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Air conditioner consumption optimization in an office building considering user comfort

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Abstract

Rapid growth of energy consumption in last decades, made the world persuaded to energy optimization and management. Therefore, producers and prosumers should be equipped with the automation infrastructures to perform the management programs, like demand response. Office buildings are considering as a proper case for implementing energy consumption minimization since they are responsible for a huge portion of total energy consumption. This paper proposes a multi-period optimization algorithm implemented in Supervisory Control and Data Acquisition system of an office building. The developed optimization algorithm is an efficient solution considered for minimizing the power consumption of air conditioners by considering the user comfort constraints. A case study with several scenarios is implemented to verify the performance of proposed algorithm in real life using real data of the building. The obtained results show the impacts of different comfort constraints of algorithm while the main target of the optimization has been reached.

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Keywords: Multi-period optimization; Air conditioner; User comfort; SCADA system; Office building

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1. Introduction

In the last decades, the fast growth of energy consumption has become a big concern around the world [1]. The harmful effects of fossil fuels on the environment due to greenhouse emission cannot be relinquished [2]. The Renewable Energy Resources (RER) have been raised recently, in order to help to overcome this issue. However, due to RERs unpredictability, they need accurate managing to provide sufficient sustainability for supplying energy demand [3]. Demand Response (DR) programs can organize the user's consumption pattern as a generic and systematic program [4]. DR programs have a desirable variety which is divided into two main groups, namely

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price-based demand response and incentive-based demand response [5]. According to Cao et al. [6], 40% of world energy consumption dedicated to all types of buildings. Office buildings can be considered as a proper option for implementing DR programs, since they have significant energy consumption and, in some cases, can be more equipped to automation infrastructures than the other types of building such as residential ones [7]. In the context of office buildings, Air Conditioner (AC) is the controllable loads for Direct Load Control (DLC) and play an important role in DR programs implementation. However, there is a critical relation among ACs usage pattern and user convenience that makes the optimization algorithms restricted [8]. In order to perform the optimal results, the buildings should be equipped to automation infrastructures such as Supervisory Control And Data Acquisition (SCADA) which is able to control and monitor the state of the building in energy context [9].

This paper proposes a multi-period optimization algorithm implemented in the SCADA system of an office building the presented algorithm intends to minimize the consumption of the ACs controlled and monitored by the SCADA system. The user comfort level is modeled in this algorithm through several constraints. Also, a case study with several scenarios is presented in this paper for verifying the performance of the proposed algorithm in real life using real data of the building.

Several types of research have been done in this context for energy consumption optimization in the buildings. In [4], an algorithm is proposed for optimizing the consumption of lights and ACs in a SCADA system by respect on the priority of each device. In [10], the authors proposed an optimization algorithm for minimizing the consumption of the lights and ACs in an office building by using a multi-agent system. In [11], the authors proposed an approach for optimizing the centralized ACs in the building for fast DR programs implementation. However, the main purpose of this paper is to propose an optimization algorithm considering user comfort levels and perform the optimization based on user preferences.

After this introductory section, the optimization algorithm and related mathematical formulation are shown in Section 2. The case study and its results are proposed in Section 3, and finally, the main conclusions of the work are presented in Section 4.

2. System description

This section presents the implemented optimization algorithm proposed in this paper. The main intention of the algorithm is minimizing the power consumption of the ACs in an office building considering user comfort. In the context of user preferences observation, an importance weight is defined for each AC to rank the priority of each device for the user. The importance weights are shown by a number between 0 and 1, which the biggest number is dedicated to the most important AC. It should be noted that the priority numbers can be adjusted by the respective user of the device. Many factors are involved in defining these numbers, such as user characteristic, location, outside temperature, weather conditions, and present time of the day. These numbers maintain user preferences to some extent; however, more constraints are needed to avoid any exorbitance power reduction. Therefore, several constraints named comfort constraints are provided to bound the power reduction. The present algorithm is a multi-period optimization algorithm able to survey entire states of devices in all periods. Therefore, the algorithm attempts to prevent successive power reduction from only certain devices. Fig. 1 represents the process of the presented algorithm with the detailed information of each step.

According to Fig. 1, the first step is defining the required input data for the system such as the rated power consumption of each AC, total power consumption of the building apart from ACs, and nominal data of each device. The existing SCADA system includes several tools such as various sensors and energy meters in order to monitor and provide the input data for the algorithm. Priority numbers are determinant parameters in the present algorithm which they have a key role in the destination of each AC during all periods of algorithm implementation. The priority criteria adjustments need a comprehensive survey on user preferences based on the history of behavior, or sometimes it can be adjusted by the user itself. Location of each AC in the building and time information are also the other aspects of priority number definition. In addition to priority numbers, there is another important parameter in the algorithm, which plays a determinative role in the amount of power reduction from each AC. The main purpose of the Power Reduction Rate (PRR) definition is balancing the power reduction among all ACs.

After defining this information, the variables should be bounded, and the desired constraints should be specified. The main purpose of the algorithm is minimizing the power consumption of the ACs at a certain value with observing all existing constraints. The desired power reduction in each period may alter depending on several aspects such as electricity price variation, the uncertainty of power generation, ON-Peak or Off-Peak hours, and situation of

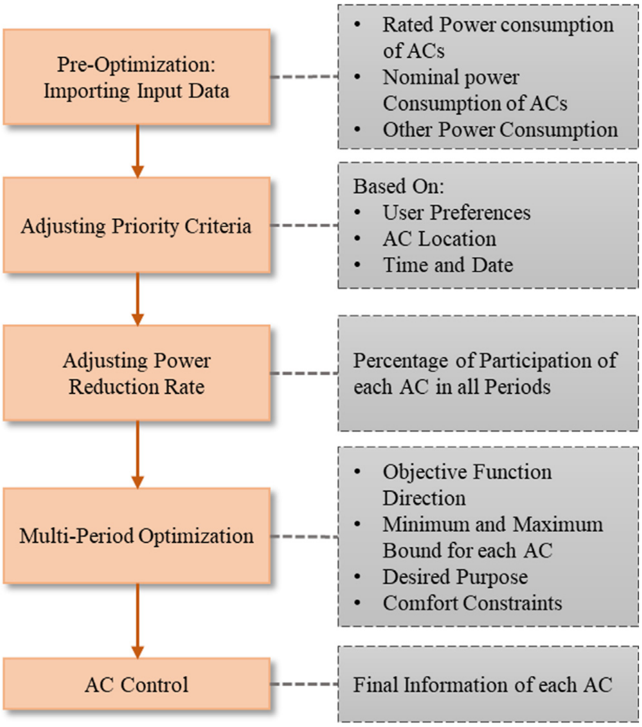

Fig. 1. Flowchart of the proposed optimization algorithm.

energy storage if exists. The proposed methodology is defined as a Linear Programming (LP) optimization problem, which is modeled via "OMPR" package of Rstudio® (www.rstudio.com) and is solved via "GLPK" library. The Objective Function (OF) of the proposed optimization algorithm is shown in Eq. (1) in order to minimize the power consumption.

$$Minimize\ OF = \sum_{t=1}^{T}\sum_{a=1}^{A} Priority_{(a,t)} \times P_{(a,t)} \tag{1}$$

Priority is a number between 0 and 1 that is dedicated to each AC for representing the importance of each, for the users and system. It should be noted that the bigger priority numbers are dedicated to more important ACs. *P* is the decision variable of the algorithm that shows the amount of power that should be reduced from each AC in each period. Also, *T* and *A* are the maximum numbers of periods and ACs respectively.

The definition of upper bounds related to the amount of power reduction of each AC in each period are developed in the scope of the author's previous work [4], and they are not mentioned in this section.

Eq. (2) is modeled to present the required power reduction in each period from all the ACs.

$$\sum_{a=1}^{A} P_{(a,t)} = RR_{(t)};\ \forall\, t \in \{1,\ldots,T\} \tag{2}$$

RR is the abbreviation of Required Reduction in each period from all ACs. Furthermore, Eq. (3) limits the power reduction of each AC individually by *PRR*, which is defined in order to avoid exorbitance reduction. This means the total power reduction of each AC in all periods can be adjusted and limited by this equation (Eq. (3)).

$$\sum_{t=1}^{T} P_{(a,t)} = PRR_{(a)} \times \sum_{t=1}^{T} init.P_{(a,t)};\ \forall\, a \in \{1,\ldots,A\} \tag{3}$$

As previously introduced, *PRR* stands for Power Reduction Rate for each AC. The impacts of *PRR* will be proposed more obviously in the next sections. *Init.P* is the brevity of initial power consumption of each AC in the normal situation. Also, as it is presented on Eq. (3), the power reduction of each AC in all periods cannot exceed a defined limitation for maintaining user comfort. *PRR* can make power reduction rigid in several ways, such as a function of time. For instance, it can limit the power reduction of certain AC in only certain periods of time. Finally, Eq. (4) is a constraint for considering the amount of power reduction in consecutive periods.

$$P_{(a,t)} + P_{(a,t-1)} \leq MaxRed;\ \forall\, t \in \{1, \ldots, T\};\ \forall\, a \in \{1, \ldots, A\} \tag{4}$$

As can be seen in Eq. (4), the power reduction in two consecutive periods cannot exceed more than a limit. *MaxRed* is a defined number that is usually equal to the nominal power consumption of the device.

3. Case studies and results

The present section demonstrates the impacts of the proposed methodology in a real case study. For this purpose, an office building is selected, which the air conditioning system includes 10 AC devices. The building consists of 9 offices and one corridor that each of them owns an AC individually. Fig. 2 shows the plan of the proposed building.

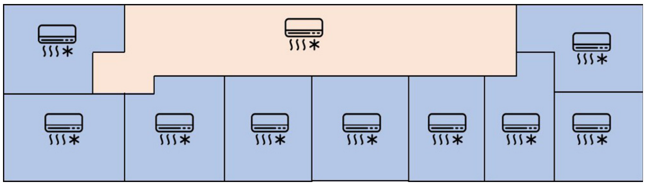

Fig. 2. The plan of the office building.

Since the nominal power consumption of each AC is considered equal to 1200 W, if all ACs work in their maximum capacity, the total power consumption of ACs stays for 12000 W. However, in reality, some of them may be used more than the other ones. The minimum power reduction for each AC is supposed to be zero, while the algorithm can turn the AC off in critical periods. Therefore, one of the main obligations of the comfort constraints is to avoid keeping an AC turned off for consequent periods. The algorithm surveys 12 h of a typical working day from 8:00 am to 8:00 pm with 15 min time intervals. As previously described, the required power reduction can be determined based on several aspects, such as electricity price variation, or the difference in power consumption and generation. However, in present case studies, different values are considered for the required power reduction to demonstrate and validate the performance of the proposed algorithm. In order to validate the impacts of comfort constraints, Eq. (3) and Eq. (4) (presented in Section 2) have been ignored in the first scenario. In fact, the first scenario is considered as a base in order to compare the results of the other scenarios. Fig. 3 shows the first obtained result of the algorithm, which compares the consumption of the building before and after the optimization.

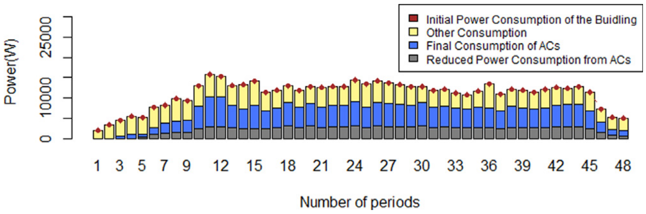

Fig. 3. Load balance after performing the optimization in the first scenario.

According to Fig. 3, the desired power reduction of the algorithm is satisfied, however, the user comfort constraints are ignored. In order to verify the effects of the other existing constraints, the next three scenarios of the algorithm are focused on user comfort constraints. The values specified for each parameter in each scenario are shown in Table 1. In the second scenario of the case study, Eq. (3) is included in order to show the effect of PRR in power reduction process. Also, PRR can be performed for a certain group of ACs in specific periods. In the third scenario, PRR is applied more rigid to ACs number 3, 4, 8, 9, from 11:00 am to 2:00 pm, and AC number 1 from 4:00 pm to 6:00 pm. This consideration means that the users of those ACs needed to use their ACs on those specific periods.

Table 1. The amounts of parameters in all scenarios.

	PRR [%]	PRR (Specific) [%]	MaxRed [W]
1st scenario	–	–	–
2nd scenario	60	–	–
3rd scenario	60	30	–
4th scenario	60	30	1200

Finally, in the last scenario, Eq. (4) is considered as a constraint for the algorithm. Fig. 4, illustrates the obtained results of the algorithm for the four proposed scenarios. It should be noted that the total required power reduction in all scenarios is considered.

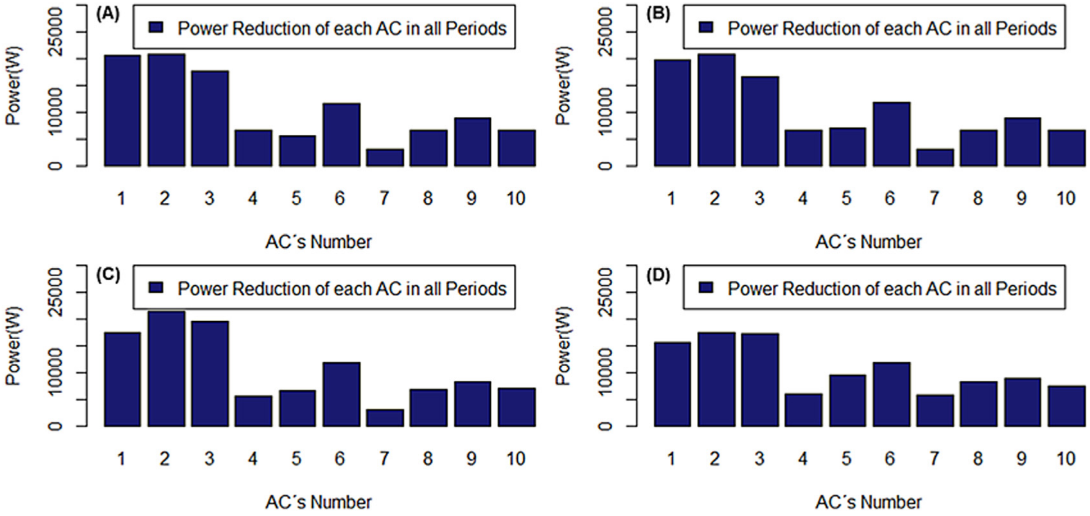

Fig. 4. Comparison of the optimization results in four proposed scenarios: (A) Scenario 1; (B) Scenario 2; (C) Scenario 3; (D) Scenario 4.

As can be seen in Fig. 4(A), the required reduction has been fulfilled, however, the optimization algorithm could not balance the required reduction in all participated ACs. As a final result, Fig. 5 provides the obtained results of optimization considering different values for MaxRed.

It can obviously see that in ACs number 1 and 2, the power reduction are significantly more than the other ones. In Fig. 4–(B), the effect of Eq. (3) and PRR in power reduction from each AC is obvious, for example, ACs number 1 and 4 have less reduction comparing with the first scenario, while the power reduction in ACs number 2, and 5 is more than the first scenario. The current power consumption of ACs is also important for the effect of PRR in the optimization. In Fig. 4–(C), PRR is applied in lower value to some specific ACs, in some specific periods. The comparison of the results shown in Fig. 4–(A) to (C) show that the amount of power reduction in ACs number 1, 4, and 8 have been decreased. Finally, Fig. 4–(D) presents the effect of MaxRed in Eq. (4), that is defined to prevent turning off any AC in consequent periods. In the last scenario, the power reduction among all ACs is more balanced compared with the other scenarios, and all the ACs are participating in consumption minimization based on their current power consumption and defined user comfort. For this purpose, all the parameters are considered equal to scenario 4 (as Table 1 showed) except MaxRed. In fact, the results are shown in Fig. 5 evaluate the performance of the algorithm considering three different values of MaxRed. As it is visible in Fig. 5, the algorithm has been attempted to achieve its reduction targets along with balances among ACs. In fact, this is the main target of the algorithm, which is respecting to user preferences and convenience. By comparing the results shown in Fig. 5, it can be concluded that the optimization algorithm has the best performance while the MaxRed is set to 800 W, which provides the most balanced reduction among all ACs of the building.

4. Conclusion

A multi-period optimization algorithm was proposed in this paper in order to minimize the power consumption of the air conditioners in an office building. In addition to minimization purposes, several constraints were defined

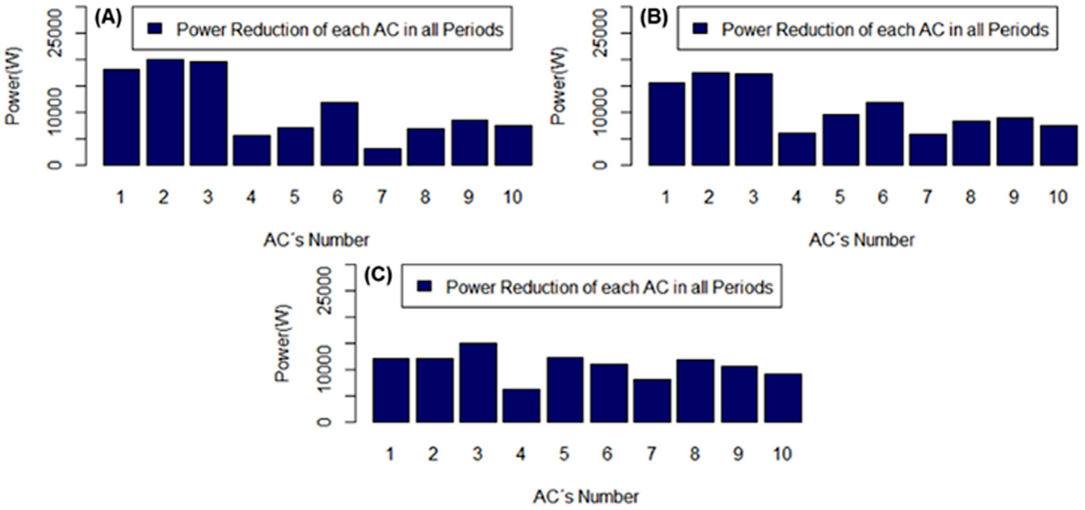

Fig. 5. Impact of MaxRed in the optimization results: (A) MaxRed is set to 2400 W; (B) MaxRed is set to 1500 W; (C) MaxRed is set to 800 W.

in order to maintain user comfort during the optimization. The proposed case study considered an office building with real power consumption data of 10 air conditioners to validate the impacts of the developed algorithm in real life. Several priority numbers were defined for air conditioners to show the importance of weight of them. The algorithm was executed by considering the different situation in order to validate its performance. Different values of determinative parameters regarding the user comfort are defined in order to show the process and the results of the optimization algorithm. The obtained results show the impacts of user comfort constraints by comparison of different scenarios. The most balanced result was proposed as an efficient implementation of the algorithm, which fulfills the system target, which is reducing the consumption of the building by fully respect to the user comfort level.

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