APPLICATION OF GENETIC ALGORITHMS IN WIRE BUSBARS DESIGN WITH 3D TRUSS PORTALS

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Abstract:

This work shows how to achieve a substation wire busbar design by means of genetic algorithms (GA). Major parameters of busbars are mapped into a chromosome like a string. This includes insulators and wire types, geometry, thrust requirements and operating parameters. GA operators are performed on a population of such strings and subsequently a natural selection is expected to occur. The design performance is obtained by using the busbar price as the fitness function. The steel structure is modelled as 3D truss. GA performance is presented in one example.

1 Introduction

The outdoor switchgear is used for the transfer of the electrical power between incoming and outgoing feeder bays and transformer bays. There are two main types of design: tube and wire busbars. This paper deals with wire busbars, which are presented in Fig. 1.

The main parts of wire busbars are: wire conductor, insulator strings, portals and foundations. Aluminium conductors, steel reinforced (ACSR) and aluminium alloy conductors (AAC) are usually used as flexible conductors. The conductor cross-section ranges from 200 to 1600 mm^2. The span length is usually from 10 to 60 m. The full span length between supports must be distinguished from the conductor span length between end points of insulator strings. Bundled conductors (for high nominal currents) are composed of two to four conductors placed within the distance between subconductors, ranging from 0.08 to 0.6 m. This distance is maintained by spacers placed at intervals along the bundle and the distance between spacers ranges from 2 to 30 m.

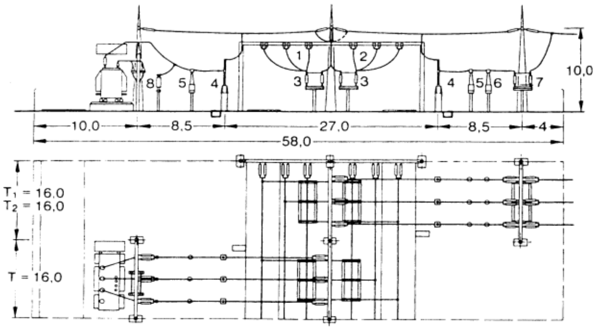

Figure 1. Typical wire busbars.

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The strained conductors are usually designed with an initial static stress of a relatively low value (compared to overhead lines) in the order of 10-20 N/mm^2. This is only a small percentage (less than 10%) of the nominal rupture conductor strength. The total sag (the sum of the conductor sag and the insulator string sag) under this tension amounts to about 3% of the span length. For the maximum permissible conductors temperature (for example 80°C), the sag is about 30% greater than the initial sag [1].

Strained flexible conductors are connected to the steel supporting structures (usually portals) with insulator strings or chains. These conductors consist of cap and pin porcelain or glass insulators or long rod porcelain insulators. Insulator chains may occur in single or double parallel arrangements.

Steel supporting structures are typically portals, usually made of latticed or solid welded steel and erected on concrete foundations. This paper considers truss type latticed steel structures. Their design is typically carried out by civil engineers. The mechanical behaviour of such structures is characterized by their spring constant and their mechanical frequency.

Clearly, short-circuited wire conductors start to swing in and out. The choice of wire busbar system parameters is complex, because not only wires and insulators must be taken into account but also steel portals with their foundations. Undoubtedly, increased static stress suggests higher investment cost of the steel structure and foundations.

An increase in static stress caused by wire conductors increases the cost of steel structures and foundations. Intermediate conductor spacing will also cause changes in cost of steel structures and foundations.

Because of the complex interrelationships between the bus parameters, a method based on the application of GAs is used. It is worth pointing out that the paper presents an original GA approach and presents results derived from several test cases.

The goal of this investigation is not only to design the cheapest wire busbars ever including costs of wire conductors, insulators, portals and foundations, but to satisfy all electrical, mechanical and civil requirements and conditions on the construction site as well.

To the author's knowledge, there are no papers dealing with the optimization of wire busbars. The paper belongs to a continuation research project of already published papers by the same author [2, 3] and follows the concept of presenting portals and L type truss elements instead of frame portal with I type beam elements. The bases for the development of the described GA method are papers [4, 5, 6] and works in the field of optimization of steel structures [7, 8]. The algorithm is developed in Matlab, using Direct Search Toolbox [9].

Certainly, the problem with aging of components can also be solved by using GAs [10], but of course this is not the subject of this paper.

2 Optimal wire busbars design

Optimal wire busbars depend upon nominal and short-circuit current effects [1, 11, 12]. The short-circuit current passing through conductor makes the conductor swing with lower phase clearances and higher tension forces. This problem is solved by employing three main strategies: the greatest tension force possible; a maximum conductor unit mass; or the greatest possible phase distance. The first and the third solution present rather more expensive steel supporting structures with their foundations than the second one.

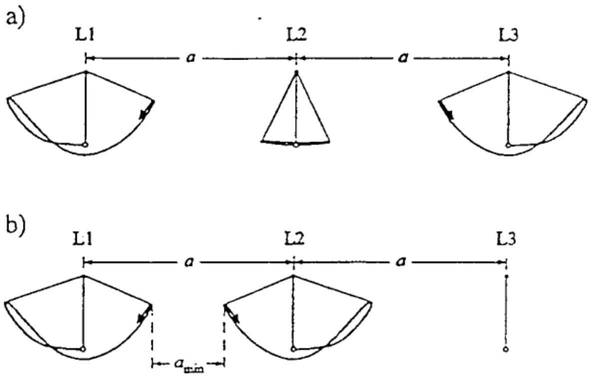

Figure 2. Conductor movement due to short-circuit current, a) three phase short-circuit, b) two phase short-circuit.

The optimization goal is to give a solution with all criteria satisfied and with the lowest overall price possible. A typical optimization problem involves searching for the minimum of the stated objective function subjects to various constraints restricted by practical minimum sizes, or dimensions of components. If design variables may be continuously varied between practical extremes, the problem is termed continuous, while if the design variables represent a selection from a set of parts, the problem is considered to be discrete.

The wire busbar design is mixed continuous-discrete problem with the following constraints:

1) load current in continuous operation,
2) load current in short circuit,
3) reduction of the corona effects,
4) limit of stresses in the conductors,
5) limit of the forces on the insulator strings,
6) limited deflection of steel structure nodes,
7) limited buckling of compressed steel L elements,
8) limited stress of tensioned steel L elements,
9) limited pressure on the foundation soil,
10) limit overturning of the steel structure,
11) restrictions on conductor deflection.

The goal is to optimize the cost of all components of the wire busbar system that meet all technical requirements (electrical, mechanical and civil).

$$C = C_1 + C_2 + C_3 + C_4 + C_5 \tag{1}$$

Wire busbar system price consists of the following prices:

C_1 conductors cost,
C_2 insulator strings cost,
C_3 spacers cost,
C_4 portal (steel construction) cost (according to portal mass),
C_5 concrete foundations cost (according to foundation volume).

Input data for the optimization process is made up of component database; data related to the specific case and set parameters of the optimization process.

The typical components database consists of the following:

1) wire conductor data,
2) string insulator data,
3) spacers data,
4) L-beam data,
5) foundation data.

The specific case values are the following:

1) continuous current,
2) ambient temperature (minimum, maximum and temperature with the occurrence of ice),
3) other parameters to determine the allowable continuous load,
4) short-circuit current,
5) short-circuit duration,
6) additional load,
7) minimum and maximum phase distance,
8) minimum and maximum conductor stress,
9) span length,
10) allowable conductor minimum distance during a short-circuit.

The results of the optimization process are discrete (integer) and continuous (real) values.

Discrete values are the following:

1) conductor type,
2) number of conductors,
3) insulator string type,
4) spacers type,
5) number of spacers,
6) conductor distance (depending on the type of spacers),
7) L-beam type,
8) foundation type.

Continuous values are the following:

1) maximum static conductor horizontal stress,
2) phase distances.

The described optimization problem is a mixed "discrete-continuous" model with some variables presenting values from countable group of values and other variables having real values.

Optimization methods are based on the search space and try to facilitate the search process or to speed it up (reduced) during the search.

There are three main categories of optimal search methods:

1) exhaustive search,
2) calculation based, and
3) stochastic.

Exhaustive search methods include searching of all possible solutions within the searched space. Disadvantages of this method are both the lack of efficiency and the use of the results of preceding tests. The advantage of this method is the ease of use.

Calculation based methods are divided into two main classes: direct and indirect. Both methods are treated first as a continuous search space of a multi-dimensional function and second as a search for finding a maximum or a minimum (value) of a function using its derivatives. In the indirect method, the idea is to seek a local optimum by solving a group of equations in order to findi the point where the derivative equals zero. The function should be smooth and a number of points when the derivative equals zero are small. In the direct search, a common technique is a Newton's search method for reaching a local optimum of the function and also for moving in the direction of the local gradient. These methods are known as hill climbing methods. They start from the current point estimates, and then they tend to increase the function in the steepest direction to the next point. These methods are not very applicable if the search space is filled with noise or nonlinearities.

Heuristic and direst methods use information from previous tests to determine the probable choice of the following points. GAsare based on the Darwinian theory of evolution where the fittest unit survives. In evolutionary strategies, the typical search space consists of vectors with real values. Adding random noise to these vector points creates a new item. Searching continues from the new points if they are better than old ones, and if the old items are then not kept. Finally, in the GAs, the search space is characterized by bit vector codes. The new vectors, which can potentially lead to the solution, are created from parent units. This is analogous to the manner in which the DNA chromosomes are passed on from parents to the new generation.

Due to a mixed type of variables (integer and real) for ingwire busbar optimization, the method of GAs is selected.

3 Genetic algorithms

Genetic Algorithm and Direct Search Toolbox for the use with Matlab [8] aims to make the GAs accessible to the design engineer within the framework of a calculation/simulation package. This allows for the retention of existing modelling, simulation tools to build objective functions, and the user to make direct comparisons between genetic methods and traditional procedures.

- GAs search a population of points in parallel but not a single point;
- GAs do not require derivative information or other auxiliary knowledge; only the objective function and corresponding fitness levels influence the directions of searching;
- GAs use probabilistic transition rules but not deterministic ones;
- GAs work on encoding of the parameter set rather than the parameter set itself (except in the case where real-valued individuals are used).

The basic concept of a GA is based on the following:

- Population - current set of solutions coded in a manner suitable for the treatment of a GA;
- Chromosome - an individual in a population that represents a coded solution;
- Gene – as part of a chromosome represents a certain property that is part of the solution;
- Generation - one step in an iterative process of measuring fitness solutions and creating a new population by applying reproduction operators;
- Selection - the mapping of chromosomes to the next step in the development of population;
- Recombination - crossover of two chromosomes, i.e., their genetic content;
- Mutations - random changes to the process values of genes in the chromosome.

The procedure method of GAs:

1) Generation of an initial population
2) Calculating the initial population fitness
3) The selection of the most appropriate individuals
4) Creating a new population by genetic crossover procedures
5) Creating a new population by genetic mutation process
6) Calculate the current population fitness
7) The selection of the most appropriate individuals
8) Checking the condition of convergence (maximum number of generations reached, stall fitness, operating time maximum reached, ...) YES – jump to 9 or NO - jump to 4
9) Print Solutions
10) Completion of proceedings

The description of the wire busbar system is defined by the values of design variables. The allowable range for each of design variables are given in Table 1. Table 2 shows a tableau for the wire busbar design.

The constraint violations were taken into consideration by penalizing the fitness value (100 000.00 €).

4 Test example

4.1 Basic Information

To illustrate the application of GAs for optimization of the wire busbar system, the busbar system with the following data has been calculated:

Table 1. Range of design variables

Design variable	Admissible values	Type
Conductor type	database index	integer
Conductor number	1 - 2	integer
Insulator string type	database index	integer
Spacer type	database index	integer
Spacer number	0 - 10	integer
Conductor stress	5 - 20 N/mm^2	real
Phase distance	2.5 - 6 m	real
L-beam – chord	database index	integer
L-beam - lacing	database index	integer
Foundation	database index	integer

Table 2. Description of an optimization procedure

Objective	Find the globally optimum combination of ten wire busbars parameters
Representation scheme	Structure: fixed length Alphabet size: real values String length: 10
Fitness cases	Only one
Fitness	Wire busbar price (1), with penalty for constraint violations. Less is better.
Parameters	Population size: 200 Maximum number of generations: 60
Termination criteria	The GA has run maximum number of generations or stall generation equals to 10
Result designation	The best so far individual in the population.

- Span length (m): 30
- Portal height (m): 8
- Continuous current (A): 1400
- Short-circuit current (A): 16000
- Short-circuit duration (s): 0.3
- Factor kappa: 1.70
- Conductor static stress (N/mm^2): 5 to 20
- Phase conductor centreline spacing (m): 2.5 to 6
- Steel Fe360 elasticity module (N/mm^2): 210 000
- Steel Fe360 permissible tensile stress (N/mm^2): 235
- Steel structure safety factor: 1.2
- Concrete density (kg/m^3): 2400
- Soil density (kg/m^3): 1800
- Allowable soil bearing pressure (N/m^2): 150.000
- Steel price (€/kg): 2.00
- Concrete price (€/m3): 70.00
- Minimum conductor temperature (°C): -20
- Maximum conductor temperature (°C): 60

The parameters of the database of the wire busbar components:

- Number of conductors: 3
- Number of insulator strings: 2
- Number of spacers: 2
- Number of steel L type bars: 7
- Number of foundations: 6

Parameters of GA:

- Population Size: 200
- Generations: 60
- Stall Generation Limit: 10
- Crossover Fraction: 0.8000
- Migration Direction: 'forward'
- Migration Interval: 20
- Migration Fraction: 0.2000
- Elite Count: 5

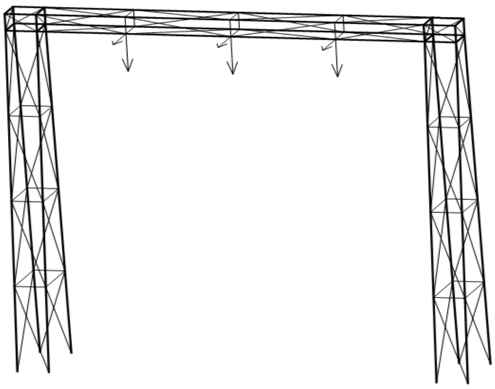

Figure 3. Lattice steel portal with chord (bold) and lacing L type elements.

The main geometric portal data:

- portal leg width (m): 0.60
- portal leg bottom length (m): 1.60
- portal leg height (m): 8.00
- portal leg top length (m): 0.6
- portal horizontal beam height (m): 0.50

The distance between the portal leg axis and the phase wire connection point equals to the distance between phases and it is optimization variable.

The total number of nodes equals to 60 and total number of elements equals to 166. Eight nodes are fixed on the foundation. On the left there are two connection nodes presenting wires connected with tension short-circuit force (the static force with the maximum value of the short-circuit force). On the third connection there is a node i.e., a wire connected with only a static tension force. On all three nodes there are the acting weighting force of insulator strings, wires and spacers.

For foundation is chosen spread footing type, as on Fig. 4.

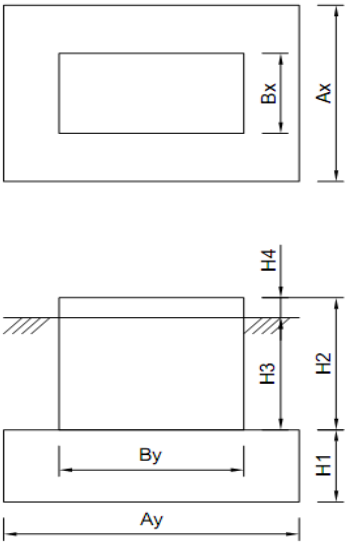

Figure 4. Concrete spread footing.

Table 3. Foundation data

Variant	1	2	3	4	5	6
Bx (m)	1,00	1.00	1.00	1.00	1.00	1.00
By (m)	2.00	2.00	2.00	2.00	2.00	2.00
Ax (m)	1.80	2.00	2.20	2.40	2.60	2.80
Ay (m)	2.80	3.00	3.20	3.40	3.60	3.80
H1 (m)	0.90	0.90	0.90	0.90	0.90	0.90
H2 (m)	1.45	1.55	1.65	1.75	1.85	1.95
H3 (m)	1.20	1.30	1.40	1.50	1.60	1.70
H4 (m)	0.25	0.25	0.25	0.25	0.25	0.25

Table 4. Wire conductor data

Variant	1	2	3
Type	AAC400	AAC625	AAC800
Area (mm^2)	400.14	626.2	802.09
Diameter (mm^2)	26	32.6	36.9
Nominal current (A)	855	1140	1340
Price (€/m)	4.00	6.00	8.00

Table 5. Insulator string data

Variant	1	2
Type	1Z1	1Z2-330
Length (m)	1.27	1.385
Mass (kg)	45.55	51.66
Conductors	1	2
Distance (mm)	-	330
Price (€)	380.00	520.00

Table 6. Spacer data

Variant	1	2
Type	A6.30.00.330	A6.35.00.330
Distance (mm)	330	330
Diameter (mm)	20-31	30-35
Price (€)	110.00	125.00

Table 7. Equal leg steel L type elements

Variant	1	2	3	4	5	6	7
a (mm)	60	70	80	90	100	110	120
s (mm)	8	9	10	11	12	12	13
m (kg/m)	7.09	9.34	11.9	14.7	17.8	19.7	23.3
J (cm^4)	29.1	52.6	87.5	138	207	280	394

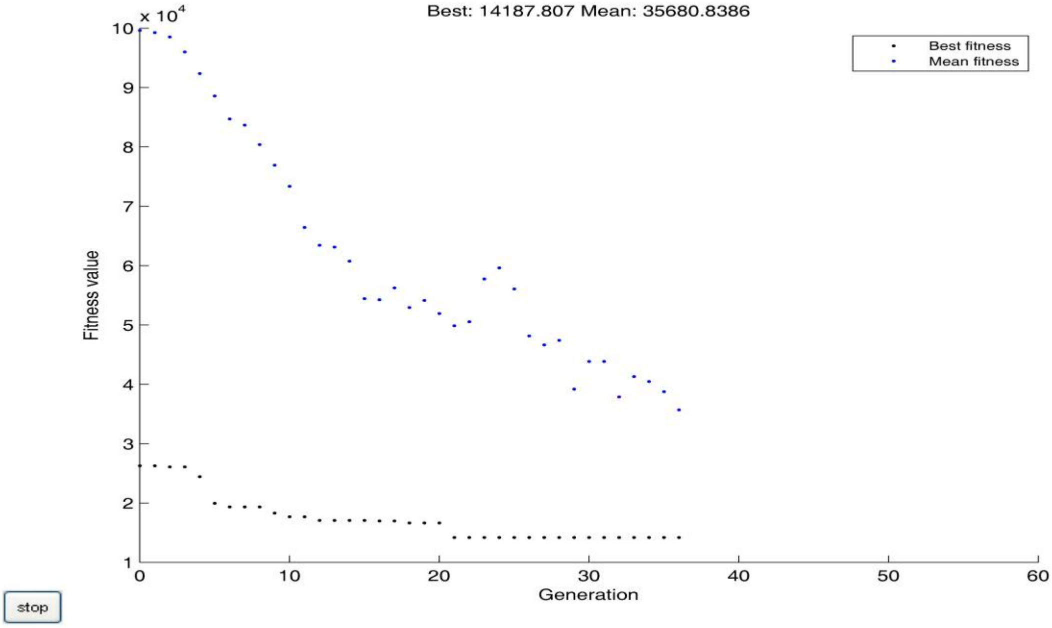

Figure 5. Best and Mean Price vs. Generations.

4.2 Results

The parameters of the optimal or the best obtained busbar system are:

- Conductor: AAC400
- Number of conductors: 2
- Insulator string: 1Z2-330
- Number of spacers: 0
- L-bar (chord): LB 70x9
- L-bar (lacing): LB 60x8
- Foundation: T1
- Conductor stress (N/m^2): 6.97
- Phase spacing (m): 2.50
- Price (€): 14 187.81

Optimization procedure ends with a maximum generation stall.

The flow of the optimization procedure is shown in Fig. 5.

The main task of optimization is to reduce costs of steel structure (C_4) and foundation (C_5) because of their influence on the total price.

5 Conclusion

This paper deals with the method for wire busbar design by implementing GA with real-value chromosomes. Some of the design variables have discrete values and the others continuous values. The reason for this choice of GA method is the simplicity of description of the stated problem - optimum wire busbars. The fitness (objective) function is a sum of the wire busbar component prices. For violating of constraints the wire busbar system receives a huge total wire busbar price (100 000.00 €) and in this way this case is excluded from possible solutions. As opposed to past published papers, this paper treats the problem of modelling of 3D truss steel structure by L-shape bars.

Optimization of the bus system by using methods of GAs is demonstrated in test examples. More importantly, the attached images present the gradual approaching to the optimal solution.

As the first generation, large population size (200) has already given at least one possible solution. The price of this starting solution till the end of optimization process (the 36th generation) has been reduced by almost half of the starting price. Due to relatively high operating continuous current optimal solution, two wire conductors per phase are given. However, due to relatively low short-circuit current optimal dimensions of L-shape bars, foundations and phase distances have finished up at the lowest possible boundary range.

Surely, complexity of the investigated problem lies in the fact that electrical, mechanical and civil calculations have to be incorporated in one programme. That is the reason why there is a lack of similar investigations.

The future work can deal with the improvement of GA efficiency. GA efficiency can be improved by selecting optimal GA parameters (selection procedure, crossover rate and mutation rates). The ultimate goal is to minimize the number of fitness evaluations (population size times number of generations) necessary to obtain the solution.

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