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Review

of the Doctoral thesis by Nikita Zemtsov entitled "Model Predictive Control for Demand Response of Thermostatically Controlled Loads"
carried out at Faculty of Mechatronics, Informatics and Interdisciplinary Studies of the Technical University of Liberec

PhD Thesis entitled "Model Predictive Control for Demand Response of Thermostatically Controlled Loads" comprises 111 pages of the text including tables, graphs, and references. Bibliography includes 8 publications co-authored by the author of the thesis himself and 106 publications written by other authors.

The thesis is focused on one specific problem in the field of power energy systems. The fast increase of the renewal energy source part in manufacture of the electric power demands optimization of the power consumption. It is necessary to update the current consumption structure according to change in time both on technical, and for the economic reasons, for example, with change of the short-term price in the market of the electric power. A model of the intellectual control is the suitable approach to cost optimization from the economics criteria point of view. In this connection the considered decision of the problem of aggregated control of group of thermostatically controlled loads based on predicting models with economic price function in a power supply system with dynamic price for the electric power is an urgent research direction.

The doctoral thesis presented on reviewing corresponds to a research topic completely. Author makes good intro of existing approaches to design of intellectual control models with emphasize on minimization of operational expenses of thermostatically controlled loads. Scientific publications of domestic and foreign authors in framework of investigations are used in work that proves by 106 references along the dissertation text.

The objectives of the thesis are outlined in pages 42–44. The list of the objectives includes advanced control algorithms for utilizing the potential of Thermostatically Controlled Loads. Actually, there is a fresh objective: the development of an identification method that allows change price depend state of grid. It my opinion, the objective of the thesis is urgent in principle. However, the treatment of many important points in the thesis is so fragmentary and the thesis is so hastily written that

it should be improved and expanded at least for the purpose of the thesis defense. In particular, the following should be improved.

Survey of the state of the art in the field of the thesis is given in the first chapter (pages 20–41). In my opinion, it is somewhat shorter than it should be. It includes references to a fairly high number of both recent and older publications but most of them are characterized just very briefly. Clearly, this chapter should have been written with greater care: is should be not only review but trends-shown part.

Final analysis of the advantages and disadvantages of the existing methods is actually a very important point. It sets the stage for the formulation of the objectives. Starting from this analysis the author can better demonstrate that thesis objectives are sound and that the thesis will bring something new and some improvement over the current state of the art. From this viewpoint, the final analysis in item 1.5 (page 36) is somewhat vague and unsatisfactory. None the less, this survey shows that the author has a generally satisfactory orientation in the literature and the survey can be considered sufficient for the purposes of the thesis in most parts.

The core of the thesis is chapter 3 (pages 45–53). This chapter includes the description of the main principles of the new method and necessary mathematical proofs and derivations. The description of the method given in the thesis is self-contained so that any person reading it could reproduce the simulation experiments or to test the method in some other suitable way. The following chapter 4 can be regarded as an application example (simulation) because it is focused on application of proposed method. Some drawback of chapter 3 is that the new identification method is actually never described in some compact and consistent form. The chapter includes a mathematical describe of problem as linear programming task. Five chapter devoted to aggregating models and simulation. This structure of thesis is ordinary and look like good.

Theoretical and practical contributions of the thesis are relatively enough. As I have already stated above, the thesis brings sound theoretical ideas with potential practical importance but the sketchy and fragmentary treatment may be much improved.

Appropriateness of chosen methods and their application are mostly appropriate to the intended purpose but not without flaws. It should be mentioned the use of numerical methods for optimization instead accounting on simple examples of small dimensions.

My overall impression from the thesis can be formulated as follows. The main underlying idea of the thesis is sound, interesting and potentially fruitful. In the context, the thesis develops a method of Model Predictive Control (MPC), that allows minimize the operational cost. In doing this approach the thesis is slightly inspired by time-invariant regression but despite this, the thesis remains largely original and interesting. The way how this idea is embodied and elaborated in the thesis is somewhat satisfactory, but some details remain fragmentary and unfinished.

Advantages of work are following:

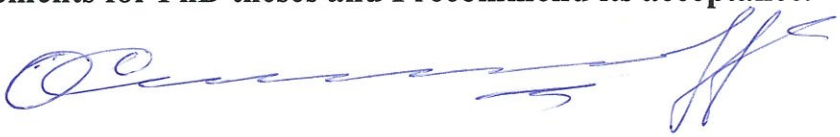
- simulating model of the current consumption group of thermostatically controlled loads depends on temperature and external conditions;
- the aggregated model of group of the thermostatically controlled loads allowing to solve the optimization problem in real time.

The presented results of modeling show that the system of power supply based on considered algorithms can be operate in economically optimum mode. It determined the practical value of work. Verification of the control system by modeling confirms validity and reliability of the results received by the author.

Disadvantage of the researches under review is follows. Author investigates the only ideal model of supplier of energy-consumer in such conditions that price is predicted and is free from risks of uncontrollable change of the price, penalties for a few consumption and large consumption of energy that is the most widespread practice in modern conditions. Change of operational cost of group of thermostatically controlled loads due expenses on service and amortization is not considered. Sure, the specified remarks are not a subject for low quality and do not reduce the general value of work.

Content of the thesis gives good representation about solved problem and about results received by the author. It has been published in eight scientific papers indexed in Scopus and Web of Science as well as verified at seven international scientific and technical conferences in good extent. The content is well structured and outlined by competent professional language.

Finally it is necessary to conclude that presented thesis represents itself the high-grade complete technical investigations concern improving of systems of the power supply, containing decision of new problems and essentially expanding our representations about complexity of optimization by criteria of energy consumption allowing to essentially make better the economic indicators of developed devices. My final opinion is that this thesis could have been a few better in some issues. However despite many critical comments I agree that its main idea is interesting and original and that it is worthy of being accepted. **I confirm that this dissertation meets the requirements for PhD theses and I recommend its acceptance.**



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Dissertation Review

Název práce: Model Predictive Control for Demand Response of Thermostatically Controlled Loads
Prediktivní řízení odezvy strany spotřeby využívající termostatické spotřebiče
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Školitel: doc. Dr. Ing. Mgr. Jaroslav Hlava

Oponent: doc. Ing. František Dušek, CSc.
Pracoviště: Katedra řízení procesů, Fakulta elektrotechniky a informatiky, Univerzita Pardubice

The opponent's review based on an appointment letter from the Dean of the Faculty of Mechatronics, Informatics and Interdisciplinary Studies, Technical University of Liberec on 18th of December 2018.

Dissertation thesis contains 111 numbered pages and 1 page of attachment. In addition to the list of used literature, there is a list of eight author's papers related to the dissertation topic. For six of them the dissertant is listed as a first author. CD with dissertation text and programs that were used in simulations is a part of the thesis.

The dissertant deals with the very actual issues of "smart grids" namely managing power consumption in large-scale power grids containing sources with variable but predictable performance. The author assumes that the consumption is influenced through a time-varying energy price. He focuses on a class of loads designated as Thermostatically Controlled Loads (TCL). They have greater consumption, significant dynamics and independent regulation with relatively simple remote control (e.g. buildings heating and air conditioning). Author proposes indirect system of control based on knowledge of the expected future energy price. Control minimizes power consumption at high energy costs while maintaining user comfort within specified limits.

In Chapter 3 there is an example of a heated swimming pool showing a design of water temperature control minimizing heating costs. The design of the controller is based on minimizing the cost function including heating costs and water temperature requirements. A prerequisite for the solution is the knowledge of a mathematical model describing the time course of the swimming pool temperature in dependence on the heating power and other variables influencing the temperature (weather conditions). In the thesis a simplified model is used in the form of a discrete linear dynamic model with time-variable parameters (LTV) and a linear cost function with constraints at the final horizon. Due to the limitation that heating is only considered on and off the controller design is formulated as Mixed-Integer Linear Program optimization problem. The example is supplemented by temperature control simulation (a 48-hour control horizon) over an interval of 216 hours.

In Chapter 4 the dissertant deals with modelling of the TCLs (electrical space heaters) population. The model is needed to simulate the proposed control. Each load is considered including the ON / OFF temperature control with hysteresis. The model is based on the same description of each load but with parameter values as random log-normal distributions. Because such a complex model is unusable for a control design proposal, Chapter 5 lists the approximate aggregate behavior model of the entire population of TLCs. Model is considered first in a standard form only with the temperature range that corresponds to the hysteresis of the temperature control and then with extension for a larger temperature range. In my opinion this extension is the benefit of the dissertation. The Modified

Aggregated Model allows to model the population of TLCs consumption depending on the setpoint temperature change with sufficient precision, while its complexity remains at the level allowing its use for the control design.

Chapter 6 is dedicated to the design of the control strategy of the population of TCLs and verification by simulation. The goal of the load management is to minimize energy consumption at a time of high energy costs with minimal interference to the user comfort (i.e., reduction of indoor temperature). The control is based on the knowledge of the energy price and the outdoor temperature forecasts. The overall reduction in energy consumption is achieved by shifting the temperature set-points of each TCL. The shift is the same for all TCLs and calculated by the proposed controller. The dissertant formulates the task of predictive control design at the final horizon as an optimization problem in a continuous-time with linear loss function, LPV model and linear inequality constraints. He designs also numerical solution algorithm for the given task. I consider this part to be the original part of the work. At the end of this chapter the dissertant compares his proposed "smart" control strategy with two others. The first "zero" strategy means keeping the temperature set-point and therefore no energy savings and the second "thrifty" strategy means the maximum allowable set-point reduction and therefore maximum energy savings.

Formally, the work is written very well and contains a minimum of typing error. The formulations are clear and understandable, images readable. The text is logically organized, the chapters follow each other and the literatures sources are listed and quoted. From the formal side I have a single comment and that marking of strategies (opt., subopt. and no opt.) in the legend text in Fig. 6.3, 6.4 and 6.6 is not consistent with the marking in the text (zero, smart and thrifty).

I have two questions that the dissertant should clarify in his defense:

1) How the dissertant made a choice of the weight of the vector **v** (in the loss function Eq. 3.10a on page 49), which extends the range of temperature limitation (slack variables relaxing the temperature constraints) i.e. vector ρ_v.
2) Why normalized operational costs of the proposed smart strategy (Figure 6.3-6 and Table 6.2) is lower than the cost of the thrifty strategy although the temperature of the smart strategy is higher all the time?

In conclusion, I can state that the dissertation thesis of Ing. Zemtsev has met the stated goals and brings new results. Especially when he formulated a mathematical description of a large TCL network and designed load management based on the forecast of the energy price. The dissertant has demonstrated good knowledge of studied and related scientific disciplines and the ability to work independently. The dissertation fulfills the requirements stipulated in the relevant paragraphs of Act No. 111/1998 Coll. about universities and despite the above comments I recommend it for the defense.

in Pardubice, January 10, 2019

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