Multi-objective Optimization Model of Source-Load-Storage Synergetic Dispatch for Building Energy System Based on TOU Price Demand Response

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Abstract—The optimized operation of building energy management system (BEMS) is of great significance to its operation security, economy and efficiency. This paper proposed a day-ahead multi-objective optimization model for a BEMS under time-of-use (TOU) price based demand response (DR), which integrates building integrated photovoltaic (BIPV) with other generations to optimize the economy and occupants’ comfort by the synergetic dispatch of source-load-storage. The occupants’ comfort contains three aspects of the indoor environment: visual comfort, thermal comfort, and indoor air quality comfort. With the consideration of controllable load that could participate in DR programs, the balances among different energy styles, electric, thermal and cooling loads are guaranteed during the optimized operation. YALMIP toolbox in MATLAB was applied to solve the optimization problem. Finally, a case study was conducted to validate the effectiveness and adaptability of the proposed model.

Index Terms—Building energy management system; demand response; indoor environmental modelling; multi-objective optimization; synergetic dispatch

I. NOMENCLATURE

\( t \) Time interval
\( n \) The number of lights
\( \phi \) Each light source flux (lm)
\( U \) Utilization factor of the light source
\( M \) Maintenance factor of the light source
\( A \) Illuminated room area (m\(^2\))
\( E_{SET} \) Standard illuminance (lux)
\( R_{eq} \) Room equivalent thermal (°C/W)
\( M_{eq} \) Indoor air equivalent quality (kg)
\( C_p \) Air specific heat capacity(J/(kg·°C))
\( T_{SET} \) Standard temperature (°C)
\( L \) Amount of fresh air (m\(^3\))
\( N_w \) Outdoor \( CO_2 \) concentration (ppm)
\( V \) Volume of the room (m\(^3\))
\( n_{co2} \) Indoor \( CO_2 \) generation at time \( t \) (m\(^3\))
\( L_{FC} \) Fresh air cooling load (kW)
\( \rho \) Air density (kg/m\(^3\))

\( h_w \) Outdoor air enthalpy (kJ/kg)
\( h_n \) Indoor air enthalpy (kJ/kg)
\( d \) Moisture content in the air (g/kg)
\( N_{SET} \) Standard \( CO_2 \) concentration (ppm)
\( \eta_{\text{CHP}} \) Efficiency of MT (%)
\( \eta_l \) Heat loss rate of CHP (%)\( \eta_{\text{GB}} \) Thermal Efficiency of GB (%)
\( \eta_{ch} \) Charge efficiency (%)
\( \eta_{dis} \) Discharge efficiency (%)
\( C_{\text{op}} \) Unit operation costs (¥)
\( C_{\text{SC}} \) Start-up costs of CHP (¥)

\( C_{\text{t}}(t) \) Electricity sale price at time \( t \) (¥/kW)
\( C_{\text{p}}(t) \) Electricity purchase price at time \( t \) (¥/kW)
\( \alpha \) Conversion factor of pollutant \( j \) (kg/kW)

\( \beta_{l,j} \) Emission factor of generation \( i \) for pollutant \( j \) (kg/kW)

\( t_d \) Starting time of deferrable loads (h)
\( x_{l\rightarrow t} \) Amount of deferrable load shift from time \( l \) to \( t \) (kW)
\( x_{t} \) Amount of deferrable load at time \( t \) before optimization (kW)
\( E(t) \) Indoor illumination at time \( t \) (lux)
\( T_{room}(t) \) Indoor temperature at time \( t \) (°C)
\( T_{out}(t) \) Outdoor temperature at time \( t \) (°C)
\( Q(t) \) Heat transferred from indoor at time \( t \) (J)
\( N(t) \) Indoor \( CO_2 \) concentration at time \( t \) (ppm)

\( P_{l}(t) \) Total electrical load power at time \( t \) (kW)
\( P_{\text{CHP}}(t) \) Electric power output of CHP at time \( t \) (kW)
\( P_{\text{P}}(t) \) BIPV power output at time \( t \) (kW)
\( P_{\text{EX}}(t) \) Interactive power with grid at time \( t \) (kW)
\( P_{\text{ES}}(t) \) Electric power output of EES at time \( t \) (kW)
\( E_{\text{ES}}(t) \) State of charge (SOC) for EES at time \( t \) (kW)

\( C_{\text{ES}}(t) \) Cost of EES at time \( t \) (¥)
\( \zeta_{\text{ES}} \) Cost coefficient of investment and loss for EES at time \( t \) (¥/kW)
This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2017.2781639, IEEE Transactions on Industry Applications

reliability and economy [3]. The building energy system kinds of information so as to ensure the operation safety, control the energy flow in the building through different energy management system (BEMS) is to manage and imminent, especially in the situations of energy crisis and building energy saving and efficiency improvement are energy consumption of buildings [1]. Consequently, a deal of buildings emerged, resulting in the increase of storage devices should be concentrated in the process of when the energy price is high. But the investment and loss during valley-load period or when the energy price is low, adds to the building’s operation optimization [11]. The dual-role (load addition, energy storage also plays a significant role in smart building integrated photovoltaic (BIPV) in modern buildings even more complicated due to the widely adoption of With the application of renewable energy sources [5], it is considered as a whole and optimized simultaneously [4]. The main function of building energy management system (BEMS) is to manage and control the energy flow in the building through different kinds of information so as to ensure the operation safety, reliability and economy [3]. The building energy system (BES) is complicated because that the structure, service and management are closely connected and have to be considered as a whole and optimized simultaneously [4]. With the application of renewable energy sources [5], it is even more complicated due to the widely adoption of building integrated photovoltaic (BIPV) in modern buildings for its eco-friendly and economic characteristics [6].

In order to improve the efficiency of BES, the optimal dispatch of generation from different technologies or loads is necessary and very important during the operation. The optimal operation of buildings is influenced by many factors. The output of photovoltaic (PV) is random because of the variation of weather conditions [7], which affect the dispatch accuracy greatly. As a result, improving the forecasting precision of PV output is an important premise for the follow-up work [8]. And as the development of demand response (DR), the demand side has to be considered to improve the system reliability [9]-[10]. In addition, energy storage also plays a significant role in smart building’s operation optimization [11]. The dual-role (load and source) of storage could realize peak-load shifting. That’s to say, energy storage devices are able to store energy during valley-load period or when the energy price is low, and export the stored energy during peak-load period or when the energy price is high. But the investment and loss of storage devices should be concentrated in the process of realizing the optimal operation for BEMS.

Researchers around the world have devoted much effort to study the optimized operation of BES and gained a lot of achievements [12]-[14]. A distributed management method for BES was proposed using multi-agent system to improve the energy efficiency and reducing energy costs [15]. Andrea Staino etc. presented a cooperative optimization approach for a group of buildings to realize economic operation and load reduction [16]. A model of BEMS considered the occupants’ comfort and the energy consumption was raised in [17]. Reference [18] integrated the plug-in hybrid electric vehicle (PHEV) into energy and comfort management in a smart building environment. All the studies achieved good results in setting BESs and operational situations, but limitations about the system economy are also existed especially with the penetration increase of renewable energy and the development of DR.

The overall optimization objective of BEMS is to meet occupants’ comfort while reduce energy consumption and improve economy for the whole system [19]. However, BES is a highly complex system and the uncertainties of BIPV’s output and load fluctuation directly affect the economic operation of BES. The problem is that the existing researches usually focus on the single optimization of sources (power supplies) or simple coordination between sources and energy storages. That means the advantages of synergetic dispatch of source-load-storage are not spared, which is important to the optimal operation of BEMS exactly. For example, when the output of BIPV is low in rainy days, other power supplies should export more energy if the storages and loads are not considered into the optimization. This is not economic or even infeasible when the cost of other power supplies is high or the output has reached the upper limit. At this time, the storages and loads are both effective means to maintain power balance if the synergetic dispatch of source-load-storage is adopted. In addition, the type of units integrated into BES is not enough compared with actual situation and the models of each unit are relatively simple, resulting in discrepancies between actual operation and mathematic model. Consequently, the optimized operation of BEMS could not be realized. On the other hand, controllable loads are usually considered as the participants for DR in existed studies, while the deferrable loads are ignored sometimes. However, deferrable loads also play an important role in DR programs and have become an effective means to improve the system economy [20], especially with the large-scale applications of different domestic appliances. So the function of deferrable loads should also be included in BEMS. Furthermore, as one of the development tendencies, time-of-use (TOU) is necessary to be considered as the operational environment for BES.

In this paper, the operation economy and occupants’ comfort level are considered at the same time for a residential building. Based on the prediction of BIPV’s output, non-controllable loads and outdoor temperature, this paper established a multi-objective optimization model with relevant constrains to improve the system economy and guarantee the occupants’ comfort simultaneously through the synergetic optimized dispatch of sources, loads and storage devices.
On the basis of the loads classification in the building, DR was carried out effectively in the conditions of TOU price. The occupants’ comfort level is described by the indoor environment, which was established by the construction of three most important factors for building indoor environment: visual comfort, thermal comfort and indoor air quality comfort. YALMIP toolbox in MATLAB was chosen to solve the model for its convenience and quickness. The main contributions of this paper can be summarized as follows:

(1) We propose a multi-objective optimization model for BEMS to optimize the system economy and occupants’ comfort by a synergetic dispatch of source-load-storage. BIPV is integrated into the building.

(2) We consider the function of controllable loads and deferrable loads in economic operation and power balance under TOU price. Then the consumption behavior variation of users is analyzed.

(3) We validate the proposed model by simulation from two aspects: one is the comparison between synergetic and non-synergetic dispatch of source-load-storage; another is the comparison between TOU and non-TOU price. The results demonstrate the effectiveness of the presented model.

The remainder of this paper is organized as follows. In Section III, the studied BES was described in detail. In Section IV, the models of indoor environment and comfort level parameters were presented. Then Section V proposed BES’s optimization model, including the optimization objectives and constraints. Section VI provided a simulation analysis and a conclusion was given in Section VII.

III. THE BUILDING ENERGY SYSTEM

The BES considered in this paper is a hybrid energy system which consists of different sources, loads and storages. Specifically, the sources include BIPV, utility grid, controllable generations such as combined heat and power (CHP) system and gas boiler (GB). Storage devices are composed of electricity energy storage (EES) and thermal energy storage (TES). Loads are consisted of electrical load (EL), thermal load (TL) and cooling load (CL). And the system CL is composed by indoor cooling load (ICL) and fresh air cooling load (FACL) which are supplied by electric compression refrigeration (ECR) combined with absorption refrigeration (AR). The structure of the BES in this paper is shown in Fig. 1.

A. Building Integrated Photovoltaic (BIPV)

BIPV is a new concept for solar power application and an advanced form of photovoltaic power generation integrated in buildings [21]. It has higher requirements for PV modules which not only need to meet the functional requirements of photovoltaic power generation but also need to take the basic functional requirements of the buildings into account. The power output of photovoltaic system changes with the seasons, weather, solar radiation, temperature and other factors, which is very unstable and difficult to adjust according to actual demands [22].

Thus, forecasting the output power of photovoltaic generation system is one of the foundations for the optimization of BES.

B. The Model of Controllable Generations and Storage Devices

CHP system, which uses micro turbine (MT) as the motive device, could provide electrical power and utilize waste heat to meet the heating or cooling load demand of buildings at the same time [23].

The model of CHP system can be expressed as:

\[ Q_{CHP}(t) = \frac{P_{CHP}(t)(1 - \eta_{CHP} - \eta_{ICL})}{\eta_{CHP}} \]  

\[ V_{CHP}(t) = \frac{P_{CHP}(t)\Delta t}{\eta_{CHP} \times LHV_{NG}} \]  

\[ C_{CHP} = \sum_{t=1}^{24} P_{NG} \times V_{CHP}(t) \]  

In (1), heat power output of CHP at each time is obtained through efficiency of MT and the electricity power output of CHP at the time. Natural gas consumption at each time by CHP is calculated in (2) via calorific volume of natural gas, efficiency of MT and electricity power output at the time. The results of (2) along with natural gas price are used to achieve the CHP fuel cost \( C_{CHP} \) for a day in (3).

GB coordinates the CHP system to meet the TL demand of the building and the mathematical model can be expressed as:

\[ Q_{GB}(t) = R_{GB} \times \eta_{GB} \]  

\[ V_{GB}(t) = \frac{Q_{GB}(t)\Delta t}{\eta_{GB} \times LHV_{NG}} \]  

\[ C_{GB} = \sum_{t=1}^{24} P_{NG} \times V_{GB}(t) \]  

The equations of (4) – (6) are applied to calculate the daily GB operation cost. In (4), heat power output of GB is obtained by using the heat efficiency of GB and rated heat of boiler. Finally, by results of (5) as well as gas price, the daily fuel cost of GB is calculated in (6).
Energy storage devices including EES and TES play a dual role as source and load. They could coordinate the imbalance between power supply and load demand within the system, improve system reliability and economy [24].

It should be noted that the impact of capacity loss (such as battery degradation) to investment recovery period must be considered in capacity configuration. That’s to say, a dynamic available capacity that decreases over time instead of a fixed capacity should be included in the mathematical model calculating the return of investment. And this feature could refer to the test data of battery making corresponding estimations. On the other hand, the influence of battery’s capacity degradation on operation is a relatively slow in terms of short-term time scale for operation. However, the battery’s actual available capacity needs to be measured, estimated and modified regularly so as to update the model parameters to prevent the impacts on BES’s operation. The investment and loss of storage devices should be considered as part of the cost of BES in related mathematical models.

The equations (7)–(8) present the EES model and equations (9)–(10) express the TES model. In (7), the SOC for EES is calculated and the hourly cost of EES operation is given in (10):

\[
E_{\text{EES}}(t) = E_{\text{EES}}(t-1) - \frac{P_{\text{EES},\text{ch}}(t)}{\eta_{\text{ch}}} + P_{\text{EES},\text{dis}}(t)\Delta t \quad (7)
\]

\[
C_{\text{EES}}(t) = \frac{\epsilon_{\text{EES}}}{\eta_{\text{ch}}} \left| P_{\text{EES},\text{ch}}(t) \right| + \left| P_{\text{EES},\text{dis}}(t) \right| \Delta t \quad (8)
\]

\[
H_{\text{TES}}(t) = H_{\text{TES}}(t-1) - \frac{Q_{\text{TES},\text{ch}}(t)}{\eta_{\text{ch}}} + Q_{\text{TES},\text{dis}}(t)\Delta t \quad (9)
\]

\[
C_{\text{TES}}(t) = \frac{\epsilon_{\text{TES}}}{\eta_{\text{ch}}} \left| Q_{\text{TES},\text{ch}}(t) \right| + \left| Q_{\text{TES},\text{dis}}(t) \right| \Delta t \quad (10)
\]

C. Load Classification

According to the characteristics, the loads in the buildings can be divided into non-controllable loads and loads that could participate in DR. The latter can be further split into controllable loads and deferrable loads, which are both important variables to optimized operation. And these two types of loads are also the concentration of this paper.

The energy consumption of controllable loads, such as lights and air conditioning, accounts for about 70% of building’s total consumption [25]. Deferrable loads mainly refer to the loads whose operation time could be adjusted, such as washing machines, disinfection cabinets and dishwashers etc. By altering the starting time of deferrable loads in appropriate period, the overall economy could be improved without changing their basic electric characteristics.

IV. INDOOR ENVIRONMENT MODELLING

In order to understand the optimization procedure preferably, a room model is shown in Fig. 2 and assuming that all the rooms were the same.

The room is an environment with a rectangular plan whose length is 20m, the depth is 10m, and the height is 3m. There are four windows in the room whose length is 1.2m and height is 1.5m.

Visual comfort, thermal comfort and indoor air quality comfort are the three basic factors that determine the environmental conditions in a building. In detail, indoor illumination level can be taken as the index for visual comfort [26]. The thermal comfort in a room is determined by the indoor temperature. CO₂ concentration is an index for evaluating the indoor air quality that can be improved by the ventilation system generally.

A. Visual Comfort

For the lighting equipment whose luminance could be adjusted, its power can be continuously changed within a certain range. That is to say, the indoor illumination will vary with the power change of lighting devices. The indoor illumination index can be expressed as:

\[
E(t) = n \cdot \frac{P_{\ell}(t) \cdot q_{w} \cdot U \cdot M}{A} \quad (11)
\]

Visual comfort index is represented by indoor illumination that changes within an acceptable range that was set by users:

\[
D_{v}(t) = 1 - \left( \frac{E(t) - E_{\text{SET}}}{E_{\text{SET}}} \right)^{2} \quad (12)
\]

where \(D_{v}(t)\) represents the visual comfort at time \(t\).

B. Indoor Air Quality Comfort

To maintain a good indoor air quality, the indoor CO₂ concentration must be remained stable and the ventilation system must provide a certain amount of fresh air into the room. The mathematical relationship between indoor CO₂ concentration and the amount of fresh air can be expressed as (13):

\[
N(t) = N(t-1) + \frac{L \times (N_{w} - N(t-1)) + V \cdot \Delta t}{V} \quad (13)
\]

And the model of fresh air cooling load is in (14):

\[
L_{\text{FAC}} = \rho \times L \times (h_{\text{o}} - h_{\text{i}}) \quad (14)
\]

where \(h_{\text{o}}\) and \(h_{\text{i}}\) are outdoor and indoor air enthalpy, respectively and both can be calculated by (15):

\[
h(t) = 1.01 \times T(t) + \frac{d(t)}{1000} \times (2500 + 1.84 \times T(t)) \quad (15)
\]

Indoor air quality comfort index is represented by indoor CO₂ concentration and it changes within an acceptable range that was set by users shown in (16):

\[
D_{a}(t) = 1 - \left( \frac{N(t) - N_{\text{SET}}}{N_{\text{SET}}} \right)^{2} \quad (16)
\]

where \(D_{a}(t)\) represents the indoor air quality comfort at time \(t\).
C. Thermal Comfort

Air conditioning is regarded as a “black box” whose internal structure is unknown when considering the energy consumption. The mathematical relationship among energy consumption of air conditioning, indoor temperature, and outdoor temperature is shown in (17):

$$T_{room}(t) = T_{room}(t-1) + \frac{R_{eq}}{M_{air}}\times Q(t)$$

(17)

And room equivalent thermal $R_{eq}$ is calculated by (18) via wall thermal and window thermal of the room:

$$R_{eq} = \frac{R_{wall}\times R_{window}}{R_{wall} + R_{window}}$$

(18)

The thermal comfort index is represented by indoor temperature and it changes within an acceptable range that was set by users which is presented in (19):

$$D_3(t) = 1 - \left(\frac{T_{room}(t) - T_{SET}}{T_{SET}}\right)^2$$

(19)

where $D_3(t)$ represents the thermal comfort at time $t$.

V. OPTIMIZATION MODEL

The operation objective of BEMS is to maximize the energy economy meanwhile guarantee the occupants’ comfort. Based on the prediction of BIPV’s output, non-controllable loads and outdoor temperature, BEMS optimizes the operation of all components of the system and proposes a synergetic dispatch scheme of source-load-storage in the presence of different physical constraints and TOU price. In this paper, the optimized results contained the power output of controllable generations, the power exchanged with utility grid, storage charge/discharge energy, the power of deferrable load, and three indoor environment parameters. The whole optimization is shown in Fig. 3.

**A. Economic Optimization Objective**

The economic objective is to minimize the total daily operational cost [27]. It includes: the fuel cost of CHP and GB; the operation and maintenance cost of BIPV, CHP and GB; the start-up cost of CHP and GB; the cost of electricity purchased from the grid and the revenue from electricity sold to the grid; the environmental conversion cost of utility grid, CHP and GB; the investment and loss cost of EES and TES. The total cost can be calculated in (20):

$$C = \sum_{t=1}^{24} [C_{CHP}(t) + C_{GB}(t) + C_{OM}(t) + C_{SC}(t) + C_{EX}(t) + C_{ES}(t) + C_{ES}(t)]$$

2) Operation and maintenance cost includes the operating and management cost of BIPV, CHP and GB which shown in (23):

$$C_{OM}(t) = \sum_{j=1}^{3} P_j(t)C_{mi}$$

2) Start-up cost of controllable generations can be expressed in (24):

$$C_{SC}(t) = max(0, U(t) - U(t - 1))C_{SC}^U$$

(24)

where $U(t)=1$ when CHP or GB is under working condition, otherwise $U(t)=0$.

4) Grid interactive power cost can be expressed by electricity sale income and purchase cost in (25):

$$C_{EX}(t) = sC_{BES}(t)P_{BES}(t) - (1-s)C_{BES}(t)P_{BES}(t)$$

(25)

5) Environmental conversion cost includes the cost of utility grid, CHP, GB and the pollutants that require conversion are $CO_2$, $SO_2$ and $NOx$. The conversion factors and emission factors are shown in Table I. $C_{ES}(t)$ is expressed in (26):

$$C_{ES}(t) = \sum_{j=1}^{3} \sum_{i=1}^{3} \alpha_j\beta_{i,j}\mu_i(t)$$

(26)

B. Comfort Optimization Objective

The occupants’ comfort is determined by three basic comfort factors as shown in Section IV.

The general dispatch objective is to maintain the comfort value within a reasonable range in different conditions and the total comfort level can be expressed in (27):

$$D = \sum_{t=1}^{24} \alpha D_1(t) + \beta D_2(t) + \gamma D_3(t)$$

(27)

where $D$ represents the total comfort objective in an optimization cycle, among which $\alpha$, $\beta$, $\gamma$ are set by users [28] according to their own preferences and satisfy $\alpha + \beta + \gamma = 1$. 

Fig. 3. Optimization overview of BEMS
\[
\begin{array}{|c|c|c|c|}
\hline
\text{Type} & \text{Conversion Factors} & \text{Emission Factors} \\
& (\text{kg/kWh}) & (\text{kg/kg}) \\
\hline
\text{CO}_2 & 6.65 & 0.1995 \times 10^{-3} & 0.2469 \times 10^{-5} & 0.0997 \times 10^{-1} \\
\text{SO}_2 & 2.735 & 1 \times 10^{-6} & 0.5 \times 10^{-4} & 0.556 \times 10^{-9} \\
\text{NO}_x & 2.12 & 0.55 \times 10^{-9} & 0.444 \times 10^{-8} & 0.278 \times 10^{-9} \\
\hline
\end{array}
\]

\textbf{C. The Overall Optimization Objective}

In multi-objective optimization problems, the objectives to be optimized are usually in conflict with each other. In this paper, the weighted aggregation method is utilized to transfer a multi-objective optimization into a single optimization objective. The overall optimization objective is expressed as:

\[
\min F = \mu C + (1 - \mu) \frac{1}{D}
\]  
(28)

where \(\mu\) is the weight between economy and comfort level which is set by the users according to their actual demand.

\textbf{D. Operation Constraints}

1) Power Balance

In each dispatch interval, the total energy consumption including electrical, heating, and cooling load should be equal to the energy supplied by the power sources which are presented in (29), (30), and (31), respectively:

\[
P_i(t) = P_{\text{PV}}(t) + P_{\text{CHP}}(t) + P_{\text{EES}}(t) + P_{\text{EX}}(t)
\]  
(29)

\[
Q_L(t) = Q_{\text{CHP}}(t) + Q_{\text{GB}}(t) + Q_{\text{TES}}(t)
\]  
(30)

\[
R_i(t) = R_{\text{SH}}(t) + R_{\text{ECR}}(t)
\]  
(31)

2) Power Output Constraints

The output of each equipment should not exceed the power or capacity range. Equation (32) is the limitation of CHP power production, limitation of power exchange with grid is in (33). Minimum and maximum electric output power of EES, heat output of TES and GB are in (34) – (36), respectively.

\[
P_{\text{CHP max}} \geq P_{\text{CHP}}(t) \geq P_{\text{CHP min}}
\]  
(32)

\[
P_{\text{EES max}} \geq P_{\text{EES}}(t) \geq P_{\text{EES min}}
\]  
(33)

\[
Q_{\text{TES min}} \geq Q_{\text{Gib}}(t) \geq Q_{\text{TES max}}
\]  
(34)

\[
Q_{\text{GB min}} \geq Q_{\text{Gab}}(t) \geq Q_{\text{GB max}}
\]  
(35)

3) Capacity Constraints

Energy stored in the storage devices at time \(t\) is equal to the amount stored at time \(t-1\) minus the energy discharged or plus the energy charged. The stored energy in EES and TES cannot exceed the designed range which are presented in (37) and (38), respectively:

\[
E_{\text{EES min}} \leq E_{\text{EES}}(t) \leq E_{\text{EES max}}
\]  
(37)

\[
H_{\text{TES min}} \leq H_{\text{TES}}(t) \leq H_{\text{TES max}}
\]  
(38)

4) Starting Time and Deferrable Amount Constraints

The starting time of deferrable loads must change within the time interval that the users defined according to (39) – (41) [29]:

\[
t_{\text{d min}} \leq t_{\text{d}} \leq t_{\text{d max}}
\]  
(39)

\[
x_{t-1} \geq 0
\]  
(40)

\[
\sum_{t} x_{t-1} = x_t
\]  
(41)

5) Indoor Environment Parameters Constraints

Indoor environment parameters including indoor illumination, temperature, and \(\text{CO}_2\) cannot exceed the defined range set by the users during the optimization process according to (42) – (44), respectively:

\[
E_{\text{min}} \leq E(t) \leq E_{\text{max}}
\]  
(42)

\[
T_{\text{room min}} \leq T_{\text{room}}(t) \leq T_{\text{room max}}
\]  
(43)

\[
N_{\text{min}} \leq N(t) \leq N_{\text{max}}
\]  
(44)

\textbf{VI. SIMULATION ANALYSIS}

\textbf{A. Simulation Environment}

1) Hardware Environment

All the simulations are carried out by MATLAB and run on an Intel Core i3-2310M CPU @ 2.10 GHz computer with a 4 GB RAM.

2) Software Environment: YALMIP Toolbox

According to the established model above, it’s obvious that the optimized operation of BEMS is a multi-constraint nonlinear optimization problem. For the past few years, intelligent algorithms instead of traditional optimization algorithms are generally adopted [30]. But the model in this paper contains many variables and constraints. As a result, it is very difficult to design an intelligent algorithm program code that is able to deal with all these variables and constraints effectively. A little negligence or error may lead to a terrible convergence and search performance, which is fatal to an optimization problem. YALMIP is a toolbox that integrates different optimization algorithms in MATLAB with the following advantages:

- YALMIP is convenient for users to describe variables and constraints with easy program statements, which save the time for programming and ensure a high accuracy;
- YALMIP could detect what kind of optimization problem the user has defined automatically, and select a suitable solver based on this analysis. If no suitable solver is available, YALMIP tries to convert the problem to be able to solve it. This characteristic avoids the drawback of artificial algorithm selection.

Based on these advantages, YALMIP is selected to solve the model in this paper. More details can be found in [31].

\textbf{B. Results Analysis}

The controllable loads in the simulation include lightings and air conditionings, while the deferrable loads contain washing machines, disinfection cabinets and dishwashers [32].
TOU price has been considered as the operation environment of BES. The system operating parameters are shown in Table II and parameters of deferrable loads are shown in Table III.

Assuming that the house wall is equivalent to building brick whose thickness is 240 mm and the windows are equivalent to glass whose thickness is 10 mm. The thermal conductivity of house wall and windows are 0.69 W/(m·K) and 1.09 W/(m·K), respectively.

Other parameters of the optimization model are listed in Table IV.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>SYSTEM OPERATING PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Supply</td>
<td>Output Power Limit/kW</td>
</tr>
<tr>
<td>BIPV</td>
<td>0</td>
</tr>
<tr>
<td>CHP</td>
<td>0</td>
</tr>
<tr>
<td>GB</td>
<td>0</td>
</tr>
<tr>
<td>EES</td>
<td>-3</td>
</tr>
<tr>
<td>TES</td>
<td>-5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE III</th>
<th>DEFERRABLE LOADS PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Power(kW)</td>
</tr>
<tr>
<td>Washing machine</td>
<td>0.4</td>
</tr>
<tr>
<td>Disinfection cabinet</td>
<td>0.7</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE IV</th>
<th>OTHER PARAMETERS OF THE OPTIMIZATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>n</td>
<td>20</td>
</tr>
<tr>
<td>Φ</td>
<td>5000</td>
</tr>
<tr>
<td>U</td>
<td>0.8</td>
</tr>
<tr>
<td>M</td>
<td>0.8</td>
</tr>
<tr>
<td>v_{CO2}</td>
<td>0.000056</td>
</tr>
<tr>
<td>P</td>
<td>1.2</td>
</tr>
<tr>
<td>A</td>
<td>200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE IV</th>
<th>INDOOR ENVIRONMENTAL PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Initial</td>
</tr>
<tr>
<td>Illuminance/lux</td>
<td>320</td>
</tr>
<tr>
<td>Temperature/℃</td>
<td>25</td>
</tr>
<tr>
<td>CO₂/ppm</td>
<td>800</td>
</tr>
</tbody>
</table>

The initial values of indoor environment parameters, standard setting values and user’s allowable variation range are shown in Table V, including illuminance, temperature and CO₂ concentration indexes. In order to validate the model, three different scenarios were designed according to weather conditions: sunny, cloudy and rainy. The TOU price adopted in this paper is shown in Fig. 4 and basic prediction values for the optimization are shown in Fig. 5.

In terms of the optimization model established in this paper, the objective function can be expressed by the decision variables as:

\[
\min F = g(P_{BIP}, P_{GB}, P_{PV}, P_{EX}, P_{EES}, Q_{TES}, E_{room}, N) \tag{45}
\]

The optimization model was solved by the YALMIP toolbox in MATLAB. The whole optimization process can be represented as:

1. Get the predicted values including BIPV’s output, uncontrollable EL and outdoor temperature.
2. Run the YALMIP toolbox according to the objective function and corresponding constraints.
3. Obtain the optimization results such as the power outputs of controllable generations, power exchanged with utility grid, storage charge/discharge, controllable load power, deferrable load power and indoor environment parameters.
The optimization results in different scenarios for EL, TL, CL and storage devices are shown in Fig. 6~9, respectively. As we can see in Fig. 6, EL was mainly supplied by the utility grid when the TOU price was low, and the CHP system ran on full power state when the TOU price was expensive. The optimization results are consistent to the objective that aims to maximize the system economy. In Fig. 8, the CL was mainly satisfied by AR and the shortfall of CL was met by ECR. AR could make use of the waste heat produced by CHP and has a series of advantages such as low cost and high energy efficiency, which is in line with the economic optimization goal. Thus, AR was prior in the operation process.

The optimization results for indoor environmental parameters and deferrable loads are shown in Fig. 10~12, and Fig. 13, respectively.

![Fig. 6. The optimization results for EL balance](image)

![Fig. 7. The optimization results for TL balance](image)

![Fig. 8. The optimization results for CL balance](image)

![Fig. 9. The optimization results for storage devices’ states](image)

![Fig. 10. The optimization results for indoor temperature parameters](image)

![Fig. 11. The optimization results for indoor visual parameters](image)

![Fig. 12. The optimization results for indoor air quality parameters](image)
From the results, it could be found that all the indoor environment indexes are limited in setting range, guaranteeing the comfort feel for occupants.

But in rainy days, the indoor environment indexes behaved greater fluctuations than those of sunny and cloudy days. That’s due to the low power generation of BIPV. Other controllable generations must be started to satisfy load demand and the cost would rise therefore. By the guidance of objective function, the cost and comfort level may perform more variations.

When the TOU price was low, indoor illuminance raised, temperature and CO\textsubscript{2} concentration values were relatively low. As a result, a relatively good indoor environmental comfort could be maintained. The reduction of controllable loads plays an important role in load shifting and improving the system economy, which has great significance for the security and stability of the energy system [33].

Changing the starting time of deferrable loads within the range set by the users could avoid the power growth on peak period and improve the economy of the system without changing its basic electrical properties [34].

From the results, it can be found that the deferrable loads have realized the time translation according to the dispatch scheme, aiming to achieve higher economic benefits without affecting people’s life quality. In order to ensure the system economy during peak price periods, the optimization results of controllable load reduced significantly resulted in a change of indoor environment parameters and the comfort level reduced slightly within an acceptable range. The results for deferrable loads are the same because TOU price are fixed in a period.

The occupants could determine the weight between economy and comfort based on the actual needs to improve overall system economy and ensure the indoor environment within an acceptable range. The optimization results reflect the balance between system economy and comfort.

Table VI exhibits the comparison with and without TOU price. It’s obvious that the simulation with consideration of synergetic dispatch of source-load-storage under TOU price obtained better performance.

Specially, the total cost reduced greatly at the expense of little comfort decrease.

### C. Discussion

This paper concentrated on the optimized operation of BES and proposed a multi-objective optimization model under TOU price environment. Through the optimization, the proposed method achieved the synergetic optimized dispatch of source-load-storage, maintaining the occupants’ comfort and enhancing the economy of the system at the same time. The following simulation validated the advantages of synergetic dispatch of source-load-storage and TOU based DR.

It should be noted that only the price based DR, TOU price, was considered in the optimization model. In the future, other types of DR technologies, such as incentive based, direct control and autonomous, would be deployed for the same region. Consequently, loads will show different response characteristics and the model proposed in this paper should make corresponding changes. That to say, effective DR control and coordination schemes [35], which could deal with the simultaneous existence of multiple DR techniques, are required to be contained in the optimization model. And this is also the future research of this paper.
VII. CONCLUSION

This paper presented a multi-objective optimization model for intelligent BEMS based on the prediction of BIPV’s output, non-controllable load and outdoor temperature. The overall economy of BES and occupants’ indoor environmental comforts were optimized through the synergetic dispatch of source-load-storage in the situation of TOU price. Indoor environment modelling quantized occupant’s comfort feel and load classification spared the functions of controllable and deferrable loads in economic operation. The simulation results showed that the model could improve the system economy without affecting occupants’ comfort feel by the synergetic optimized dispatch.

ACKNOWLEDGMENT

This work was supported in part by the National Natural Science Foundation of China (grant No. 15177067), the Beijing Natural Science Foundation of China (grant No. E2015050600), the State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources (grant Nos. LAP16007, LAP16015), the Science & Technology Project of State Grid Corporation of China (SGCC), the Open Fund of State Key Laboratory of Operation and Control of Renewable Energy & Storage Systems (China Electric Power Research Institute) (No. 524201601F8), the China Scholarship Council. M. Shafie-khah and J. P. S. Catalão acknowledge the support by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under the projects SAICT-PAC/0004/2015 - POCI-01-0145-FEDER-016434, POCI-01-0145-FEDER-006951, UID/EAE/0014/2013, UID/CE00213/2013, and UID/EMS/00151/2013, and also funding from the EU 7th Framework Programme FP7/2007 –2013 under GA No. 309048. Moreover, the authors appreciate the suggestions of Prof. Wei-Jen Lee, the director of the Energy Systems Research Center, the University of Texas at Arlington.

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