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Multi-Criteria Design Optimization of Ultra Large Diameter Permanent Magnet Generator

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***Abstract*—This paper presents a novel design optimization procedure for an ultra large diameter permanent magnet generator. As the machine features unorthodox electromagnetic and mechanical layouts, basic principles for determining structural loads together with material quantities for cost estimation are described. Finite element modelling with beam elements is used for retrieving stresses and deformations of the novel carrier structure. Mathematical system response model of the generator is created with artificial neural networks, while genetic algorithm with gradient method is utilized for determining the optimal solutions. Input dataset for the model build-up is constructed with a help of a full factorial experimental method. Achieved results are utilized for describing the relationship between the structural response and efficiency values of the generator. As the design of the machine has to fulfil contradicting technical and economical requirements, Pareto optimality concept is employed. As an example, a set of optimal solutions is determined for the particular case.**

***Index Terms*—Artificial neural networks, finite element analysis, Pareto optimization, permanent magnet machine.**

I. INTRODUCTION

Central issue in the development of wind energy conversion systems has been scaling up to higher turbine capacities and bigger rotor diameters [1]. Consequently more effort and innovation has been put into developing optimal solutions for subcomponents of wind turbines in order to comply with increasing technical and commercial requirements [2]. One of the favourite topics for analysis has become the layout of the electrical generator in terms of increasing its energy density and decreasing cost [3]. Various electromagnetic topology options have been presented and researchers have developed deterministic and probabilistic methods for prediction of structural properties including mass and overall dimensions [4], [5].

It also has become clear that design principles and restrictions which were suitable at lower power outputs have to be reviewed. For example the price of active materials has been in general declining and therefore its influence in determining the end cost of generators has also become less important [6]. Some researchers have utilized various approximating methods known from other industries [7] to optimize existing concepts and provide better understanding for the selection of initial design parameters. For example Li and Chen [8] have successfully used improved genetic algorithm (GA) for design optimization and site matching of generators with different power ratings and rotational speeds. Isfahani *et al.* [9] have used GA to carry out simultaneous multiobjective optimization of the electromagnetic setup of a permanent magnet (PM) generator to minimize machine mass and increase annual energy output.

Present study proposes to use a novel design optimization procedure for an ultra large diameter permanent magnet generator and presents results based on an example machine. Aim of the described methodology is to find the most suitable design values in terms of structural response, cost and efficiency for a machine with novel electromagnetic and mechanical layout. Finite element modelling (FEM), artificial neural networks (ANN) and hybrid genetic algorithm (HGA) are combined to carry out the proposed procedure [10]–[13]. As the obtained design values are evaluated against multiple criteria, Pareto optimality concept is applied in the analysis phase.

II. METHODOLOGY

Design activities regarding an electrical generator extend throughout different disciplines, including electromagnetic and structural engineering. Therefore, a procedure of obtaining an optimal solution for the machine's layout demands taking into account multiple criteria from their specific fields. In current study various analytical methods and software tools are utilized to evaluate the considered complex large scale structure. The principle flow chart of the design procedure is given in Fig. 1. In engineering process commonly certain FEM, design of experiments (DOE), optimization and evaluation blocks are utilized to reach a qualified decision regarding the effectiveness of the design. Main novel and specific features of the proposed optimization procedure can be outlined as:

– Presence of the pre-design block containing thoroughgoing preliminary analysis and simplification of initial problem;

– Presence of electromagnetic modelling and structural

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response modelling blocks, specific for the particular problem.

In next chapters, the basic blocks of the proposed optimization procedure are described.

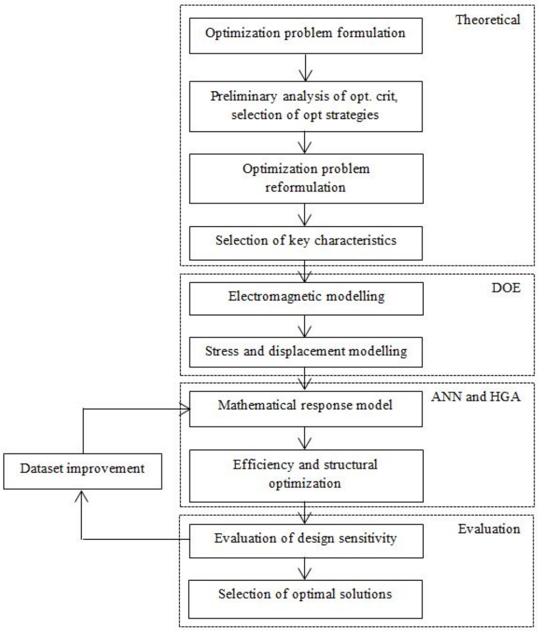

Fig. 1. Flow chart of the design procedure.

III. GENERATOR DESCRIPTION

The subject of optimization is a 3 MW ultra large diameter PM radial flux generator with concentrated electrical windings. The machine prototype built for testing is presented in Fig. 2 and basic characteristic figures are given in Table I.

Fig. 2. Full scale generator prototype.

TABLE I. GENERATOR CHARACTERISTICS.

Electrical power	P_{el}	kW	3000
Rotational speed	ω	rpm	15.3
Torque	τ	kNm	2090
Air-gap radius	R	m	6.3
Air-gap width	g_{air}	mm	9
Magnet height	h_m	mm	18
Magnet width	w_m	mm	100
Magnet length	l_m	mm	600
Coil height	h_c	mm	17
Coil width	w_c	mm	200
Coil length	l_c	mm	800

A. Electromagnetic Model

Detailed description of the electromagnetic conversion principles of the machine can be found in previous work [14]. Electrical layout of the generator describing one rotor pole and corresponding concentrated electrical stator winding is presented in Fig. 3. The loads induced for the carrier structure of the machine are directly influenced by the electromagnetic energy conversion principle. In [15] the authors have used FEM and Taguchi method to investigate the relative importance of main active forces for the initial selection of design parameters for the described generator solution. Mass of the material located on the rotor outer and stator inner radiuses, normal component of Maxwell stress and operational torque have been identified as they key driving factors for the stresses and deformations of the structure.

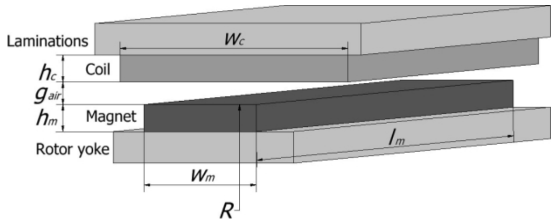

Fig. 3. Air-gap layout and symbols.

As the generator torque depends on the air-gap radius squared (1) and stator armature has a slotless design (resulting in low magnetic field density in the air-gap), the machine has unconventionally large air-gap radius. Torque τ of a radial flux generator can be given as [6]

$$\tau = 2\pi\sigma_{\tan} R^2 l, \tag{1}$$

where $\sigma_{\tan}$ is tangential component of Maxwell stress, R generator air-gap radius and l generator axial length.

Normal component of Maxwell stress can be estimated by

$$q = n_m w_m l_m B_n^2 / (2\mu_o), \tag{2}$$

where n_m is the magnet number, w_m magnet width, l_m magnet length, B_n normal direction air-gap flux density and μ_0 permeability of vacuum.

Mass on rotor outer radius m_{rot}^{oR} to be used in further structural simulations is found according to

$$m_{rot}^{oR} = m_{mag} + m_{yok} + m_{fixR}, \tag{3}$$

where m_{mag} is the permanent magnet mass, m_{yok} rotor yoke mass and m_{fixR} constant lump sum mass of smaller structural fixing items and flanges for the rotor. It is considered that m_{fixR} is not dependent on the exact electromagnetic parameters and structural loading of the generator. The mass on stator inner electrical radius m_{stat}^{iR} is found according to

$$m_{stat}^{iR} = m_{con} + m_{lam} + m_{cprf} + m_{fixS}, \tag{4}$$

where m_{con} is the conductor mass, m_{lam} lamination mass,

m_{cprf} cooling profile mass and m_{fixS} constant lump sum mass of smaller structural fixing items and flanges for the stator. It is considered that m_{fixS} is not dependent on the exact electromagnetic parameters and structural loading of the generator.

B. Structural Model

General description of the mechanical layout of the generator and corresponding beam model in ANSYS FEM software can be found in [15]. FEM model used in the simulation is given in Fig. 4. Time stepping method is used to realize all loading, while results are computed as stationary solutions. Mechanical behaviour of rotor and stator structures is assessed based on resulting deformations $£_{rot}$ and $£_{stat}$ and stresses $\pm_{rot}$ and $\pm_{stat}$. For rotor only positive (maximum) and for stator only negative (minimum) deformation values in a cylindrical coordinate system are evaluated, as they describe most accurately closing of the generator air-gap. For stress characteristics, highest absolute value from the linear combination of direct stress and maximum local bending stress is used. Both stresses and deformations are kept within reasonable limits to avoid nonlinear effects of strain stiffening or unreasonable big air-gap deflections resulting in collision.

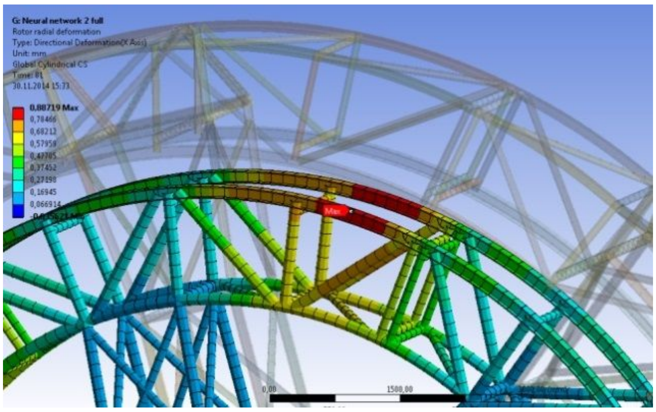

Fig. 4. FEM model of the generator.

C. Cost Model

Generator cost is approximated only based on the prices of active materials, as the investigation of exact relationship between the electromagnetic loading and needed structural mass is not considered to be part of the current research. In order to find the most optimal solution for the generator in terms of price, the cost of active materials p_{act} can be approximated as

$$p_{act} = p_{rot}^{act} + p_{stat}^{act}, \tag{5}$$

where p_{rot}^{act} and p_{stat}^{act} are the active material costs for rotor and stator, respectively. For particular machine rotor active material cost can be found by

$$p_{rot}^{act} = p_{mag} m_{mag} + p_{yok} m_{yok} + p_{work} \left(m_{mag} + m_{yok} \right), \tag{6}$$

where p_{mag}, p_{yok}, and p_{work} are the specific costs of permanent magnets, rotor yoke and work done for assembly, respectively. For the generator under consideration, stator active material cost is found according to

$$p_{stat}^{act} = p_{con} m_{con} + p_{lam} m_{lam} + p_{cprf} m_{cprf} + \\ + p_{work} \left(m_{con} + m_{lam} + m_{cprf} \right), \tag{7}$$

where p_{con}, p_{lam} and p_{cprf} are the specific costs of conductor, laminations and cooling profile, respectively.

Values for the specific costs (€/kg) of the materials used in cost approximation are described in Table II. Numbers are obtained as an average value of supplier quotations given for the actual parts of the prototype generator.

TABLE II. SPECIFIC MATERIAL COSTS.

Permanent magnets	56.5
Rotor yoke	5.0
Conductor	8.6
Laminations	1.6
Cooling profile	5.2
Assembly work	4.3

IV. OPTIMIZATION PROCEDURE

A. Preliminary Analysis of Optimality Criteria

In the case of complex multi-criteria optimization problems, the preliminary analysis of the optimality criteria and constraints is extremely important like pre-processing in FEM analysis. Preliminary theoretical analysis and simplification allows to avoid principal miscarriages in selection of optimization strategies, reduce computational time, complexity etc. [16]–[18].

The first question to be solved is the selection of objectives and constraints which can often be reformulated as “objectives vs. constraints”, since certain characteristics can be often considered in form of an objective or a constraint. There are no unique rules available for latter task and the decisions should be made according to the character of each particular problem.

The objectives selected in the current study can be listed as: cost, efficiency and maximum values of four structural response characteristics (rotor deformation, stator deformation, rotor maximum stress, stator maximum stress). The most widely used approach - minimization of the strain energy density is not applied herein due to following considerations

– An attempt is made to control simultaneously both stiffness (max. strains) and strength (max. stresses) properties;

– In context of the current problem, the values of deformations are extremely important (in order to avoid collision) and an approach introduced allows for flexible separate handling of the characteristics.

The multi-criteria optimization problem described above can be formulated as:

$$\begin{cases} F\left(\bar{x}\right) = \left(F_C\left(\bar{x}\right), \ldots, F_{SRn}\left(\bar{x}\right)\right) \to \min, \\ F_E\left(\bar{x}\right) \to \max, \end{cases} \tag{8}$$

subjected to constraints:

$$\begin{cases} g_i\left(\bar{x}\right) \le g_i^*,\ i = 1,\ldots,n_1, \\ h_j\left(\bar{x}\right) = h_j^*,\ j = 1,\ldots,n_2, \end{cases} \tag{9}$$

where $x_i \le x_i^*$, $x_{i*} \le x_i \le x_i^*$, $-x_i \le -x_{i*}$, $i = 1,\ldots,n$, $F_c\left(\bar{x}\right)$ and $F_E\left(\bar{x}\right)$ stand for cost and efficiency, respectively. The objectives $F_{SR1}\left(\bar{x}\right),\ldots,F_{SRn}\left(\bar{x}\right)$ describe structural response of the construction (maximum rotor and stator deformations $\pounds_{rot}^{max}$, $\pounds_{stat}^{max}$ and stresses $\pm_{rot}^{max}$, $\pm_{stat}^{max}$, characterizing stiffness and strength of the structure), $\bar{x} = \left[x_1,\ldots,x_n\right]$ is vector of design variables and g_i^*, h_i^*, x_{i*}, x_i^* are given constants.

The second question to be solved is the handling of multiple optimality criteria considered i.e. selection of optimization strategies. In order to compare and analyse optimality criteria, normalization should be performed, since the magnitudes and the units used to measure the objectives may be different. The objective functions subjected to maximum and minimum can be normalised by formulas (10) and (11) respectively:

$$f_E\left(\bar{x}\right) = \frac{\max F_E\left(\bar{x}\right) - F_E\left(\bar{x}\right)}{\max F_E\left(\bar{x}\right) - \min F_E\left(\bar{x}\right)}, \tag{10}$$

$$f_{SRi}\left(\bar{x}\right) = \frac{F_{SRi}\left(\bar{x}\right) - \min F_{SRi}\left(\bar{x}\right)}{\max F_{SRi}\left(\bar{x}\right) - \min F_{SRi}\left(\bar{x}\right)}. \tag{11}$$

Preliminary analysis performed for particular problem considered can be summarized as:

– The four structural response characteristics $f_{SRi}\left(\bar{x}\right)$ are not conflicting with each other and can be combined into one objective $f_{SR}\left(\bar{x}\right)$;

– The structural response characteristics and efficiency have conflicting character thus, the Pareto optimality concept can be applied to $f_{SR}\left(\bar{x}\right)$ and $f_E\left(\bar{x}\right)$;

– The small values of strains are safe, but the values nearing to the value of air-gap are critical i.e. risk is increasing with increasing value of the strains and this relation is not linear (higher order). Thus, the most widely used strategy for combining objectives – “weighted summation” is not satisfactory. The compromise programming technique can be employed, which provides that the larger distances from an ideal solution are penalized more than smaller distances $\left(c > 1\right)$;

– The combined objective $f_{SR}\left(\bar{x}\right)$ and cost are not conflicting. The minimum value of the cost and $f_{SR}\left(\bar{x}\right)$ coincide. Thus, the cost as an objective can be omitted or combined with $f_{SR}\left(\bar{x}\right)$.

Finally, the posed optimization problem (8)–(9) can be reduced to minimization (due to normalization function (10) lower values of efficiency correspond to higher values in reality) of two objectives as

$$f\left(\bar{x}\right) = \left(f_E\left(\bar{x}\right), f_{SR}\left(\bar{x}\right)\right) \to \min, \tag{12}$$

subjected to constraints given by (10). The combined objective $f_{SR}\left(\bar{x}\right)$ in (12) is defined as

$$f_{SR} = \left[\sum_{i=1}^{4}\left(w_i f_{SRI}\right)^c\right]^{1/c}, \tag{13}$$

where $\sum_{i=1}^{4} w_i = 1$, $0 < w_i \le 1$.

In (13) the parameter $c \ge 1$ $i = 1,\ldots,n$ and in the case of $c = 1$, the compromise programming technique reduces to weighted summation technique. It can be noted that the reason, why the initial formulation of the optimization problem needs often improvement, is that large amount of theoretical and numerical analysis should be performed before corresponding decisions can be accomplished.

B. Design of Experiments

Full factorial experiment (FFE) technique is utilized to create numerous of electromagnetic configurations for optimization input with an aid of a spread sheet program. This enables to identify the effect each factor has on the response variables and also how different interactions between the factors influence the response variables [19]. Designs are created with nominal generator rotational speed, air-gap radius, ambient wind speed and same type NdFeB permanent magnets. In order to achieve comparable results, electrical output power P_{el} is kept constant while the required mechanical power P_{meh} varies due to the change in generator efficiency η. Consequently masses of required active material, total normal stress and torque are freely varying and can be used to investigate corresponding structural responses.

Number of factors k is selected to be 4: air-gap width g_{air}, magnet height h_m, magnet length l_m, and coil height h_c (see Table III). Based on the previous conducted research it is known that these factors have the highest influence on both the mechanical response of the support structure and efficiency of the generator. The number of levels n for each factor is set to be 3 in order to provide protection against potential nonlinearity in the factorial effects. It also enables to easily modify the method to perform further optimization with response surface modelling if desired. The dataset results in $3^4 = 81$ generator configurations.

TABLE III. FACTORS AND LEVELS USED IN FFE.

Factor	Symbol	Unit	Level 1	Level 2	Level 3
Air-gap width	g_{air}	mm	6	10	14
Magnet height	h_m	mm	18	22	26
Magnet length	l_m	mm	600	800	1000
Coil height	h_c	mm	14	18	22

C. ANN and HGA

Numerical modelling of the large scale structure considered, is extremely time consuming and complex task, even after simplifications introduced above (analysis of optimality criteria, key parameters selection, use of beam elements in FEM analysis, etc.). Furthermore, the evolutionary algorithms in general and HGA need a huge number of function evaluations. For that reason the ANN and HGA are combined in optimization procedure. The response modelling is performed by employing feed forward ANN and the obtained mathematical model is used for evaluation of the four objective functions. The input and output data for ANN learning are gathered from FEM analysis. No unique rules are available in literature for determining the architecture of the ANN (should be configured for each particular problem). A criterion used in the current study is minimization of the mean square error (MSE), but the robustness of the network is also kept in mind. However, certain initial considerations about network architecture are needed for starting point and final decision. Review on methods to determine architecture of the ANN featured for function approximation is given in [20]. Hecht-Nielsen and others have proved that an ANN with a single hidden layer can approximate any continuous function to arbitrary accuracy on a compact set and an ANN with a two hidden layers can approximate any complex function to arbitrary accuracy [21]. By omitting the rules of thumb, the following formulas involving capacity of the training data are considered [20]:

$$N_h = \left(N_{in} + \sqrt{N_{tr}}\right) / L, \tag{14}$$

$$N_h = C\left(N_{tr} / (N_{in}\log\left(N_{tr}\right)\right)^{1/2}, \tag{15}$$

where L is a number of hidden layers and N_{tr} the capacity of the training data, N_h, N_{in} stand for number of neurons in hidden and input layers, respectively. The expression (15) contains the parameter C, which should vary for determining N_h. For that reason, herein formula (14) is used as a starting point and the number of neurons in hidden layer is increased up to the upper bound determined by right hand side of the formula (15) (see [20])

$$N_h \leq N_{tr} / N_{in}. \tag{16}$$

According to dataset size and (14) seven neurons in hidden layers are used as starting value in an ANN with two hidden layers. Next the number of neurons is increased by one until the MSE reaches a satisfactory level. Final configuration of the selected ANN, includes eight neurons, 5 and 3 in first and second hidden layers, respectively. ANN with one hidden layer was also considered. In that case the starting point and optimal configuration were found to include 13 and 14 hidden neurons, respectively. The ANN with two hidden layers and smaller number of neurons is used for design optimization. The hybrid genetic algorithm employed herein contains GA for global search and gradient method for local search. Local search is performed only for the individuals satisfying the following requirements:

– Individuals belong to first 15 % of population based on values of the fitness function;

– The distance between individuals is not less than given value (diversity condition).

The proposed HGA is less time consuming in comparison with traditional GA and also allows to overcome problems with convergence to exact minimum (not near-minimum).

V. Results and Discussion

In the following figures, output data are given in normalized form in order to retain collation determined by normalization and Pareto concept. In case of efficiency the lowest normalized values correspond to the highest non-normalized values as defined by (10). Results regarding the relation between efficiency and the structural response obtained from the DOE are depicted in Fig. 5. It can be seen that in general higher efficiencies tend to cause also higher stresses and deformations. This is to be expected, as stronger magnetic flux for the needed higher efficiency also tends to lead to larger normal stress values. But even for the higher efficiency values it is possible to keep the structural response close to the average value of entire population. In all of the efficiency ranges it is also possible to find bad designs with very high response values. Number of those configurations compared to general population is quite low and the overall spread of structural responses for a particular efficiency is not very high. The best efficiency values are obtained with large magnet thickness and length combined with medium to large air-gap and small coil thickness.

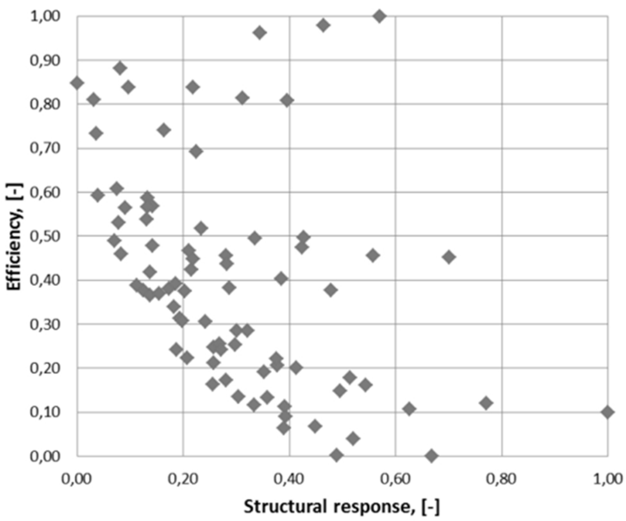

Fig. 5. Structural response vs. efficiency.

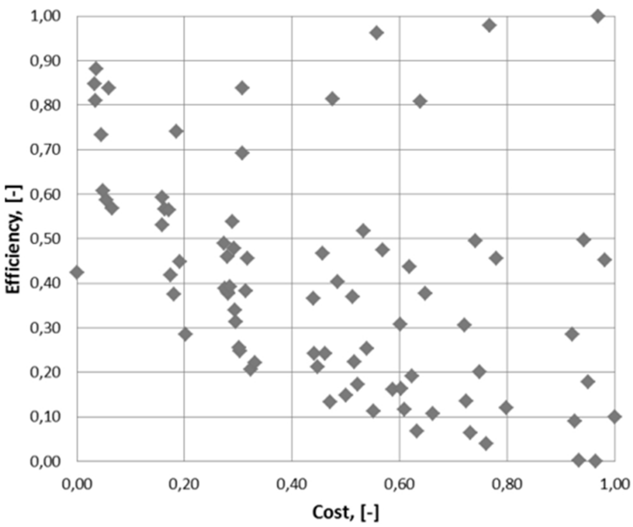

Fig. 6. Cost vs. efficiency.

Relation between the cost of active material and efficiency depicted in Fig. 6, shows much clearer tendencies in the high efficiency area, although the overall scattering of design points is much larger. For cases with extremely high efficiency, the cost of active material cannot be kept low and a clear trade-off between the two variables exists. The higher the efficiency, the steeper the cost increase curve. For the medium high area, numerous designs with costs near the average values are possible. Due to large scattering, the possibility of having a bad design in terms of costs is higher. This is true for both high and low efficiency ranges and indicates that the relation between active material and air-gap needs to be carefully considered. It also has to be noted that some designs with over average efficiency and very low cost figures have to be discarded, as they are feasible only with the lowest air-gap value and even structural responses slightly below average could cause an air-gap closure.

The Pareto front "structural response vs. efficiency" is depictured in Fig. 7. It can be seen that the increase rate of the efficiency is growing with decreasing values of the structural response. One possible/meaningful selection of the optimal solution in Pareto curve is (0.1; 0.5). In this point the structural response reached near possible minimum value and further improving structural response leads to extremely rapid increase (worsening) of the efficiency. The other interesting point in Pareto curve is (0.5; 0.11) where the efficiency reaches near ideal value and further improvement of the efficiency leads to rapid increase (worsening) of the structural response. The optimal set of design variables corresponding to selected points (0.1; 0.5), (0.5; 0.11) in Pareto front is presented in Table IV.

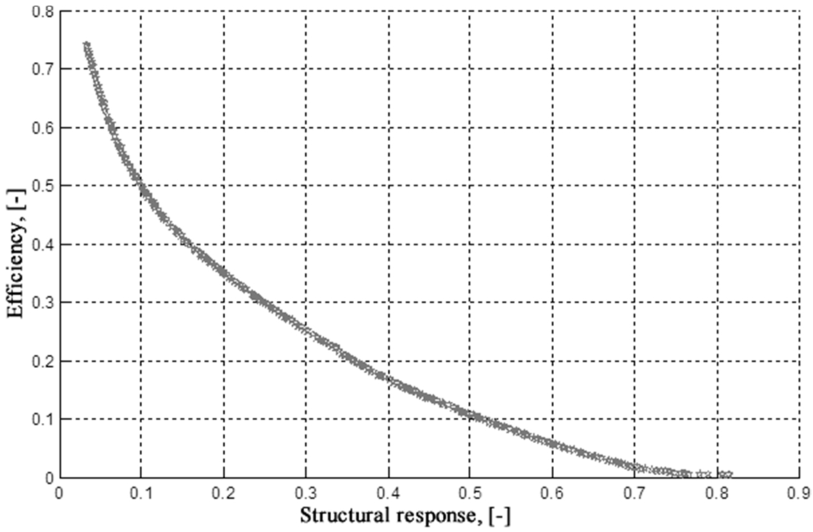

Fig. 7. Pareto front: structural response vs. efficiency.

TABLE IV. POSSIBLE OPTIMAL LAYOUTS.

Air-gap	Magnet thickness	Magnet length	Coil thickness	Comment
mm	mm	mm	mm	-
13.9	19.9	708	21.9	(0.1; 0.5) low resp, lower eff.
13.9	21.5	969	15.9	(0.5; 0.11) high eff., higher resp.

Thus, the Pareto front provides much more information in comparison to physical programming techniques. However, certain additional considerations are needed for selection of final design(s), as all solutions given by Pareto curve are optimal to some respect.

The relation between structural response and cost is found to be proportional as stated in section earlier. The cost as objective has been omitted from the multi-criteria optimization procedure. An alternate approach is to combine the cost with structural response $f_{SR}\left(\bar{x}\right)$. However, it has been numerically verified, that including cost in combined objective has marginal impact on the final design.

VI. CONCLUSIONS

Current research has been performed on the Goliath Cyclos 16/3 generator. Novel optimization procedure is proposed to aid in the design procedure of an ultra large diameter permanent magnet generator. Specific features of the proposed multi-criteria optimization procedure introduced include pre-design block for the analysis of optimality criteria and constraints, electromagnetic and structural modelling blocks. An analysis of the optimality criteria performed allows significant simplification of the initial optimization problem. The objective space is reduced from six to two.

An electromagnetic design tool together with a structural FEM model is used to generate multiple machine configurations at the same power level by varying magnet volume, generator axial length and air-gap width. Obtained structural responses, efficiencies and costs of the active material are used as an input for artificial neural networks to compose a mathematical response model of the machine. The optimization itself is realized by combining genetic algorithm with gradient method.

Performance characteristics of the objectives obtained during the DOE and optimization are evaluated against each other. The scattering of designs is larger for the "cost vs. efficiency" criteria, however also for the "structural response vs. efficiency" criteria it is possible to have so called bad designs and especially in the middle efficiency area.

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