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Degenerate optimization problems of economy and power engineering

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Abstract

Optimization of large economy and power engineering systems leads to degenerate solutions of a high dimensionality. This is a very strong mathematical complication. It however allows the future evolution of power engineering to be considered both as based on joint operation of nuclear power plants (NPP), coal-fired power plants (PP) and gas-fired PPs, and based on only NPPs. This requires a system optimization of the NPP parameters.

Computational studies on optimal high-dimensionality systems have led to the degenerate space of admissible economy and power engineering solutions to be understood as a set of points on a lunar surface with a finite number of craters. Such degenerate space may be referred to as "non-convex, non-concave".

In other words, an N-dimensional degenerate "non-convex, non-concave" space of a high-dimensionality optimization problem ($N \geq 10{,}000$) looks like a "lunar surface" with craters of different depths. Craters form the neighborhood of locally optimal plans, and the locally optimal plan as such is on the bottom of a crater. The crater depth defines the value of the functional being optimized. Occasionally, the deepest but different craters include equally deep craters, that is, craters with equal values of the locally optimal plan functionals. The local optimum (local plan) in different craters may differ structurally, and the optimization problem functionals for these points may be equal in value.

Calculations show that equally sized craters (with equal values of economy and power engineering development locally optimal plan functionals) occasionally include craters with locally optimal plans of economy and power engineering evolution (in a diversity of the potential combinations of economy and energy technology states) based only on coal- or gas-fired PPs, or on coal-/gas-fired and nuclear PPs, or on NPPs. By weighing the values of the locally optimal plan functionals in different craters, one can find an optimal solution – a locally optimal plan with the best functional value (e.g., in the event of the functional minimization, with the minimum objective functional value out of the entire number of the considered craters).
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Nature of degeneracy

Optimization of large energy (or economy) systems represents a mathematical programming problem in which the optimal plan is found on a convex set of solutions from a concave or concavo-convex functional (objective function). The dynamics in such problems makes allowances of its own. The material balances in optimization problems are described by equalities and inequalities, and the commissioning of capacities, as well as the installed capacity diagram, are described using delta functions from the commissioning times of these capacities; the current loading (production) diagram also exhibits a leap either at the time of the capacity commissioning or at the time of the capacity switchover from the demand following mode to the full (threshold) loading mode. There are also other optimization model relations that disrupt the convexity of the set of solutions. The difficulty of

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solving such problems was noted already by classical authors [1–4]. As we see it, it would be better to classify such mathematical programming problems as "*non-convex*, *non-concave*" optimization problems. Such problems normally have a high dimensionality. In an optimization problem like this, a typical inverse matrix dimensionality of $10{,}000 \times 10{,}000$ (a larger dimensionality is possible) is not a surprise to anyone nowadays.

The theory of solving separately "concave" and "convex" mathematical programming problems is well developed, while numerical solution methods for such problems often make part of a standard computer software library.

The class of "non-convex, non-concave" optimization problems is not so well developed. Meanwhile, it is exactly them that are *actual* economy and power engineering problems. Such problems have another important complication (as S.Vajda, one the classical authors, put it [1]). In the event of high-dimensionality optimization problems looking for the optimal plan of developing large power engineering and economy systems, the locally optimal plan normally turns out to be *degenerate*. In terms of a linear programming problem [2], a degenerate reference (admissible, agreed) plan is that having a certain variable x_i equal to zero, with i coinciding with the number of one of basis vector for the plan under consideration. A degenerate situation is characterized by the fact that all coefficients $x_i \geq 0$ and at least one of them is equal to zero in the expansion of the vector P_0 for the vectors of a certain basis P_1, P_2 , … , P_{m}

$$P_0 = x_1P_1 + x_2P_2, + \cdots + x_mP_m.$$

Mathematical methods aimed at finding the optimal plan for a problem, e.g., a simplex process, suggest that all reference plans for the problem are *non-degenerate*. This assumption guaranteed a decrease in the linear form value (where the linear form, either a functional or an objective function, has minimized) after each iteration of the simplex method. Since any problem (following a linearization) possesses only a finite number of bases, then the optimal plan is determined through a finite number of iterations.

This logic breaks down as soon as the existence of degenerate reference plans is assumed, which is, clearly, more close to reality.

Besides, high-dimensionality optimization problems have *cyclicity* as a property. In other words, optimization algorithms select the sequence of bases leading to a cycle, that is, a sequence of the bases periodically selected and failing to satisfy to the criterion of optimality. In this case, evidently, the optimal plan will never be achieved. It is possible to get out of "cyclicity" through generation of algorithms for recognizing and coming out of cycles.

To date, no spaces of permissible solutions have been described in literature in the class of degenerate "non-convex, non-concave" optimization problems of a high dimensionality. These dynamic optimization problems are of interest to us primarily from the point of view of the NPP applicability and competitiveness as part of small, medium and large power grids.

Degenerate optimization problems and the space of their permissible solutions (empirical space description)

Optimal solutions for Russian energy sector depending on the effective rate of exchange in Russian economy are presented in [5]. Russian economy differed in the discounting rate value which was numerically equaled to the effective interest rate for construction and operation of power facilities. The effective interest rate was changing numerically from 0.05 (1/year) to 0.25 (1/year). It has been shown that, with the rates being 0.15 (1/year) or more, nuclear power (NP) stays beyond the optimal structure of Russian energy sector. Actually, this is *one* of the solutions for the evolution of Russian power engineering that can be referred to as a locally optimal degenerate solution. There are *other* degenerate solutions for the evolution of Russian power engineering (including nuclear power) with an equally sized solving functional. Prior to considering them, we shall note some properties of "non-convex, non-concave" degenerate spaces of permissible solutions. These properties were experimentally obtained by Ya.V. Shevelev and the author back in the early 1980s in the process of modeling and solving power engineering evolution problems of a high dimensionality, but it was only several years ago that it shaped into a non-contradictory representation of a degenerate space of solutions.

We shall describe geometrically the notion of degeneracy.

In terms of a linear programming problem, the optimization problem looks as:

$$\boldsymbol{F} = \boldsymbol{cx} \rightarrow \min \tag{1}$$

with the constrains

$$\boldsymbol{Ax} = \boldsymbol{b}, \tag{2}$$

$$\boldsymbol{x} \geq 0. \tag{3}$$

Here, $\boldsymbol{F}$ is the objective function (functional) to be optimized, $\boldsymbol{c}$ is the row vector of the objective function coefficients; $\boldsymbol{A}$ is the matrix of constraints for the optimization problem; $\boldsymbol{x}$ is the column vector of the optimization problem variables; and $\boldsymbol{b}$ is the column vector of free terms (the right side of the constraints). The solution of such problem, $\boldsymbol{x} = \boldsymbol{A}^{-1}\boldsymbol{b}$, provides for the minimum of the function $\boldsymbol{F}$ where $\boldsymbol{A}^{-1}$ is the inverse matrix to the matrix $\boldsymbol{A}$.

We shall show the geometry of an N-dimensional degenerate space graphically in two dimensions (a sheet of paper).

We shall reduce the dimensionality of the optimization problem such that the dimensionality of the matrix $\boldsymbol{A}^{-1}$ will be 3×3. Let the set of permissible solutions for such problem be a cube (a convex set) shown in Fig. 1. A permissible solution of the optimization problem is achieved at any point inside or on the surface of the cube. It is proved in the linear programming theory [1-4] that the optimal solution is achieved at the cube corner. All the corners of this cube for the shown system of coordinates are non-degenerate, so the coordinates of the random corner $A(x, y, z)$ are not equal to zero. Dash lines show the projections of this cube on the surfaces (X, Y), (Y, Z), (Z, X).

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