Power-Comfort Optimized Scheduling of Air Conditioning System

MOHAMAD FADZLI HANIFF [a], HAZLINA SELAMAT [a(corresponding author)], SALINDA BUYAMIN [b]
[a] Centre for Artificial Intelligence & Robotics
Universiti Teknologi Malaysia
Jalan Semarak, 54100 Kuala Lumpur
MALAYSIA
[b] Electrical Engineering Faculty
Universiti Teknologi Malaysia
81310 Johor Bahru, Johor
MALAYSIA
Djaqeel2000@gmail.com

Abstract:- In air-conditioning(AC) operation, providing comfort to occupants in a room leads to the production of a specific air temperature(T_{air}) by AC system to oppose the outdoor temperature ($T_{outdoor}$). From Carnot's theorem, it can be concluded that the wider the gap between the value of $T_{outdoor}$ and T_{air} , the higher the cost and power consumption gets. Power consumption increases depending on the weather outside if comfort is an objective. Meanwhile in order to safe cost or power, comfort may be need to be sacrificed by reducing the gap between $T_{outdoor}$ and $T_{air.}$

In this paper, an optimized pre-cooling AC scheduling method to provide comfort without increasing power consumption is proposed. In this method, instead of simply using T_{air} scheduling. a 24 hours schedule of comfort index called predicted mean vote (PMV) is used . The 24 hours operation is divided into five sections; pre-cooling, morning, noon, afternoon and off hours. Particle swarm optimization (PSO) is used to obtained a set of T_{air} and mean radian temperature (T_r) combinations which corresponds to the specific value of PMV without consuming high power . A Neural Network model that define the relationship of outdoor parameters and T_{air} with T_r is used to test the PSO generated T_{air} and T_r combination in order to determine which T_{air} will be used for the AC system. The performances of the proposed method are compared with the most energy saving existing AC scheduling method. The proposed method named PSO-NN AC scheduling is able to reduce power and cost about 9.3% and 12.6% respectively. In this work, MatLab and EnergyPlus software is used.

Key-Words: - air-conditioning system, comfort, energy saving, pre-cooling.

1. Introduction

[1-6] mentions that it is well known that AC system is the main contributor of building energy consumption when compared to lighting and other appliances due to its excessive use for a long hours operation. Due to this reason, many researches had been done in order to reduce AC system energy consumption hence also reduce the operation cost.

[7-13] stated that AC system scheduling system is a basic method of reducing power consumption especially the ones that uses pre-cooling technique. In scheduling technique, the AC is pre-programmed as desired by the consumers in order to fulfill their comfort according to occupancy density. Normally the pre-programmed parameter of AC system is T_{air}. T_{air} values throughout the day are simply determined by assumption that the values will be able to provide comfort to the occupants in the building. Meanwhile pre-cooling AC scheduling is a schedule of T_{air} which pre-cools a space with lower temperature from before occupied hours. In pre-cooling, at the end of the occupied hours, comfort is provided by using the pre-cooled air in order to reduce the AC work load (by increasing T_{air}).

The existing AC system scheduling techniques does show some impressive energy and cost saving performance as stated in [13] which discusses AC scheduling methods such as baseline, step-up, linear-up and extended pre-cooling. But in most of the techniques, comfort cannot be confirmed since the T_{air} value is determined by assumption without considering other factors such as indoor parameters and outdoor parameters. EnergyPlus; a software that able to simulates a thermal condition of a space, shown that the indoor thermal parameters such as T_r are affected by the outdoor environment aside from T_{air}.

Due to this a new AC scheduling which will also take into account the outdoor environments in determining the parameter setting is proposed. In order to reduce energy and cost of AC system operation while maintaining comfort, the proposed AC scheduling will also includes optimizing process.

2. PSO-NN AC Scheduling

Due to the inability for current scheduling techniques to confirm exact comfort, an AC scheduling technique based on comfort PMV is proposed in order to provide exact comfort and at the same time reducing energy usage. The proposed work is divided into three processes as shown in Figure 1.

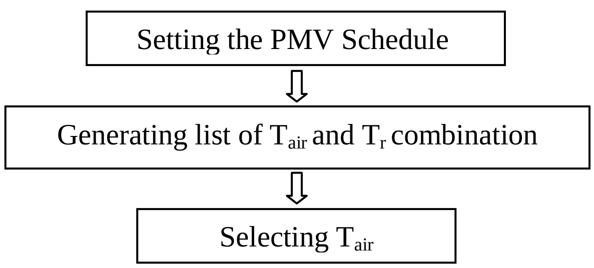

Figure 1: PSO-NN AC scheduling processes

2.1. Setting the PMV Schedule.

In this work, instead of scheduling the T_{air}, comfort index PMV scheduling with be implemented. Predicted mean vote (PMV) according to [14] and [15] is the most used comfort index which uses six parameters; temperature (T_{air}), mean radian temperature (T_r), occupant activity/metabolism rate (Met), clothing insulation (I_{clo}), air humidity (ϕ) and air velocity (v_a) in its calculation of comfort level. Comfort level in PMV varies from -3(cold) to +3(hot) as shown in Table 1.

Table 1: PMV Value classification

PMV Value	Comfort Condition
-3	Cold
-2	Cool
-1	Slightly Cool
0	Neutral
+1	Slightly Warm
+2	Warm
+3	Hot

For PSO-NN AC scheduling, aside from T_{air} and T_r, the other PMV parameters are set to be fixed. Metabolism rate is set to be 70W/m^2 or 1.2met where it is suitable for office work. Clothing insulation is set to be at average of 1 for common indoor clothing. Air velocity relatively is set to be 0.25m/s which is generally favorable. Meanwhile air humidity is set to be 60% which is maximum during warm season but does not cause sweat skin. In [16] values of these four PMV parameters for different conditions are listed and elaborated.

From Figure 2, it can be observed that PSO-NN AC scheduling is not a 24-hours scheduling like baseline, step-up and linear-up scheduling discussed in [13]. The AC system is set to be operate from 0400h until 1800h with occupied hours from 0700h to 1800h.

At 0400h to 0800h, PMV value of -2.5 is set to pre-cool the space. Using too low T_{air} will cause cool energy loss since $T_{outdoor}$ is much greater than T_{air} [13]. Due to this, instead of -3, higher PMV -2.5 is used to reduce energy loss. From Carnot's theorem, the value difference between $T_{outdoor}$ and T_{air} is proportional to the AC power consumption. Since pre-cooling is done with T_{air} which is much lower than $T_{outdoor}$, the power consumption tend to get high. But in Malaysia, buildings that are implementing medium voltage peak/off-peak commercial tariff, are charged with 31.2 cent/kWh during peak period (0800h to 2200h) and 19.2 cent/kWh during off-peak period (2200h to 0800h). With this, the pre-cooling AC energy consumption may be high, but the cost will be 38.5% lower compared to when it is done during peak period.

The space is occupied starting from 0800h, the PMV values after the pre-cooling are set to be higher than 0. From 0800h to 1200h, a set of PMV values of +0.25, +0.5, +0.75 and 1.0 is implemented. In this period, comfort will be provided by combination of current AC system air and the pre-cooled air. The PMV set value increases from +0.25 to +1 will gradually lowers the AC system power consumption without causing obvious discomfort. PMV value of +1 represent slightly warm situation in which AC system is to provide set of T_{air} values which will not cause any serious discomfort.

From 1200h until 1500h, PMV value of -1.5 is assigned in order to pre-cool again the space when most of occupants are expected to leave the area for break hours (1200h to 1400h). This is done during low occupancy level in order to avoid cool energy loss. The second pre-cooling PMV is higher than the first pre-cooling. This is due to higher $T_{outdoor}$ compared to early morning period. The pre-cooling is done longer than break period (1200h to 1400h) in order to compensate with the incoming flow of occupants after the break hours.

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Then, from 1500h to1800h, PMV is set to be +0.75 which is lower than slightly warm PMV. During this hours, comfort will be provided mostly by the pre-cooled air, with minimum help of AC system in order to reduce power consumption without causing the occupants feeling warm.

It is expected that by using the PMV schedule, demand during busy hours (0800h to 1200h and 1500h to 1800h) can be shifted to early morning during the off-peak electrical tariff is used. Pre-cool is also done during noon due to low activity and low occupancy which enable the conservation of cool energy.

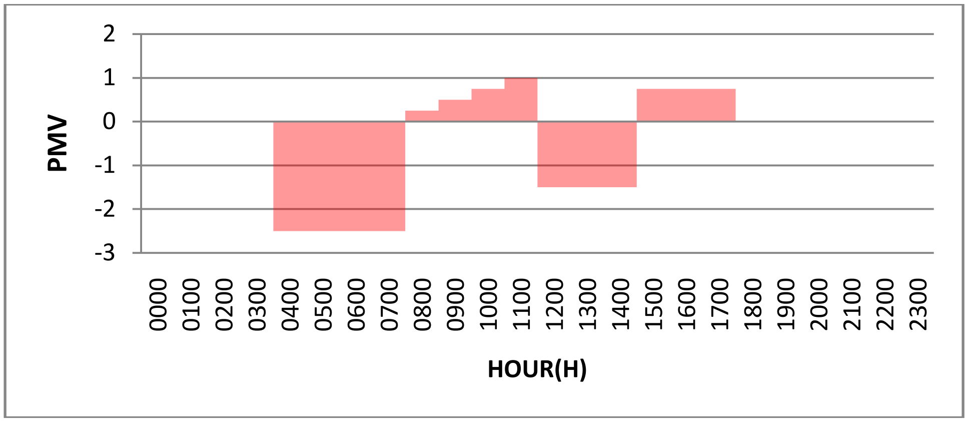

Figure 2: PMV Schedule setting

2.2. Generating list of T_{air} and T_r combination corresponds to PMV value

Particle swarm optimizer (PSO) is an algorithm which able to find an optimized point of two variable in an objective function [17,18]. In this work a two objective PSO is used in order to get a list of possible combination of T_{air} and T_{mrt} that able to produce PMV that is close to expected PMV and able to produce low power consumption.

First objective is PMV as shown in Equation (1) to (7) which the parameters can be referred in Table 2.The other four of PMV parameters are already set to be fixed. Metabolism rate is set to be 70W/m^2 or 1.2met where it is suitable for office work. Clothing insulation is set to be at average of 1 for common indoor clothing. Air velocity relatively is set to be 0.25m/s which is generally favorable. Meanwhile air humidity is set to be 60% which is maximum during warm season but does not cause sweat skin to occupants.

The second objective is hourly power consumption using the equation below based on the first law of thermodynamics as shown in Equation (8),(9) and (10). BTU/h is British thermal unit per hour (set as 17070 J/h). COP is AC coefficient of performance. $T_{COOLING}$ is HVAC setpoint air temperature in this case T_{air}. $T_{outdoor}$ is outdoor temperature from weather forecast.

$$PMV = (0.303 \cdot e^{-0.036M} + 0.028) \ . L \qquad (1)$$

$$L = M - W - 3.05 \cdot 10^{-3} \cdot (5733 - 6.99 \cdot (M - W) - p_a) - 0.42 \cdot \big((M - W) - 58.15\big) - 1.7 \cdot 10^{-5} \cdot M \cdot (5687 - p_a) - 00.0014 \cdot M \cdot (34 - t_a) - 3.69 \cdot 10^{-8} \cdot f_{cl} \cdot ((t_{cl} + 273)^4 - (t_r + 273)^4) - f_{cl} \cdot h_{cl} \cdot (t_{cl} - t_a) \qquad (2)$$

$$t_{cl} = 35.7 - 0.028 \cdot (M - W) - I_{cl} \cdot \big(3.69 \cdot 10^{-8} \cdot f_{cl} \cdot ((t_{cl} + 273)^4 - (t_r + 273)^4) - f_{cl} \cdot h_{cl} \cdot (t_{cl} - t_a)\big) \qquad (3)$$

$$p_a = \frac{p_s RH}{100} \qquad (4)$$

$$\ln p_s = \frac{C_1}{T} + C_2 + C_3 \cdot T + C_4 \cdot T^2 + C_5 . T^3 + C_6 \ \cdot \ln T \qquad (5)$$

where,

$$C_1 = -5.8002206 \cdot e^3$$
$$C_2 = 1.3914993$$
$$C_3 = -4.8640239 \cdot \mathrm{e}^{-2}$$
$$C_4 = 4.1764768 \cdot \mathrm{e}^{-5}$$

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$C_5 = -1.4452093 \cdot e^{-8}$
$C_6 = 6.5459673$
$T \ = t_a + 273.15$

$$h_{cl} = \begin{cases} 2.38(t_{cl} - t_r)^{0.25} & for\ 2.38(t_{cl} - t_r)^{0.25} > 12.1\sqrt[2]{v_a} \\ 12.1\sqrt[2]{v_a} & for\ 2.38(t_{cl} - t_r)^{0.25} < 12.1\sqrt[2]{v_a} \end{cases} \quad (6)$$

$$f_{cl} = \begin{cases} 1.00 + 0.2I_{cl} & for\ I_{cl} < 0.5clo \\ 1.05 + 0.1I_{cl} & for\ I_{cl} > 0.5clo \end{cases} \quad (7)$$

Table 2: PMV parameters.

Symbol	Quantity	Units
M	Metabolic rate	W/m^2
W	Effective mechanical power	W/m^2
I_{cl}	Clothing insulation	m^2K/W
f_{cl}	Clothing surface area factor	-
t_a	Air temperature	°C
t_r	Mean radiant temperature	°C
v_a	Relative air velocity	m/s
p_a	Water vapor partial pressure	Pa
hc	Convective heat transfer coefficient	$W/(m^2K)$
tcl	Clothing surface temperature	°C

$$Power\left({}^{W}/_{h}\right) = \frac{{}^{BTU}/_{h}}{0.1 \times COP \times 3.41} \quad (8)$$

$$COP_{MAX} = \frac{T_{COOLING}}{T_{OUTDOOR} - T_{COOLING}} \quad (9)$$

$$COP = 0.1 \times COP_{MAX} \quad (10)$$

The output of this process is a list of low power consumption T_{air} and T_{mrt} combinations which are able to produce PMV value close to the hourly expected PMV(tolerance of ±0.05) schedule and also enable low power consumption as portrayed in Table 3 in which j ≠ k ≠ m. Among the combination, one T_{air} for each hour will be chosen.

Table 3: PSO generated T_{mrt} and T_{air}

Hour	**Expected PMV**	**Generated PMV**	$\mathbf{T_{air}}$	$\mathbf{T_{mrt}}$
0400	-2.5	PMV_{41} PMV_{42} . . PMV_{4j}	T_{air41} T_{air42} . . T_{air4j}	T_{mrt41} T_{mrt42} . . T_{mrt4j}
0800	+0.25	PMV_{81} PMV_{82} . . PMV_{8k}	T_{air81} T_{air82} . . T_{air8k}	T_{mrt81} T_{mrt82} . . T_{mr8k}
0900	+0.5	PMV_{91} PMV_{92} . . PMV_{9m}	T_{air91} T_{air92} . . T_{air9m}	T_{mrt91} T_{mrt92} . . T_{mrt9m}

2.3. Selecting T_{air}

A Neural Network (NN) room temperature model is developed using Energyplus and Matlab NN toolbox. As shown in Figure 3, the model relates five outdoor environment parameters (temperature, air humidity, air barometric pressure, wind speed, and direct solar radiation) and T_{air} with T_{mrt}. EnergyPlus is used to generate hourly data of the seven parameters for a year period for a specific room with particular characteristics. 80% of the data is then fed in to Matlab NN toolbox to generate the model. 20% of the data is used to validate the model.

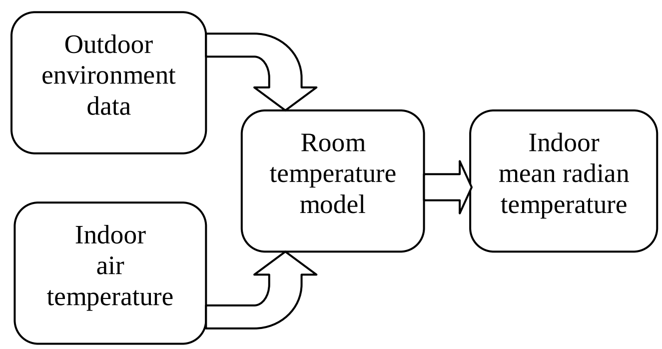

Figure 3: Room temperature model

T_{air} from the list generated by PSO and the five outdoor parameters (for specific chosen date) generated from EnergyPlus will then be fed into the NN model to be tested. The output of the model is a list of actual mean radian temperature (T_{amrt}) that corresponds to T_{air} value fed into the model. As shown in Table 4 as example, the T_{amrt} will be compared with the corresponding T_{mrt} from hourly T_{mrt} and T_{air} list generated by PSO. T_{air} with the least T_{amrt} - T_{mrt} error will be chosen to be used by AC system for that particular hour.

Table 4: T_{mrt} and T_{amrt} comparison.

Hour	T_{air}	T_{mrt}	T_{amrt}	$T_{amrt} - T_{mrt}$
0400	T_{air41} T_{air42} T_{air43} . . T_{air4j}	T_{mrt41} T_{mrt42} T_{mrt43} . . T_{mrt4j}	T_{amrt41} T_{amrt42} T_{amrt43} . . T_{amrt4j}	$Error_{41}$ $Error_{42}$ $Error_{43}$ . . $Error_{4j}$
0800	T_{air81} T_{air82} T_{air83} . . T_{air8k}	T_{mrt81} T_{mrt82} T_{mrt83} . . T_{mrt8k}	T_{amrt81} T_{amrt82} T_{amrt83} . . T_{amrt8k}	$Error_{81}$ $Error_{82}$ $Error_{83}$ . . $Error_{8k}$

3. Simulation Results & Discussion

At the beginning of this work, a simulation on the basic scheduling techniques discussed in [13] is done in order to determine which is the most power and cost saving technique. As the implemented electrical consumption model uses $T_{outdoor}$, hourly weather forecast temperature from 31st December 2013 extracted from EnergyPlus as in Figure 4 is used. The result of simulation is shown in Table 5 which clearly states that extended pre-cooling(EXPC) technique is the most power and cost saving compared to the other basic scheduling technique. This is due to the power during peak hours are shifted to off-peak hours with the implementation of pre-cooling technique. EXPC will be used to be benchmarked with PSO-NN AC scheduling.

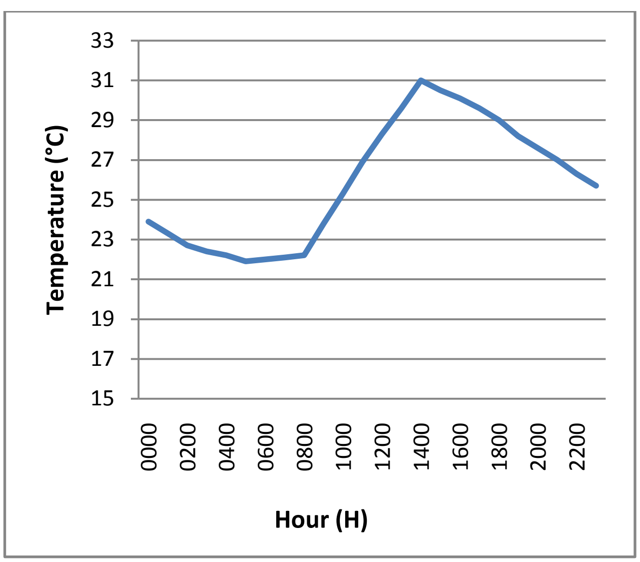

Figure 4: $T_{outdoor}$ from 31st December 2013.

Table 5: Cost and power saving potential of basic AC scheduling technique for 31st December 2013

	Baseline	StepUp	LinearUp	ExPC
Cost Saving (%)	Reference	24.58	15.09	34.68
Power Saving (%)	Reference	21.19	13.01	38.17

Next, a simulation is done in order to compare the proposed scheduling technique, PSO-NN with the extended pre-cooling (EXPC) technique in term of actual PMV produced, air temperature produced, electrical energy consumption and operation cost with the use of the same $T_{outdoor}$ in Figure 4.

Figure 5 shows the T_{air} generated by PSO-NN and EXPC compared with $T_{outdoor.}$ It can be observed that T_{air} generated by PSO-NN is closer to $T_{outdoor}$ when compared to EXPC generated T_{air} especially during the discharge of pre-cooled air (0800h to 1200h and 1500h to 1800h). This will enable power/cost saving potential by the PSO-NN.

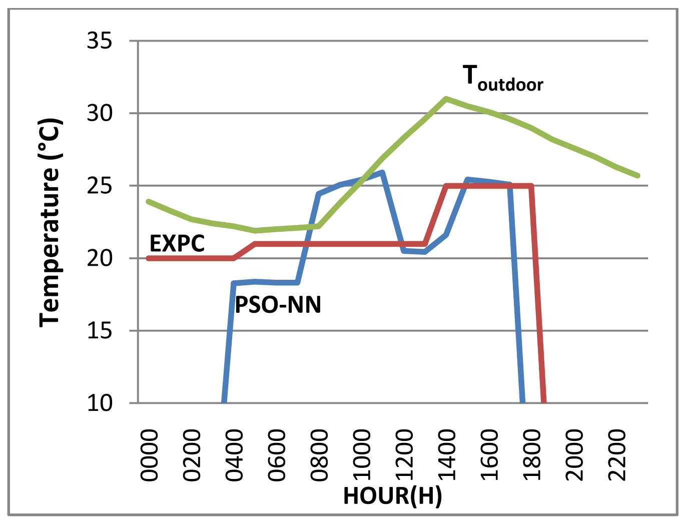

Figure 5: T_{air} generated by PSO-NN and EXPC

From the power consumption result shown in Figure 6, it can be seen that during electrical tariff peak hours (0800h to 2200h), PSO-NN consumed less power than EXPC due to the close T_{air} of PSO-NN with $T_{outdoor}$. PSO-NN consumed more power than EXPC during the two pre-cooling period, but the first is done during off electrical tariff peak hours so it is expected that the cost would not be very high.

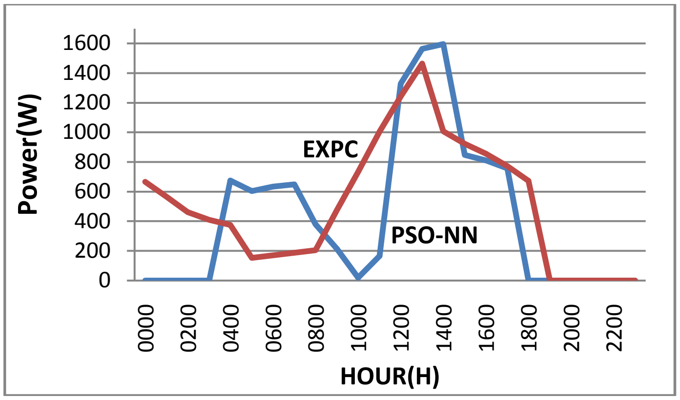

Figure 6: Power consumption by PSO-NN and EXPC

As shown in Figure 7, the cost consumption pattern of both PSO-NN and EXPC are similar with power consumption in Figure 6. But it can be seen that the cost consumption of both during off peak hours (2200h to 0800h) are low due to the use of off peak electrical tariff. Due to this, cooler pre-cooling like in PSO-NN can be done without causing too high cost. PSO-NN also costs lower due to late pre-cooling which is done at 0400h instead of 0000h by EXPC.

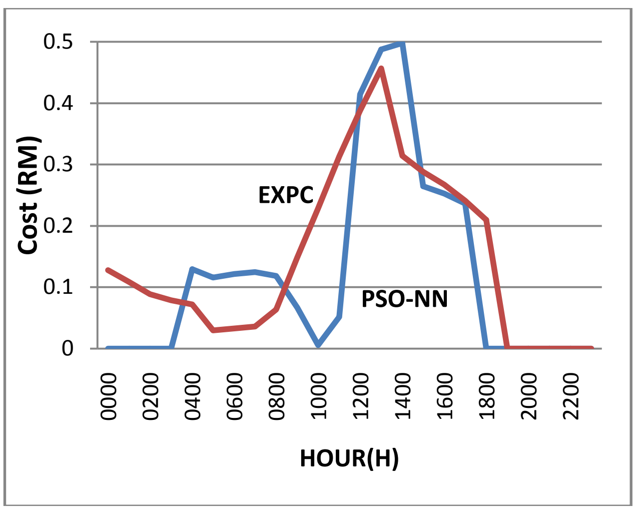

Figure 7: Cost consumption by PSO-NN and EXPC

From Figure 8, it can be seen that the actual PMV generated by PSO-NN is almost similar to the expected PMV in Figure 2. The slight difference is due to the outdoor environment and the need of low power/cost consumption. It is also can be seen that the PMV generated by EXPC is always lower than except during 1500h to 1900h. This means, pre-cooling is done for 15 hours just for the sake of 4 hours pre-cooled air discharged. PSO-NN pre-cooled the space for two times for equal duration with duration of pre-cooled air discharge duration (4 hours each) in order to reduce cool energy loss, because it is stated in [13] than pre-cooling should not be done longer than discharge duration in order to avoid cool energy loss.

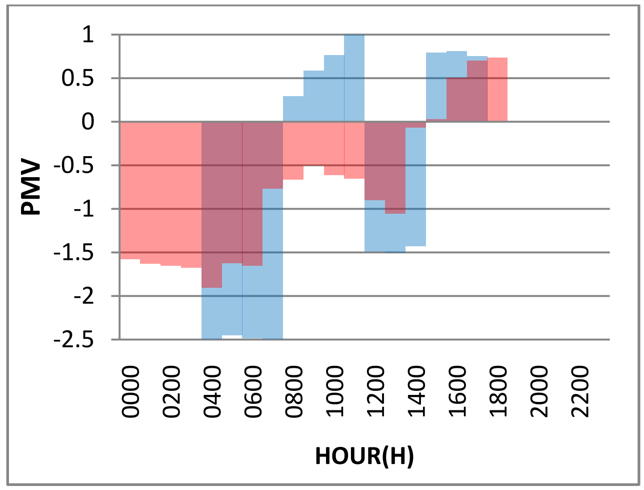

Figure 8: PMV by PSO-NN and EXPC

4. CONCLUSION & RECOMMENDATION

From the results and discussions, it can be concluded that by replacing EXPC with PSO-NN is able to reduce power consumption up to 17%. PSO-NN also able to reduce 17.3% cost consumption compared to when EXPC is implemented. Also, due to the off-peak electrical tariff, more efficient pre-cooling can be done without causing too high cost. The disadvantage of PSO-NN is that the resultant comfort during cool energy discharge period (0800h to 1200h and 1500h to 1800h) cannot be confirm. A work need to be done to develop a thermodynamic model which able to determine the resultant comfort at specific hours. As an addition, a more efficient optimizer need to be developed to increase the effectiveness of the proposed scheduling method.

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