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SMART GRID DESIGN FOR EFFICIENT BUILDING MANAGEMENT

ZASNOVA PAMETNEGA OMREŽJA ZA UČINKOVITO UPRAVLJANJE ZGRADB

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Abstract

The existing methods of automated building management are faced with critical challenges in the modern smart grid movement. Remote data transmission, efficient data processing and the ability to adapt rapidly to changes are severely limited as a result of the poor connectivity and rigidity of the existing systems. As an effective solution to such challenges, a new generation of smart microcontroller systems has been designed, which in addition to the above-described factors delivers many new features and holds yet relatively unexplored potentials for further development. The major advantage of these systems is integration with a cloud service that already enables the more efficient management of remote buildings and delivers enhanced user and environment-friendly solutions. In addition, with the quick adaptation ability, these systems also offer effective solutions for new, yet unforeseen, smart building challenges in the future.

In the first part of this article, we present the basic module for controlling an individual smart building and its integration into the wider concept of smart grids and smart city networks: DIALOG EQ microcontroller system, which is aimed at the efficient, distributed management of smart buildings. We describe the process of its development and current capabilities. The basic guideline for the development was user and environment friendliness. The second part is dedicated to the development potentials of the system, the challenges of the future and certain aspects of automatic (machine) learning from the data obtained through the operation of these systems in individual buildings.

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Povzetek

Obstoječi načini avtomatiziranega upravljanja zgradb so v sodobnem trendu pametnih omrežij postavljeni pred pomembne izzive. Prenos podatkov na daljavo, njihova učinkovita obdelava in zmožnost hitrega prilagajanja spremembam so zaradi nepovezanosti in togosti obstoječih sistemov zelo težko uresničljivi. Kot učinkovito rešitev tovrstnih izzivov smo zasnovali novo generacijo pametnih mikrokrmilniških sistemov, ki prinašajo poleg opisanih še veliko novih, tudi še dokaj neraziskanih potencialov za nadaljnji razvoj. Bistvena prednost teh sistemov je povezljivost z oblačno storitvijo, ki že v tem trenutku omogoča bolj učinkovito upravljanje zgradb na daljavo in uporabniku ter okolju bolj prijazno rešitev. Z dodano zmožnostjo hitrega prilagajanja, ponujajo ti sistemi učinkovito rešitev tudi za nove, še nepredvidene izzive pametnih stavb v prihodnosti.

V prvem delu predstavljamo osnovni gradnik upravljanja delovanja posamezne zgradbe in njenega povezovanja v koncept pametnih omrežij in mest – mikrokrmilniški sistem DIALOG EQ, ki je namenjen učinkovitemu porazdeljenemu upravljanju pametnih zgradb tudi na daljavo. Opisujemo proces njegovega razvoja in njegove trenutne zmožnosti. Osnovno vodilo razvoja je bila prijaznost do uporabnika in okolja. V drugem delu pa se posvečamo razvojnim potencialom sistema, morebitnim izzivom prihodnosti ter nekaterim konceptom avtomatskega učenja iz podatkov, pridobljenih pri delovanju teh sistemov v posameznih zgradbah.

1 INTRODUCTION

Buildings are major consumers of energy on a global scale. In developed countries, buildings account for at least a third of all energy consumed. Approximately half of the energy consumption in a building is accounted for by facilities for heating, ventilation and air conditioning (HVAC). Due to this fact, HVAC system is subjected to intensive research and improvements. Unfortunately, this is more a result of rising energy costs than a higher level of environmental consciousness. In spite of this, the fact that buildings' energy consumption and its impact on the environment have never been dealt with as intensely as right now is of great significance.

The field of HVAC systems management in buildings has a few unresolved problems. With the development of technology and knowledge, most of the problems are gradually solved, but some remain quite prominent. The efficiency of HVAC systems is an example of an optimization problem that can be continuously improved. It is influenced by many internal and external factors. Both groups vary considerably among individual buildings. Therefore, it is necessary that the solution consistently adapts to the specific characteristics of each building separately. In doing so, we usually have to satisfy two often contradictory constraints:

- energy consumption,
- user comfort.

Regardless, we always want to consume a minimal amount of energy, but we also have to attempt to meet users' requirements: to ensure their comfort and well-being.

With the help of modern technologies and (above all) smart grids, we can solve many problems in a more efficient, faster and cheaper way. This can be done mainly because of modern concepts of connectivity and accessibility of devices (the so-called “Internet of Things” (IoT)) and device-oriented online data warehouses and services – often generally denoted as “the cloud”.

It is well known that each building has unique characteristics; weather conditions also vary significantly in time and space. Therefore, the adjustment to each case and current weather conditions is inevitable and must be carried out very carefully. A significant step in this direction is a new generation of smart controllers that enable two-way communication between the building and the cloud (Internet) service; therefore, both sides can exchange adequate data about current weather and building status. On this basis, the optimal process control procedure for building management can be determined more efficiently.

The article is structured as follows. The following section presents the basic building block of the proposed smart grid system design for efficient building management: DIALOG EQ (DEQ) HVAC controller. More specifically, it describes its development and current functionalities. The next section includes an analysis of its future potentials in line with the latest findings in the interconnected areas of building management and smart grids. The article is concluded with a short practical demonstration of an example of a contemporary self-learning software model, which is also applicable for efficient building management: Evolving Fuzzy Neural Network (EFuNN). This universal model represents the advanced use of the self-learning paradigm in this field of research interest.

2 SMART GRID BUILDING MANAGEMENT MODULE – DIALOG EQ

PROF.EL Ltd. is a SME that is engaged in research and development in the field of control systems for heating, cooling, ventilation (HVAC) and building management. Since the year 2000, we have had our own production line for controllers. Over the years, we have acquired quite a substantial number of users of our products. In contrast to legacy systems, a new generation of smart controllers must be properly maintained and continuously complemented, if we want to continue to ensure competitiveness and user satisfaction.

Maintenance of building controllers is not an easy task. They are commonly installed in grounded electrical cabinets in dedicated technical rooms. The most effective maintenance would be on the spot, but this is often related to time- and money-consuming logistics. Another possibility is that the controller is removed from the system to be tested in our development laboratory, but only a basic test can be performed outside its native environment. Coping with such problems over the years, we have realized that it would be most effective if controllers could be maintained and tested remotely from our development laboratory. This way, we can also remotely maintain and control the entire structure of various subsystems in buildings.

These needs, as well as the users’ demands, have led to the development of a new generation of smart grid building controllers named DIALOG EQ (DEQ) with the following features:

- remote control operation,
- over-the-network maintenance and upgrades,
- remote monitoring of the operation,
- optimization of control algorithms,
- storage for user and system settings,

- chronological logging of selectable events,
- multi-level access (security),
- multilingual user interface,
- and many other options.

With the DIALOG EQ line of controllers, the majority of tasks became much simpler and cheaper to perform; moreover, substantial time savings can be noted, as a physical presence at the locations of the systems is generally no longer necessary.

2. 1 Development of DIALOG EQ controller

Today, when most of the electronic assemblies (HW) are produced in China for a very low price, the decision to develop one's own product is quite difficult. Furthermore, the market is crowded with a variety of microcontrollers and printed circuit boards. Nevertheless, it is difficult to find a product that offers high-quality production, the possibility of upgrades, longer-term availability, and acceptable pricing. The products that would meet all of the above criteria are practically non-existent. In addition to this fact, we (as developers) are also interested in having a declaration for the product's robustness, electromagnetic compatibility, temperature resistance and the influence of aging on components' speed and their tolerances. However, users are not interested in all of these details; it only matters that the controllers work without problems and can be easily managed.

At the beginning of 2013, we embarked on the development of a microcontroller system, which was named DIALOG EQ (Figure 1) at the end of the project. HW development was entrusted exclusively to local experts who specialized in the development of telecommunications hardware equipment. Standards in the telecommunications sector are much more stringent than standards for industrial and home electronics, which comprise the DEQ. Consequently, telecommunications standards were used to a certain extent. Selection of the microcontroller was not easy. In the end, we chose the ARM-based microcontroller from the Kinetis family (manufacturer Freescale, now NXP). It has the MQX RTOS operating system with integrated TCP/IP stack and other needed software modules (web server, FTP client, etc.).

***Figure 1:** The basic component of smart grid – DIALOG EQ controller*

2. 2 Internet connectivity and cloud services (cloud)

Our development policies included the advantages offered by two rapidly evolving technologies: the Internet of Things (“IoT”) and cloud computing (“cloud”).

The dilemma of whether the DEQ will use the wireless or wired connection to the Internet ended with the selection of the latter. Wireless (Wi-Fi) access is a more “elegant” solution (mostly also less invasive), but in the grounded metal electrical cabinets (where controllers are usually located) wireless signals are often weak or non-existent. In contrast, wired access can be easily extended with Wi-Fi access point or data transmission through domestic electric installation (“Ethernet over Powerline”) to the nearest router.

DEQ can be considered to an IoT device. For such devices, it is vital to work properly as soon as they are connected to the network (“Plug&Play”). If we want to offer direct remote access to DEQ from an external network, the settings for domestic routers and networks can be quite complex. It is much simpler to communicate in the opposite direction; DEQ is programmed to connect automatically to the nearest gateway router and then through the Internet to the chosen cloud service.

Server facilities for our cloud services were hired from a selected provider, who (according to our criteria) offers an acceptable level of safety and reliability. We have registered the dedicated domain name (www.deq.si). In addition to offering cloud services, there is also a central database with all the necessary software modules. Everything is accessible to users through a Web interface application. All communications between the user and the server take place over a secure, encrypted connection (SSL/TLS protocols).

2. 3 User interfaces

Nowadays, users are reasonably entitled to expect simple and user-friendly interfaces from virtually all computing devices. During the development of DEQ, we devoted particular attention to this segment. In order to offer the user the greatest possible freedom in the control and management of the system, we prepared user interfaces for all common devices of an average user: phones, tablets, and laptops. A user can freely choose the device he will use: either a computer with a large screen or a phone/tablet with a small screen. In any case, the user can use the device that is available at the moment or which is the most convenient for him to communicate over the Internet. Since users have different preferences and lifestyles, we have prepared three types of user interfaces in five different languages:

- Local access (LAN)

  There is a local, embedded web server on DEQ and it provides the user with direct access to configuration parameters and a few basic visualization screens. Because of the safety of the local network, the user is not required to enter any special identification. The internal server also works without an Internet connection.

- WEB application (WAN)

  This interface is intended for users with PCs connected to the Internet; they can access the WEB application from anywhere. The program is stored on the cloud server, and the user is required to enter proper password identification. The visual appearance is similar to that of local access but offers a richer graphical representation of the measured data (Figure 2). Data is also available for a shorter amount of time.

- Application for smartphones (Android, iOS, Windows Phone)

A smartphone application has been implemented for users preferring mobile devices. The application only needs to be installed on the phone and provided with proper access credentials. A screenshot of the application is shown in Figure 3.

With such a variety of user interfaces, the user can monitor and manage the heating, cooling, ventilation or any other subsystem or device in his building at any time and from any place.

HP power (%)= 35
Flow (l/min) = 15
Power (W) = 5300
Cons.(W) = 1600
Work. hours = 1415

***Figure 2:** Main screen of the WEB application – www.deq.si*

2. 4 Description and installation of DIALOG EQ

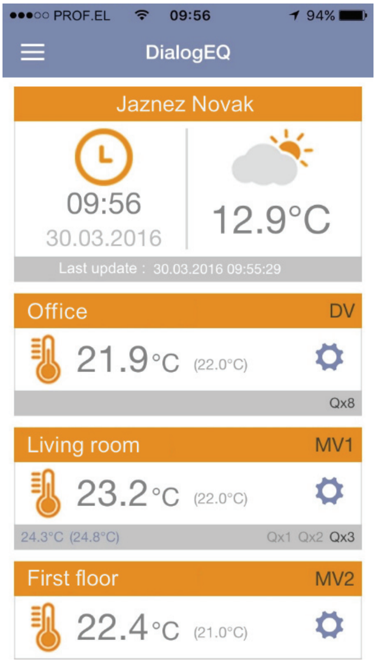
DEQ is designed as a basic block for building automation systems and represents a two-way connection link to the concept of smart grids. In addition to the basic HVAC regulation functions (heating, cooling, ventilation), it can also control other aspects of smart buildings, e.g. illumination, shading, security, and others.

DEQ is essentially a device with the following connectors:

- 20 inputs (16 analog, 4 digital),
- 16 outputs (2 analog and 14 digital).

These connectors are sufficient for most heating, cooling and ventilation control applications. For other smart building segments, DEQ offers local wired connectivity to additional extended automation modules that can connect through CAN or serial buses that are present exclusively for this purpose.

DEQ already embeds software modules for the control of heating and cooling systems (oil and gas boilers, biomass boilers, heat pumps, solar panels) as well as modules for in-building energy distribution (direct and mixing branches). We have also implemented software functions for the measurement of power consumption, the production of heat and electricity, and other functions.



Jaznez Novak

09:56
30.03.2016

12.9°C

Last update : 30.03.2016 09:55:29

Office DV

21.9°C (22.0°C)

Qx8

Living room MV1

23.2°C (22.0°C)

24.3°C (24.8°C) Qx1 Qx2 Qx3

First floor MV2

22.4°C (21.0°C)

Figure 3: *Main screen of the Android smartphone application*

The integrator in the process of DEQ installation only has to select (tick) the appropriate software modules and adjust the values of the selected operating parameters. After purchase, each DEQ user receives the identification code that provides access to the system through the web or mobile applications. Servicemen and technicians receive special service codes that allow them to have a higher level of access rights for setting up the systems they maintain. The user is allowed to change the basic settings (e.g. temperature set points), while the adjustment of systems settings requires a service code access level. DEQ is not freely programmable, so it is even more necessary to adapt the functionality to the user's demands. However, this task can be pursued remotely with minimal cost and effort for the manufacturer and integrators. Software modules simply need to be prepared, selected, transferred and activated.

2. 5 DIALOG EQ and cloud service

During the development process, the effective cooperation and communication between DEQ and the customer were our main goal. At the same time, we were also aware of possible pitfalls related to this standpoint. Nonetheless, the primary task of DEQ is the management of various systems in the building, and it is necessary to ensure adequate priority for this task. Cloud connectivity, remote control, and access certainly affect the stability of the controller. We have tried to minimize such risk to the lowest possible level. Therefore, DEQ establishes communication with the cloud server only once a minute. First, data is uploaded to the server and then a query for any waiting messages is performed. If they exist, they are sent back to DEQ and processed. If this is not the case, DEQ then suspends communication with the server until the next transfer. Any remote changes in DEQ's settings can only happen within the active connection.

To monitor the operation of each DEQ, there is a built-in virtual "black box" device (similar to flight recorders in airplanes) that monitors and logs all events that affect system performance. Circular log memory (FIFO) is large enough to record events in the period of the previous six months. Based on user's choice, the data can also be saved on a cloud server.

The memory for logging alerts and alarms is organized in a similar, circular way. All software modules can generate events, warnings, and alarms at three priority levels:

- "Minor" – lower,
- "Major" – higher,
- "Critical" – the highest.

Remote upgradeability is also one of the strongest features of DEQ. Therefore, we can remotely update the firmware on each DEQ. This is a critical process, because if anything goes wrong, the device could become dysfunctional and require manual intervention. To prevent this, an extended level of safety was implemented for this particular case. Two instances of firmware are constantly saved in external Flash memory: "main" and "backup" FW. If anything goes wrong with the main FW (including corruption), then the backup FW is activated; it connects to the cloud server and enables fixing problems remotely (even repeat remote upgrade process). Main FW damage could theoretically happen in the remote upgrade process although current practice demonstrates the extraordinary reliability of this procedure.

3 SYNERGETIC POTENTIAL OF SMART GRID AND DIALOG EQ IN BUILDINGS

Among the most important aspects of buildings, we must highlight at least two: first, they are the major energy consumers; second, we spend the majority of our everyday life in them (as residential or professional environments). In accordance with the principles of sustainable development, the former energy consumption aspect deserves special attention: it represents one of the most significant impacts of human activity on the environment at present and especially in the future. In addition to the research and development of renewable energy sources, there is also much space for improvement in the optimization of energy consumption in buildings. Of course, we must take into account the fact that we live in buildings, and therefore it is necessary to ensure optimal living conditions. Aspects of energy consumption and user comfort are to some degree in conflict, but both must be considered major factors in the optimization process of building management.

3. 1 Model-based effective management of smart buildings

The common approach to the optimal management of buildings takes into account the two above-mentioned main factors: energy consumption and user comfort. Typically, the major component of the system is a ThermoDynamic Model (TDM) that simulates the operation of the building. The model's main purpose is to predict the building's state or response to various external and internal factors or events. On this predictive basis, more optimal process settings for the acceptable outcome of the regulation process in the building can be found. Examples of the most significant external factors are outside temperature, insulation, the wind, dynamic energy prices, renewable energy sources, etc. There are also many internal factors that are sometimes even more difficult to predict in advance; typical examples include users' presence, needs, and habits, the number of inhabitants, internal heating or cooling resources, etc.

As already explained, for effective building management, we need a model that predicts the impact of all (internal and external) factors on the "internal state" of the building. On this basis, we are able to determine the optimal control or regulation procedure that will satisfy the constraints of user comfort, minimize the energy consumption and the impact on the environment. This approach is quite common today and is denoted as "Model-based Predictive Control" (MPC) of buildings. Since this approach is quite generic, it exists in many different variants, but a common feature to all is to sense the available information from the environment and use predictive model-based regulation procedures (on local or remote computing resources) for optimal control of the smart building *[1, 2]*.

The basic process model

In order to create a good basic model, we usually need domain-specific knowledge about the process or problem. In our case, we also need a more generic model that will be able to adapt to the actual data of a particular building. Doing this, we can utilize only knowledge or actual data aspects individually, or both together. According to this decision, we distinguish three main groups of such models, which are commonly used in the management of buildings:

- Mathematical and physical models ("White Box")

The building's behaviour is modelled using expressions and equations that express the relation and the impact of input data on the output of the model. This approach requires the greatest level of domain-specific knowledge and often results in a quite complex model that is difficult for non-professionals to understand.

- Empirical models ("Black Box")

In this approach, we do not have any predetermined structure or expressions; the model is freely determined according to the existing data. Domain expertise is not required, but it is often difficult to understand or explain the models' predictions. Normally, we do not mind as we can effectively use these models even without an explanation feature.

- Hybrid models ("Grey Box")

This type of model is a combination of "White Box" and "Black Box" models. Here we need less domain-specific knowledge and more extensively empirical data in comparison to "White Box" models. Predetermined, but unknown parameters in expressions are adjusted accordingly to real data from the operation of a specific building. This approach produces simpler models (expressions) that are typically more understandable.

The reader can find more details and comparisons between different groups of models in *[2, 3]*.

Using the basic process model in smart buildings

Thus far, we have mentioned only a few basic aspects of using predictive models for effective building management, especially in terms of energy consumption and user comfort. However, these models contain a more generic potential for further development. Among the most significant potentials, we highlight the following inherent features of predictive models that already are or could be exploited in the near future:

- Modelling the operations of elementary processes and devices

We can form specific predictive models for each elementary process or device in the system. Therefore, we can predict the behaviour of smaller scale devices and make deductions for a whole building's behaviour.

- Detection of irregularities in the operation of elementary processes and devices

Based on the discrepancy between the output of the predictive model and the actual data, we could identify the irregularities or inefficiencies in the operation of devices or elementary processes. This feature could vastly improve the self-diagnostic capabilities of such systems.

- Self-learning and model adjustments during operation

One of the essential features of the self-learning type of predictive models is the ability to adapt to the real situation and data and gain domain-specific knowledge during operation processes. In most cases, there is a huge gap between learning and working environments; therefore, laboratory-based models need to adapt to real operation data continuously. If this is not done, the whole concept can become quite useless in practice.

- Distributed building management optimization based on predictive models

In control theory, we always strive to adjust our actions to the expected outcome, which comes only after some time. Therefore, in this case, the availability of the environment data and accurate prediction is of extreme importance. Both give us the opportunity to perform optimal regulation algorithms regardless of the location of computing resources: local, remote or both (distributed paradigm).

3. 2 The role of smart grids in building management

Efficient building management processes rely on the predictive model(s) and optimal control procedure or (better said) algorithm. To perform both optimally, we also need a large amount of accurate empirical data from actual building operation and both types of influence factors (internal and external). Nonetheless, we need to process data to gain information that is used for adaptation of the models and determination of optimal control procedures. All this usually requires the establishment of sensor networks and the availability of computing resources for the necessary analysis and calculations.

For the optimal performance of the model, we need to obtain accurate data from the environment. In most cases, their resources at a lower level are regulators and controllers of individual processes by themselves. For them, it is vital to provide two-way communication with higher levels of the system management structure. Smart grids offer the arbitrary allocation of computing resources; models and control procedures can be implemented at a local or distant location. In the latter case, the key element is the existence of a connection. This way the buildings can be easily integrated into the broader context of smart grids or smart cities, *[4]*.

DIALOG EQ as a smart grid gateway in the smart building

DEQ is a modern microcontroller-based system that allows the implementation of all the described optimal strategies for the effective management of buildings. It transmits operational data (only with the user's consent) to the cloud service. Currently, data is stored in the cloud database. In the next development cycle, we also plan to process data locally to a certain extent, particularly focusing on the creation of corresponding predictive models and optimal control algorithms for individual buildings.

3. 3 An example of the predictive model for sanitary water heating process

To illustrate our development strategy for the future, we present selected example from preliminary research on the mixed “black and gray” type of predictive model in the form of an Evolving Fuzzy Neural Network (EFuNN) shown in Figure 4. This type of network merges concepts of neural networks and fuzzy logic, *[5]*. More details about preliminary research can be found in *[6]*. Here we will present only a brief summary of the results and a short discussion.

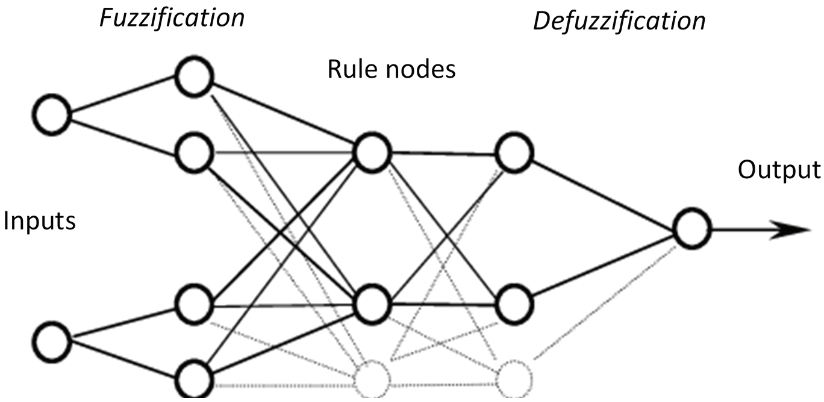


Figure 4. *Architecture of Evolving Fuzzy Neural Network (EFuNN)*

In this selected case, we have modeled the operation of a sanitary water heater (boiler). Cooling of the water is influenced by its surroundings (parameter “ambient temperature”) and consumption (parameter “hot water consumption”) through showers and taps. This parameter was artificially estimated from the derivative of current sanitary water temperature. Its value can only be 1 (on) or 0 (off). Water temperature is increased by the heating process (parameter “water heating”). All these parameters represent the input data to the model (all values except the last, are at time instance t):

• ambient temperature	(in degrees Celsius),
• water heating	(1-heating, 0-inactive),
• hot water consumption	(1-consumption, 0-inactive),
• current hot water temperature	(in degrees Celsius),
• “previous” hot water temperature at time t-1	(in degrees Celsius).

The output of the model predicts the temperature of the water in the boiler at the next time instance t+1. We have tested the performance of the model on two separate datasets. The first dataset covers the period from 20th to 24th of May (spring season), and the second from 9th to 14th of June (early summer season). The first dataset was used as a training set and the second dataset as a test set. The network was initially used in its on-line self-learning mode when processing the first (training) dataset. In this self-learning mode, the network first predicts the value of the output parameter (water temperature at the time instance of t+1) and then learns (adapts) from the actual measured value of the same parameter at the time instance of t+1. The network, therefore, learns and improves with each new vector of input and output parameters. After processing the training set, the network was used to process the test set with slightly different season conditions in the same on-line self-learning mode.

For assessment of model predictions, Root Mean Square Error (RMSE) metrics between predicted and measured values was used. Figures 5 and 6 show RMSE on the discrete time axis for the training and test sets. The time instances on the time axis (t) are uniformly distributed with a spacing of 100 seconds and numbered sequentially (t and t+1 are 100 seconds apart in time). It can be seen that the EFuNN model learns during operation. In both figures, the prediction error is bigger at early time instances and then degrades with time. The graph in Figure 5 shows that after a relatively short time (approximately when t>400), we can obtain quite accurate predictions of water temperature during processing the training dataset. However, if we also check the model's performance on the test set (Figure 6), it is shown that the prediction becomes more accurate even faster. This is surely caused by accumulated knowledge from the training set. We can conclude from both figures that using this acceptably accurate predictive model; we could determine a more optimal control procedure for heating sanitary water that will simultaneously consider user's hot sanitary water needs and energy consumption.

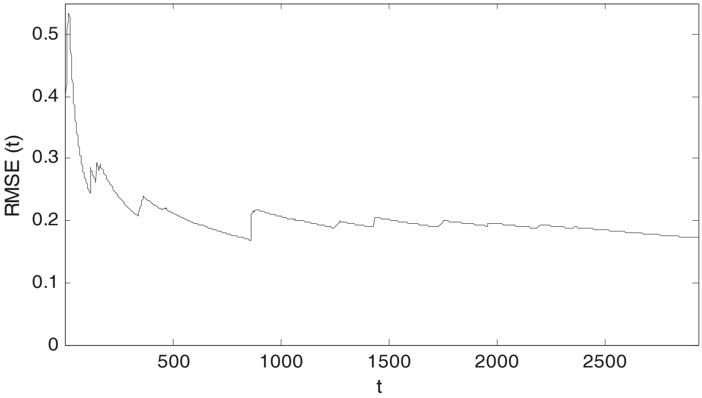


Figure 5. *Root Mean Square Error (RMSE) of EFuNN model prediction on the training set*

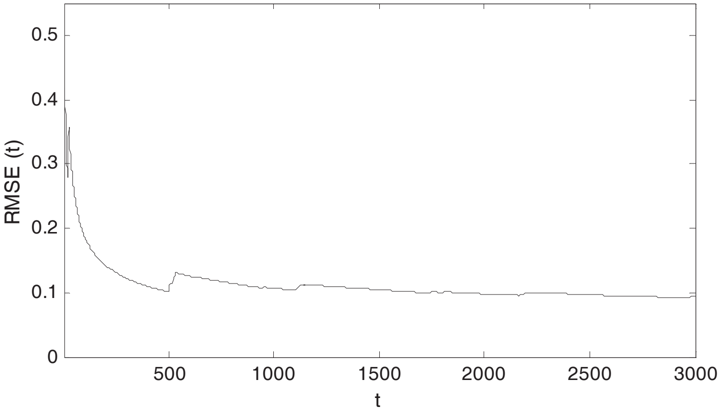


Figure 6. *Root Mean Square Error (RMSE) of EFuNN model prediction on the test set*

4 CONCLUSION

The described smart grid building controller DIALOG EQ is a result of our initial development cycle. In this paper, we have presented the present features of DIALOG EQ and its major development potentials for the future: first in more general and then also in more concrete terms that will influence its further development. Above all, DIALOG EQ is a reliable smart building controller, which is also capable of connectivity to cloud services and acts like an IoT and smart grid gateway. On this basis, it also holds potential for further development and integration of smart buildings, IoT, and smart grids into a common smart network system of the future. During this process, we will continue focusing on synergetic connection points between present and upcoming concepts in this field.

On the applicative side of the development, we will focus primarily on enhancing our cloud and customer service, in the sense of better visualization of the operation, easier control of user parameters, the addition of efficiency analysis, the creation of a thermodynamic model of individual buildings, etc.

The research focus will remain on the efficient creation of thermodynamic models for individual buildings and optimization of the control procedure for each building individually. Furthermore, we will attempt to enhance the efficiency of automatic learning from data, self-detection of malfunctions and inefficiencies of the system and many other aspects of efficient smart building management.

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Nomenclature

t	time
MPC	Model Predictive Control
TDM	ThermoDynamic Model
RMSE	Root Mean Square Error
EFuNN	Evolving Fuzzy Neural Network