(x))/3)+159.24*x(1);
```

45.Reactive part of no-load current$I_{0\mu 1}$ (strujaporeaktivna.m)
```
function z = strujaporeaktivna(x)
z = magnetennapon(x)/(sqrt(2)*namotka1(x));
```

46. No load currentI_0 (strujapo.m)
```
function z = strujapo(x)
z = sqrt((strujapoaktivna(x))^2+(strujaporeaktivna(x))^2);
```

47.Sub-functions of nonlinear constraints (nelinearniogranicuvanja.m)
```
function [c, ceq] = nelinearniogranicuvanja(x)
c = [
     masazelezo(x)-140
     120-masazelezo(x)
     masabakar(x)-50.4
     40-masabakar(x)
     zagubibakar(x)-1121
     750-zagubibakar(x)
     zagubizelezo(x)-206
     140-zagubizelezo(x)
     naponkv(x)-4.4
     3.6-naponkv(x)
     megjurastojanie(x)-0.03
0.008-megjurastojanie(x)
     ];
ceq = [
     ];
```

48. Total power lossesP_γ (vkupnizagubi.m)
```
function z = vkupnizagubi(x)
z = zagubizelezo_1(x)+1.06*zagubibakar(x);
```

49. Function fmincon for total losses power optimization
```
X0 = [1.676 2.393 2870000 3420000 0.181  0.01 0.006 0.025
0.014];
LB = [1.65  2.2  2540000  2480000  0.14  0.01  0.004  0.02
0.007];
UB = [1.75  2.5  3640000  3500000  0.20  0.02  0.006  0.03
0.015];
%X0 = (LB+UB)/2;
opcii = optimset('Display','Iter');
[X,FVAL,EXITFLAG,OUTPUT] =
fmincon(@vkupnizagubi,X0,[],[],[],[],LB,UB,@nelinearniogranic
uvanja,opcii)
```

3. RESULTS AND DISCUSSION

3.1. Input data

Utilizing the command window of MATLAB, Global Search Algorithm (GSA) can be activated by calling the function "*fmincon* ". In the command window, all tools and settings of the algorithm are set up, while in the objective function window the target function is running.

There is inserted starting point of optimization in the respective window. It is adopted the initial values of variables to be the corresponding values of the original transformer; thus the starting point vector is:

$\mathbf{x_0}$ = [1.675 2.393 2870000 3420000 0.181 0.01 0.006 0.025 0.014]

In the dialog boxes *Bounds* are entered the lower x_{lb} and upper x_{ub} bounds for the 9 selected variables; they are accepted to be:

X_{lb} = [1.65   2.0   2540000   2480000   0.14   0.01   0.004   0.02   0.007]

X_{ub} = [1.75   2.5   3640000   3500000   0.22   0.02   0.006   0.03   0.015]

The window *Nonlinear constraint function* calls the function which used for definition of the non-linear constraints.

3.2. Results/prototype

In this part only solution of the optimization process and results with nonlinear constraints will be presented. After setting up all the necessary values, functions and variables, the program is activated. Two runs are performed (Fig.1): with and without inclusion of the non-linear constraints.
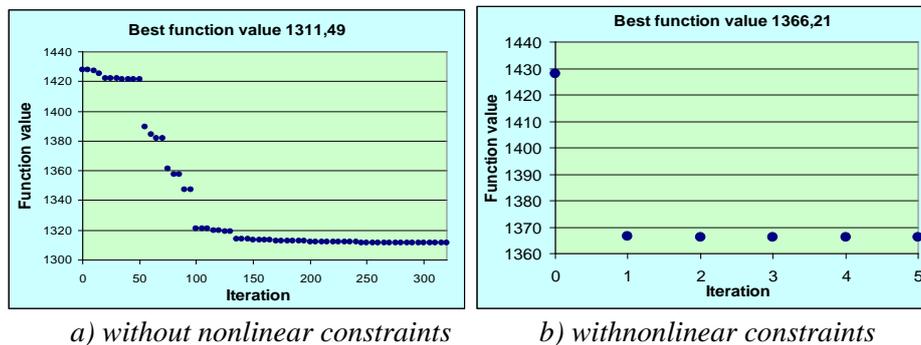

a) without nonlinear constraints   b) withnonlinear constraints
Fig.1. Iterative process - convergency

However, more accurate calculation is obtained by including non-linear constraints, because it is closer to the real physical phenomena in the transformer. From Fig. 1 the convergence of the iterative process and the best function value-equivalent to the minimum value of the transformer losses, (the maximum value of the efficiency) is obtained for $Z = P_\gamma = 1366$ (W).

It should be pointed out that when the optimization process is carried out at nonlinear constraints, it converges very quickly, the scope of the search is very narrowed and as seen in the figure in a few iterations the global minimum of the target function is found.

The output vector, containing the values of the optimal solution variables is as follows:

x_{opt}=[1,668　2,2　2870000　3340000　0.2　0.0126　0.004　0.03　0.008]

In the next step, by using the optimal values of the variables, defining the main geometrical dimensions of the new transformer design, is it proceeded with the preparations for manufacturing the new prototype of the transformer.

4. CONCLUSION

The new design of prototype power distribution transformer has reduced total losses of 65W or 4,55% less losses from the original one (Table 1). Energy efficiency coefficient is enhanced for 0,127%. Figure 2 shows the new prototype power transformer.

Table 1. Transformer losses and efficiency

Transformer	Original	Optimized	Prototype
$P\gamma(W)$	1429	1366	1364
η (%)	97,221	97,341	97,344

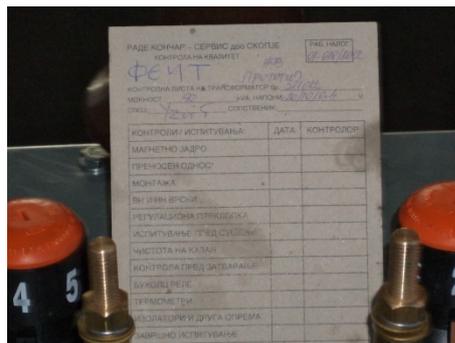*Fig.2. The design of new prototype transformer*

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