Technologies and Practical Implementations of Air-conditioner Based Demand Response

Muhammad Waseem, Zhenzhi Lin, Yi Ding, Fushuan Wen, Shengyuan Liu, and Ivo Palu

Abstract—**Nowadays, the most notable uncertainty for an electricity utility lies in the electrical demand of end-users. Demand response (DR) has acquired considerable attention due to uncertain generation outputs from intermittent renewable energy sources and advancements of smart grid technologies. The percentage of the air-conditioner (AC) load over the total load demand in a building is usually very high. Therefore, controlling the power demand of ACs is one of significant measures for implementing DR. In this paper, the increasing development of ACs, and their impacts on power demand are firstly introduced, with an overview of possible DR programs. Then, a comprehensive review and discussion on control techniques and DR programs for ACs to manage electricity utilization in residential and commercial energy sectors are carried out. Next, comparative analysis among various programs and projects utilized in different countries for optimizing electricity consumption by ACs is presented. Finally, the conclusions along with future recommendations and challenges for optimal employment of ACs are presented in the perspective of power systems.**

Index Terms—**Air-conditioner (AC), commercial load, cooling demand, demand response (DR), energy consumption, residential load.**

I. Introduction

THE indoor temperature of a building may get changed due to heat loads, solar energy, internal heat sources, and losses of heat for low-temperature heat sinks. As a result of indoor temperature increment beyond the acceptable level, residents may suffer several health problems and significant reduction of productivity may occur [1], [2]. To minimize the negative impacts of indoor heating, several natural and passive techniques can be applied. Passive techniques applied for cooling dissipate excess heat in naturally available sinks like ground, air or thermal mass of a building [3]. Both natural and passive techniques may contribute to the cooling demands in a building [4], [5]. However, to handle all climatic conditions and meet the requirements of indoor comfort, passive techniques are not enough. Therefore, mechanical cooling may be required to address the indoor temperature, humidity level and comfort degree of residents. In USA, only around 2% of houses were installed with mechanical cooling systems until 1955. However, the air-conditioner (AC) market had boosted between 1950 and 1980 due to economic development. Nearly 50% of houses in USA were installed with ACs by 1990 [6].

At present, the annual revenue of the AC industry approaches 100 billion US dollars and significant growth is expected. Furthermore, the penetration of ACs is still expanding in Japan and cooling planet zones in addition to USA, which is even more than the corresponding income growth of these regions. For instance, the usage of ACs in urban residences of China annually increased around 1% in 1990 [7] and around 100% in 2010 [8]. Similarly, the annual sale of ACs in India increased around 20% in 2010. Higher ambient temperature introduces climatic variations that increase the demand for ACs. Climate variations decline the usage of passive cooling such as ventilated approaches, and hence boost the usage of mechanical cooling [9]. The overall electricity consumption and peak demand of electricity raise due to the increased usage of ACs. Due to the notable increase in cooling demand, more generation capacity may be required. In India, it is predicted that electricity usage due to ACs will increase up to 239 TWh/year by 2030 and additional 143 GW in the peak demand will be introduced in the power system concerned. Hence, around 300 generation units with 500 MW capacity need to be built to meet the power requirement of ACs [10]. In Europe, it is forecasted that the annual cost for additional cooling electricity demand by 2050 is between 22 and 89 billion euros, and the costs for procuring new ACs are around 8 and 20 billion euros by 2050 and 2100, respectively [11].

The usage of ACs has been acknowledged as an important contributor, especially for the peak load during long and hot summer. In a hot period, the probability of the outage or even the blackout increases as a result of enormously rising power demand. Also, generation and transmission sectors are affected severely due to the high percentage of AC load in a given power system. Similarly, the peak power demands in several warmer global regions are caused by extensive use of ACs. In California, commercial AC usage contributes to al-

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M. Waseem, Z. Lin (corresponding author), Y. Ding, F. Wen, and S. Liu are with the School of Electrical Engineering, Zhejiang University, Hangzhou 310027, China, and F. Wen is also with the Department of Electrical Power Engineering and Mechatronics, Tallinn University of Technology, Tallinn 19086, Estonia (e-mail: mwaseem@zju.edu.cn; zhenzhi.lin@gmail.com; yiding@zju.edu.cn; fushuan.wen@gmail.com; eelsy@zju.edu.cn).

I. Palu is with the Department of Electrical Power Engineering and Mechatronics, Tallinn University of Technology, Tallinn 19086, Estonia (e-mail: ivo.palu@taltech.ee).

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most 45% of the peak power demand, while in Australia, it is about 30%-40% [7]. In many areas, residential ACs are also a significant contributor to the peak load demand of the power system concerned [9]. In South Australia, ACs play a major role in the increase of peak power demand, where almost 90% of residences are equipped with ACs due to frequent heat waves [3]. In summer, residential ACs contribute about 20%-25% to the peak load demand of Ausgrid, the largest distribution utility supplying the Sydney region in the state of New South Wales (NSW) of Australia [12]. With the increased prevalence of ACs, the power company concerned faces some problems or even challenges such as the imbalance between the power supply and load demand, efficiency reduction, extra energy waste, pollution emission, and voltage sags. The imbalance between the power supply and load demand is even worse with extensive integration of renewable energy generation in many countries [13]. In USA, 30% of electrical energy is consumed by the buildings [14], while in Hong Kong, China, it is 90% [15]. Hence, the load demand of buildings can play an important role in demand response (DR). In fact, many DR measures have been applied in buildings during peak demand hours for reducing load demand or smoothing the load profile [16].

Although some review papers on DR programs are available, most of them focus on DR programs with thermostatically controlled loads (TCLs). There does not exist a comprehensive review on DR programs in the context of ACs. In this background, different models and control actions to manage the increasing demand of ACs in both residential and commercial sectors will be investigated in this work. In addition, contributions of DR programs in the context of AC manipulations in several countries will also be discussed.

The rest of this paper is arranged as follows: Section II presents the introduction and overview of various DR programs; Section III describes various AC-based DR programs in both residential and commercial sectors; Section IV investigates AC-based DR programs implemented in various countries; Future trends and major challenges are presented in Section V; and Section VI concludes the paper.

II. DR Programs

The most important challenge for an electricity utility is to reliably supply power to customers. Electrical demand is variable and uncertain during different horizons of a complete day. Traditionally, only the electricity utility adopts different options to manage demand fluctuations. Nowadays, due to a variety of factors such as penetration of intermittent energy source (IES) generation in an existing power system, the minimization of energy cost with less energy consumption and energy efficiency improvement creates a space for end customers to properly manage electricity consumption. Demand-side management (DSM) is commonly referred as activities for the involvement of the demand side in electricity usage. DSM is defined by Electric Power Research Institute (EPRI), USA as follows: "DSM is a basic method designed by electricity utilities for modification in ways of electricity usage by customers and it includes planning, implementation and monitoring of that suggested utility activities [17]. Utility methods generally adopted for DSM comprise modifications in market share, generation by customers, load management, electrification and strategic conservation". DSM, in the context of industrial customers, has been adopted to reduce electricity consumption of customers or minimize power system stress during critical peak hours. Normally, DSM acts to tackle issues including load demand, energy savings, energy efficiency, self-production and savings [18]. Recently, in power system operation, DR approaches are attracting more attention. DR is well-defined by the USA Energy Department as "variations in user's electricity consumption patterns due to changes in electricity prices" [19]. Due to technology advancement of smart grid such as intelligent energy management systems (EMSs), information technologies and advanced metering infrastructure (AMI) compatible with smart grids, power system operators in several developed countries have adopted DR strategies.

A. Infrastructure Required for DR Implementation

Practically, DR programs have been permitted by system operators in different countries because of the development in technology. For DR implementation, enabling infrastructures are primarily required. Mainly three data communications domains, i. e., home-area network, smart meter field and the Internet, are considered. The smart meter field is an AMI comprising several smart meters. The Internet is a wide-ranging public accessible platform of IT industry obtained by means of different internet providers. The home-area network is the entry to the Internet and AMI for controllable appliances and their exchanges with the EMS within the end-users [20], [21]. EMS is crucial for automatic control and effective participation of end-users in a DR program. AMI in EMS has the ability of bi-directional communication between a load serving entity (LSE) and end-users. They have the compatibility to accept signals from the LSE during a certain period for power-level control, e.g., to decrease local transformer loading, or execute desired actions by means of the home-area network according to price signals.

The well-established wide-area network (WAN) and neighborhood-area network (NAN) are other communication ways employed in EMS depending upon communication range for DR implementation [22]. Moderate bandwidth, low latency, and capability to transfer a larger amount of data are the main requirements for DR execution [23]. Generally, communication techniques can be categorized as wired and wireless ones. Less cost is required for wireless communication because of less wiring cost. Still, during propagation, these techniques may have more signal losses [24]. In comparison to this, wired communication techniques utilize outdoor lines for transmission of signal including fiber-optics, Ethernet, etc [25]. Further investigation on the EMS communication infrastructure for DR practical implementation can be found in [26]-[28].

Certain regional differences can be observed if EMS implementation is globally observed. EMS is generally employed in the power industry around the globe, and relevant pilot projects are also supported by European utilities in home EMS (HEMS) [29]. There are benefits of EMS for both the end-users and the utilities [30] as well as many attempts for the regulation of DR-related operation characteristics of smart grid. The US National Institute of Standards and Technology (NIST) proposed standards by engaging investors, industry partners, academia, and the administration for mutual operation-based DR [31]. Several IEEE standards have also been developed particularly from the communication viewpoint for DR [32]. In addition to IEEE and NIST, numerous other standards have also been practiced in USA, Europe, New Zealand and Australia for DR implementation [29].

B. Classification of DR Programs

DR programs may be categorized as incentive-based program (IBP) or price-based program (PBP). In IBP, end-users can get payments if they perform a certain load reduction as required. While in PBP, end-users willingly perform certain load reductions in the response of economic signals [33]. Different types of DR programs are clarified as follows.

1) IBP

A utility company may directly control appliances like ACs, water heaters and pool pumps in IBP. IBP can be further divided into classical and market-based programs. Firstly, classical IBP comprises direct load control (DLC) programs and interruptible load programs (ILPs). In DLC programs, the utility interrupts end-users' appliances without any intimation for interruption. In these programs, many small consumers, e.g., residential and small commercial customers, are engaged [34]. The involvement of an end-user in these programs is reimbursed via discounted electricity bill by making additional payments. In contrast to DLC programs, participants in ILP are medium and large customers. They obtain advantages if they turn off certain loads or even detach their energy use in reply for utility calls. Like DLC programs, ILP usually takes the comfort level of residents into consideration [35].

Secondly, the market-based IBP consists of emergency DR programs, demand bidding, capacity market, and ancillary service markets. If end-users bid for certain load reductions in a wholesale electricity market, this may be termed as demand bidding or buyback. A bid is acknowledged if it is less than the market price. If end-users acknowledge a bid, then it is the liability of end-users to follow load reduction instruction defined in a bid [36]. Alternatively, end-users are rewarded with certain benefits if they reduce their loads in emergency situations called emergency DR programs [37]. In addition, end-users who must provide a certain amount of load reduction during the disturbances in the concerned power system are categorized as DR programs in capacity market. End-users get notice before the emergency from DR programs in capacity market, and the penalty is imposed if they do not follow the instruction of load reduction from the utility [38], [39]. In an ancillary service market, bidding for load reduction is permitted for end-users in the spot market environment. This load reduction works as an operation reserve and will be utilized if load curtailment is vital [40].

2) PBP

In contrast to IBP, variable electricity tariff-based programs are categorized as PBPs. These variable pricing schemes consist of the time of use (TOU) rate, critical peak pricing (CPP), extreme day pricing (EDP), extreme day CPP (ED-CPP), and real-time pricing (RTP) [33]. Many users of electricity are not familiar with approaches of dynamic electricity pricing. Therefore, they usually select flat prices. If there are variations in electricity price, this dynamic pricing scheme is termed as TOU. In TOU, the utility defines the electricity rates for peak, off-peak and possibly shoulder-peak periods. And the cost of longer-term electricity consumption is considered. To address short-term electricity consumption, CPP can be utilized. The maximum number of days that bring about unpredicted demand fluctuations under extreme weather conditions or other disturbances for the whole year will be specified in CPP contracts. EDP and ED-CPP are further two options that can be applied in the context of CPP. EDP charge remains operational for a complete extreme day if it has been applied and comparatively costs more in comparison to EDP. ED-CPP utilizes the same rates as that of CPP for extreme days but applies conventional approaches in normal days [41]. If the price is updated for a short duration like an hour, it is categorized as the RTP scheme. In this approach, end-users are familiar with variations of electricity consumption cost. At present, for residential end-users, two noticeable RTP programs have been practiced in USA by PJM and another RTP program by the Midcontinent ISO (MISO) [42], [43].

The benefits of DR programs will be achievable only due to proper market mechanisms. The wholesale markets and retail markets are two market levels for DR participation. End-users can participate directly in retail markets but the involvement in wholesale market is possible by system operators [44]. Among DR programs, classical IBP and PBP are considered in retail markets. But market-based IBP DR programs such as demand bidding, capacity market, ancillary service and emergency DR programs are analyzed in the wholesale market category. DSM has been discussed from the perspective of electricity market in [45]-[47]. Also, numerous approaches and mechanisms for end-users to select appropriate contracts have been discussed in [48]-[50]. Active participation of end-users in DR programs is beneficial for both end-users and the electricity market [29]. Energy usage optimization is the main benefit that has been achieved. In addition, due to proper DR program, the power systems become reliable and the risk of outages get reduced [33].

DR which benefits for residential consumers in real-time electricity market are investigated in [16]. In addition, incentives achievable for commercial end-users due to DR adoption have been discussed in [23]-[25]. DR implementation based on ACs due to variable electricity prices has been investigated by several researchers. The control of residential electric appliance in variable electricity prices has been highlighted in [51] for DR programs. Similarly, electricity rate design taking variable pricing schemes from utilities at power distribution level has been discussed in [52]. In [53], load management technique in the residential sector has been proposed, considering both real-time prices of electricity and the generation of intermittent sources. DR control methods are primarily required for residential ACs so that they effectively respond to real-time prices of utilities.

III. Models and Control Strategies for AC-based DR Programs

ACs share a significant percentage in the total energy utilization of a building. As reported by an energy demand report of California, the peak demand in the utilization of electricity during summer is generated due to the wide use of

ACs [54]. Building new power plants is one of the possible solutions to handle this problem in energy consumption. The expenditures in building new generation plants and transmission lines are very high and cannot be managed by increasing electricity prices during peak demand hours, since critical peak demand usually happens for a very short duration in a complete year. One of the most appropriate solutions is to minimize the energy utilization due to ACs. The most efficient and simplest way to minimize AC usage is to apply possible control strategies. DSM and AC control for optimal energy usage are significant ways to handle global energy challenges. DR measures in addition to control approaches can be applied [55]. In existing literature, several thermal models have been developed in addition to control strategies for AC-based DR programs and are discussed below.

A. Models for DR Programs of ACs

Several studies have been conducted based on modeling approaches for DR implementation in different residential and commercial energy sectors [56] - [60]. Broad modeling approaches can be roughly classified as top-down and bottom-up models. In top-down models, social and economic factors such as population and weather are applied to model thermal characteristics of buildings. While bottom-up models consider processes in energy consumption for the development of model [61]. Room thermal models are applied in residential ACs for both energy utilization prediction and power reduction. EnergyPlus [62] and eQUEST [63] are building modeling software that has been utilized to observe thermal dynamic characteristics for the manipulation of different DR approaches. In [63], comparisons have been carried out among different DR programs by making use of eQUEST. Another room thermal model, i. e., an equivalent thermal parameter (ETP) model, has been extensively used to model thermal dynamic characteristics of a room. The ETP model has been applied to investigate the influence of residential and small commercial scale control techniques of ACs on distribution feeders for DR manipulation in single and multiple buildings [64]. In [65], this modeling approach has also been applied to represent the thermal characteristics of individual loads and several heterogeneous loads. An intelligent residential AC system controller has also been suggested in [66] by using ETP with the consideration of comfort and cost for residents.

In addition, GridLAB-D has also applied the ETP model during DR periods to observe energy utilized by ACs [67]. However, the main problem associated with the ETP model is its over-simplification. These model parameters were developed over 20 years ago and were applicable only for buildings in USA [68]. In addition to the minimization of energy usage, the thermal comfort of residents is also an important parameter for effective DR implementation. In AC systems, control mechanisms have been developed that maintain the thermal comfort of occupants and reduce AC energy utilization [69], [70]. Numerous optimization tools have been applied in developing control approaches for electricity cost minimization and the comfort of residents. By making use of the bottom-up type model in [71], electricity usage reduction during peak hours from Japanese homes has been explored. In [72], the second-order nondisruptive models have also been developed for TCLs. These models have shown better results for the thermal comfort of residents. Predicted mean vote (PMV) is considered as the most popular model for thermal comfort modeling. But for smart buildings, building management system (BMS) predicts comfort with PMV. Machine learning approaches can be applied in combination of BMS and PMV for efficient modeling of thermal comfort [73].

Moreover, a graphical probabilistic model has been investigated for the prediction of building energy characteristics. This probabilistic model makes use of several parameters associated with energy utilization of the building like outside air temperature and energy use [74]. A two-state resistance-capacitance (RC) model has also been validated in [75], [76] for DR manipulation of TCL aggregated residential loads and ACs. The physical-statistical method has been studied in [77] and [78] to observe the consumption and forecasting of building energy. Software tools like EnergyPlus and ESP-r have been applied to develop physical models of building thermal characteristics. TRNSYS and DOE-2 are simulation environments used for this purpose. Furthermore, the correlations between different building thermal systems have been explored by these software tools. Meanwhile, autoregressive moving average (ARMA) models have also been utilized to observe thermal characteristics of the building for DR applications [79], [80]. ARMA makes use of a greater number of AC parameters like power usage, indoor and outdoor environment temperature and other data for required model validation [81], [82]. Several models have been developed in existing literature to develop efficient DR programs for building thermal loads and ACs.

Control methods for energy management of ACs can be broadly classified as traditional, advanced or hard, intelligent or soft control, and hybrid control methods [83], [84]. Traditional methods can be categorized as on and off control and proportional, integral and derivative (PID) control methods. These methods have a simple structure with less initial cost [85]. Rather than traditional approaches, optimal control approaches have been widely used for consumption control of building energy and the comfort of end-users. Optimal controls can efficiently monitor the system with real-time control of all parameters in a system [86]. Black-, grey-, and white-box models have been applied for optimal control approaches in building energy management. In [87], the linear quadratic Gaussian (LQG) controller has been investigated for the temperature and humidity control of ACs. Energy-saving can be achieved by efficient controllers, but they require an appropriate system model as in [88]. Due to the uncertainty and nonlinearity in the system, robust control methods are considered more suitable. Therefore, a nonlinear robust control method has been applied for building ACs in [89]. This approach achieves promising results in case of any sudden disorder. A multi-input multi-output (MIMO) robust control that provides better performance compared to classical methods is discussed in [90].

Furthermore, adaptive control yields better performance due to nonlinear, uncertain, and stochastic variables during the operation of TCLs [91]. Novel adaptive back-stepping control for ACs is explored in [92]. As a nonlinear system, disturbances have adverse effects on the operation of ACs. Therefore, nonlinear control methods show significant performance for optimization of energy consumption and the comfort of end-users. But these techniques require complex mathematical modeling. Different nonlinear control approaches for ACs have been explained in [84]. Model predictive control (MPC), a multi-variable control strategy, optimizes both cost and energy effectively in the presence of disturbances and uncertainties in ACs [93]. MPC is an effective and simple method widely recognized and practiced for the process industry [94], [95]. In MPC, the process-based mathematical model has been developed to forecast and optimize future system actions. MPC for ACs that incorporated thermal energy storage of buildings has also been discussed in [96] and [97]. RTP incorporation into the MPC to handle ACs energy usage is introduced in [55]. Nonlinear MPC approach has been applied [98] to maintain the thermal comfort of residents and ACs energy minimization. A grey-, white-, or black-box model can also be applied to develop MPC model for effective energy utilization [99]. Grey- and black-box thermal models are considered as the most appropriate for the calculation of MPC parameters [100]. In [101], a grey-box room thermal model is developed for the exploitation of DR approaches associated with residential ACs such as indoor room temperature and precooling. It has been explained in [102] that the grey box is a linear, low-order thermal model that requires fewer computations. In contrast, the black box exhibits nonlinear behavior with complex calculations. In order to handle weather forecast uncertainties, a stochastic centralized MPC has also been introduced in [103].

Also, it is difficult to develop a standard mathematical model for the system due to consumers with varying energy utilization patterns. In intelligent or soft control methods, controller design is only based upon the comfort of end-users and it does not require a system model. Such control methods do not need mathematical model for buildings. Due to this reason, these models have been more widely adopted for energy utilization control of ACs compared with traditional strategies [104]. Intelligent or soft control methods include artificial neural network (ANN) control, fuzzy logic (FL) control, control by genetic algorithms (GAs), and other evolutionary methods discussed in [105]. ANNs can be a promising choice for nonlinear systems control due to their greater prediction abilities and robust performance [106], [107]. In addition, FL control is based on human behavior, suitable for integrated and complex nonlinear systems. This control strategy comprises fuzzification, fuzzy inference and defuzzification. For the management of air quality and energy of ACs in addition to the comfort of end-users, an FL control approach has been discussed in [108]. However, this approach is not suitable for high performance and also increases the operation time of the system. For optimal solutions, GA can be applied for parameter tuning of FL controllers [109]. In [110], GA-based FL approach for ACs has been investigated by considering both the comfort of end-users and energy management. GA is an optimization technique that does not require mathematical modeling, but it is not suitable for real-time applications. Hybrid methods are a combination of soft and hard control approaches that provide better results compared with conventional control methods. In this context, advanced hybrid controllers that provide optimal results for ACs energy management have been presented in [111] and [112]. ANN has also been applied for MPC modeling [113]-[115]. The Gaussian process has also applied to model MPC for building thermal characteristics. This approach shows better results in energy predictions as compared with grey-box models [116]. A hybrid MPC and PID control approach has been suggested in [117]. ANN-based adaptive and predictive control techniques that provide efficient AC energy-saving and the comfort of end-users have been investigated in [118]. A hybrid model is developed in [119] by combining both grey-box and Gaussian process approaches. Energy predictions are improved by employing this hybrid approach. Different control strategies applied for AC-based DR programs have been compared in Table I in terms of their benefits and limitations.

TABLE I
COMPARISON OF DIFFERENT CONTROL MODELS FOR DR PROGRAMS OF ACs

Control method		Benefit	Limitation
Traditional	On and off control	Simple and easy to implement; quick response [118]; less initial cost	Less accurate; no controlling moving processes; take only binary inputs
	PID control	Dominant method [89]; feedback controller; compatible with sudden load-variations	Nonapplicable for uncertain and complex system for inadequate parameter tuning [120]
Advanced or hard	Optimal control	Energy saving; multi-variable control [88]; comfort of end-users	Complication; appropriate system model
	Robust control	Competent control methodfor external disturbances and uncertainties [90]; no uncertain input information	In-valid under extreme weather conditions
	Adaptive control	Improved stability [89]; energy saving; better performance	Appropriate system model
	Nonlinear control	Competent to deal with nonlinear and uncertain parameters [105]	Increase in complexity; require additional measurements
	MPC	Energy saving; cost effective; disturbances handling; indoor air quality improvement; comfort of end-users	Additional costs; proper system model [83]
Intelligent or soft	ANN control	Great prediction ability [113]; without mathemati cal model; ability to handle huge data; ability to handle nonlinear systems	Long time for large NN training; massive data for quality predictions
	FL control	Human-reasoning-based; simple mathematics [121]; great performance; robust operation	Long system run time; no feedback; limited input variables; less accuracy
	Control by GA	Optimization-based; without mathematical model	Not always suitable for real-time applications [110]
Hybrid		Combination of different methods [118]; complex problem solving	Massive data; difficult to tune traditional and hard controllers

B. Control Strategies for DR Programs of ACs

Different software models have been developed to observe characteristics of building thermal loads and ACs for effective DR programs. Furthermore, by making use of AC controllers, DR benefits can be achieved more significantly. These AC controllers must be innovative and intelligent so that they are adopted practically by end-users. Also, these controllers should modify AC load efficiently in response to utility action. There are several controlling techniques developed for AC-based DR to manage AC loads of buildings. References [122]-[125] explore that different control strategies have been applied for indoor temperature control of buildings, which are conventional control methods, shift of load and limitation of excess demand. In [126]-[128], load management by shaving peak demand has been proposed. Similarly, load minimization by providing additional reserves has also been explored in [129]. Furthermore, load management strategies focusing on minimizing operation costs and profit achievement for both utility and end-users have been elaborated in [130]-[132].

DR programs provided about 13036 MW peak load reductions and 26% of total peak reductions in 2016 from the residential energy sector as reported by USA Energy Information Administration [133]. Residential customers have shown their significant contributions to DR manipulation [134]-[137]. Residential ACs among home appliances contribute significantly to DR program implementation [138], [139]. Smart energy meters have been deployed in numerous homes to achieve DR benefits from residential appliances [140]. DR that benefits from ACs becomes easily attainable by the use of smart HEMSs. ACs consume about 40% of the energy in commercial buildings like the residential sector. Their energy usage can be optimized by making improvements in the efficiency [141]. Optimal chiller sequence control offers a significant contribution in efficiency improvement of AC. If ACs have disturbed sequence, they will operate at low efficiency and will show greater contributions to overall cooling demand. Data fusion is one of the most promising approaches that has been practiced to resolve the issue of sequence disturbance [142], [143]. Different strategies have been investigated to tackle this issue, but due to their complications and data requirements, they are not applicable for real-time systems [144]. Meanwhile, a control method has also been developed in [145] by use of basic principles in [146] to optimize the chiller sequence.

In addition to this, AC efficiency for commercial buildings can be controlled by proper equipment maintenance. Faulty equipment and incorrect temperature scheduling have been considered as the most prominent factors that affect the efficiency. It is revealed that these issues can be handled by minor costless modifications like switching off unoccupied ACs and their proper maintenance [147]-[149]. Different control techniques applied to manage AC energy consumption and its availability for DR programs of residential and commercial buildings have been discussed below.

1) Temperature and Humidity Independent Control (THIC)

Temperature set point adjustment is a more realistic way of energy usage control of ACs. The control of temperature can lead to AC efficiency improvements and a significant reduction of cooling demand in buildings. Different THIC-based control strategies and DR programs for residential and commercial ACs are discussed below.

1) THIC for ACs in residential building

Temperature set-point adjustment is a more realistic way of energy control of ACs. DR can be achieved for ACs by temperature adjustment and maintain the comfort of residents [150]. The control of indoor temperature with dynamic and real-time electricity prices is observed as the most commonly used DR control method in residential ACs [151]. A price control-based controller to manage energy consumption due to residential ACs has been proposed in [62]. AC temperature will be controlled if the difference between retail and preset price is increased by this controller. Energy cost savings up to 10.8% and about 24.7% reductions in peak power are observed due to this price-based controller. AC energy usage can be optimized by improving its efficiency. The control of cooling demand by adjusting indoor temperature has also been investigated in [152].

In addition to the indoor temperature setting, humidity level improvement of ACs has been explored as an important parameter for improving its energy efficiency. In [153], it has been suggested to utilize the separate air de-humidification system to achieve better energy efficiency for ACs. An AC has been proposed which uses Calcium chloride ($CaCl_2$) as liquid de-humidifier with the ability to hold water vapor [154]. Furthermore, with solid de-humidifier in existing ACs, greater energy savings can be achieved in comparison to conventional systems [155]. A cooling system is proposed in [156], aiming that it can deliver the required cooling demand and the thermal comfort of the residents more efficiently. A solar energy-based liquid-desiccant system has a 10% decrease in indoor humidity [157]. An air cooler is developed using a wet layer of material and it is observed that electrical energy consumption is significantly reduced as compared with traditional coolers in [158]. AC efficiency is upgraded by utilizing variable speed compressor [159]. Related to this in [160], it is described that a partial variation in compressor speed leads to more than 10% improvement in the AC energy efficiency. Furthermore, a complete variable compressor has given about 30% efficiency improvement. Inverter ACs have increasingly replaced single-speed ACs due to its greater efficiency during part-load situations in recent years [161].

In addition to efficiency improvement, the comfort of residents is also an important parameter for consideration. Numerous AC control methods have been explored in [162] and [163] to enhance energy efficiency and tackle the comfort requirements of residents. Fuzzy control methods have been applied for ACs in [164] and feedback-based control strategy is also investigated in [165]. Additionally, various logical control approaches are discussed and explored in [166] and [167] to control the energy consumption and comfort of residents due to ACs. Various standards are explained in [168] and [169] to observe the relationship between dry bulb temperature and indoor humidity in order to maintain indoor comfort levels. For AC efficiency enhancement and energy management, dry bulb temperature and indoor humidity are measured and kept under control at the same time to change room air conditions for AC. A novel control approach is explored in [170], namely the evaporation pressure control reading (EPCR) method, which is based upon evaporation pressure and humidity reading. A Fokker-Planck model has also been explored in [171] to control the aggregate AC demand.

2) THIC for ACs in commercial building

Controlling the temperature can lead to AC efficiency improvements and a significant reduction of cooling demand in commercial buildings. One common energy-efficient approach for temperature control is investigated to manage temperature set-point as discussed in [172] and [173]. The additional energy can be reserved by temperature setbacks during unused AC periods. This approach is validated for Middle East buildings in [174] - [176]. Furthermore, adjusting temperature setbacks according to the requirements of residents enhances energy savings [177], [178]. The major challenge in temperature setback deployment is to maintain the comfort of residents during their availability. This issue is handled by applying air pre-conditioning. The pre-conditioning time differs with respect to the parameters of buildings and weather situations. Energy savings will be attained without violating the thermal comfort by pre-conditioning with temperature setbacks [179].

Building thermal mass like ACs in commercial buildings can be used to modify the load profile in peak hours by shifting loads to fewer demand periods. The main drawbacks associated with buildings thermal mass are the control of cold energy discharge, low efficiency and negative impacts on the comfort of residents [180]. Peak demand will be controlled by utilizing cold energy generated during off-peak hours and storing it as ice-chilled water. The ice-chilled water storage is an efficient control and has optimum operation costs as compared to ice [181]. It has been investigated that the volume requirement for the chilled water storage is much greater as compared to ice storage. That is why a large storage tank will be required with high cost for chilled water storage. This problem is resolved by increasing storage density through an increase in temperature difference, which is temperature variation between terminals of supply and return ACs. However, the indoor temperature and level of humidity are controlled separately in THIC system based ACs. Therefore, an innovative AC system is proposed in [182] to effectively exploit DR potentials in response to electricity utilities. In addition, it is observed that de-humidification may utilize greater energy during hot temperature zones in traditional ACs [183]. Up to now, ACs are extensively used in buildings with traditional compression mechanism, which gives a low-performance coefficient.

Furthermore, both indoor temperature and humidity are not controllable only with traditional de-humidification mechanism. Thus, THIC has suggested to handle the latent load by solid or liquid desiccant system. As a result, the greater performance coefficient is achieved. Also, different probable configurations of solid desiccant hybrid systems are proposed. It has been observed that a significant amount of energy savings could be attained in comparison to vapor compression system. In addition, the system efficiency could be upgraded with an integrated solid hybrid desiccant system and heat pump. An integrated evaporative cooling and liquid desiccant hybrid system is also proposed with significant improvements in performance coefficient. It has been observed that THIC is a substitute for conventional vapor compression system, but for desiccant regeneration, auxiliary heaters are still obligatory. The initial cost increases and the system becomes complex due to auxiliary heaters usage. The heat released from vapor compression system can be utilized to tackle this issue. An advanced liquid desiccant hybrid system with heat released from vapor compression system is introduced, which results in the significant comfort of residents and energy savings.

The heat pump desiccant unit for heat regeneration is also proposed to handle this issue. Similarly, an innovative solid desiccant heat pump is explored with a mathematical model in EnergyPlus to observe heat regeneration. Another issue is that fresh air cannot be delivered by the variable refrigerant AC system. Therefore, additional ventilation mechanism will be usually necessary. Heat recovery ventilator system with variable refrigerant flow AC system has been implemented for high energy efficiency. A THIC system with the composition of a solid desiccant heat pump and a variable refrigerant AC system is proposed. It has been observed that by using this system, 17.2% energy savings can be achieved with an increase in the performance coefficient by 25.7%, which has been validated for office rooms in Shanghai, China. Furthermore, it has provided better indoor thermal comfort for residents [184], [185]. In addition, THIC system has also been validated for ACs in museum store-room, which shows a reduction in energy consumption by 21.7% [186]. The uncertainties in AC use and its flexible demand for renewable energy integration in power systems are observed by using a two-level optimization [187], [188].

The thermal comfort of residents and AC usage reduction can also be achieved by using phase change materials (PCMs) in buildings. A significant variation in electrical demand is observed due to different environmental situations and the nature of users. Many approaches have been widely adopted worldwide for the encouragement of users to shift their loads. Therefore, during off-peak hours, cold energy can be stored by applying PCMs and will be stored later. As a result, economic benefits and reduction in AC sizes will be achieved. In addition, the shifting of cooling and heating demand during peak demand periods will be possible in different seasons. AC usage in commercial buildings can be reduced by using shape stabilized phase change material (SSPCM) under high-temperature conditions [189]. The effects of SSPCM and load control have been validated in variable pricing policies for Hong Kong, China and Beijing, China during summer.

2) DLC for ACs

DLC is deemed as a convenient approach for abrupt load reduction in a very short duration in both residential and commercial buildings. Different DLC-based control strategies and DR programs for ACs in residential and commercial buildings are discussed as below.

1) DLC for ACs in residential buildings

Energy consumption due to ACs increases to a greater extent in some regions of the world. DLC strategies for residential ACs based on both the change in temperature set points and on/off switching are discussed in [190] - [193]. A hybrid model that considers temperature set-points and end-users involvement is discussed in [194] and [195] for residential AC. Furthermore, uncertain variables that affect the residential AC operation are explored in [196]. Meanwhile, an innovative dynamic control-based approach for residential AC-based DR is investigated in [197]. Several areas of North America suffer electricity peak demand mainly due to the use of ACs. Due to the increasing usage of ACs, the electricity utilities may increase their capacity in order to meet the peak demand. In some regions of the world, electricity usage during peak hours is greater than the overall consumption of the electricity. Therefore, this issue is handled by abolishing some peak demand using DLC. Utilities modify AC load profiles during peak hours. Several AC-based DLC pilot projects executed in North America vicinity have been discussed and reported that there are possible reductions of about 1.2 kW per AC during peak demand periods [198].

DLC approach based on pre-cooling during early morning hours with buildings in thermal mass is suggested in [124] to control AC energy use. Various DLC methodologies with regression techniques are investigated in [199] for the control of aggregated ACs. A DLC algorithm applying the linearization of bilinear equations has been developed. DLC-based approach has been demonstrated for a residential building in DR. Load reduction may be obtained through the synchronized response of many ACs by this approach [200]. It has been explored that DLC is an efficient and direct method for AC load management as required by electric utilities. But end-users install ACs for their ease and convenience so that they can easily switch on and off it when required. The main purpose of AC installation is completed as DLC restrictions have been imposed on end-users. Therefore, applying DLC and taking the comforts of residents to meet indoor temperature requirements are the main challenges that have been addressed in [201] and [202].

For ancillary services under critical system conditions such as valley filling, peak clipping, and frequency regulation, DLC plays an important role [203]. For large-scale residential end-users, a distributed two-layer DLC approach is suggested in [204]. In addition, various appliance level DR models for TCLs are investigated in [205] and [206] by considering different parameters of loads. Frequency regulation reserve plays an important role in the power balance between the supply and demand. DLC can be applied for frequency regulation as discussed in [207] and [208]. Room thermal model and electrical model of inverter AC are developed for frequency regulation services in [209]. The power system stability and frequency randomness are improved by this approach. Furthermore, the lead rebound effect is proposed in [210] for operation reserve and thermal comforts of residents. Quantitative assessment of operation reserve for individual and aggregated ACs is performed and analyzed in [211]. Many approaches like GA, particle swarm optimization, and game theory have been applied to optimize the in-home power scheduling problem [212]-[214]. Energy scheduling of AC load and electric vehicle in a house is jointly optimized in [215] for cost minimization. Mixed-integer linear programming (MILP) approach has also been applied in [215] and [216]. MILP for the minimization of electricity cost and DR achievement has been formulated in [217]. Furthermore, AC usage MILP has been investigated for price-based and demand limiting-based DR strategies [218].

Moreover, as an optimization problem, the formulation of the residential AC control problem is observed to minimize energy utilization and the thermal discomfort of residents in variable prices [219]-[221]. AC load optimization has been explored to reduce energy costs without violating customer comfort in [222]. The potential of AC loads to provide services in load balancing is addressed in [223]. Also, a centralized AC loads control mechanism is proposed in [224] for AC contribution in load balancing. Furthermore, centralized and decentralized DR frameworks are also compared in [225] to signify the worth of utilizing decentralized models. Decentralized DR approaches for different nature end-users are investigated in [226] and [227]. A distributed DR framework validated for residential ACs of a Finland network is developed by applying the iterative approach. A significant load factor improvements and peak load reductions are achieved by the iterative approach [228].

2) DLC for ACs in commercial buildings

DLC is deemed as a convenient approach for abrupt load reduction in a very short duration like THIC in commercial buildings. In this approach, electricity companies have an authority to tackle the specific devices of end-users. In response, a certain incentive will be given to end-users based on their actions [229]. In commercial buildings, AC loads contribute largely to the overall energy consumption. When utilities require instantaneous and urgent load reductions, they will shut down ACs depending on the agreements. This is an effective DLC approach widely adopted in several real projects such as DR program, i. e., automated DR program, which is a DLC launched in Hong Kong, China to manage energy use of commercial buildings. There will be certain disturbances and uncertainties introduced in ACs system due to sudden switching off of ACs by supplier companies based on the agreements [230]. An innovative feedback-based control strategy is developed to effectively solve this problem in [231]. The direct chiller power limiting control approach in the starting periods of ACs during peak demand is proposed in [232].

In addition to disturbances and uncertainties in a power system, one more challenge relevant to DLC is to manage and control the AC units by a utility. Still, the utility and end-users are inconvenient in this practice although they had an agreement. Each user does not want to switch off his/her ACs, and the utility must control hundreds of small AC loads. A load management technique is proposed in [233] to manage and control a large number of ACs which is beneficial for both end-users and the utility. The proposed technique aggregates and manages AC loads and permitted end-users with small AC loads to participate in several load management programs. They will receive extra benefits in addition to lower electricity bills with a required thermal comfort level. This proposed load management approach has been validated for large apartment complexes in Seoul, Korea. Fuzzy AC control can be applied for conserving energy and maintaining the comfort of residents. It has been particularly used in the control of operation room where uncertain constraints require additional control. In [121], it has been explored that fuzzy AC control provided more consistent and reliable controls. A two-stage payback approach is discussed in [234] for AC load curtailment by varying temperature setpoint for DR programs. It has been reported that conventional control methods for ACs as described in [96] and [235] are not enough to address the DR challenges with various constraints like demand fluctuations, the comfort of residents and variable electricity pricing schemes. In addition to control approaches and efficiency improvements, DR can be implemented for ACs if the use of ACs for certain location is known. In [236], the percentage of ACs use is determined by measuring CO_2 indirectly from the number of people that occupy a certain residence. Future AC power demand requirement can be predicted for certain residences from the number of people. It is also expected that the comfort of residents can be addressed, and power consumption can be reduced for a specific location.

TCL-based DLC is also presented in [237] in combination with optimization approach for load minimization and the comfort of end-users in consideration. In [238], stochastic battery model is used for TCLs and its applications for frequency regulation is investigated. Also, the control of TCLs is observed in [199] with differential equations. Markov transition matrix is also used to model aggregated TCLs in [239] for load minimization. Coordinated and decomposed dispatch approaches for TCLs are investigated in [240] and [241], respectively. Furthermore, the impact of TCL on microgrid operation is observed in [242]. Optimal models are explored to not only minimize energy utilization but consider the comfort of end-users [243]. Therefore, in [244], DLC-based approach for day-ahead TCLs scheduling has been investigated considering the comfort of end-users. Different control strategies and DR programs for ACs in residential and commercial buildings are summarized in Table II.

TABLE II
DIFFERENT CONTROL STRATEGIES AND DR PROGRAMS FOR RESIDENTIAL AND COMMERCIAL ACS

Control strategies	Techniques	Case study	Benefits achieved
THIC (residential buildings)	Modelling of optimal DR control [51]		Cost saving; peak power reduction; comfort of residents
	Dry bulb temperature/relative humidity measurement [170]		Better comfort; efficiency improvement
	AC load profiles in one second resolution [245]	HEMS	Cost saving; peak power reduction
	Stochastic dynamic programming [66]		Optimal trade-offs between comfort of residents and AC energy cost
	Distributed control algorithm [228]	Finnish network	Peak reduction; impact on load factor, network losses and service reliability
	MILP [218]	HEMS	Cost saving; peak power reduction
	Termal model of grey-box room in combination with optimization techniques [101]	Hong Kong, China (summer day)	26% power reduction; thermal comfort
THIC (commercial buildings)	THIC [246]	Virtual building in Hong Kong, China	Considerable energy saving
	Novel THIC [184], [185]	Office room in Shanghai, China (July to August 2013)	Less energy consumption; better thermal comfort
	Novel THIC and its associated control [186]	Museum	Reduction of energy consumption (20%-30%); higher precision level of temperature and humidity
	THIC for moisture and temperature control [182]	Office building in Shenzhen, China	Comfortable indoor environment; magnificent energy saving potential
	SSPCM in building [189]	Test case in summer for Beijing, Hong Kong, China	Peak load reduction (20%); improvement in indoor thermal comfort; building electricity cost reduction
	Fuzzy expert system [121]	AC in operation room	Energy conservation; human comfort; economical, reliable and consistent control
	Utilizing temperature set backs and energy efficient measures (EEMS) [179]	Two churches located in College Station, Texas, US	Meaningful energy and cost saving; occupant comfort not disturbed by EEMS
DLC (residential buildings)	MPC [55]		Total energy consumption reduction; thermal comforts of residents
	Program of DLC [198]-[200]	Southern Ontario, Canada	Peak load reduction; peak power reduction
DLC (commercial buildings)	Queuing system modelling [233]	Large apartment (Seoul, South Korea)	Lower electricity bill; customers incentives, conveniences and thermal comfort levels are moderated
	Strategy of robust AC sequence [146]		3% energy saving compared to original strategy
	Fast DEM and response control approach [231]		Power reduction (about 23%); acceptable temperature maintained
	Control of direct power limit [232]	Central AC plant in Hong Kong, China	Peak demand reduction during AC start-up period
	Control of AC usage according to number of people in a building by measuring CO_2 [236]	University building in Japan	Overall power consumption to be optimized; comfort maintained

IV. Practical Applications of AC-based DR Programs

The sales of ACs have increased worldwide over the last few years. AC usage is dependent on several social, economic and climatic factors. The AC market increased up to 98 billion US dollars in 2014. It represented about 58% of the world total market and nearly 10% total increase as compared with that in 2013 [247]. According to statistics, about 43 TWh of the electricity is annually required to meet the residential AC demand for 7.7 million households in Texas, USA [248]. ACs contribute significantly to the peak demand in South Australia as about 90% of households have one or more ACs. Household-installed ACs contribute approximately 20%-25% in peak demand for Ausgrid during high-temperature periods [12]. The AC load demand in 2017 increased by about 8.1% as compared with that in 2016. The largest AC sales are observed in China with about 42% of total AC demand of the world [249]. Cooling demand will significantly rise in the coming years, especially for the developing regions like Asia and Africa, which is mainly due to climatic variation, income growth and population increase [198]. International Energy Agency (IEA) has predicted about 244% increase in the number of ACs worldwide up till 2050. Worldwide energy demand by 2050 has expected to reach about 6205 TWh due to AC use. The IEA forecastes that global energy demand could be 3407 TWh if AC efficiency can be improved [250]. There are several approaches developed in managing electricity use based on AC. One way is energy efficiency measures [251] which consist of various methods such as insulation addition, windows closing or implanting trees. Then, total electricity utilization and peak demand due to ACs may be reduced.

DR potential of ACs in residential and commercial buildings has been enhanced. The need of power system investment could be avoided by applying DR. Several studies have proved the effectiveness of DR in providing constant power supply with cost minimization for end-users [252]-[256]. AC-based DR has revealed obvious effects in load control during peak demand hours, high-temperature hours and system load improvement [257]. In addition, if variable pricing schemes are associated with AC use, end-users have to shift AC loads to off-peak periods for the reduction of electricity bill, and it provides a reduction in peak demand of the total system. Several variable pricing policies for peak demand minimization have been investigated in [258].

Reference [12] shows that residential ACs present a significant DR opportunity, resulting in about 9% of the total peak demand under certain situations for NSW of Australia. Furthermore, the centralized and coordinated control of residential ACs for Austin, Texas, USA reduces the total electricity peak by 8.8% [259]. In recent years, THIC for AC systems in commercial buildings of China has been observed extensively. Practical THIC implementations have confirmed their considerable dominance to conventional systems in terms of operation costs [260]. Different control strategies and DR programs for ACs in residential and commercial buildings of different world regions are summarized in Table III.

V. Future Trends and Major Challenges

ACs significantly contribute to the total energy utilization of residential and commercial buildings. It is not a possible solution to build new power plants in energy consumption. The most appropriate solution is to minimize energy utilization of ACs by developing control techniques with AC infrastructure modifications and without the replacement of the whole equipment. DR measures and AC control for optimal energy usage control are the ways to mitigate global energy challenges [12].

Different available DR programs for AC energy management have been discussed in [29]. Conventional control methods for ACs as explained in [96] and [235] are not enough to address the DR challenges with various constraints like demand fluctuations, the comfort of residents and variable electricity pricing schemes. Control strategies for AC-based DR have been explored for residential and commercial buildings such as indoor temperature control, humidity level control, THIC, and DLC. DLC is considered as a convenient approach for abrupt load reduction in a very short duration. In this approach, electricity companies have the authority to tackle the specific devices of end-users. There will be certain disturbances and uncertainties in ACs system when sudden important and instant load reduction is required. Several approaches have been discussed in existing publications to address these issues but are still challenging.

In addition to disturbances and uncertainties in the power system, one more challenge relevant to DLC is to manage and control a large number of AC units by utilities. Still, utilities and end-users are inconvenient although they have an agreement. Each user does not want to switch off their ACs and utilities are in a challenge to control hundreds of small AC loads. Numerous optimization tools, machine learning approaches, and hybrid models have been applied to observe thermal characteristics of buildings. These approaches require further improvements for energy usage minimization and the comfort of residents. Besides, SPM application in buildings requires further improvements [189]. ACs contribute primarily to building energy consumption, and the repairing and replacement of the equipment require proper scheduling mechanism for energy management. Moreover, AC load forecasting can be performed for energy optimization. Normally, DR programs and several pilot projects have been initiated for residential and commercial energy sectors at regional and household levels, but not appliance level. Therefore, DR programs at appliance level need more considerations. Several approaches have been discussed in the literature to address these issues but there are still some challenges enlisted as follows.

1) DLC requires more improvements to tackle the comfort of residents and energy management in both residential and commercial buildings [183].

2) AC power scheduling and control mechanisms for large number of ACs by utilities are also considerable challenges.

3) Different optimization techniques such as MILP [218] and SDP [66] have been adopted in residential buildings for indoor temperature and humidity control, and such approaches still require the improvements to meet the requirements of both end-users and utilities.

TABLE III
PRACTICAL APPLICATIONS OF AC-BASED DR PROGRAMS

Main location	Location	Control strategy	Benefits achieved
Asia	Cities in southern China, i.e., Guan zhou, Shenzhen, Zhuhai [261]	Fuzzy adaptive imperialist competitive algorithm (FAICA) for proposed DLC model	Significant impact on customer thermal satisfaction
	Shenzhen, China [182]	THIC system for office building	Improvement in energy efficiency
	China [262]	THIC system with chilled water at high temperature and liquid desiccant system for industry workshop	Acceptable indoor temperature and humidity; 50% less operation cost
	India [10]	Efficient improvement methods for room ACs	40% of consumed energy saving
	Singapore [263]	Testbed for AC remote controlling	Remote control; energy management
Europe	Sweden [264]	Several household-based DR	Modification in load profile
	Romania [265], [266]	DR-blocks of buildings pilot project	Reduction in overall and peak demand; environmental benefits
	Portugal [267], [268]	Evora-DR pilot project	Improvement in energy efficiency; comforts of residents
		NEDO-LNEG collaborative project; NetEffiCity (VPS project)	Energy savings; remote control
	Finland [268]	DR-pilot projects by Finland TSO	Electricity bill discounts; real-time control
	Czech Republic [269]	DR-based CRC project	Load minimization
	Italy, Spain, and France [270], [271]	ADDRESS project for DR	Energy savings; energy consumption management
	Latvia [272]	Consumption feedback approach from smart meters	Peak loads minimization; demand flexibility achievement; dynamic prices
	Greece [273]	Mobile-based application for DR	Energy management for future
	Turkey [274]	Several DR-based pilot projects	Reduction in energy usage during peak hours
	Flanders, Belgium [275]	LINEAR project with active demand management techniques	Dynamic prices; Technologies improvements
	Spain [269]	DR-based OPTIGES project	Losses minimization; Environmental benefits
Oceania	South Australia [29]	Peak smart ACs pilot project with 1000 households	19%-35% peak demand reductions; thermal comforts of residents
	Australia [12]	Clustered AC load profiles by Ausgrid with possible load control strategies in [101] and [258] for NSW	Almost 4%-9% of peak demand reductions
		Cool saver program with control ACs events and usage hours	Price incentives; smart devices for customers
	Sydney, NSW [276]	Different pricing schemes by EnergyAustralia	23%-25% power reduction
	Western Sydney, NSW [258]	Different pricing schemes by EnergyAustralia	7%-15% power reduction and 5% additional reduction with in-home display (IHD)
	Jerrabomberra and Queanbeyan, NSW [258]	Different pricing schemes by country energy	25% reduction in peak demand with 8% overall reduction
America	USA [277]	Energy saving alignment strategy for 1000 units of ACs considering the temperature	21%-42% energy savings subject to region climate
	Austin, USA [29]	Rush hour reward pilot project for 2000 end-users (2013)	Incentives and smart thermostats
	California, USA [12]	Cool saver program with control ACs events and usage hours	Price incentives; smart devices for customers
	Texas, USA [259]	Economic MPC	Overall peak reduction
	Austin, USA [278]	Integrated thermal energy and rainwater storage (ITHERST) for typical home in hottest summer 2011 in Texas, USA	Peak compressor demand reduction by (about 29%-53%); peak power reduction
	California, USA [258]	Dynamic peak pricing (DPP) by Californian statewide pricing pilot	Reduction in overall and peak demand
		DPP and DLC by Californian state wide pricing pilot	20%-60% peak load reduction
	USA [279]	TOU, DPP, IHD, and timer technology by east-coast utility, USA	26% peak load reduction and 5% overall consumption reduction

4) THIC-based ACs are becoming popular worldwide in recent years in commercial buildings [261]. THIC also needs more improvements for efficient and reliable operation.

5) Nowadays, adaptive control has been proposed for the building energy management. In the future, the impacts of the adaptive AC control model for DR programs require more attention.

6) Several contributions from AC based on DR like frequency regulation services and operation reserves require more considerations.

7) For the real-time implementation of AC-based DR, data collection methods at the appliance level should be im-

proved.

8) End-users do not intentionally agree to engage in DR programs. Thus, the involvement of end-users in DR programs needs more attention. Policy barriers and technologies need to be updated to implement AC-based DR more efficiently.

VI. Concluding Remarks

In this paper, the overall electricity consumption in buildings due to the ever-increasing number of ACs is discussed. To handle this challenge, different control methods have been compared for ACs in the context of energy savings and the comfort of consumers. Furthermore, different control approaches like THIC and DLC have been presented for ACs in residential and commercial buildings. DR programs have been introduced and classified. Different optimization approaches have been applied to make AC participation effective in DR programs. Moreover, DR programs available for ACs are explored, and different AC-based DR projects worldwide have also been investigated and overviewed in this paper. It has been observed that hybrid control methods are a combination of soft and hard control approaches that provide better results compared to conventional methods. Similar to THIC, DLC is an efficient and direct method for AC load management as required by electric utilities. To tackle the comfort of consumers in DLC, the manipulation will be a major challenge in the future. The modeling of thermal characteristics of a building and modifications in the AC design for control approaches need to be explored for the optimization of energy usage and the comfort of resident. Different control approaches proposed in existing literatures need further improvements and validation to implement in real sense. AC load forecasting approaches should be explored for efficient energy optimization. The repair and replacement of the equipment require proper scheduling mechanisms. Frequency regulation services and operation reserves are the main applications attainable from AC-based DRs as discussed in this paper, which represents a significant research challenge.

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Muhammad Waseem received the B.Sc. and M.Sc. degrees in electrical engineering from University of Engineering and Technology Taxila, Taxila, Pakistan, in 2012 and 2017, respectively. He is currently pursuing his Ph.D. degree in the College of Electrical Engineering, Zhejiang University, Hangzhou, China. He is also with the Department of Electrical Engineering, University of Engineering and Technology Taxila. His research interests include power system analysis, demand side management, and smart grids.

Zhenzhi Lin received the Ph.D. degree in electrical engineering from South China University of Technology, Guangzhou, China, in 2008. He was a Research Assistant in the Department of Electrical Engineering at The Hong Kong Polytechnic University, Hong Kong, China, from 2007 to 2008, a Research Scholar in the Department of Electrical Engineering and Computer Science at the University of Tennessee, Knoxville, USA, from 2010 to 2011, and a Research Associate in College of Engineering and Computing Sciences at Durham University, Durham, UK, from 2013 to 2014. He is currently a Professor in the College of Electrical Engineering, Zhejiang University, Hangzhou, China. His research interests include power system wide-area monitoring and control, controlled islanding and power system restoration, and data mining in power systems.

Yi Ding received the B. Eng. degree from Shanghai Jiao Tong University, Shanghai, China, and the Ph.D. degree from Nanyang Technological University (NTU), Singapore, both in electrical engineering. He is a Professor in the College of Electrical Engineering, Zhejiang University, Hangzhou, China. Before he joined in Zhejiang University, he was an Associate Professor in the Department of Electrical Engineering, Technical University of Denmark, Copenhagen, Denmark. He also held research and teaching positions in University of Alberta, Alberta Canada and NTU. He was a consultant as Energy Economist for Asian Development Bank in 2010. He is Editorial Member of international journals of Electric Power System Research and Journal of Modern Power Systems and Clean Energy. He is also a guest editor for the special section of IEEE Transactions on Power Systems. Dr. Ding is the member of IEC working groups for microgrid standards. His research areas include power system planning and reliability evaluation, smart grid, and complex system risk assessment.

Fushuan Wen received the B.E. and M.E. degrees from Tianjin University, Tianjin, China, in 1985 and 1988, respectively, and the Ph.D. degree from Zhejiang University, Hangzhou, China, in 1991, all in electrical engineering. He joined the faculty of Zhejiang University in 1991 and has been a Full Professor since 1997. He is also a part-time distinguished Professor under Yusheng XUE Education Foundation in Hangzhou Dianzi University, Hangzhou, China. He had been a university distinguished Professor, the deputy dean of the School of Electrical Engineering and the director of the Institute of Power Economics and Electricity Markets in South China University of Technology, Guangzhou, China, from 2005 to 2009. He is a Professor in the Department of Electrical Power Engineering and Mechatronics, Tallinn University of Technology, Tallinn, Estonia, taking leave from Zhejiang University. Prof. Wen is the Editor-in-Chief of IET Energy Conversion and Economics, and a deputy Editor-in-Chief of Automation of Electric Power Systems. He also serves as the editor, subject editor and associate editor of a few international journals. His research interests include power industry restructuring, power system alarm processing, fault diagnosis and restoration strategies, as well as smart grids and electric vehicles.

Shengyuan Liu received the B.E. degree in electrical engineering from Shandong University, Jinan, China, in 2017. He is currently pursuing his Ph.D. degree in the College of Electrical Engineering, Zhejiang University, Hangzhou, China. He is also a visiting Ph.D. student at The University of Tennessee, Tennessee, USA, for one year from 2019 to 2020. His research interests include wide area monitoring and control of power systems, situation awareness of power systems, and data-driven approaches in power systems.

Ivo Palu graduated from Tallinn University of Technology, Tallinn, Estonia, and received the Ph.D. degree in electrical power engineering in 2009. He has taught various courses, including wind energy and electrical materials. He is currently a Professor and the Head of the Department of Electrical Power Engineering and Mechatronics, Tallinn University of Technology. He is a Member of the Board of Estonian Society for Electrical Power Engineering and the Supervisory Board of Estonian Power Company Eesti Energia AS. His main research interests include wind turbine co-operation with thermal power plants and grid integration of new energy sources.