Electrical Power Consumption Profile Modelling of Air Conditioner for Smart Grid Load Management

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***Abstract*—Air conditioning (AC) system will be an inherent part of smart grid (SG) demand response as it is responsible for a substantial amount of power consumption in total infrastructure. It is invaluable to estimate the nature of operational characteristics of AC compressors in order to implement associated optimization strategy for energy preservation in residential premises. In this paper, the electrical power consumption profile, i.e., *On-time* and *Off-time* durations and power consumptions during these time durations is modelled for a split type AC compressor in terms of co-efficient of performance, AC capacity and environment condition. Dead-band temperature and room dimensions are considered as environment condition and the effect of various parameters on *On-time* and *Off-time* durations and energy consumption is studied. The factors that can be optimized to reduce the energy consumption are also analyzed.**

***Index Terms*—Smart grid, Air conditioning, Thermodynamics, Dead-band, Set-point, On-time, Off-time, Power consumption**

I. Introduction

The conventional electrical grid system is centralized which supports one directional power flow from the grid plant to the customers through the transmission and distribution lines without any intelligence at the customer premises. To overcome the limitations of the conventional electrical grid, researchers introduce the notion of *Smart Grid* which uses two-way flow of electricity and computational intelligence across the electrical infrastructure to attain a system featuring safety, security, reliability, efficiency and sustainability [1]. Smart management system is one of the sub-systems of smart grid (SG) system which is introduced for energy efficiency improvement, demand and supply balance, emission control, cost minimization and utility maximization through demand side management (DSM) [1], [2]. DSM is an initiative implemented by electricity utilities to encourage consumers to adopt procedures preferable to both parties [3], [4].

Based on field applications, DSM can be classified into two types: residential DSM and industrial DSM. Residential DSM emphasizes on maximum load factor without receiving customer dissatisfaction, whereas industrial DSM focuses on the energy-efficient use of electricity by providing maximum possible industrial production. In residential dwellings, there are existing three types of electrical loads: fixed load, interruptible load and elastic load. Interruptible loads such as air conditioner, light bulb, fans have flexible power consumption usages. Hence, they can be utilized for load scheduling to attain better energy efficiency. Based on a survey result, the average usage of energy interruptible appliances of a working Turkish family provides us with the observation that AC and heating devices occupy a significant portion of total power consumption [5]. Thus, scheduling of AC loads plays a vital role in minimizing system peak load [6].

For optimal scheduling of AC loads, the power consumption profile of the air-conditioner is required. During the operation of an AC, its compressor turns on and turns off periodically and the power consumptions during *On-time* is significantly higher compared to the power consumption during *Off-time*. Further, *On-time* and *Off-time* durations and power consumptions for a split type AC compressor depend on AC capacity, dead-band temperature, difference between outside and inside temperature, occupancy and room dimensions. Thus, models need to be developed for *On-time* and *Off-time* durations and power consumption during on-off compressor states in terms of various parameters to schedule the AC loads dynamically. In addition to optimal load scheduling, simple power profile model of AC can be useful for optimal configuration of AC design parameters during manufacturing.

There has been limited studies on profile modelling of AC. In [7], the authors provide power consumption model of AC in terms of outdoor temperature and load factor. In [8], the authors introduce on-off time model of residential AC system using environment variables along with thermal resistance. In [9], the authors derive a probabilistic estimation of the duty cycle of a heater/AC system unit using maximum likelihood estimation theory. However, the above studies do not provide the complete power consumption profile with on-off time duration modelling. A complete electrical power consumption profile of an AC is needed for optimized load management in smart grid. It can also be used to predict the operational behaviors of air conditioners and forecast the load under different circumstances. Hence, developing a simplistic model of on-off time durations and power consumption of AC compressor in terms of environmental parameters is the main motivation of this research work.

In this paper, a non-inverting split type AC unit is considered for residential uses. Models for *On-time* and *Off-time* durations and power consumption during these durations in terms of various system and environment parameters are developed.

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Effect of various system and environment parameters on power consumption profile is studied. The optimal energy efficient size of AC unit for different room areas is also determined.

The rest of the paper is organized as follows. In Section II, the models are developed. The effect of various parameters on power consumption profile and optimal size of AC unit are studied in Section III. Section IV concludes the paper.

II. Model Development

In this section, the models of *On-time* and *Off-time* durations, power consumptions during corresponding on-off states and one-hour energy consumption of the air conditioner compressor are developed.

A. Models for On-time, On-time and Cycle Time

1) On-time Modelling: According to the classic thermodynamics equations mentioned in [10],

$$\frac{dT^r(t)}{dt} = \frac{1}{M_{air}C_p}\{(\frac{dQ}{dt})_{HVAC} - (\frac{dQ}{dt})_{losses}\} \quad (1)$$

$$(\frac{dQ}{dt})_{HVAC} = \dot{M}C_p\{T^h(t) - T^r(t)\} \quad (2)$$

$$(\frac{dQ}{dt})_{losses} = \frac{T^r(t) - T_{out}(t)}{R_{eq}} \quad (3)$$

with T^r the room temperature, M_{air} the mass of air inside the room, C_p the specific heat of air at constant pressure, R_{eq} the equivalent envelop resistance of the room, $\dot{M}$ the air flow rate through the AC, $(\frac{dQ}{dt})_{HVAC}$ the quantity of heat exchanged between the room and the AC, $(\frac{dQ}{dt})_{losses}$ the quantity of heat exchanged between the room and the outside, T^h the supply air temperature and T_{out} the outside temperature. It is also mentioned that the quantity of exchanged heat between room and AC $(\frac{dQ}{dt})_{HVAC}$ is a constant, P_h and $P_h < 0$ when the cooling rate of AC is greater than heating rate of air (during *on-time*) and $P_h > 0$ when the heating rate of air is greater than the cooling rate of AC (during *off-time*). The value of P_h can be determined using the following equation shown in [11], $P_h = \eta P_{input}$ where η is the co-efficient of performance of AC and P_{input} is the power consumption (input power). From (1), (2) and (3), we get,

$$dt = M_{air}R_{eq}C_p\frac{dT^r}{P_hR_{eq} + T_{out} - T^r} \quad (4)$$

The compressor will be on whenever the room temperature is greater or equal to $T_{set} + \frac{\Delta T}{2}$ where T_{set} is the set point and ΔT is the dead-band. During the *on-time*, the room temperature will be decreased from $T_{set} + \frac{\Delta T}{2}$ to $T_{set} - \frac{\Delta T}{2}$. So, integrating (4) over this temperature range, the desired equation for on-time will be found.

$$T_{ON} = M_{air}R_{eq}C_p \ln\frac{P_h^{on}R_{eq} + T_{out} - (T_{set} + \frac{\Delta T}{2})}{P_h^{on}R_{eq} + T_{out} - (T_{set} - \frac{\Delta T}{2})} \quad (5)$$

where P_h^{on} is the heat exchanged between air conditioner and the room during on-time and $P_h^{on} < 0$. So, $P_h^{on} = -\eta P_{ON}$ where P_{ON} is the power consumption (input power) of air conditioner during on time. Now, by the definition, $\eta = \frac{3517C}{P_{ON}}$ where C is the capacity of air conditioner in *ton*. So, it stands that,

$$P_h^{on} = \eta P_{ON} = -3517C. \quad (6)$$

Now, M_{air} can be written as $M_{air} = \rho v$ where ρ and v are the density of air and volume of the room respectively. Again, $v = Ah$, where A and h are the area and height of the room. So, $M_{air} = Ah\rho$. Hence, the *On-time* can be found as,

$$T_{ON} = \alpha AR_{eq} \ln\frac{-3517CR_{eq} + T_{out} - (T_{set} + \frac{\Delta T}{2})}{-3517CR_{eq} + T_{out} - (T_{set} - \frac{\Delta T}{2})} \quad (7)$$

where $\alpha = hC_p\rho$ which we are defining as a co-efficient of our mathematical model. Let $\beta = \frac{-\frac{\Delta T}{2}}{-3517CR_{eq}+T_{out}-T_{set}}$. Using the value of β in (7), T_{ON} can be written as $T_{ON} = \alpha AR_{eq}\ln\frac{1+\beta}{1-\beta}$. Since $\beta \ll 1$, T_{ON} can be approximated as $T_{ON} \approx 2\alpha AR_{eq}\beta$. Finally, the simplified expression of T_{ON} can be obtained as,

$$T_{ON} \approx \frac{\alpha AR_{eq}\Delta T}{3517CR_{eq} - T_{out} + T_{set}}. \quad (8)$$

2) Off-time Modelling: During the off-time, the room temperature increases from $T_{set} - \frac{\Delta T}{2}$ to $T_{set} + \frac{\Delta T}{2}$. So, by integrating (4) over this temperature range, the equation for *off-time* can be found.

$$T_{OFF} = \alpha AR_{eq} \ln\frac{P_h^{off}R_{eq} + T_{out} - (T_{set} - \frac{\Delta T}{2})}{P_h^{off}R_{eq} + T_{out} - (T_{set} + \frac{\Delta T}{2})} \quad (9)$$

where P_h^{off} is the heat exchanged between the fan of the air conditioner and the room and $P_h^{off} > 0$. So, $P_h^{off} = \eta P_{OFF}$. P_{OFF} is the power consumption during the off-time. Using similar approximation of on-time modelling, the simplified expression of T_{OFF} can be obtained as,

$$T_{OFF} \approx \frac{\alpha AR_{eq}\Delta T}{P_h^{off}R_{eq} + T_{out} - T_{set}}. \quad (10)$$

3) Cycle Time Modelling: Let T be the *cycle time* of the AC compressor which is the summation of T_{ON} and T_{OFF}. Thus, using (8) and (10), the mathematical model of Cycle time can be written as,

$$T \approx \alpha AR_{eq}^2\Delta T\frac{(3517C + P_h^{off})}{3517CP_h^{off}R_{eq}^2 + \gamma R_{eq}(3517C - P_h^{off}) - \gamma^2} \quad (11)$$

where, $\gamma = (T_{out} - T_{set})$

B. Power Consumption and Energy Consumption

1) Power Consumption: During *On-time* of the compressor, power consumption of an AC P_{ON} is given as follows from (6), $P_{ON} = \frac{3517C}{\eta}$. During *Off-time*, only fan of the AC operates. So, if the power consumed by the fan. is P_{fan},, the power consumption during off-time P_{OFF} can be obtained as $P_{OFF} = P_{fan}$.

2) Energy Consumption: During operation of the AC, the one-hour energy consumption E_h is given as, $E_h = \frac{P_{ON}T_{ON}+P_{OFF}T_{OFF}}{T}$. The energy consumption depends mainly on the cycle time of the compressor. But during short-cycling, the compressor turns on and off frequently and consumes huge amount of additional energy. The number of times an AC switches on or off in the duration of T_{cycle} will be $\frac{T_{cycle}}{T}$ where T_{cycle} is the average ideal cycle of a totally fitted air conditioner. If AC consumes $q\%$ energy of its capacity for switching between ON and OFF during a cycle, then, for switching energy consumption in one-hour is $\frac{q}{100} \times P_{ON} \times \frac{T_{cycle}}{T} = \frac{q}{100} \times \frac{3517 \times C}{\eta} \times \frac{T_{cycle}}{T}$ Wh. Including switching energy with energy consumption during on-time and off-time, one-hour energy consumption E_h can be written as

$$E_h = \frac{P_{ON}T_{ON}+P_{OFF}T_{OFF}}{T} + \frac{35.17qCT_{cycle}}{\eta T} \tag{12}$$

The on-off time durations, power consumptions and one-hour energy consumption can be determined using different system and environment parameters from the proposed electrical power consumption profile. Similarly, for desired on-off time durations, system parameters, for e.g. set-point temperature, dead-band temperature range etc. can also be calculated using the mathematical models. Using those set-point temperature and dead-band range, the cycle time can be controlled.

III. Results

In this section, the results by using the developed models are presented.

A. System Parameters

Throughout the paper, the values of A, ΔT and C are taken to be $37.16m^2$, $4K$ and $1ton$, respectively if they are not mentioned separately. P_{fan}, η and R_{eq} are considered to be 373 watt, 2.9 and 0.35 respectively. T_{cycle} and q are taken to be 1200 s and 30, respectively as mentioned in [12]. The dead-band for an ideal compressor is about 4 to 5 K and the range of cycle time is about 15-20 minutes. If cycle time of an AC is less than 10 minutes, it is over-fitted for the room. On the other hand, if the cycle time is more than 25 minutes, it is under-fitted. Considering these two facts, the co-efficient α of the developed model is determined in such a way that the compressor has a cycle time of 15-20 minutes when the dead-band is about 3 to 4 degree. Using the various system parameters and practical data from literature, the best-fitted values of the co-efficient α is found to be 466.150.

B. Effect of Various Parameters on On-time, Off-time and Cycle Time

1) Effect of the Dead-Band: The effect of dead-band ΔT on *On-time*, *Off-time* and cycle time is presented in Fig. 1.The results show that all the *On-time*, *Off-time* and cycle time increase with increasing the range of dead-band. This can be attributed to the fact that the compressor needs to remain ON (resp. OFF) for a longer period to reach the lower dead-band temperature (resp. upper dead-band temperature) temperature from the upper dead-band temperature (resp. lower dead-band temperature) of the dead-band for removing (resp. conducting) heat from (resp. to) the room. Thus, the overall cycle time increases with increasing the range of dead-band temperature.

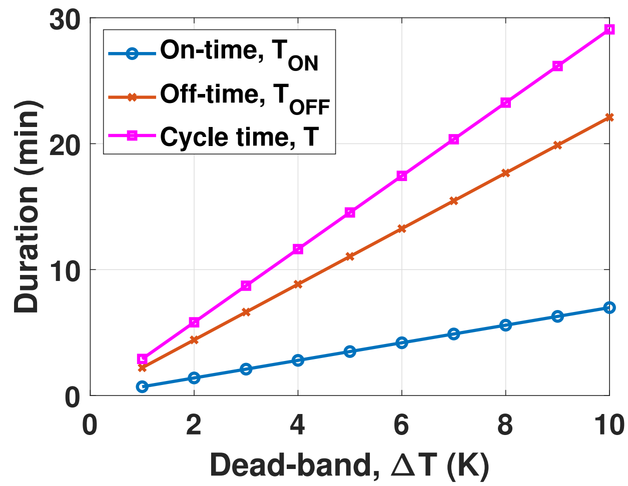

Figure 1. Effect of the range of dead-band temperature on duration

2) Effect of Area of the Room: The effect of room area on *On-time*, *Off-time* and cycle time is shown in Fig. 2. It can be seen that on-time and off-time both increase significantly with increment of the room area. As a result, cycle time increases with increasing room area. The reason of the variation of the on-time is that more time is required for a compressor to decrease the room temperature if the room area is large. Similarly, it requires more heat to increase the room temperature. So if the conduction rate is assumed fixed, then the off-time will increase. Thus, the cycle time eventually increases.

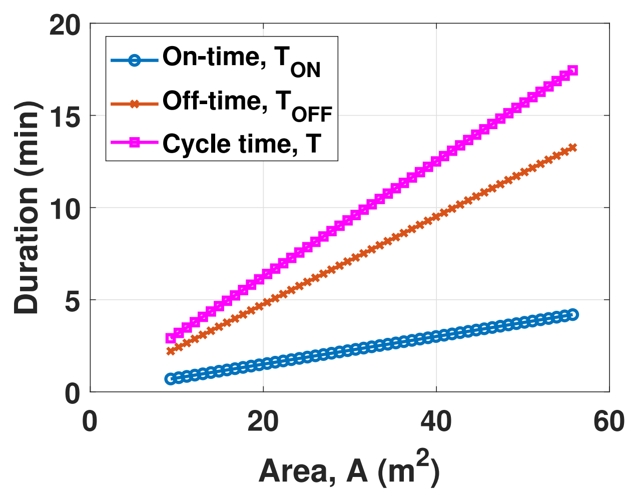

Figure 2. Effect of the area of the room on duration

3) Effect of Capacity of Air Conditioner: The effect of AC capacity on *On-time*, *Off-time* and cycle time is presented in Fig. 3. The results show that off-time is not related to AC capacity but the on-time decreases with the increasing of AC capacity for better cooling rate. As a result, the cycle time decreases with the elevating AC capacity.

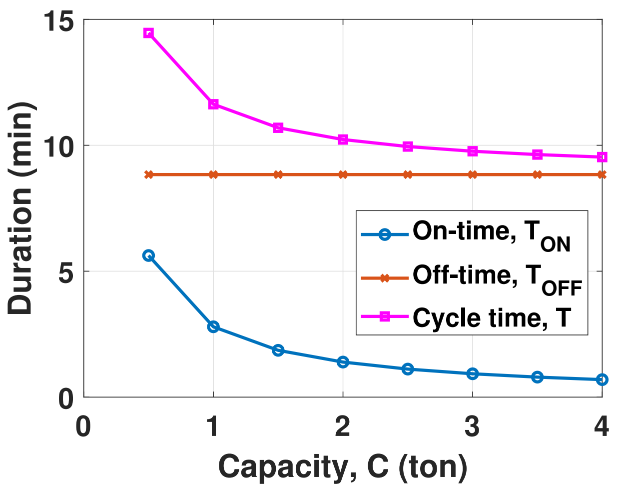

Figure 3. Effect of the capacity of air conditioner on duration

C. Energy Consumption

The parameters on which energy consumption of air conditioner depend have been investigated. The goal is to minimize the consumption and save energy. So, at first, the parameters that can be controlled to save energy are needed to be investigated. Two such important parameters are- set-point and dead-band. Energy consumption decreases with the increment of dead-band as well as for increment of set-point which is mentioned in [13] and [14]. This can also be shown using our mathematical model. The effect of dead-band for different set points is shown in Fig. 4.

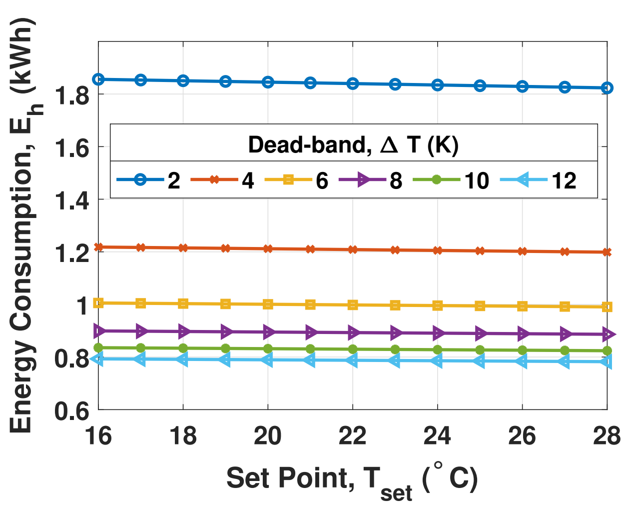

Figure 4. Effect of set-point and dead-band on energy consumption

The results show that energy consumption decreases with the increment of dead-band and set point. But there still remains one issue. If dead-band and set point both are increased too much, it will become a discomfort factor.

So, it is decisive that the set-point should be kept closer to the outdoor temperature and the dead-band should be large to save energy without user discomfort.

IV. Conclusion

In this paper, mathematical models for on-time, off-time and cycle time durations, power consumptions and one-hour energy consumption for a non-inverting split type AC are developed. Analyzing the results obtained by the models, the relation between the system parameters and power consumption is understood easily. These models can be helpful in terms of predicting the cycle time and power consumption in a particular environment where the parameters are known. On-time, off-time durations and power consumptions are required to be determined to forecast and schedule the loads optimally in smart grid. Thus, the proposed electrical power consumption profile can be helpful in smart grid load management.

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