Predictive Control of Ancillary Services Using Direct Search Methods

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Abstract: The paper is focused on usage of direct search methods of an optimum in the area of predictive control. The aim of the process is to find an optimal coverage of a given predicted course of output variable by means of a set of sources. Proposed approach can be used in multi source tasks where overall output is given as the sum of outputs of individual sources. Each source is described by its characteristic behaviour and its individual set of constraints. The general approach is applied to the problem of predictive control of ancillary services in the European power energy system. Simulation examples are applied to the situation of the transmission system in the Czech Republic.

Keywords: Direct search methods, Predictive control, MATLAB, Ancillary services.

1. INTRODUCTION

This paper deals with predictive control of ancillary services under the conditions of interconnected electricity system. Most European transmission systems of electric power are interconnected under the UCTE (Union for the Co-ordination of Transmission of Electricity). The basic idea of this system is based on free market of electric power. Another very important role of the UCTE system is to define conditions to ensure reliability and accessibility of electric power supply.

Individual members of UCTE are responsible for fulfilment of condition defined by UCTE. Each member – usually country – establishes Transmission System Operator (TSO) who is responsible for transmission system of this country. The TSO is responsible for ensuring that contracted cross-border supplies will be realized and possible deficits will be covered (CEPS, 2008).

The deficits can occur on both production and consumption side. Typical problem on the production side consists in failure of some power plant block. And typical problem on consumption side can be an increase of electric power consumption due to greater air conditioning systems in operation caused by a change of weather.

The TSO buys ancillary services in advance and can use them in these situations. The ancillary services can be seen as reserved power of power plants or an electric power bought from abroad. In case of oversupply, the surplus energy can be used in hydro pumped storage power plants or sold abroad.

In case on known or reliably estimated time course of the deficit, the problem could be solved by predictive control approach

2. DEFINITION OF THE PROBLEM

The basic problem has risen in solving the problem of predictive control of transmission system of Czech Republic. Contrary to classical control tasks, the goal is not to control plant output using its model. The goal is optimal coverage of predicted (given) reference course of the plant output using a set of available sources. The plant output is given by the sum of outputs of the sources.

In case of predicted control of ancillary services, the predicted course is the difference between contracted and actual cross-border transmission of electric power (*dP0*). The sources can be considered as individual power plants (under admissible simplification).

The task has also more general usage for systems consisting of more sources where total system output is given as sum of outputs of individual sources. Each source can have its own specific constraints and the costs of different sources also differ.

From the control point of view the goal is to find optimal plan of production of individual sources. The output of each source has its specific unit price. The optimum is given by economical point of view according to the following approach:

1. The predicted reference output must be cover as accurate as possible
2. If this coverage can be reached by different courses ways, the one with the lowest costs is to be used.

The complexity of the problem lies especially in technical constraints of individual sources. This typically involves following parameters:

- The maximal possible speed of change of source output or the time required for particular change of output
- Minimal and maximal possible output of the source

- The ability of the source to change its output continuously or only on on/off levels

In practical application, the receding horizon principle is to be applied. The principle of the receding horizon lies in computation of time sequences of individual sources for a longer time period (prediction horizon) while just initial part of the sequences is used and then the sequences are computed again (Kwon & Han, 2005) .

3. DEMONSTRATIVE EXAMPLE

This chapter presents basic demonstrative example of the system consisting of two sources. The output of the system is given by the sum of the outputs of the sources and time course required output of the whole system is known for next 5 hours. The goal is to find optimal setting of output sequences of both sources.

Constraints are given by technical possibilities of both sources. The output of both systems can be changed continuously and the change out the outputs be performed in any time. However, the speed of change of the outputs is limited and a maximal speed of increase and decrease of the output is defined for both sources.

The costs of both sources are different. The source which is able to change its output more quickly is also more expensive. In other words, the unit of electric power produced by this source is more expensive then the unit produced by the other source.

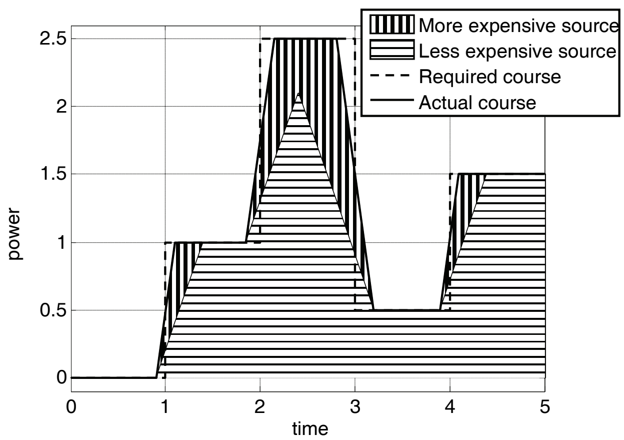

Fig. 1: Coverage of the given course using two sources

The coverage of given output is performed according to rules defined in chapter 2. Coverage of the output is fundamental and if possible the economically optimal coverage is used (i.e. less expensive source is used).

The courses of reference value and its coverage are presented in Fig. 1. It is obvious that the reference signal could not be covered totally because of step changes. The course of outputs of individual sources is shown in Fig. 2.

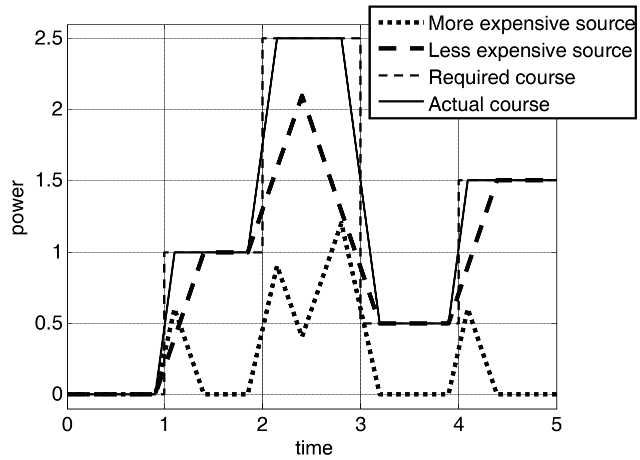

Fig. 2: Course of output of individual sources

The less expensive source was preferred for coverage of reference output. But this source is not able to change its output as quickly as the second, more expensive, source. This configuration results in usage of the more expensive source especially around the step changes of the reference signal.

Considering knowledge of reference signal in advance leads to the possibility of reaction of the sources on the change of reference signal earlier then the reference signal actually changes. Thus, smaller differences between actual output and required output are reached comparing to the case of classical, non-predictive control.

4. CRITERION FUNCTION AND CONSTRAINTS

Criterion used in predictive control is based on principles presented in chapter 2. In general, the minimization of the sum of cost of control error (C_{error}) and the costs power produced by individual sources (C_{source}) is performed. The control error is defined as a difference between actual output of the system and the reference output. The criterion can be written as:

$$J = \min_{\boldsymbol{P}} \left(C_{error} + \sum_{i=1}^{ns} C_{source,i} \right) \tag{1}$$

where ns is the number of sources in the system and $\boldsymbol{P}$ is a matrix which contains outputs of all sources during predictive horizon using a given simple time. In case of linear cost function of control error and linear cost function of all sources, the whole predictive control problem is linear. Usage of linear cost functions represents utter preference of suppressing control error as defined in chapter 2. Usage of generally more common quadratic criterion would not cover the definition of the problem as exact as linear criterion.

The cost function of the control error can be simply defined as the sum of absolute values of control errors according to (2).

$$C_{error} = \sum_{k=1}^{nk} |e_k| \tag{2}$$

where nk is the number of sample times corresponding to prediction horizon and e_k is control error sequence in individual sample times.

The costs of individual source are computed as weighted sum of absolute values of its outputs:

$$C_{source,i} = \lambda_i \sum_{k=1}^{nk} \left| \boldsymbol{P}_{i,k} \right| \quad (3)$$

where λ_i is the weight corresponding to price of one unit of energy produced by this source. To ensure the preference of control error, all weights must be less then 1 (λ_i <1).

The simple linear case presented in previous paragraphs is further complicated by costs of staring of individual sources. If the source represents an operating plant which just can change its output, the starting costs are small or zero. But, if the plant represents a "stand-by" power plant, the starting cost can be essential.

The source costs must be calculated on basis of analysis of whole sequence $\boldsymbol{P}_i$. Considering just individual values of the $\boldsymbol{P}_i$ sequence can produce misleading results because 2 zero values can represent following different cases:

1. The source was not started even once – in case of two subsequent zeros at the end of the sequence
2. The source was started once – in case of two subsequent zeros in the middle of the sequence of in case of first zero in the middle of the sequence and the second zero at the end of the sequence
3. The source was started once – in case of non-subsequent zeros and non of them at the end of the sequence

Fundamental constraints are technical properties of individual sources. The problem lies especially in the continuity of the output power both in time and in its value. The following four basic cases can occur:

1. Output of a source can be changed continuously in both value and time. It is possible to change the output of the source at any time to any value (within the available range)
2. The change of the output of a source is continuous in time and discrete in value. The change of the output can be performed in any time but the value of the output must be selected from a given, source specific, set.
3. The change of the output of a source is discrete in time and continuous in value. The change of the output can be performed only at particular time but the output can be set to any value (within given range)
4. The change of the output of a source is discrete in both time and value. The change of the output can be performed only at particular time and the value of the output must be selected from a given, source specific, set.

Furthermore, required source output must respect technical capabilities of the source – especially minimal and maximal output and maximal speed of change of the output.

5. CRITERION MINIMIZATION USING DIRECT SEARCH WITH GENETIC ALGORITHMS

Solution of general problem presented in chapters 2 and 4 was simulated and solved using real data prom the transmission system of Czech Republic. Sources mentioned in previous chapter correspond to power units which offer ancillary services contracted by TSO.

Following ancillary services were taken into account when searching for optimal coverage of the error (*dP0*). Thus, the "control error" term defined in previous chapter corresponds to the difference between *dP0* and the sum of all ancillary services.

- *TR+* – positive tertiary regulation, available immediately, small amount
- *TR-* – negative tertiary regulation available immediately, small amount, the only negative ancillary service
- *QS* – quickstart, available almost immediately, expensive, limited total amount (hydro pumped storage power plants)
- *DZ* – dispatch reserve, available in 30, 60 or 90 minutes, starting costs
- *EregZ* – energy bought from abroad, availability depends on current situation on the market

Besides *QS* and *EregZ* all other units work in only on/off regime.

The goal was to find optimal sequence of individual ancillary services within prediction horizon 6 hours. Individual unit constraints were also respected (Chalupa et al, 2008).

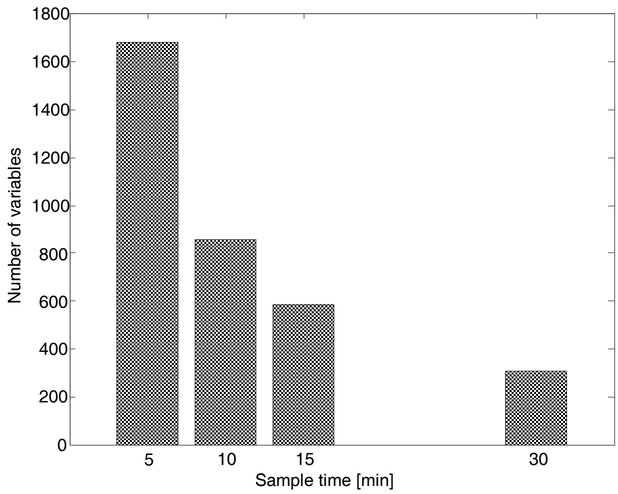

Fig. 3: Dependence of number of variables and sample time

The solution was performed using MATLAB system (Mathworks, 2008) and its toolboxes (Mathworks, 2007). The binary characteristics of the inputs represents great nonlinearity of the problem and essentially suppresses usage of classical optimization methods based on usage of derivation of the cost function.

One possible approach of solving this problem is based on modified version of gradient search which involves discrete characteristics of some inputs (Solberg, 2008).

The solutions presented further in the paper are based on direct search methods, which do not use derivation of the cost function. The solution was designed under MATLAB toolbox Genetic Algorithms Direct Search. All inputs were converted to binary values which were used in optimization algorithm. The number of binary variables which are to be optimized depends on sample time used. This relation is presented in Fig. 3.

Various courses real *dP0* were used and sequences of individual ancillary services were computed. Results for one particular course of *dP0* are presented further in this chapter.

Results of a basic setting of the optimization algorithm are presented in Fig. 4.

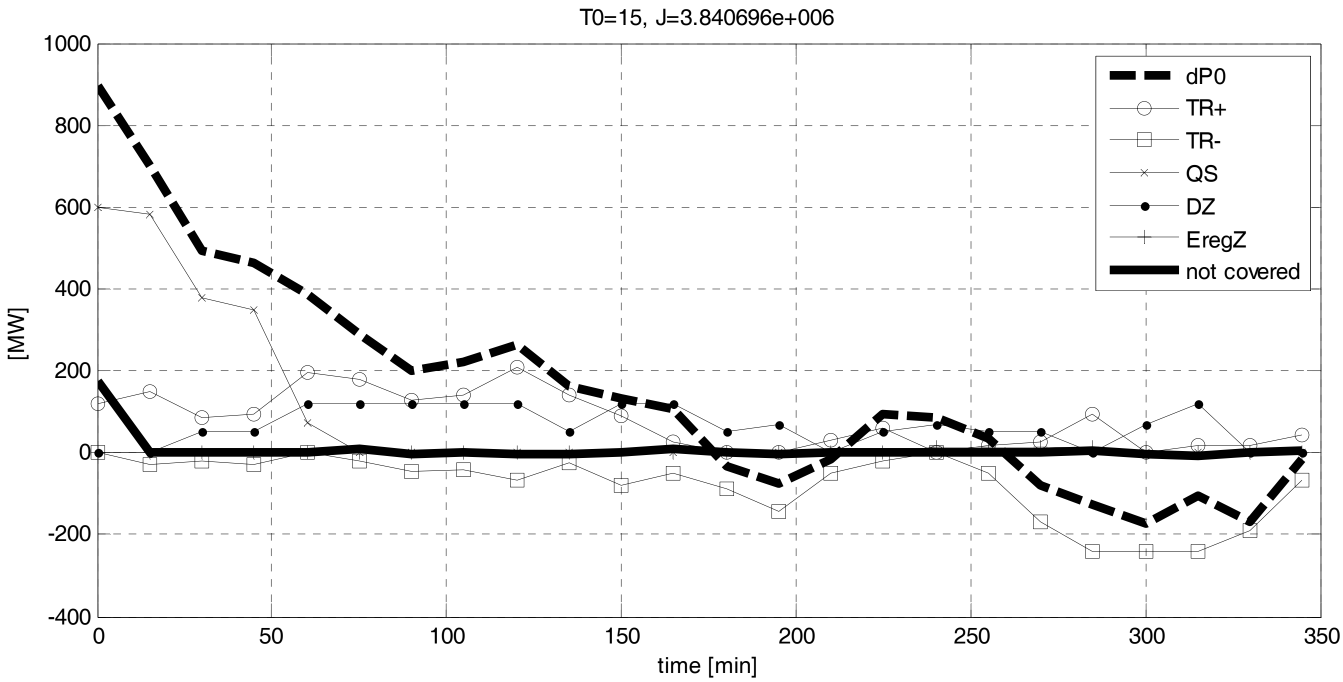

Fig. 4: Courses resulted from basic setting of optimization algorithm

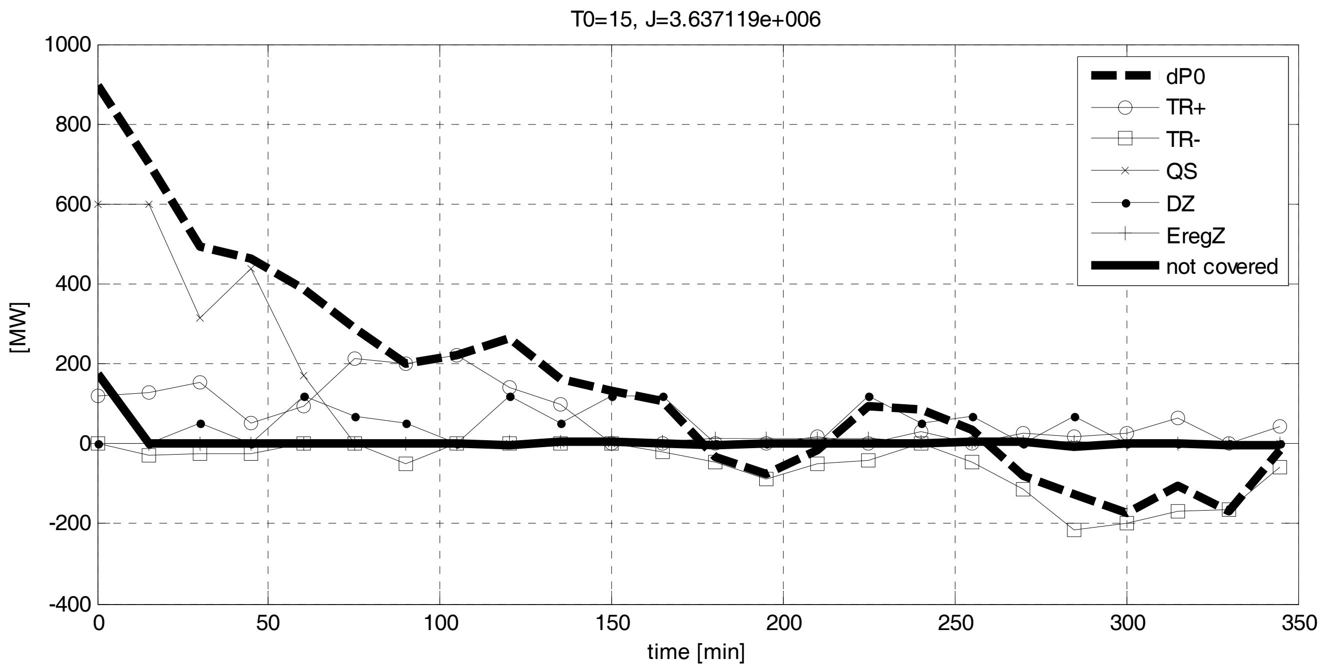

Fig. 5: Optimization result obtained by greater population size

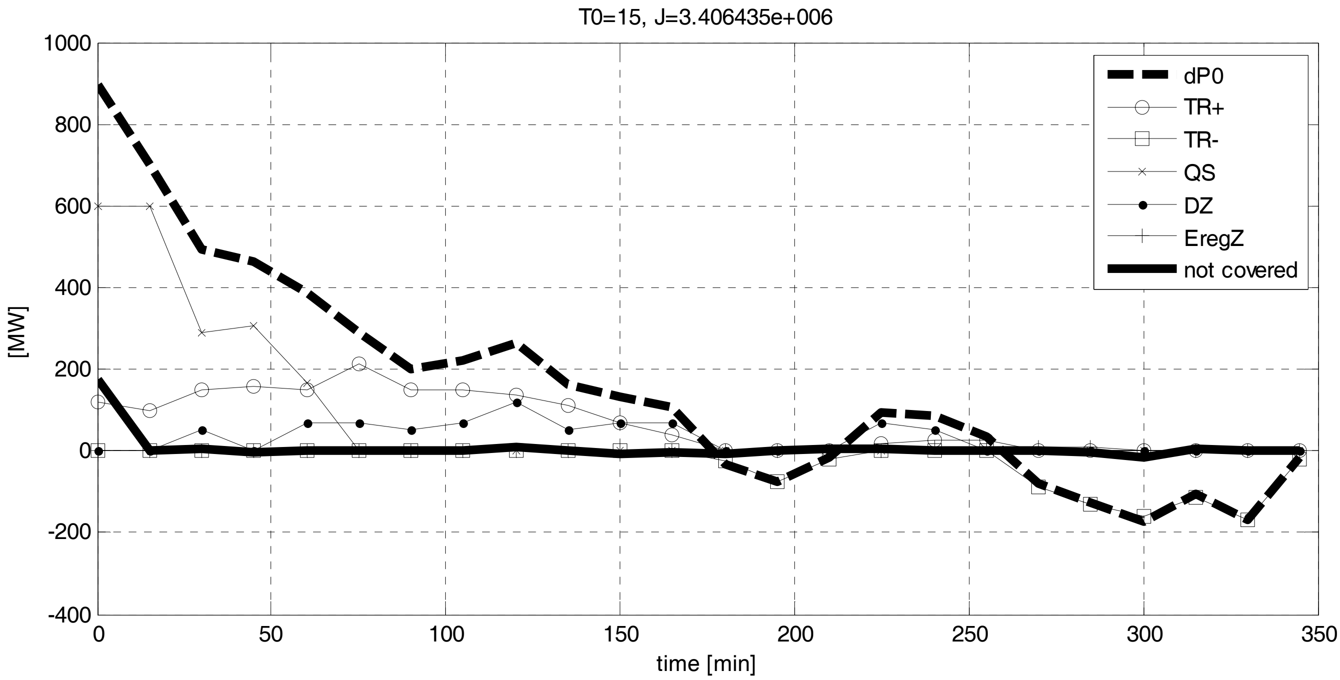

Fig. 6: Explicit suppression of contraregulation

The *dP0* course represents differences in the transmission system which are to be covered by ancillary services. Course *not covered* represents the part which was not covered by ancillary services. Parts which are not covered can be caused by two reasons:

- Technical constraints of the units in the transmission system (i.e. there is not enough ancillary services available to cover given course)
- The algorithm did not reach global optimum, just local optimum was found

A problem which can be seen in Fig. 4 is contraregulation. Contraregulation is the state of the ancillary services where both positive and negative (*TR-*) services are used. Presence of contraregulation indicates that global optimum was not found.

One of the possible improvements of the results leading to suppression of contraregulation lies in the increase of the population used by genetic algorithm. Results presented in Fig. 4 correspond to population of 500 individuals. Results obtained by increasing population size to 5000 individuals are presented in Fig. 5. It is obvious that the contraregulation was significantly smaller then in the case of 500 individuals. The criterion value has decreased by 10%.

Another approach of coping with contraregulation consists in its explicit suppression in the optimization algorithm. This intervention leads to change of the cost function and thus restricts the optimization algorithm. The resulting courses are presented in Fig 6. The population size was decreased back to 500 individuals. Naturally, to contraregulation is not present in this case but it should be noted that explicit suppression of contraregulation also suppresses one of the advantages of predictive control. In this case it is impossible to react to change of *dP0* from positive values to negative values (or from negative values to positive values) in advance.

The criteria values, the population sizes as well as the CPU time required to perform optimization is summarized in Table. 1

Table 1. Comparison of individual settings of optimization algorithm

Setting no.	*Population size*	*Criterion value* [10^6]	*Optimization CPU time* [s]
1	500	3,84	171
2	5000	3,64	2602
3	500	3,41	290

An explicit suppression of contraregulation was used in setting no. 3. Comparison of computational demands of these three settings is presented in Fig. 7.

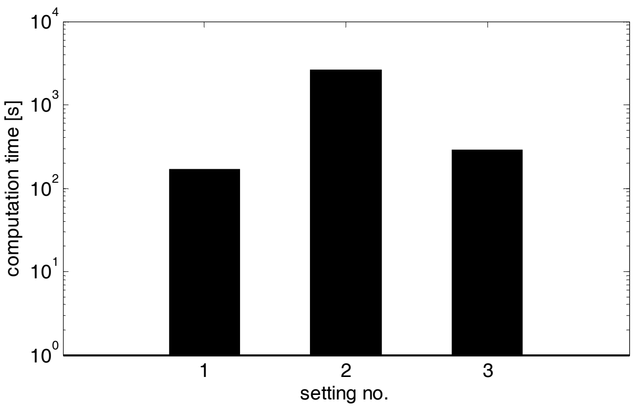

Fig. 7: Computational demands of algorithm

6. CONCLUSION

A highly nonlinear optimization problem of a predictive control of a transmission system using ancillary services was presented in the paper. The complexity of the problem consists in a huge number of optimization variables and discrete characteristics of some of them. The problem was solved by conversion of the continuous signals to binary representation and usage of genetic algorithm to solve the optimalization problem itself.

The presented approach was verified using real data from the transmission system of the Czech Republic. The results confirm usability of the direct search methods to this kind of highly nonlinear optimization problems.

Nowadays the results cannot be used directly especially due to the indeterminateness of the predicted signal but the same approach can be used as the starting point for the dispatch operator. Nevertheless, presented approach can be directly used to retroactively compute optimal control course and compare it with the one actually applied to the transmission system.

7. ACKNOWLEDGEMENT

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