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Controlling of aggregate split-type air-conditioners under the thermal comfort conditions for energy management

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Abstract. Due to an electricity demand peak in Thailand is critically high in the summer period every year. This high electricity demand peak is mainly caused by the use of air-conditioners in residential section and too low setting of thermostat set-point (over cool setting) of air-conditioners. Moreover, split-type air-conditioners are operated individually, which resulted in a highly electricity peak from randomly compressors working of a group of aggregated air-conditioners. Based on the problems mentioned above, the direct load control (DLC) is a solution to solve these problems under demand response (DR) program. Therefore, the objective of this study is to control an aggregate split-type air-conditioners by setting thermostat set-point under a thermal comfort range of university's students in Thailand. In this study, the four split-type air-conditioners without any modification were controlled by a microcontroller. The upper range of thermal comfort of university's students was chosen at 27ºC. In order to investigate the potential for reducing electricity peak, the thermostat set-point conditions were used at 25ºC (conventional thermostat setting condition) and 27ºC (upper limit of thermal comfort condition). Moreover, the control strategy was designed and tested to compare the results of electricity peak and electricity consumption between with and without the control of aggregate split-type air-conditioners within 8 hours of testing. The results showed that when using the control strategy, an electricity peak can be reduced by 20.4% and 31.3% at the thermostat set-point conditions of 25ºC and 27ºC, respectively, as compared to the conventional thermostat control condition. Additionally, the results of electricity consumption showed that the condition of control strategy at upper limit of thermal comfort condition setting of 27°C can be reduced electricity consumption by 45.2%, as compared to the condition of conventional thermostat control setting of 25°C.

1. Introduction

The electricity peak demand and electricity consumption in Thailand have increased every year due to the growth of economic. In particular, the highest electricity peak demand was shown during the summer months because of relatively high ambient temperatures, which leads to increasing use of air-conditioners. The increased peak demand can cause electrical system failure if the peak demand is greater than generating capacity of the power plants.

Annual report 2014 of the energy balance of Thailand [1] shows that electricity consumption increases every year. The average growth rate is approximately 2.8% per year during 2009-2014 (as shown in Figure 1). The peak demand for electricity also increased. Normally the peak demand occurs in April-May. However, the recent peak demand in 2015 (27,346 MW) offered in June (as shown in Figure 2).

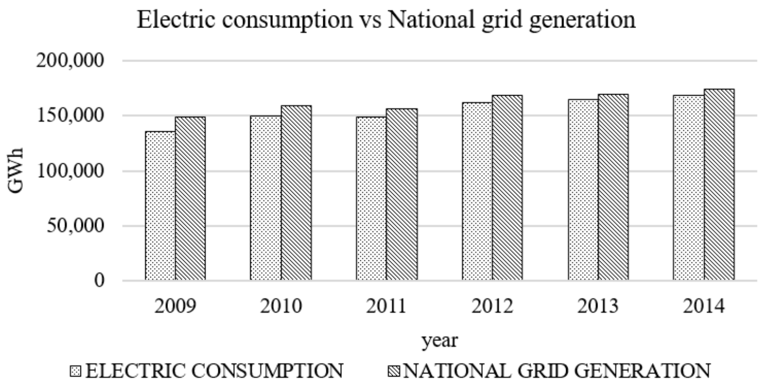

Figure 1. Thailand's electricity consumption in 2009-2014.

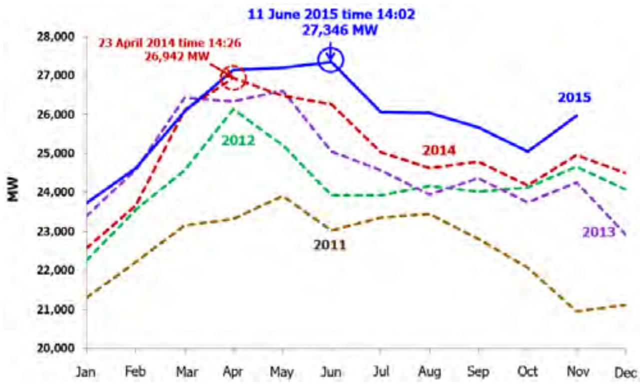

Figure 2. The peak demand for electricity in Thailand during January, 2011-December, 2015.

The energy statistic shows that in the year 2004 the total electricity consumption of a residential section was accounted for 23% of Thailand's national electricity consumption [2]. Besides, energy consumption for air-conditioning system was accounted for about 60% of the total electricity consumption of a residential section in Thailand [3]. Additionally, the Ministry of Energy of Thailand reported that statistical data of electricity consumption demand for air-conditioning was increased by 350 MW for every 1°C temperature increased in air conditioner thermostat setting [4].

Almost all air-conditioners in residential sector use the split-type air-conditioners. Most of the residential air-conditioners use fixed-speed compressor type that has ON and OFF working characteristic. When the air-conditioners are ON, it means that the compressors are being operated. On the other hand, if the air-conditioners are OFF, the compressors stop operation. If many air-conditioners are ON at the same time, the demand for electricity increased rapidly.

The most promising solution for energy's stability and energy's security is to apply the concept of demand-side management (DSM). At present, this DSM concept has already been operated in Thailand for preventing energy emergency's situations. DSM is one of the promotion methods of electricity energy efficiency. The main advantages of DSM concept are that it requires a short time for the preparation and cheaper than build a new power plant to overcome this problem. One of the DSM measures is reducing peak demand from air-conditioners. In many cases, increasing thermostat setting of air-conditioners can reduce electricity peak demand. However, the increased thermostat setting should be within thermal comfort zones.

The investigation of thermal comfort zone for human has gained worldwide interest in the air-conditioning field. ASHRAE standard provides the criteria and methodology for evaluating thermal comfort zone, so that ASHRAE standard-55 [5] is commonly used to refer. ASHRAE standard describes the survey methodology for the calculation of an effective temperature with acceptability value of the survey's subject, which can be used to define thermal comfort zone. Several studies have been investigated thermal comfort based on a survey of randomly subjects using questionnaire that referred to ASHRAE standard, the survey check sheets that use to collect necessary data of subjects and a survey room, for examples, gender, type of clothing, operative temperature, relative humidity, air-velocity and mean radiant temperature [6-9]. Besides, Delphi technique was used, in which the data was collected from the medical expert brainstorming, as well as to collect additional non-quantity factors such as a number of air-conditioners at home and educational level [10]. Moreover, the thermal comfort zone of four hundred and one university's students was investigated. The survey check sheet was prepared according to ASHRAE standard 55-2010 to calculate the actual mean vote (AMV) and the percentage of sensation vote for thermal sensation [11].

The results of thermal comfort zone for Thai people showed that an effective temperature ranged from 24 to 27ºC and a relative humidity ranged from 50 to 60%RH for the air velocity of 0.2 m/s. Moreover, the results also showed that the higher air-velocity affected to higher neutral temperature for subjects [6]. After surveyed three climate zones of Thailand, Yamtraipat et al. (2004) reported that the thermal sensation range of all three zones was between 25 to 26.2ºC in which considered of 80% acceptability, whereas the results of humidity range that most subjects voted "just right" was 50 to 60%RH for all three zones. Moreover, this previous study found that the people, who normally used air-conditioners at home, preferred a lower neutral temperature (25.4ºC) than the other groups (26.3ºC). In addition, the factor of education level was showed that the post-graduate preferred the lowest neutral temperature (25.3ºC) than graduate and scholar level [7]. In the study of Srivajana (2003) found that the Predict Mean Vote (PMV) model of Fanger (1970), which used to calculate PMV value in ASHRAE standard, was not suitable for air velocity and the subjects who preferred a higher relative humidity related to higher air velocity. Based on the 80% acceptability, the thermal sensation was ranged from 23.0 to 26.3ºC with the air velocity of not greater than 0.9 m/s [8]. In addition, De Dear et al. (1997) reported that the subjects preferred a higher temperature in the naturally ventilated building because of a higher velocity from the naturally ventilation room. Besides, for air-conditioned room with a mean velocity of 0.11 m/s and a mean indoor relative humidity of 56%, the result of an operative temperature ranged from 23.6 to 25.1ºC was obtained [9]. The study of Sookchaiya et al. (2010) showed that the results of thermal comfort of human for health that were obtained from the Delphi technique, after three rounds brainstorming of medical expert group, the questionnaire was created and analysed to 40 items. This previous study concluded that the suitable temperature in air-conditioned room should be at 25 to 26ºC and the suitable relative humidity should be around 50 to 60%RH. However, no any acceptable range was considered in this previous study [10]. Moreover, the results of literature review also showed that operative temperature range is 23.6-27.4°C at 90% acceptability of university's students and the most university's students preferred acceptable relative humidity range of 40-50% [11].

Because electricity demand has grown rapidly related to rapid economic growth, while the price of electricity has risen every year. Therefore, the demand response (DR) program presents as a promising alternative solution for more security of electricity system, as well as to prevent any new power plants that cannot be beneficial for such a short period of electricity peak in summer time. Several previous studies have been investigated on demand response with respect to the potential of demand response measures applying to commercial buildings in Thailand, in which the data was first collected from hospital and two shopping malls in Bangkok, and followed by monitoring the high electricity-consumed equipment and system to use as electricity baseline [12]. Furthermore, a direct load control of central air-conditioning loads with thermal comfort control in Taiwan was focused on central air-conditioning load that accounted for 25.8% of Taipower electricity summer peak [13]. In addition, a strategy to address residential air-conditioning peak load in Australia by collected the data of electricity used and found that the electricity peak period of an average household demand was occurred when the local average temperature became lower than 18ºC and above 20ºC, which meant that the average demand peaks for hot and cold days related to air-conditioning system were used [14].

The results obtained by the study of Pasom et al. (2015) showed that the total electricity peak reduction was 1,759 kW, which accounted 64% from the backup generator method and 36% from the various peak reduction method. Also, the results showed that the peak reduction method could be reduced a peak accounted for 636.5 kW and the item of rising the temperature in the building could be reduced 23.5 kW by demand response [12]. In addition, the study of Chu et al. (2005) reported that the fuzzy controller was better than conventional thermostat for controlling thermal comfort level. Besides, the fuzzy controller was also better for power consumption of air-conditioning system, as the power consumption was 32.5% lower than conventional thermostat [13]. Based on the collected data, Smith et al. (2013) also showed that the 60% of air-conditioners was turned on during the peak summer day, whereas the 83% of air-conditioners was turned on in the extreme hot day. Moreover, the utilities were used air-conditioners over the period of 12 hours on the peak summer day [14].

Due to global warming situation, a number of air-conditioning systems has increased both for the residential and commercial sectors. The split-type air-conditioners (which are also named as unitary air-conditioners) are the most popular type and commonly used. There is a number of research focused on controlling the aggregated air-conditioners; however, with different proposes such as to reduce electricity peak [15] and to reduce electricity consumption during controlling temperature of air-conditioned room for more steady [16].

In the study of Wu et al. (2013), the infrared remote control system from monitoring and controlling the aggregate air-conditioners was designed. The 56 unmodified air-conditioners were controlled by microcontroller via the infrared remote control module. Moreover, the control strategy was designed as each cycle had 5 minutes of air-conditioning mode and 10 minutes of fanning mode. In addition, if a room temperature was below 26ºC (set point), the air-conditioners could change the operating mode from air-conditioning to fanning mode [15]. However, Chiou et al. (2009) was used fuzzy control for multi-unit room air-conditioners. The fuzzy logic controller (FLC) was designed by the language variable inputs, which were the temperature difference (ΔT_i) between indoor and set temperature, and the temperature gradient (heat load, $\Delta \dot{Q}_i$). The experimental works were used two slit-type air-conditioners with the outdoor ambient condition controlled at 35ºC and 60%RH, where the indoor temperature setting at 27ºC.

The results obtained by these two previous studies showed that the electricity peak value decreased 57 kW from demand strategy used, which could be possible to maintain the room temperature at around 26ºC as well [15]. Moreover, based on the fuzzy control, the results showed that 8.92% of energy consumption can be saved compared with ON/OFF method. Also, the fuzzy control can control the room temperature steadier than ON/OFF method [16].

Based on the above literature review, the problem statements of this study can be drawn as follows, the literature review of thermal comfort for human showed that the previous researches were obtained the results of thermal comfort in air-conditioned room, but never considered these results to use as thermostat setting of split-type air-conditioners for direct load control in demand response program. Moreover, the literature review of Demand Response (DR) showed that previous researches have never been studied DR on aggregated split-type air-conditioners for reducing electricity demand peak, as well as for decreasing energy consumption. The literature review of controlling of aggregated air-conditioners has never been focused on controlling split-type air-conditioners based on control strategy combined with thermal comfort condition.

Above problem statements will be used to design research objectives as to control the aggregate split-type air-conditioners for reducing electricity demand peak and energy consumption in response with the thermal comfort zone of air-conditioning room.

2. Methodology

According to the ASHRAE standard, it was recommended that the operative temperature should be obtained based on 80% of occupant acceptability; however, the higher occupant acceptability was also suggested to define a range of operative temperatures for using as temperature set-point for air-conditioned rooms [5]. Thiangchanta and Chaichana (2016) used this approach to investigate thermal comfort condition of air-conditioning operations for the lecture rooms in tropical climate countries, in which resulted in the upper limit thermal comfort condition of 27°C. Moreover, this previous study [11] also reported a higher occupant acceptability of 90%, as compared to other studies [7-8]. However, in other studies, for examples [6, 10], the occupant acceptability was not considered. Based on these results, the current study will be considered the upper limit thermal comfort condition at 27°C as thermostat setting condition for investigating the reduction potential of electricity demand peak and energy consumption in air-conditioned rooms.

2.1 Experiment procedure

The methodology procedure of this study is described as in Figure 3, and the details of methodology procedure are further explained as follows.

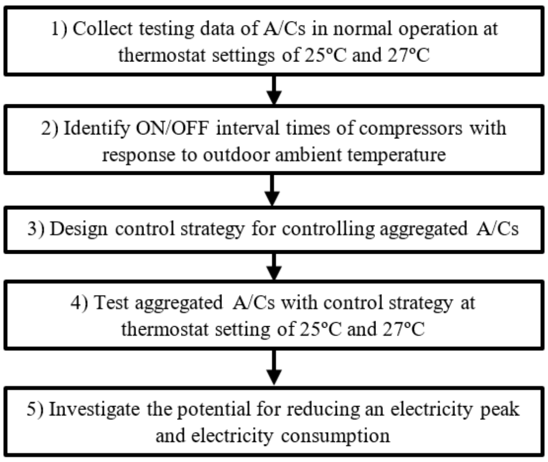

Figure 3. Methodology procedure used in this study.

1) The first process is to collect working behavior's data of four air-conditioners in normal operations with two thermostat settings of 25ºC and 27ºC. The collected parameters of this process are outdoor ambient air temperature, air-conditioned room's temperature and electric power of air-conditioners. The data was collected with testing air-conditioners for 8 hours.

2) In the second process, the collected data obtained by the first process was used to identify ON/OFF interval time of compressors that response to ambient air temperature. Normally, the ON interval times of compressors is long where the ambient air temperature is high. In the other hand, the OFF interval time of compressors is short where the ambient air temperature is high. These affect to a large surge peak demand from using air-conditioners during hot period. The results from this process were the difference of ON/OFF interval times with respect to the various cooling capacity of air-conditioners.

3) The results of ON/OFF interval times, which obtained from the second process, were then used to design the control strategy of controlling aggregated air-conditioners in order to investigate the electricity peak and electricity consumption. The main purpose of this control strategy was to prevent each compressor working ON at the same time. In case, it was not possible to prevent compressors working ON at the same time, the control strategy must be then designed to minimize a number of compressors working ON at the same time, and/or to minimize an interval time of compressors working ON at the same time.

4) In the fourth process, the designed control strategy was used to test air-conditioners at thermostat setting conditions of 25ºC (conventional thermostat setting) and 27ºC (upper limit of thermal comfort condition), the tests of air-conditioners in all conditions were performed for 8 hours.

5) Finally, the testing results of designed control strategy of aggregated air-conditioners were used to investigate the potential for reducing an electricity peak, as well as, for reducing an electricity consumption.

2.2 Experiment Set Up

Four experimental rooms that are located in Faculty of Engineering, Chiang Mai University were selected. An air-conditioner was installed in each room. Each air-conditioned room was installed 200 W of incandescent light bulb that used to simulate the heat load of air-conditioned rooms. The details of experimental rooms and air-conditioners specification are shown in Table 1.

Table 1. Air-conditioners specification.

Experiment room No.	1	2	3	4
Floor area (m^2)	16.8	16.8	16.8	23.65
Cooling capacity (BTU/hr.)	12,300	13,624	12,300	20,103
Power consumption (W)	1,060	1,110	1,040	1,688
Max. Electric current (Amp.)	4.9	5.0	4.8	7.67
Power source	1Ø, 50 Hz, 220 V	1Ø, 50 Hz, 220 V	1Ø, 50 Hz, 220 V	1Ø, 50 Hz, 220 V

In this study, air-conditioners were controlled by a microcontroller. The microcontroller was installed with the source code and used to send a signal to control the power relay that used for switching a supplied power to air-conditioners. The power relay has a current rating of 10A at 250 VAC, while voltage requirements are 5 VDC (Relay Power) and 3.3-5 VDC (Input Signal).

The microcontroller received input signal from the temperature sensor (DHT22) that is used to measure the ambient air temperature. Then the microcontroller sent a signal to control aggregated air-conditioners under a designed control strategy. The specification of temperature sensor is as follows;

- humidity operating range of 0-100%RH,
- temperature range of -40°C to 80°C,
- humidity accuracy of ±2%RH (Max ±5%RH), and
- accuracy of temperature is less than ±0.5°C with an average sensing period of 2 seconds.

A schematic of the control system is shown in Figure 4.

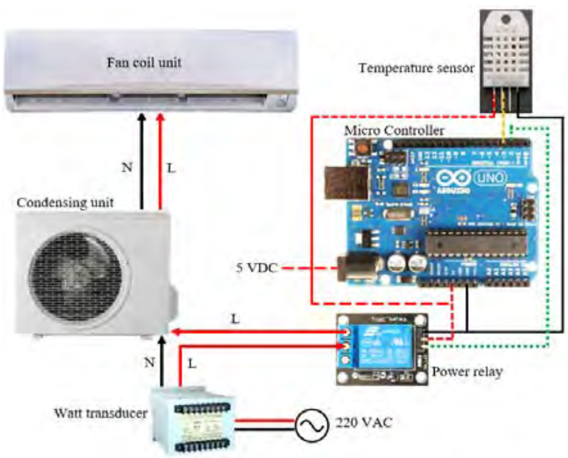

Figure 4. A schematic of the control system.

2.3 Measurement devices

The measurement device used in this study was thermocouple T-type for measuring the temperatures of outdoor ambient air and indoor temperatures of air-conditioned room. The thermocouple T-type was also used to measure the dry bulb temperatures and wet bulb temperatures. The T-type thermocouple has the measuring range of 0°C to +200°C. The accuracy of the thermocouple is ±0.5°C or 0.4%. The data from thermocouples was automatically recorded every 1 minute by data logger.

As shown in Figure 4, watt transducer was used to measure electricity used by the air-conditioners. It converts single or three phases unbalance load active power into a proportional load independent DC output, which applied to measure the power of each air-conditioner by sending a measuring data into the data logger every 1 minute. The watt transducer can measure up to 5Amp of the current used by air-conditioners at 220 VAC, 50 Hz. The output of the watt transducer is 4-20 mA and 0-10 mVDC.

3. Results and discussion

In this study, the data were collected during the period of March to April 2017, which was the summer season of Thailand. The results was separated into three parts, which were the results of ON/OFF interval times of compressors, the results of designed control strategy, and the results of electricity peak and electricity consumption. The details of these results are as follows.

3.1 Working interval times of compressors

The results of collected testing data of air-conditioners in normal operation response with ambient air temperature were used to identify ON/OFF interval times of compressors. The tests were divided into two different conditions of thermostat setting temperature as 25°C (conventional thermostat setting) and 27°C (upper limit of thermal comfort condition). The detailed results of ON/OFF interval times of compressors in second are shown as in Table 2.

It was found that the ON interval times of compressors were increased when the ambient air temperature increased. This is because of the air-conditioners have to work longer for rejecting heat load of air-conditioned rooms in order to remain the room’s temperature at the thermostat set point.

In the other hand, the OFF interval times of compressors have an inverse variation with the ambient air temperature. This is because of higher ambient air temperature affects a rapidly risen of air-conditioned room’s temperature when air-conditioners stop working, so that air-conditioners have to restart quicker for remaining the room’s temperature at the thermostat set point.

Table 2. ON/OFF interval times of compressors with respect to different ambient temperatures.

	Ambient temperature (°C)	28	29	30	31	32	33	34	35
AC No.1	ON_25°C (sec.)	120	120	120	120	120	120	180	180
	OFF_25°C (sec.)	300	300	300	300	300	300	240	240
	ON_27°C (sec.)	180	180	180	180	180	180	180	180
	OFF_27°C (sec.)	330	330	330	180	180	180	180	180
AC No.2	ON_25°C (sec.)	105	105	240	240	240	240	240	240
	OFF_25°C (sec.)	300	300	180	180	180	180	180	180
	ON_27°C (sec.)	150	150	150	180	180	180	180	180
	OFF_27°C (sec.)	360	360	360	180	180	180	180	180
AC No.3	ON_25°C (sec.)	135	135	150	150	150	150	240	240
	OFF_25°C (sec.)	360	360	330	330	330	330	315	315
	ON_27°C (sec.)	180	180	180	204	204	204	216	216
	OFF_27°C (sec.)	300	300	300	291	291	291	288	288
AC No.4	ON_25°C (sec.)	135	135	210	210	210	210	375	375
	OFF_25°C (sec.)	360	360	270	270	270	270	180	180
	ON_27°C (sec.)	180	180	180	285	285	285	324	324
	OFF_27°C (sec.)	300	300	300	210	210	210	180	180

3.2 The results of designed control strategy

The results of ON/OFF interval times of compressors response with different ambient air temperatures were used to design the control strategy for controlling aggregated air-conditioners. The control strategy should prevent each compressor working ON at the same time. However, if it is not possible to prevent compressors working ON at the same time, the control strategy must be then designed to minimize a number of compressors working ON at the same time, and/or to minimize an interval time of compressors working ON at the same time. The designed control strategy of thermostat setting at 25°C and 27°C are illustrated in Figure 5(a) and Figure 5(b), respectively.

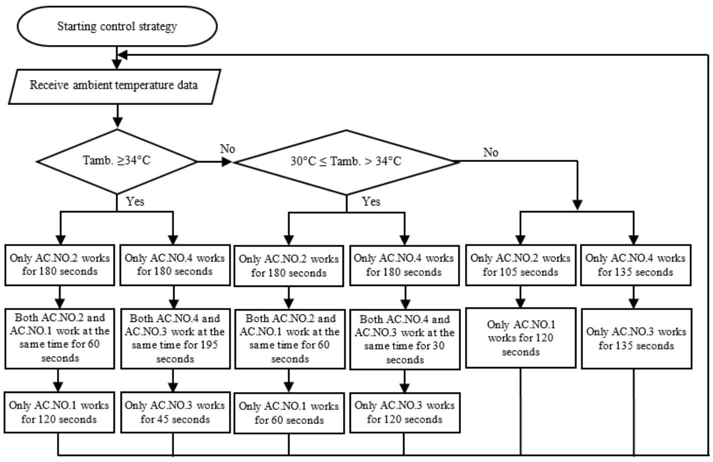

Figure 5(a). The designed control strategy of thermostat setting at 25°C.

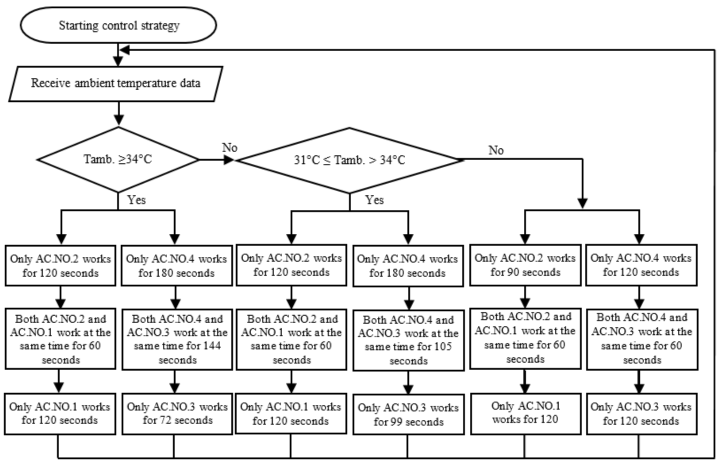

Figure 5(b). The designed control strategy of thermostat setting at 27°C.

3.3 The results of electricity peak and electricity consumption

The results of electricity peak in related to the different ambient air temperatures are shown with three different conditions, including the conventional thermostat control setting of 25°C, the control strategy with thermostat setting of 25°C and the control strategy at upper limit of thermal comfort condition setting of 27°C (Figure 6).

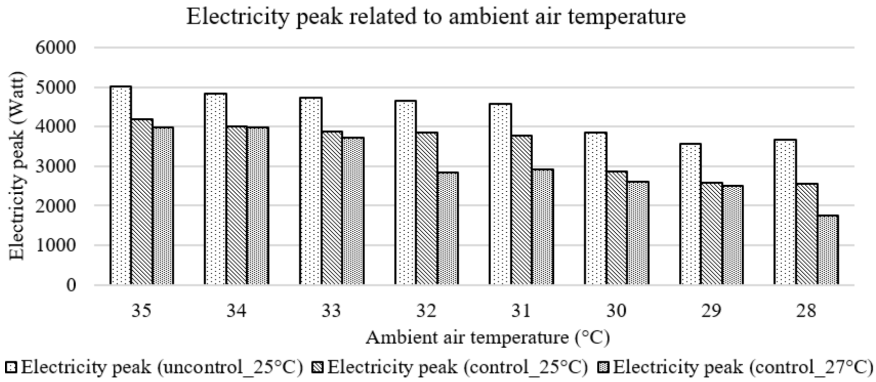

Figure 6. The results of electricity peak related to different ambient air temperatures.

The results of electricity peak in related to the different ambient air temperatures show that the electricity peak has a direct variation with the ambient air temperature for all conditions. The condition of conventional thermostat control setting of 25°C presents a highest electricity peak in every ambient air temperature. Besides, with the control strategy at the upper limit of thermal comfort condition setting of 27°C, a lowest electricity peak in every ambient air temperature was obtained. Additionally, the results show that the control strategy can be efficiently reduced electricity peak. It was found that the increasing of thermostat setting to the upper limit of thermal comfort condition resulted in a significant reduction in electricity peak.

By using the method of root mean square deviation (RMSD) from every ambient air temperature, the results obtained with the condition of control strategy with thermostat setting of 25°C show that electricity peak can be reduced by about 20.4%, as compared to the condition of conventional thermostat control setting of 25°C. Moreover, when using the condition of control strategy for thermostat setting at upper limit of thermal comfort condition setting of 27°C, electricity peak can be reduced by about 31.3%, as compared to the conventional thermostat control at 25°C. From the results of electricity peak, it was found that the method of increasing thermostat setting temperature becomes more effective if this applied with the control strategy.

Based on the results of electricity peak obtained from the three conditions, the results can be further extended to investigate the linear correlation of electricity peak in related to ambient air temperature with the coefficient of determination (R^2) that can be beneficial for applying in simulation work in the future, as shown in Table 3.

Table 3. Linear correlation of electricity peak in related to ambient air temperature and coefficient of determination (R^2).

	Linear correlation	R^2
Electricity peak (uncontrol_25°C)	y = -220.51x + 5350.7	0.883
Electricity peak (control_25°C)	y = -257.46x + 4625.6	0.873
Electricity peak (control_27°C)	y = -313.85x + 4453.2	0.928

Electricity consumption of the three conditions was investigated with 8 hours period of testing. Due to the electricity consumptions normally depends on ambient air temperature, the average ambient temperature was reported in order to compare the results of electricity consumption in each condition. The results of electricity consumption are shown in Figure 7.

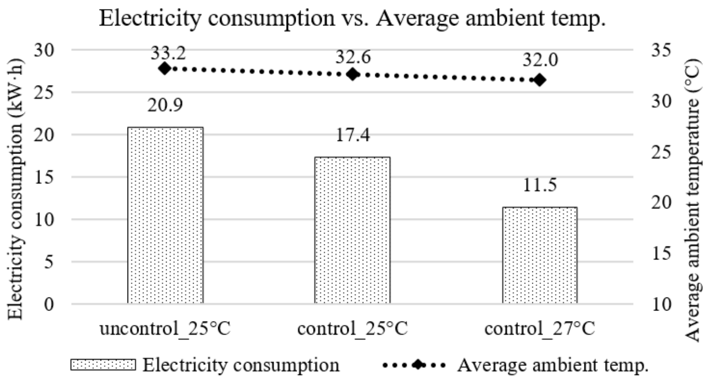

Figure 7. The results of electricity consumption with average ambient temperature.

As shown in Figure 7, electricity consumption obtained from the condition of conventional thermostat control setting of 25°C had a highest electricity consumption, whereas a lowest electricity consumption was found when applied the control strategy at upper limit of thermal comfort condition setting of 27°C.

The electricity consumption obtained from the condition of conventional thermostat control setting of 25°C was 16.8% higher than electricity consumption obtained from the control strategy with thermostat setting at 25°C. Moreover, with the condition of control strategy at upper limit of thermal comfort condition setting of 27°C, electricity consumption can be reduced by about 45.2%, as compared to the condition of conventional thermostat control setting of 25°C.

The average ambient temperature of all three conditions were similar, with the condition of conventional thermostat control setting of 25°C, the average ambient temperature was only 3.6% higher than the condition of control strategy at upper limit of thermal comfort condition setting of 27°C.

4. Conclusion

This study aims to investigate a concept of demand response program by reducing electricity peak from the use of air-conditioners. The microcontrollers were used to control the four spit-type air-conditioners at different room's temperature settings. The room temperature settings that were investigated in this study are under Thailand thermal comfort range. The behavior data of air-conditioners during operation was collected and used to design the control strategy.

The results show that electricity peak has a direct correlation with ambient air temperature for all conditions. The electricity peak can be significantly reduced with the right control strategy. Observing of compressors behaviour during normal operation can form new control strategy to preventing the compressors to work at the same time. At thermostat setting of 25°C, this control strategy leads to reduce electricity peak demand by 20%. Further reduction in electricity peak demand can be achieved when increasing thermostat setting to 27°C and using the control strategy. Moreover, the results also show that electricity consumption can be reduced with the control strategy, as compared to the conventional thermostat control with only small difference in average ambient temperature.

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