Application of Neural Networks for Analysis in Bolted Busbar Connections of New Design

Snejana T. Yordanova[1] and Raina T. Tzeneva[2]

Abstract -**The work reported describes how introducing slots (design S), slots, ending with small holes (design SH) and perforation groups of small holes (design G) in a proper way around the bolt holes in high power bolted busbar connections increases significantly the true contact area and therefore reduces contact resistance. Neural network analysis is applied for every of the three designs in order to find possible better solutions in the design.**

Keywords –**Bolted busbar high power connections, Bolt holes, Neural network analysis, New design shape.**

I. Introduction

Steadily increasing energy consumption in densely populated regions imposes severe operation conditions on transmission and distribution systems, which have to carry greater loads than in the past and operate at higher temperatures.

Power connections are generally the weak links in electrical transmission and distribution systems – both overhead and underground systems.

Mainly, there are two factors that affect the reliability of a power connection. The first is the design of the connection and the material from which it is fabricated. The second is the environment to which the connection is exposed.

The fundamental requirements for the design of reliable high-power connections used in bare overhead lines are given in [1]. The basic design criteria for power connectors are: maximization of electric contact true area, optimization of frictional forces with conductors (buses), minimization of creep and stress relaxation, minimization of fretting and galvanic corrosion, minimization of differential thermal expansion along and normal to interfaces. Summarizing the major connection design criteria, mentioned above it is worthwhile noting that all the criteria can be met simultaneously by working out an outline that achieves a sufficiently large contact load, a large area of metal-to-metal contact and sufficient elastic energy storage in the connection to maintain an acceptable connector's contact load throughout the service life of the connection.

The aim of the present investigation is to apply neural network analysis in bolted busbar connections of new design in order to find possible better solutions in the design.

[1]Snejana T. Yordanova is with the Department of Process Control, Faculty of Automation, Technical University of Sofia, 8 Kliment Ohridski, 1000 Sofia, Bulgaria, E-mail: sty@tu-sofia.bg

[2]Raina T. Tzeneva is with the Department of Electrical Apparatus, Faculty of Electrical Engineering, Technical University of Sofia, 8 Kliment Ohridski, 1000 Sofia, Bulgaria, E-mail: tzeneva@tu-sofia.bg

II. Theoretical Background

The new slotted hole shape arises from [2, 3]. Boychenko and Dzektser have shown that changing the connection design can equally be effective in increasing the contact area. In other words, cutting longitudinal slots in the busbar, the actual surface area of a joint can be increased by 1.5 to 1.7 times of that without slots. The contact resistance of joint configuration with slots is 30-40% lower than that of the classical case and is mechanically and electrically more stable when subjected to current cycling test [4], [5]. The beneficial effect of sectioning the busbar is attributed to a uniform contact pressure distribution under the bolt, which in turn, creates a larger contact area. This case is investigated in [6].

This idea is developed in [7], [8] and a new slotted hole shape for bolted high power connections – **design S** is proposed. Fig. 1 shows the hole shape of the 11 investigated cases. A significant rise in contact pressure and contact penetration is obtained.

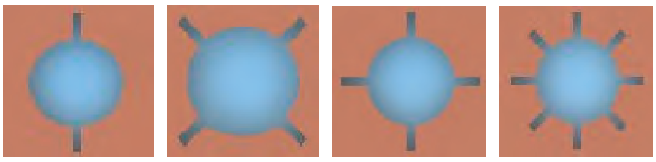

Fig. 1. Hole shape of design S with 2, 4 or 8 slots

The cases are as follows:

case1– classical case – copper busbars with 2 bolt holes;

case2– the slots are parallel to the busbar axis;

case3– the slots are perpendicular to the busbar axis;

case4– mixed case – one of the busbars belongs to case 2 and the other one to case 3;

For cases 2 to 4 all bolt holes have two slots of length 3mm and width 1mm.

In cases 5 to 8 the busbar holes have 4 slots, 3mm long with variable width, arranged in such a way that the pairs of slots are on mutually perpendicular axes, rotated at 45 degrees about the busbar axes. Widths are:

case 5 – 0.3mm; case 6 – 0.5mm;

case 7 – 0.7mm; case 8 – 1mm;

case 9 – the 4 slots are not rotated;

case 10 – mixed – the first busbar corresponds to case 8 and the second one to case 9;

case 11 – a busbar hole with 8 slots of length 3mm and width 1mm;

Considered next is **design SH**, investigated in details in [9] and illustrated in Fig. 2. The new shape is that of bolt hole slots ending with small circular gaps. There is ample of contact pressure and contact penetration data gathered.

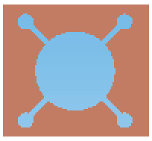

Fig. 2. Bolt hole slots, ending with small circular gaps

Table I describes the 11 investigated cases of different slot width and radius of the small circular holes.

TABLE I

Case No	1	2	3	4	5	6	7	8	9	10	11
Slot width, mm	0	0.3	0.3	0.3	0.3	0.5	0.5	0.5	0.7	0.7	1.0
Small hole radius, mm	0	0.3	0.5	0.7	1.0	0..5	0.7	1.0	0.7	1.0	1.0

Cutting thin slots in copper or aluminum poses certain difficulties that could be overcome effectively by changing the slots with groups of two or four small holes - **design G**.

There have been studied 13 different design G cases.

case 1– classical case – copper busbars with 2 bolt holes;

case 2– two horizontal groups of two holes of diameter Ø1mm and distance of 0.9mm between the holes, parallel to the busbar axis;

case 3– two vertical groups of two holes of diameter Ø1mm and distance of 0.9mm between the holes;

case 4– mixed case – one of the busbars in the connection is of case 2 and the other one is of case 3;

case 5 – eight groups of two holes of diameter Ø1mm and distance of 0.9mm between the holes, displaced at angle of 45 degrees;

case 6 – two horizontal groups of three holes of diameter Ø0.8mm and distance of 0.2mm between the holes, parallel to the busbar axis;

case 7 – two vertical groups of three holes of diameter Ø0.8mm and distance of 0.2mm between the holes;

case 8 –four groups (two horizontal and two vertical) of three holes of diameter Ø0.8mm and distance of 0.2mm between the holes;

case 9 – four groups of three holes Ø0.8mm and distance of 0.2mm between the holes, laying on two mutually perpendicular axes, rotated at an angle of 45 degrees in relation to the busbar axes;

case 10 – 2 horizontal groups of 3 holes of diameter Ø0.9mm and distance of 0.1mm between the holes ;

case 11 – two vertical groups of three holes of diameter Ø0.9mm and distance of 0.1mm between the holes;

case 12 - four groups (two horizontal and two vertical) of three holes of diameter Ø0.9mm and distance of 0.1mm between the holes;

case 13 - four groups of three holes Ø0.9mm and distance of 0.1mm between the holes, laying on two mutually perpendicular axes, rotated at an angle of 45 degrees in relation to the busbar axes;

Fig. 3 shows the hole shapes of the cases with two, four and eight groups of small holes.

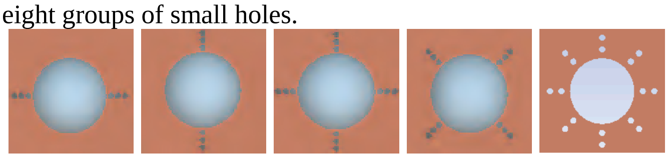

Fig. 3. Hole shape for design G with 2, 4 and 8 groups of small holes

All the cases are supposed to: decrease radial loadings on bolts that emerge after the connection is assembled; increase the contact penetration in the busbars near the bolts area; maximize the true area of metal to metal contact in an electrical interface.

Computer models for all the cases are realized, using software products ANSYS Workbench and ANSYS and they confirm significant rise of contact penetration and contact pressure in the interface between the buses [6], [7], [8] and [9].

III. APPLICATION OF NEURON NETWORKS FOR ANALYSIS

Artificial neural networks (ANN) have gained recently popularity in many engineering applications for their capability to model non-logical data, classify, store and present numerous sensors readings and experimental knowledge in terms of logical symbolic structures. ANNs perform function approximation/mapping as well, being tolerant of data imprecision and noise, which can be successfully applied for interpolation and prediction [10-12].

A two-layer neural network with non-linear differentiable and monotonic increasing activation functions in the hidden layer can be off-line trained to reproduce any deterministic non-linear input-output relationship using a vectors of representative input-target training couples and applying the backpropagation rule. The matrix block diagram of a network with Q batching input vectors **p** and with logistic sigmoid activation functions in both layers **F1** and **F2** is shown in Fig.4. The output **Ai** (i=1, 2) of each *l* log-sigmoid function **Fi** in the i-th layer is given by:

$$Ai = (1+e^{-Ni})^{-1}, \quad Ni = \sum_{k} Wi_{kl}.p_{\kappa} + bi_{l}, \qquad (1)$$

where **Ni** is the function input and the weight Wi_{kl} and the bias **bi** are the adjustable ANN parameters. The log-sigmoid function allows to map the input from the interval (-∞, +∞) into the interval (0.1). The number of the inputs **R** corresponds to the number of the geometrical parameters of the design problem (slots and holes), Q is the number of measurements available.

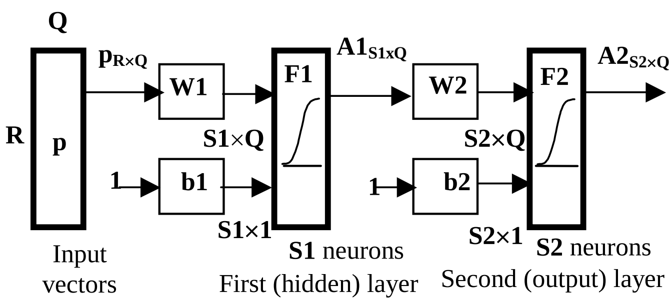

Fig.4. Backpropagation ANN

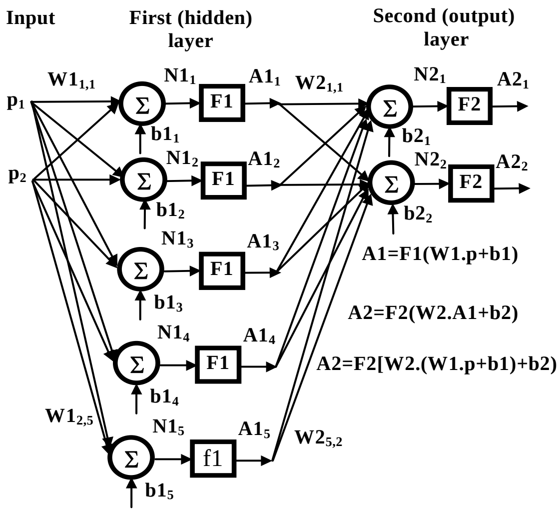

Fig.5. Backpropagation ANN model of **design SH**

While the number of the output layer neurons S2 depends on the number of problem outputs (here S2=2 - the maximal contact penetration M and the contact area CA), the number of the neurons in the hidden layer S1 can be freely selected in order the optimization problem to have a satisfactory with respect to time and accuracy solution.

The weight matrices **W1** and **W2** and the bias vectors **b1** and **b2** are being continually adjusted in the direction of the steepest descent with respect to minimization of the mean squared error (MSE) of the network. Derivatives of error called delta vectors δ are calculated for the network's output layer and then backpropagated through the network until delta vectors are available for each hidden layer.

The error E is the difference between the target T vector of measured/desired values and the ANN output A vectors (E=T-A) that corresponds to a given input vector from the batch of input vectors. The steepest descent method is used with adaptive learning rate in order to increase convergence of the gradient procedure in the surroundings of the minimum, to decrease the number of iterations, and to avoid local minima and instability at large rates. Initialization of the network is provided by a random number generator that produces values within the range (-1, 1). The new weights $W_{i,j}$ connecting neurons from layer *i* to layer *j* and the biases b_i at the k+1 iteration are calculated according to the backpropagation rule:

$$W_{ij}(k+1) = W_{ij}(k) + \Delta W_{ij}(k) = W_{ij}(k) + \alpha.\delta_i p_j \quad (2)$$

$$b_i(k+1) = b_i(k) + \Delta b_i(k) = b_i(k) + \alpha.\delta_i \, , \quad (3)$$

where δ_i is the delta vector for the current *i* layer, $\mathbf{p}_i$ is the corresponding input vector, α is the learning rate.

The calculations move from the output to the input layer of the network. When a desired accuracy is reached in the target points, the network is tested with more input vectors than the ones used in training to see if it has learned to generalize the function it is learning. If the approximated function is smooth and monotonic in-between the target points, the training is considered to have ended successfully. Else, it should be started from different initial conditions, or else the number of the neurons in the hidden layer or the number of hidden layers should be increased. Often more inputs and corresponding targets are added to the training vectors. Specialized software assists the design and training of the ANN.

The ANN used for modelling in the different design tasks is a two-layer log-sigmoid backpropagation ANN with five hidden neurons (S1=5) and two output neurons (S2=2).The required accuracy in training is 1^{-10} and the training algorithm with adaptive learning rate is the Levenberg-Marquardt optimisation (a modification for speeding up the steepest descent method); default criterion (stop condition) is MSE.

The ANN model of **design SH** is depicted in Fig.5. Here R=2 (radius r and slot's width w), Q=11. The final results after training are shown in Fig.6 for M and for CA correspondingly.

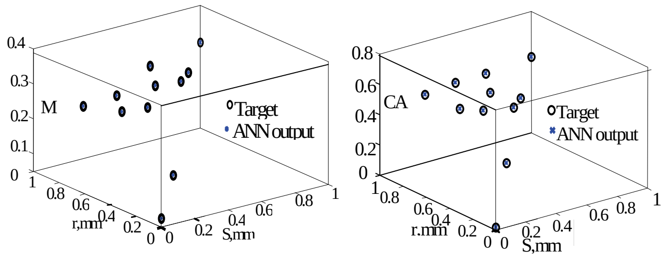

Fig.6. Accuracy of ANN model of **design SH**

The maximum of both M and CA with respect to S as function of r is depicted in Fig.7.

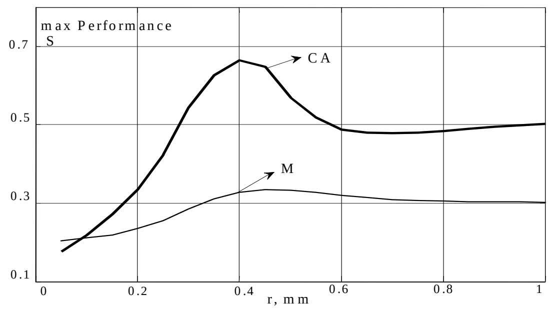

Fig.7. Influence of r on maximum of M and CA with respect to S

The ANN model of the **design S** is obtained for R=3 (number of slots N, angle of rotation α and slot's width w), Q=8. It allows studying the relationship of maximal M and maximal CA with respect to N as functions of w and α– Fig.8.

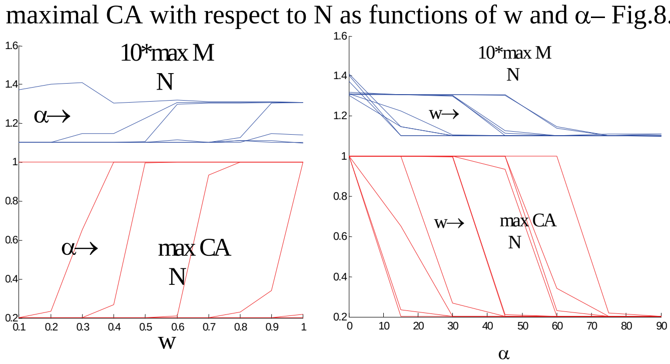

Fig.8. Relationship between maximum of M and CA with respect to N and geometrical parameters w and α

The ANN model of the **design G** is obtained for R=5 (number of hole groups n=0÷8, number of holes in a group N=0÷3, diameter of holes d=0.1÷1mm, distance between holes *a*=0.1÷1mm and angle of rotation α=0÷90^0), Q=13. The relationship of M and CA as function of the combination number, that determines a specific set of parameters [n, N, d, a, α], is shown in Fig.9, from which the maximal values for M and CA are determined respectively - M_{max}=0.9469 for n=3, N= 2, d= 0.8mm, *a*= 0.9mm, $\alpha=90^0$ and CA_{max}= 0.9931 for n=3, N= 3, d= 0.4mm, *a*= 0.9mm, $\alpha=75^0$.

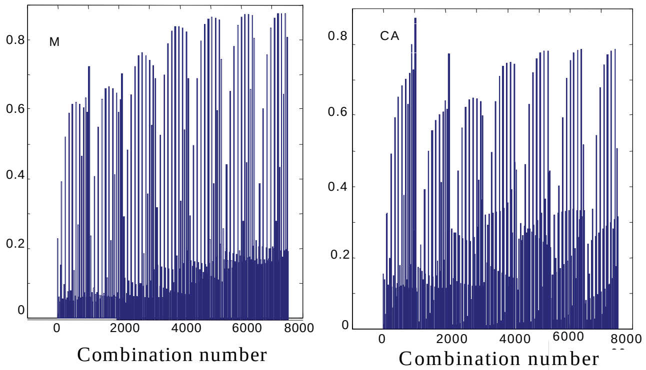

Fig.9. Relationship between M and CA and combination number (determined set of input parameters)

The parameters of the three ANN models for the three different design tasks - weight matrices W1 and W2 and biases b1 and b2 for each of the two neuron layers are given in Table II.

IV. Discussion and Conclusions

1. Based on the results from the application of neuron network analysis in bolted busbar connections of new design for **design SH** (slots, ending with small holes) the case with radius of ending holes r=0.4 mm have to be modelled.
2. The recommended cases for **design S** (sloted bolt holes) are already investigated.
3. The ANN model for **design G** (groups of small holes) establishes 2 cases for max. values of M and CA – (n=3, N=2, d=0.8mm, a=0.9mm, α=90 degrees) and (n=3, N=3, d=0.4mm, a=0.9mm, α=75degrees) for additional investigation.

TABLE II

Type of design model	W1	b1	W2	b2
SH	$\begin{bmatrix} -7.16 & -13.51 \\ -12.68 & -2.89 \\ -10.80 & -41.16 \\ -13.80 & 8.50 \\ -8.46 & 2.04 \end{bmatrix}$	$\begin{bmatrix} 12.91 \\ 7.90 \\ 18.14 \\ 0.09 \\ 1.17 \end{bmatrix}$	$\begin{bmatrix} 0.04 & 0.37 & -1.44 & -0.53 & -0.42 \\ -1.98 & 4.77 & -1.77 & 0.89 & -7.04 \end{bmatrix}$	$\begin{bmatrix} -0.86 \\ 0.04 \end{bmatrix}$
S	$\begin{bmatrix} 5.86 & -0.82 & 0.005 \\ 3.98 & -5.32 & -0.37 \\ -5.84 & 47.86 & -0.14 \\ -0.94 & -6.18 & -0.38 \\ 2.54 & -47.80 & 0.44 \end{bmatrix}$	$\begin{bmatrix} -9.51 \\ 3.36 \\ 2.41 \\ 3.23 \\ -0.75 \end{bmatrix}$	$\begin{bmatrix} 1.18 & 0.25 & 0.26 & 0.61 & 0.07 \\ 5.96 & 0.16 & -12.46 & 6.89 & -12.25 \end{bmatrix}$	$\begin{bmatrix} -3.59 \\ 4.74 \end{bmatrix}$
G	$\begin{bmatrix} 0.31 & -1.36 & -4.37 & 8.92 & 0.09 \\ 3.9 & -3.01 & -8.48 & 7.74 & -0.02 \\ 2.4 & 2.32 & 2.93 & 0.88 & -0.06 \\ -0.40 & 0.47 & 2.11 & -0.45 & 0.002 \\ 0.43 & 0.78 & -6.63 & -1.28 & 0.11 \end{bmatrix}$	$\begin{bmatrix} 7.23 \\ -0.55 \\ -5.87 \\ 0.96 \\ -3.20 \end{bmatrix}$	$\begin{bmatrix} -3.27 & 4.83 & -0.004 & 6.35 & 1.39 \\ -4.24 & 5.39 & 3.48 & 2.26 & 1.95 \end{bmatrix}$	$\begin{bmatrix} -5.63 \\ -3.48 \end{bmatrix}$

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