Agent-based modeling of distributed energy resources regarding power system control

THESIS BOOKLET

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INTRODUCTION

The transmission system operator is responsible for the balance of production and consumption in the power system. Due to market liberalization and the decreasing energy price the structure of the domestic generation capacity have been changed. Consequently the number of power plants traditionally involved in the system control has been significantly decreasing. On the other hand numerous distributed energy resources (DERs) have been installed in the last decades. Integrating the distributed generation (DG) into the system control raises several organizational and technical questions. However by their integration in controlling centers they can provide ancillary services as virtual power plants with larger built-in capacity.

There are several kinds of generating technologies worldwide. In Hungary nearly the half of the distributed generation is based on gas-engines, the fifth part applies steam-turbines, and the wind-turbines give also the 20% of installed DG capacity. The use of gas-turbines and combined cycle gas-turbines (CCGT) has to be taken into account too. Sometimes more units using different technology are applied with the common economic and contractual interests. The applied technology determines the considerable technological constraints and these have strong influence on the daily operation. The cogeneration units are usually focused on satisfying the local heat demand while the electric energy production has secondary importance. The characterization of the heat demand and the structure of district-heating system are different in each case. Finally the whole question has to be investigated using profit-oriented method: the prices of electric energy, heat and primal energy (usually gas) have strong influence on usual operation. Parts of these prices are determined by the valid legal system (e.g. feed-in-tariffs) that is often modified in the last years.

Summarizing the operation of a given DER is influenced by the applied generation technologies, the character of the local heat demand and system, the current market environment and the valid legal system. Consequently the optimization of the virtual power plant, including 40-60 units, is a more complex problem than the optimization of a real power plant with same built-in capacity.

The investigation of the distributed generation regarding power system control is not very universal as only a few TSOs – including the Hungarian one – have difficulties with the balancing control. However the DERs have larger and larger weight in the generation opposite to the centralized power plants. The balancing of the generation and consumption in a localized area (microgrids) is deeply studied in several researches. The related papers are usually focused on the economic dispatch the different units. Therefore the problem of the energy management in microgrids is similar to the optimal dispatch of controlling centers. Consequently I made a deep literature overview regarding these researches; on the other hand the methods presented in the dissertation have larger perspective.

My research was aimed to develop a generic model for DERs in which the behavior of the units can be simulated considering several technical and economic viewpoints. Their optimal operation can be determined based on the results of the simulations.

The implemented model was expected to have large flexibility and not to focus on the Hungarian special problem. It is easy to parameterize, the considered viewpoints can be changed and altered without difficulties. Although the above expectations were done by long-term plans these was extremely useful during the research too. The domestic legal system and market environment have been change several times in last years; however these were easily followed by the flexible model.

LITERATURE OVERVIEW AND THE CONTRIBUTION OF THE RESEARCH

There are a very few papers focusing on the integration of DERs into power system control, meanwhile several researchers deal with the optimal energy management of microgrids. The third section of the dissertation (Page 10-22) summarizes the most important papers, only the results of three research centers are highlighted here.

The work of the School of Electrical and Computer Engineering (NTUA, Athens) is discussed first. They developed a skeleton for multi agent system (MAS) analyzing microgrids [24] that have been applied by several other researchers too. Further they published some algorithms applying different optimization techniques [25-27], and they developed and installed intelligent microgrid control as a pilot project in Kythnos Island of the Greek archipelago [31-32].

T. Logenthiran (Newcastle University, Singapore) developed their MAS model based on the Greek structure too [36-38]. He used the unit-commitment procedure, which is widely applied in the North-American markets, to determine the optimal operation of the DERs. The introduced LRGA algorithm takes several technical constraints into account.

Finally the GECAD group of the university in Porto makes significant research in the multi-agent modeling of markets. They developed the MASCEM model (Multi-Agent System for Competitive Electricity Markets, [43]) in 2003, continuously extended and improved later [44-45]. In MASCEM the behavior and the interactions of market participants can be investigated. The agents try to realize more profit within their different objectives and constraints, for which several algorithms have been published [46-49]. The DERs are managed by Virtual Power Plant (VPP) agents having several dispatching methods [50-52].

After the careful literature overview the contributions of my dissertation are:

1. There are two approaches to handle the technical constraints of the DERs with different technologies. In most case the researchers developed dedicated algorithm for each technology and DER, while the most complicated units (e.g. CCGT) are not modeled. The other solution, mainly in the market-focused studies, supposes generic DERs with common parameters (minimum and maximum power, variable and fix costs). In the latter case generic algorithms have been developed for all agents; however the technical constraints are simplified.
I developed a method for the generalization of different technologies that facilitates considering several technical constraints deeply whereas it provides an interface to implement generic algorithm for all kinds of DERs.
→ *Thesis 1, 4th section of the dissertation, and 'Generalization of technologies' section below.*

2. The presented methods in the literature give solutions for particular applications or are general studies. Therefore the considered viewpoints are usually too general and the methods cannot be applied for the Hungarian problem (e.g. 75% yearly efficiency requirement to obtain feed-in-tariff in Hungary). The objective functions are focused on the profit as opposed to the secondary objectives in practice (e.g. satisfying the contractual heat demand).
This problem has been managed by the developed new algorithm dealing several viewpoints in a flexible and easy-to-understand framework. Due to structure of the algorithm it can be applied of any DERs operating in different market environment and using different generation

technologies, whereas the objective function can be formed to consider every necessary viewpoint.

→ *Thesis 2, 6th section of the dissertation, and 'Flexible framework' section below.*

3. Several adaptive algorithms have been applied in the papers regarding the distributed generation. However the agents are always adaptive only in the bidding strategy, or during the negotiation process in the markets: how it can determine its energy price on the micro market so as to reach the optimal operation in short and long-term too. However the technological constraints are neglected, the agents cannot derive the optimal operation in techno-economical way. Furthermore none of the presented algorithms takes the heat service into account having significant influence on the usual operation in Hungary.

    → *To eliminate the above summarized deficiency I developed a method using knowledge-based reinforcement learning (RL). In that agent considers the technical constraints including the aspect of heat service too. Due to adaptive RL method the agent is able to estimate the profit-optimal operation considering the starting costs and amortization as well. The method requires only the cost-parameters of the agent.*

    → *Thesis 3, 7th section of the dissertation, and 'Adaptive behavior' section below.*

METHODOLOGY

The operation of DERs is modeled in an agent-based approach. The terminology and the structures of agents are interpreted according to the book of S. Russel and P. Norvig titled 'Artificial Intelligence. A Modern Approach.' The section 5.2 in the dissertation (from page 40) introduces the developed PEAS framework – Performance, Environment, Actuators and Sensors. This structure is in fact the formulation of the problem in the agent terminology. Simulating different agents in this structure the behavior and operation of DERs can be investigated.

After recognizing the possible contribution to the international research I developed the model supplementing the deficiency, and then implemented it in software to demonstrate its capability. The results are presented in the dissertation and have been compared to the real operation of DERs in order to provide validation of the method. (The structure of developed software is detailed in the Appendix.)

The developed model is related to only one agent trying to operate a DER in an optimal way. However the presented methods can be the base of several multiagent studies published in the literature, as they provides a flexible and technology-independent way to handle different and complex generation technologies in changing market environment.

A diversity of generation technology is handled by the generalization of actuators (thesis 1). I present a utility-based agent-program to handle the different viewpoints in a flexible way (thesis 2). Although the agent-program needs to give several fictive parameters, I present a knowledge-based reinforcement learning method to alleviate this problem (thesis 3). The methods of the three theses are detailed in their own sections.

Thesis 1
GENERALIZATION OF TECHNOLOGIES

(details in the 4th section of the dissertation, page 23-29)

Introduction

The different generation technologies mean different technological limits for the operation. Gas-engines, the most spread in Hungary, have small built-in capacity, relatively high gradient, and high efficiency on partial load. They usually serve domestic heat demand. Gas-turbines are mainly applied in combined-cycle power plants having several types with different efficiency and complexity. Usually these have higher built-in capacity but lower gradient, and these provide high-temperature steam for industrial demand. Finally there are several biomass or garbage fired boilers providing steam of steam-turbines. Regarding the operational constraints the extraction-type and back-pressure steam-turbines are different. Besides the cogenerating technologies the wind-turbines have significant built-in capacity in the Hungarian distributed generation.

Methodology

The technical constraints therefore depend on the applied generation technology. Furthermore in a DER there can be more units with different technology with the common interests; therefore the optimal operations of these units have to determine together. Instead of implementing technology-specific algorithms I developed the state-based approach. In the approach the operational states have generalized parameter in a well-defined structure facilitating to implement one unified algorithms for all technologies. The attributes of the generalized operating states consist all necessary information for the algorithm (e.g. electric power, heat, gas consumption, operating units, efficiency, etc.), however they have generic structure with the same content. The specialties of technologies are deeply considered during the construction of the state-space. The state-space of a DER having 2 gas-engines is presented in Fig. 1 with small explanations. I presented further state-spaces in the dissertation to demonstrate conception.
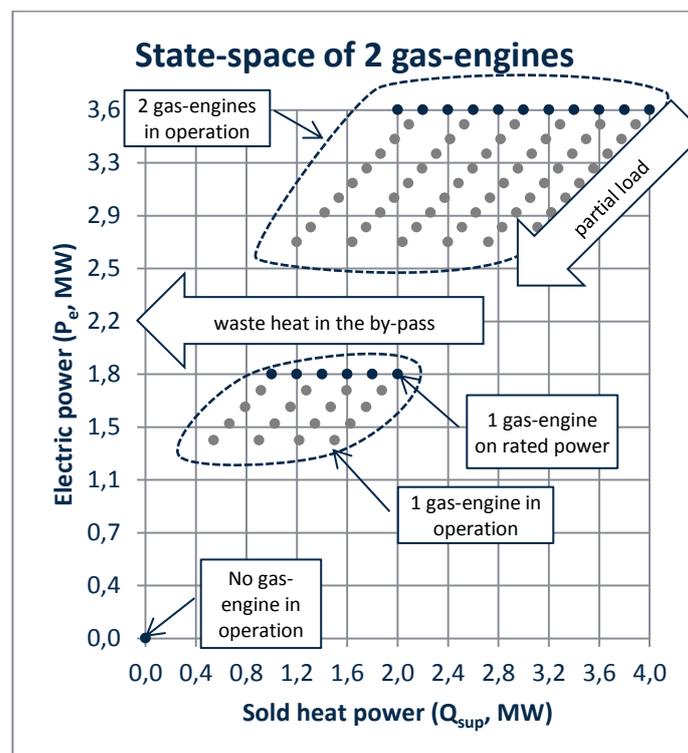

Fig. 1 Example for the state-space of DER possessing two gas-engines

In several studies the required time of ramping of units cannot be neglected. For these cases a model has been extended with transient states where the generalized structure of operational states contains the current load of each unit in the beginning of the operating states. With this supplement the powers of the transients can be linearly interpolated between the time units. The approach is remained to be independent of the technologies and it does not increase the number of the generic operating states. The method is detailed and demonstrated in section 4.2 (page 30).

Results

Using the state-based approach the DERs with different technologies can be generalized. After the construction of their state-space the researcher can implement unified algorithms to investigate a given question. To demonstrate the conception I discussed the uploading and downloading possibilities of different DERs: cost of controlling, effect on the aggregate efficiency, available gradients. Although the results depend on the selected units, general statements can be drawn as presented in Table 1.

	DOWNLOADING		UPLOADING		
	Available power	Price [HUF/kWh]	Available power	Price [HUF/kWh]	Efficiency decrease
gas-engines	significant	[−10; −9]	significant	[20; 25]	4-12%
CCGTs	significant	[−13; −9]	significant	[10; 15]	0-1%
steam-turbines	negligible		negligible		

Table 1 Summarizing the results of investigations based on the state-based approach

Thesis 1

The state-based approach is developed for distributed energy resources applying different technology. Due to generalization it makes possible to eliminate the technology-specific constraints from the controlling algorithm. Applying the method the same algorithm can be developed for a given study to all DERs independently of the used technologies. Meanwhile the technical specialties are taken into account during the construction of the state-space in details, more deeply than the known procedures till now. These parameters appear in the character of the state-space and in the values of the generalized attributes.

Subthesis 1 of Thesis 1:

The attributes of the operation states can be supplemented with the loads of each unit valid in the beginning of the given operational state. This supplement makes the state-based approach capable to the proper considerations of the load-change of the units fulfilling the technology-independent expectation.

Publications

The main part of the Thesis 1 has been published in [S5] journal, further related [S1]-[S4].

Thesis 2
FLEXIBLE FRAMEWORK

(details in the 6th section of the dissertation, page 48-56)

Introduction

The optimal operation of each DER is influenced by several viewpoints that have to be considered altogether. Each viewpoint has different weight regarding a given DER, furthermore the weight of them can be changed along the time (e.g. legal system modifications). The following structure for the viewpoints has been established in the model:

- – Profit: DERs are oriented to make higher profit. It depends on the revenue from electric power and heat supply, and the fix- and variable costs. There are different market structures for each product that significantly influence the applied strategy (e.g. feed-in-tariff, power exchange, bilateral contracts for electric energy).
- – Heat service: satisfying the actual heat demand considering the physical parameters of the related heating-system.
- – Efficiency: different requirements were in effect regarding the minimum efficiency to obtain the ability for feed-in-tariff, or later for the supported heat price.
- – Generation unit management: operating each unit according to its specification (frequency of start and load changing, start-up time, number of daily cycles, maintenances)
- – Fuel consumption: the amount of consumption reported day-ahead must be kept in a given tolerance band.
- – Storage heater: scheduling the filling and emptying periods of a possible storage heater.
- – Weather: in case of wind turbines.

Methodology

I implemented a utility-based agent program to model the operation of each DER. It has modularized structure to provide a flexible framework for the different considerable viewpoints. The agent-program has three steps to select the optimal generic – see in the previous section – operating state for a given period. The viewpoints are considered by separate strategies that have been implemented so as to evaluate each possibility according to their own viewpoint. During the first step the operation states that are physically unreachable are excluded from the selectable ones. The second step is the qualification enhancing those states that are more probable for the final selection or there are no weighty arguments against them. Finally the utility-calculating step gives a value for each enhanced states. The states obtained the highest utility will be selected for the operation. I provided a calculation method for the last step based on partial utilities: strategies evaluate each state with a normalized partial utility while the total utility is the weighted sum of the partial ones. In that case the formulas for each strategy and the weight of each partial utility have to be given by the researcher.

Strategies can be involved in any of the three steps if required. Having this flexible structure the agent-program can be tuned for each study including the determination of the applied strategies, their participation in each step, the formulas of the partial utilities, and the weights of them in the total utility. Section 6.2 presents the results of my suggested structure in different market and legal environments.

I suggest an adaptive method for the utility-calculation based on the profit reinforcements. Due to this approach the application of independent profit strategy becomes unjustified.

Results

Applying a suitable structure of the suggested framework the aggregated electric energy schedule and production of the domestic distributed generation have been compared to the real aggregated schedule and production respectively (page 56-58). Regarding the latter case the unexpected outages of the DERs have been taken into account too.

The validation process has been carried out for each DER comparing the schedule given by the model with the real one. The dissertation presents more validation results for different technologies and environment too (page 58-60). Based on the results the structure of the three-step agent-program can be tuned for any DERs applying any kinds of generation technologies and participating in different markets.

Finally several studies have been performed regarding the integration of distributed generation into power system control. Detailed results have been published in [S4] and [S8] the main conclusions are listed below:

- The amount of available controlling reserve depends on the season and the direction. Regarding downloading reserves the distributed generation could have performed 90% of the required controlling. Better results can be reached in winter. However there is no significant amount of uploading reserves.
- The time between two reserve demands does not influence the availability of downloading reserves as opposed to uploading reserves.
- The duration of reserve demands is in correlation with the availability of them: reserve demand for longer time can be performed with lower reliability.
- Based on the reliability of each DER a priority order has been established according to the preference of integration into the system control. In beginning of the list there are DERs with gas-engines dominantly.

Thesis 2

The planning and control of distributed generation units is influenced by several technical and economic viewpoints. Based on the utility-based agent-program skeleton I developed a three-step algorithm providing a flexible solution. The method provides a decision-support tool for controlling centers and microgrids even more adjustable than the previously published works as the objective function can be tuned up for any viewpoints of different distributed energy resources.

Publications

The main part of the Thesis 2 has been published in [S5] journal, further related [S4]-[S8], [S10].

Thesis 3 ADAPTIVE BEHAVIOR

Introduction

Due the variations of market prices and heat demand each DER should continuously adapt to the changing environment. Depending on the applied formulas, the partial-utility-based agent-program is adaptive to some extent but its objective function (the sum of partial utilities) is not easy to interpret. Therefore this agent-program is primary formed to describe the operation of a given DER where the parameters can be adjusted to fit the results to the real measurements. Applying the well-adjusted model the behavior of agents can be studied in case of changing the environment or the viewpoints. However I provided another method to determine the optimal operation of a DER that is not obviously consistent with the practice.

Regarding the future-oriented studies the measurements are not available to do the necessary adjustments; we suppose fictive DERs and environment. Generally the units are given, but a different environment is supposed stimulating the units to choose a totally different behavior. For these studies an easy-to-interpret algorithms is required where the results are easy to analyze. Adaptive methods to the unknown environment can be developed by implementing learning algorithms considering the whole interest of the given DER, not only the separate strategies.

Methodology

The presented method is suggested to apply as the third step of the three-step agent-program, although it can work on its own too. Knowledge-based reinforcement learning (RL) has been implemented to provide adaptive character for the algorithms that have been configured along the following ideas:

- The market positions of the agents are interpreted as the situations of the RL model.
- According to the time unit of power markets (15 min) each day is represented by 96 consecutive time units resulting in sequential situations.
- The reward of each situation is the realized profit in the given quarter-hour by the DER.
- The transients between two situations are characterized by transient costs to describe to costs of start-up and unit-ramps.
- In order to decrease the computing time the rewards are stored separately (page 74, equation (22)), and the situation-transient model is implemented independently of the actions (page 76, equation (23)).
- The total utility of a given generic operating state are calculated from the adaptive knowledge of the agent according to the equation (45) on page 83.

Due to the separately registered reward values and a simplified situation-transition model there is significant spare of computing time regarding the exploration of the environment and the observation of its changes. This is further encouraged by the explore-objected actions that have been implemented in the agent-program to recheck the rarely or long-time used situations (equations (41)-(43) on page 82).

The knowledge-based RL approach is unique in this domain. Opposite to the Q-learning [26] it is more effective in complex environment and it is able to evaluate the situations with longer prediction. Although its resource requirement is larger therefore it can be hardly applied for extremely large problems. The applied methods (separate rewards, simplified situation-transition model) serve to decrease this disadvantage.

Results

Applying the RL-based agent-program the operation of different DERs in different environment (market, weather, legal) have been analyzed. The dissertation presents the detailed results, only a few of them are demonstrated here.

–   Fig. 2 presents the electric energy production of a DER possessing 6 engines (details on pages 85-89)

–   Fig. 3 presents the revenues, costs and profit for each quarter-hour of the same DER. The results take the start-up costs and load-changing costs into account too.

–   Fig. 4 presents the learnt level of a possible storage heater that is applied by a DER belonging to the feed-in-tariff balance-group (details on pages 89-91).
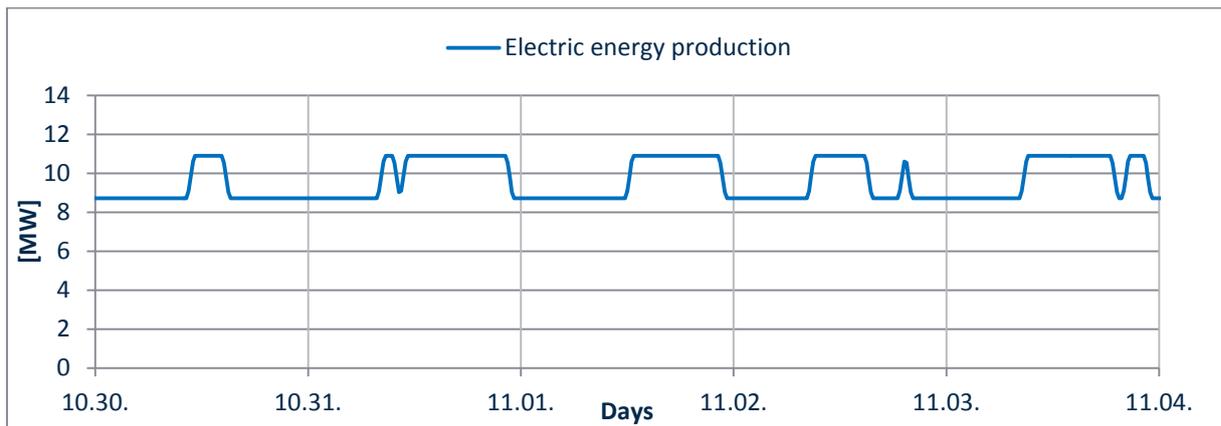

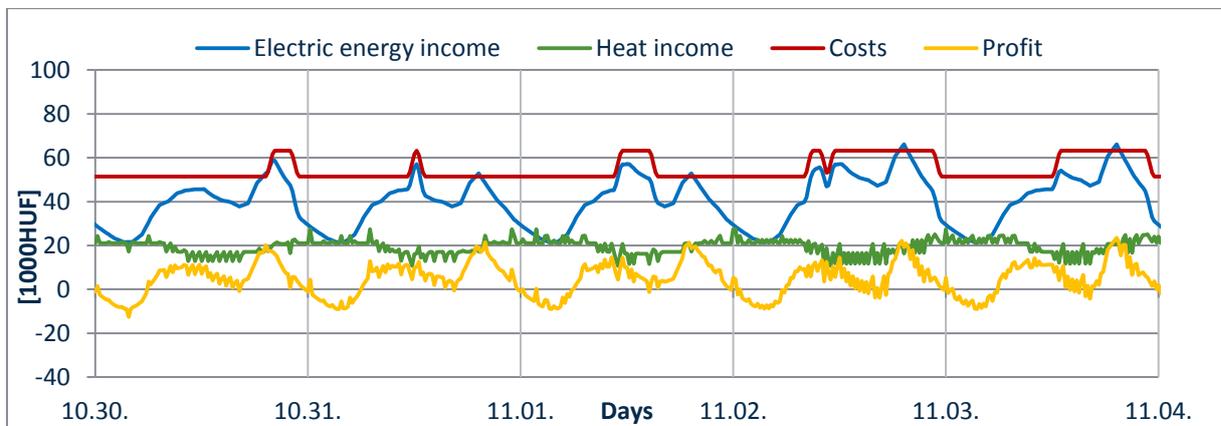**Fig. 1: Electric energy production of a DER possessing gas-engines in autumn**

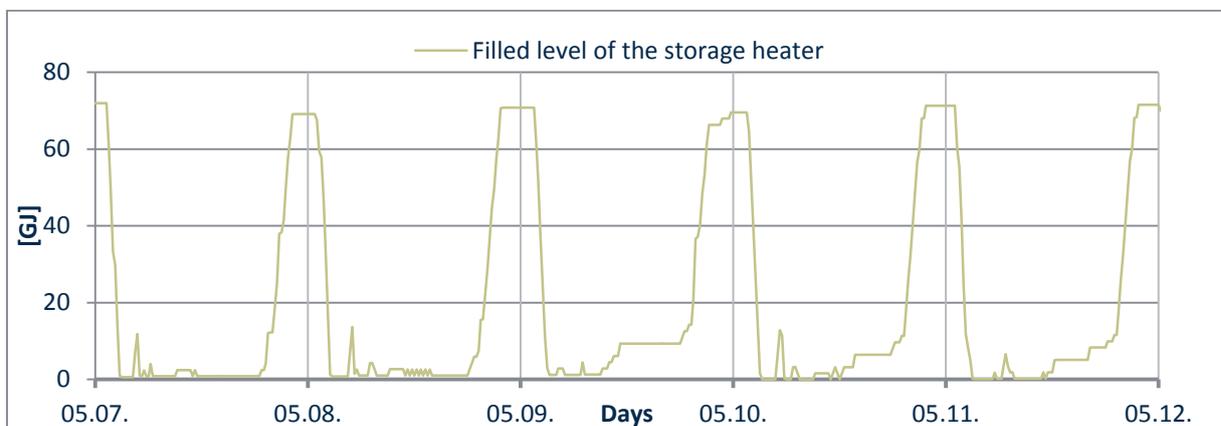**Fig. 2: Revenues, costs and profit of the same DER possessing gas-engines in autumn**

Fig. 3: Applied level of storage-heater used by a cogenerating DER belonging to the feed-in-tariff balance-group

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Thesis 3

I developed an adaptive algorithm applying knowledge-based reinforcement learning method to determine the profit-optimal control of distributed energy resources regarding the technical constraints. The method requires only the real cost and technical parameters of the given DER, and by executing several learning cycles in the changing environment it determines the operation of a cogenerating DER that yields in the maximum profit. The knowledge-based approach – applying the presented simplifications to decrease to resource requirements – has been successfully applied to solve this complex problem.

Publications

The main part of the Thesis 3 has been published in [S13] journal, further related [S10]-[S12].

POSSIBLE APPLICATIONS

The demonstrated tools give support to the research especially related the modelling and simulation of the distributed generation. As there are various technologies applied in the distributed generation the studies are soon faced to the problem of dealing with this great variety. Based on the literature overview of the dissertation the studies are rather focused on the communication between the units, on the optimal dispatch of a virtual power plant than the description of the behavior of one given DER. Consequently most papers simplify the question above either supposing technology-independent generic units or implementing simple technology-specific algorithms.

The presented state-based approach provides a solution for this problem. The method separates the technological specialties from the selection of the operation state. In fact it converts the complex problem into two smaller tasks: firstly constructing the state-space considering several technical specialties deeply and then implement a generic algorithm to select the most appropriate operation state. The interface between them is the state-space, which is the output of the first task. The introduced agent-programs facilitate to make decision in sequential problem too.

Constructing different state-spaces for each DER the technological specialties can be deeply considered without implementing any special algorithms. The operation of each DER then can be modelled and simulated, or based on the results the day-ahead schedule can be planned by implementing generic algorithm. As the technological specialties are hidden by the state-based approach the researchers can focus the algorithm on the relevant strategic viewpoints of operation. The implementation of the objective function depends on the study (e.g. multi-agent approach for microgrid scheduling, planning the optimal DER portfolio for a given demand). Applying the presented agent-programs based on the state-based approach each agent can represent a DER possessing wind-turbines, solar-cells, or cogeneration units. Considering the energy and local heat demand of a microgrid, the optimal technological distribution of the built-in capacity can be modelled and simulated to make investment decision.

Regarding the Hungarian power system my work gives a tool for the controlling centers. They are continuously monitors their DERs, which typically use gas-engines, spread all over the country. The ancillary services are managed through own dispatching centers receiving the order from the transmission system operators and then dispatching the relevant units to modify their operation. Based on the results of this dissertation (state-based approach, three-step flexible algorithm) deci-

sion-support software can be implemented. Although most units are gas-engines the first thesis generalizes the different type of engines too, not only above the generation technologies. Tuning the formulas and weight of the three-step program, or based on the learnt knowledge, the decision of the dispatcher in the controlling center can be modeled previously in order to demonstrate its effects. Furthermore it provides useful information to the bidding strategy of controlling centers.

Results coming from the learnt knowledge of the agent according to the third thesis are relevant only to the current situation. Predictions based on them are restricted for short-term periods. However these kinds of knowledge can serve information for high-level, multi-agent model of controlling centers. On the models describing the actual situation of DERs the effect of a supposed up- and downloading order can be studied. Giving a determined electric energy setpoint the agent will simulate how the DER can perform the reserve demand:

- how much time is required to reach the given setpoint,
- how much heat is stored in the heat-system and how will it change due to control,
- how many costs will emerge as a consequence of load-changing, or the increased fuel consumption,
- how much the consequent change in the profit that have to be compensated by the income of ancillary services.

Executing the agent program on each DER of the controlling center, the most appropriate one can be selected. In my long-term plan I would like to develop a multi-agent model based on the results of the dissertation to determine the optimal dispatch of controlling centers.

RELATED PUBLICATIONS OF THE AUTHOR

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