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# Dynamic Energy Management System based on the Multi-Criteria Control Strategy

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Abstract: This study gives an overview about the developed Dynamic Energy Management System (DEMS) for complex infrastructures (e.g. idustrial or commercial buildings). The created DEMS provides different working modes and control strategies for energy efficiency enhancement. The DEMS enables improvement of electricity consumption according to ecologic, economic and multi-criteria control strategies. The focus of this study is to present a multi-criteria optimization of electricity consumption for a real office building, based on the usage of the method of mixed-integer linear programming.

**Keywords** : Dynamic Energy Management System, Mixed-Integer Linear Programming, Multi-Objective Optimization, Renewable Energy Sources, Dynamic Electricity Tariffs, Energy Storages.

## 1. INTRODUCTION

The limited primary energy sources together with the continually increasing world energy consumption have provoked rising electricity prices. This in turn leads to more precise consideration of possibilities for energy efficiency improvement. In order to save primary energy sources, minimize $CO_2$ emissions and reduce electricity costs, a more efficient energy usage is needed. This is especially important for the industrial and commercial consumers, where even a small improvement of the energy efficiency provides a large costs saving potential. In order to ensure the energy efficiency enhancement as well as to provide the optimal functioning of new system components, like decentralized energy sources (e.g. wind turbines or Photovoltaic (PV) systems), electrical storages (mobile and stationary) and controllable electrical devices, an effective energy management is required.

This study describes a Dynamic Energy Management System (DEMS) for complex infrastructures (e.g. office or industrial buildings). The developed DEMS is based on the international standard ISO 50001 and has also the new functions. The presented DEMS has different working modes and control strategies to improve the energy efficiency of the whole system, to reduce the electricity consumption and to minimize the electricity costs.

## 2. ENERGY MANAGEMENT SYSTEM

### 2.1 CONCEPT OF ENERGY MANAGEMENT SYSTEM

The energy management is the method for control all kinds of energy (electrical and thermal) within an enterprise. The energy management can be realized with the optimal long-term or short-term programs for purchasing, generation and consumption of energy at the enterprise taking into account the investigation of energy costs, economic factors, energy availability (e.g. by the consideration of renewable energy), etc. [1]. The Energy Management System (EMS) permits to an enterprise to attain its policy commitments, to realize the measures for energy efficiency improvement, to prove the conformity of the system according to the requirements of the international standard ISO 50001 [5]. The standardized EMS provides to an enterprise the continual improvement of energy related performance.

The main concept of an EMS is presented in the Figure 1. The system receives the information from consumers and generators about their actual state. Using this information the EMS makes the prediction for the future states for the main system components and then, based on the actual measurements, evaluates the best working schedules for each system´s component [2]. An effective energy management leads to a reliable energy supply, energy efficiency enhancement, extension of the system´ components lifetime, reduction of operation costs, as well as to the $CO_2$ emissions reduction.

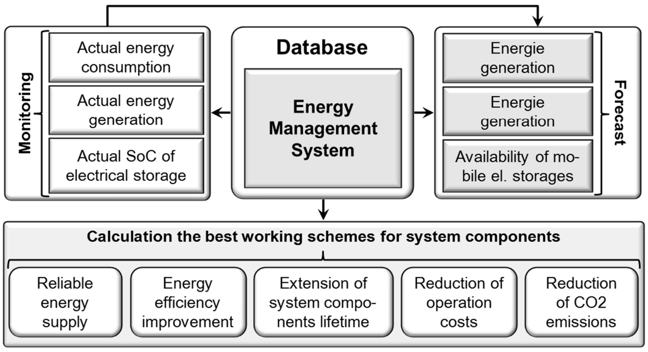

Fig. 1. The main concept of Energy Management System.

The majority of software for energy management applications, that are available on the market, provides chiefly the monitoring of electricity consumption. Only 50% of investigated systems provide the predictions of the future state of system components [3]. The large amount of EMS systems enables relatively simple management of the main system components. Notably, the system measures and analyses the actual electricity consumption of the main system devices. When the peak loads appear, the EMS

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ensures turning off the controllable devices, while during periods of low electricity consumption the EMS activates these consumers. Such management of system components is not always optimal, because some systems has relatively low amount of controllable devices (e.g. some industrial enterprises like aluminum plant etc.), and because it can lead to new peak loads in the system electricity consumption, if a large amount of electrical devices are switched on at the same time.

Because of these facts in order to enable the effective load management inside an enterprise, a Dynamic Energy Management System was developed, which provides the integration of additional energy capacities (like renewable energy sources and electrical storages) and provides the improvement of the total energy consumption due to the different control strategies.

This study gives an overview about the developed working modes and control strategies for DEMS in order to minimize the energy consumption within a building and to improve the work of all system components.

### 2.2 FUNCTIONS OF DYNAMIC ENERGY MANAGEMENT SYSTEM

The developed Dynamic Energy Management System meets not only requirements according to the international standard ISO 50001, but also has the other features [4], [10]. For example, DEMS provides the integration of new system components (e.g. the controllable electrical loads, Renewable Energy Sources (RES) and electrical storages) into the building complex. From the other side the DEMS enables to make the dynamic forecasting of the electricity consumption and electricity generation, which is especially important by renewable energy sources. The prediction functions make it possible to carry out the better planning for future operation of the whole system. Moreover, the DEMS realizes the dynamic optimization of electricity consumption according to the actual electricity tariffs. Such optimization can be carried out due to different control strategies.

### 2.3 WORKING MODES OF DEMS

The developed Dynamic Energy Management System has 3 different working modes: online-monitoring; forecasting; and operation (Figure 2). The “Online-Monitoring” mode provides with measurements about actual electricity consumption and actual energy generation for main system components. Due to this mode the system can realize the load management (disconnection of controllable devices in the periods of peak loads).

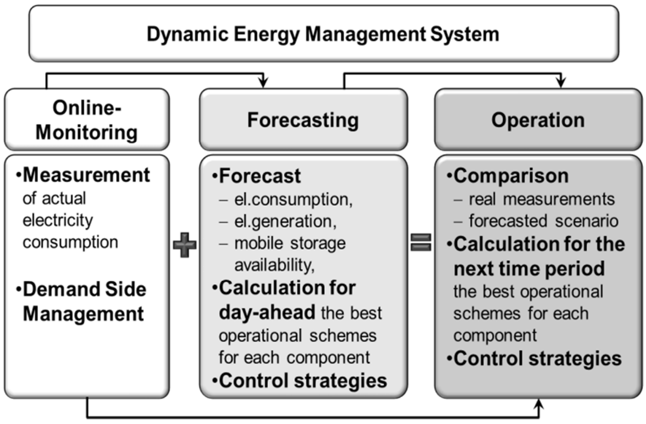

Fig. 2. The working modes of Dynamic Energy Management System.

The working mode „Forecasting“ enables to the system two different options. The first option is the prediction of the future state of system components. The DEMS makes the dynamic forecasting for total electricity consumption, for energy generation, as well as it predicts the availability of electric vehicles that are used in the system as mobile storages. The second option is the usage of the forecasted values of the system components to calculate the best operation schemas for each group of system components (consumers, generators, storages) for day-ahead. The day-ahead calculation of system operation schemas can be realized with different control strategies.

The “Operation” working mode uses the information about actual measurements from “Online-Monitoring” and compares it with the calculations for day-ahead from “Forecasting” mode. Based on this comparison the system calculates the best operational schemes for the next short time period (15 minutes, 1 hour, etc.) for each group of components according to different control strategies. Due to this mode it can be achieved the real-time improvement and optimization in the behavior of main groups of components.

### 2.4 CONTROL STRATEGIES OF DEMS

As it was mentioned above the “Forecasting” and “Operation” working modes use the different control strategies for the calculation of operation schemas for system components. Three different control strategies were developed based on the usage of renewable energy sources and electrical storages. The first control strategy is *economic-oriented*, the second one is *ecologic-oriented* and the third one presents a *multi-criteria* method of system optimization. The main task for all these strategies is to improve the electricity consumption within a building complex. Each control strategy leads to the total electricity consumption minimization and to the reduction of load peaks. However, each strategy has its own features. Thus, the economic strategy provides the electrical storage charging according to the actual electricity tariffs and, due to this fact, minimization of the total electricity costs. The ecologic control strategy ensures the maximal usage of produced renewable energy and, as a result, reduces the greenhouse-gas emissions. The mobile and stationary storages are charged only with produced renewable energy. Because of this fact, this strategy strongly depends on weather conditions and is not always profitable. The results of operating the Dynamic Energy Management System with economic and ecologic control strategies are presented in detail in [4]. The Multi-Criteria Control Strategy (MCCS) looks for the global optimum for the whole system operation according to the different conditions. The Multi-Criteria Control Strategy is described in details in scope of this study.

## 3. MULTI-CRITERIA CONTROL STRATEGY

### 3.1 IDEA OF MULTI-OPTIMIZATION PROCESS

The multi-criteria control strategy makes it possible the system optimization according to different conditions. This control algorithm provides the linearization of electricity consumption, the optimal scheduling of electrical storage charging/discharging processes, the extension of battery lifetime and, as a result, the reduction of system costs. In order to meet all these criteria the concept of multi-objective optimization was used.

The multi-objective optimization composes in its structure several objectives needed to satisfy in order to find the optimal solution. The main definition of multi-objective optimization problem is to determine the vector of decision variables, which meets all objectives and constrains, as well as optimizes a vector of function whose components mean the different objective functions. These different conditions, presented with objective functions, create the mathematical description of performance criteria that often conflict with each other. To optimize means to find such a solution, that will give the values for all objective functions, acceptable to the decision maker [6].

The developed in this study objective function for energy management system composes of the number of objectives and has the following view:

$$F(i) = [f_1(i), f_2(i), f_3(i)] \tag{1}$$

- Objective: minimization of electricity costs for 1 day

$$f_1(i) = min \sum_{i=1}^{t} Cost(i) = \sum_{i=1}^{t} Tariff(i) \cdot P_{grid}(i) \tag{2}$$

- Objective: maximization of the lifetime of electrical storages. It can be achieved with minimization of battery charging/discharging cycles. Thus the objective function will have the following view:

$$f_2(i,j) = min \sum_{j=1}^{n} \sum_{i=1}^{t} \left(N_{ch\,j}(i) + N_{disch\,j}(i)\right) \tag{3}$$

- Objective: mobile storage is fully charged at user defined moment.

$$f_3(i) = C_{end\,j}(i) = C_j \cdot SOC_{max\,j} \tag{4}$$

The following constrains were used:

- Power balance,

$$P_{grid}(i) + \sum_{n} P_{wind}(i) + \sum_{m} P_{PV}(i) - \sum_{j} P_{ch}(i) +$$

$$+ \sum_{j} P_{disch}(i) = \sum_{k} Consumption(i) \tag{5}$$

- Storage energy balance,

$$E_{ch\,j}(i) - E_{disch\,j}(i) = C_{end\,j}(i) - C_{begin\,j}(i) \tag{6}$$

$$E_{ch\,j}(i) = P_{ch\,j} \cdot \eta_j \cdot \frac{T}{n} = U_{ch\,j} \cdot I_{ch\,j} \cdot \eta_j \cdot \frac{T}{n} \tag{7}$$

$$E_{disch\,j}(i) = \frac{P_{disch\,j}}{\eta_j} \cdot \frac{T}{n} = \frac{U_{disch\,j} \cdot I_{disch\,j}}{\eta_j} \cdot \frac{T}{n} \tag{8}$$

- Storage capacity balance,

$$C_{end\,j}(i) = C_{begin\,j}(i+1) \tag{9}$$

- Storage state by charge/discharge,

$$C_{begin\,j}(i=1) = C_{initial\,j} \tag{10}$$

- Storage charging is limited by the maximal storage capacity $SOC_{max}$,

$$E_{ch\,j}(i) + C_{begin\,j}(i) \le C_j \cdot SOC_{\max j} \tag{11}$$

- Storage discharging rate shall not exceed the actual storage capacity,

$$P_{disch\,j}(i) \le \left(C_{begin\,j}(i) - C_j \cdot SOC_{max\,j}\right) \cdot \frac{T}{n} \cdot \eta_j \tag{12}$$

- Control of the consumption value using the value of maximal allowable electricity consumption (MAEC):

$$0.9 \cdot MAEC \le \sum_{k} Consumption_k(i) + \sum_{j=1}^{n} P_{ch_j}(i) -$$

$$- \sum_{j=1}^{n} P_{disch\,j}(i) \le 1.1 \cdot MAEC \tag{13}$$

The boundary conditions used in the simulation are:

$$\begin{aligned}
&0 \le P_{grid} \le \infty \\
&0 \le P_{wind} \le P_{wind\_rated} \\
&0 \le P_{PV} \le P_{PV\_rated} \\
&0 \le P_{ch\,j} \le P_{ch\_rated\,j} \\
&0 \le P_{disch\,j} \le P_{disch\_rated\,j} \\
&C_j \cdot SOC_{min\,j} \le C_{begin\,j} \le C_j \cdot SOC_{max\,j} \\
&C_j \cdot SOC_{min\,j} \le C_{end\,j} \le C_j \cdot SOC_{max\,j} \\
&0 \le MAEC \le Consumption_{max}
\end{aligned} \tag{14}$$

Where:
$C_j$ –capacity of the $j^{th}$ storage,
$C_{begin}$=$C_{initial}$ – capacity of storage at the begin of charging/discharging,
$C_{end}$ – capacity of storage at the end of charging/discharging,
Consumption – consumed power by electrical consumers at the time period *i*,
Cost – one-day operation cost,
$E_{ch}$, $E_{disch}$ – energy needed to charge/discharge the storage during the time period (T/n),
i=1..t is the time period,
$I_{ch}$, $I_{disch}$ – charging/discharging current of the storage,
j=1..n is the number of storages,
k – number of electricity consumers,
MAEC – maximal allowable electricity consumption,
n – number of ticks during 1 hour,
$N_{ch}$, $N_{disch}$ – number of full charging/discharging cycles of the storage,
$P_{ch}$, $P_{disch}$ – charging/discharging power of the storage,
$P_{ch\_rated}$, $P_{disch\_rated}$ – rated charging/discharging power of the storage,
$P_{grid}$ – imported electricity from the grid,
$P_{pv}$ – generated power by PV-systems,
$P_{pv\_rated}$ – rated power, generated by PV-systems,
$P_{wind}$ – generated power by wind turbine,
$P_{wind\_rated}$ – rated power, generated by wind turbine,
$SOC_{min}$, $SOC_{max}$ – minimal/maximal state-of-charge of the storage,
t – time period 24 hours,
T – time period 1hour,
Tariff – electricity tariffs for the enterprise,
$U_{ch}$, $U_{disch}$ – charging/discharging voltage,
η - efficiency of the storage.

The MAEC determines the maximal boundary of electricity consumption that can be reached during the day. This parameter depends from the maximal electricity consumption during the day, available electrical capacity of electrical storages, generated energy (in this case from RES), and electricity tariffs. The calculated value of MAEC shows the maximal electricity consumption that can be bought from the grid with minimal electricity costs. This parameter is very important to control the electricity consumption in order to avoid the new peak loads during the storages charging [4].

### 3.2 CONCEPT OF MULTI-CRITERIA CONTROL STRATEGY

The solution of the multi-objective function finds the good compromises between all objectives and constrains, but does not present the global optimization of the system. In order to determine the global optimum for the whole system the system optimization was realized using the mixed-integer linear programming (MILP). Mixed-integer linear programming is the optimization method that has the objective function as a function of variables and a number of constrains on these variables. In this method objective function and constrains are all linear in form and some or all variables are integer [7], [8]. The mathematic model of mixed-integer linear programming can be written in a common view as follows [9]:

$$min( cx + fy ) \tag{15}$$

$$Ax + By \geq b \tag{16}$$

$$x \geq 0 \tag{17}$$

$$y \geq 0, \quad y \in Z \tag{18}$$

Here:

$c=(c_1, \ldots, c_n)$, $f=(f_1, \ldots, f_p)$ – row-vectors with real numbers that form the coefficients of objective function,

$x=(x_1, \ldots, x_n)^T$ – column-vector with variables of the problem, which has non-negative real values,

$y=(y_1, \ldots, y_p)^T$ – column-vector with variables of the problem, which has non-negative integer values,

A, B – the matrixes ($m \times n$) and ($m \times p$) correspondently with rational values of components, that determine the coefficients in the system with m constraints,

$b=(b_1, \ldots, b_m)^T$ – column-vector with real components of right parts of constrains.

The multi-criteria control strategy presented in this study is based on the mixed-integer linear programing. The optimization is realized with respect to the objective function $f_1$ for electricity costs for 1 day minimization, see (2). The other objective functions are considered as constrains. In such a case the program enables to calculate the global optimum for the whole system.

## 4. STUDY CASE

### 4.1 OVERVIEW OF STUDY SYSTEM

The simulation scenario was considered for the electric network of an office building. The analysis of system consumers presented in [10] has shown that their controllability potential is relatively small. That is why the improvement of total electricity consumption can be achieved using the additional energy capacities, like energy generators and electricity storages. Thus the main components of this building complex can be divided into three main categories:

- electrical consumers (represented as office loads and large system, like ventilation systems, heating systems, air condition systems. The basic electricity consumption for the selected building is about 60 kW and the peak electricity consumption is about 120 kW, see Fig. 3);
- electrical storages (mobile storages represented as 2 electric vehicles with $LiFePO_4$ batteries with a total capacity of 50 kWh together, charging power of 3.7 kW, discharging power of 4.1 kW; and stationary storages represented as 2 Li-ion batteries with a total capacity of 60 kWh, charging power of 3.7 kW, discharging power of 10 kW);
- small energy generators (wind turbine with rated power of about 10 kW and PV-system with rated power of about 33 kW).

The considered office-building is supplied with electricity using the following dynamic electricity tariffs [11]:

- high tariff from 06:00 to 22:00 (for winter it is about 12.4 €ct/kWh, for summer it is about 8,9 €ct/kWh),
- low tariff from 22:00 to 06:00 (for winter it is 7,2 €ct/kWh, for summer it is about 7.0 €ct/kWh),
- peak load price (about 161 €/kW/a).

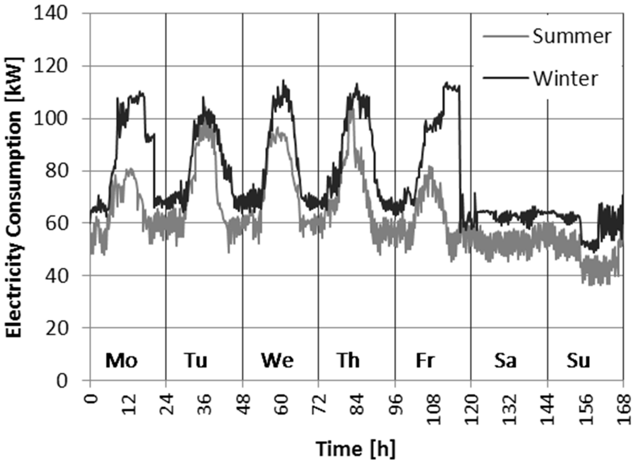

Fig. 3. Electricity consumption in test office-building.

### 4.2 CALCULATION SCENARIO

The calculations were made for every 15 minutes for the 24-hour time period. For calculation the day-ahead optimal working schemes of system components the system uses the information about forecasted data (forecasted values of electricity consumption, generated electricity by renewable energy sources and mobile storages availability) and information about electricity tariffs for determining the optimal value of maximal allowable electricity consumption. After that system makes the optimization of electricity consumption and storages charging/discharging processes using the calculated MAEC.

In order to investigate the simulation principle of MCCS and the calculation of maximal allowable electricity consumption depending on the energy produced by RES, two simulation scenarios were considered. The first case presents a scenario with a large amount of energy generated by the RES, while the second case considered a scenario with a small amount of energy produced by RES.

### 4.3 SIMULATION RESULTS

Figure 4 and Figure 5 present the results of simulations according the multi-criteria control strategy with different scenarios. The blue curve indicates the actual electricity consumption for one day of the real office building; it is equal to 1779.74 kWh. The produced renewable energy is shown with a green curve (for the first scenario it is corresponds to 325.68 kWh and for the second one – only 24.69 kWh). The red curve shows the residual load, which represents the difference between electricity consumption and produced energy by renewables. The light blue line determines the maximal allowable electricity consumption (MAEC), its value for the first scenario is 57.6 % and for the second case it is 71.45 % of maximal electricity consumption. The primary electricity consumption should be optimized according to this boundary, and should be in interval ±10% of this parameter.

The calculation results show, that in both cases the optimized electricity consumption (the dark-blue line) is more linearized. Its value for the first scenario is about 1459.65 kWh it is up to 19.9% lower than the initial one; for the second scenario the optimized electricity consumption has the value about 1774.86 kWh, here the improvement up to 2.6 % is observed. The Table 1 presents the simulation results for the both cases.

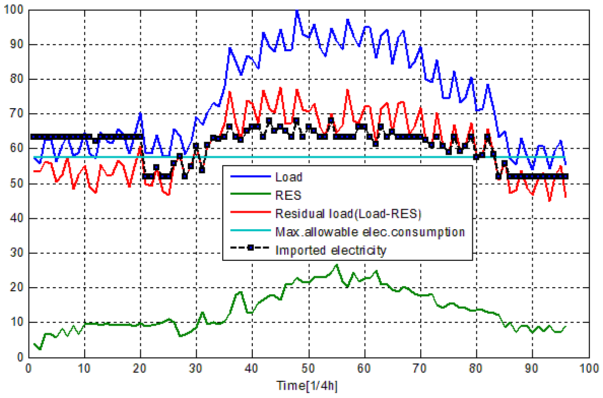

Fig. 4. Simulation results scenario with a large amount of generated renewable energy.

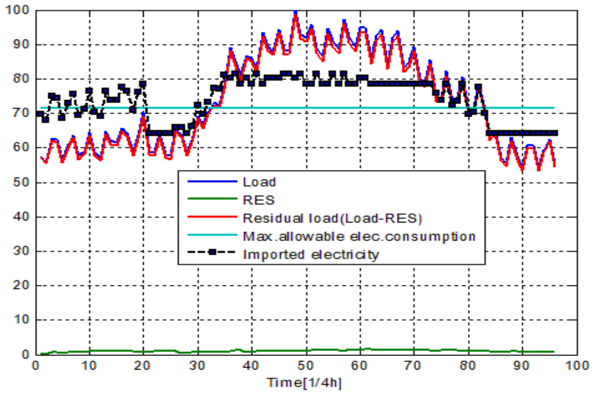

Fig. 5. Simulation results scenario with a small amount of generated renewable energy.

TABLE 1 SIMULATION RESULTS

| **Simulation scenario** | **MAEC [%]** | **Electrical energy for 1 day [kWh]** | | **Improvement compared with primary elec. costs [%]** | **Net costs [€]** |
|---|---|---|---|---|---|
| | | ***generated by RES*** | ***bought from the power grid*** | | |
| Scenario 1 | 57.6 | 325.68 | 1459.65 | 19.9 | 183.33 |
| Scenario 2 | 71.45 | 24.69 | 1774.86 | 2.6 | 223.98 |

## 5. CONCLUSION

This study presents an overview of the developed Dynamic Energy Management System with new functions, which provide the realization of different working modes (online monitoring, forecasting and real-time operation) and control strategies (economic, ecologic, and multi-criteria). The focus of this study is on the multi-criteria control strategy, which provides the calculation of the global optimum for the whole system. The calculation results according to the MCCS were carried out for a test office building. The optimization was realized using mixed-integer linear programming with leading objective function to minimize the electricity costs for one day. The simulation results show that the optimized electricity consumption is more linearized in both scenarios. The reduction in electricity consumption can be achieved up to 19.9 % in the first scenario and up to 2.6 % in the second case.

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