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Research of roof solar power plant in hot water supply installations

***Abstract**. Hot water supply system is controlled by a microprocessor system based on neural network that allows utilizing solar panels capacity at a maximum level in the most efficient way, to calculate and adjust in real-time mode amount of consumed hot water, take into consideration weather forecast for the next day and to utilize reduced tariffs for feeding heat pump during night-time in winter. Proposed system operates using renewable energy and does not pollute the atmosphere. Economic calculations prove the cost-effectiveness of the unit.*

***Streszczenie.** System zaopatrzenia w ciepłą wodę jest sterowany przez system mikroprocesorowy oparty na sieci neuronowej, który pozwala na maksymalne wykorzystanie mocy paneli słonecznych w najbardziej efektywny sposób, obliczanie i regulowanie w czasie rzeczywistym ilości zużywanej ciepłej wody, uwzględnienie prognozy pogody na następny dzień oraz korzystać z taryf ulgowych do zasilania pompy ciepła w porze nocnej w okresie zimowym. Proponowany system działa z wykorzystaniem energii odnawialnej i nie zanieczyszcza atmosfery. Obliczenia ekonomiczne dowodzą opłacalności urządzenia. (**Badania dachowej elektrowni słonecznej w instalacjach ciepłej wody użytkowej**)
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Keywords: solar power stations, heat pump, hot water supply, renewable energy sources..
Słowa kluczowe: elektrownie słoneczne, pompa ciepła, zaopatrzenie w ciepłą wodę, odnawialne źródła energii.

Introduction

Significant interest to efficiency of solar heat supply systems (in terms of hot water supply and heating) and cold supply is caused by fast-paced deterioration of interrelated energy and environmental problems.

These very important problems for us as mankind were outlined in Kyoto Protocol in 1997, which dealt with greenhouse gas emissions and global warming issues, as well as in Montreal Protocol of 1987 aimed at ensuring ozone layer protection.

In order to satisfy household needs of Ukraine's populace, approximately one fifth of hydrocarbon fuel and energy resources is used each year, while its reserves are being depleted and prices soar each passing year. In urban hot water supply networks, water is heated centrally, in which case approximately 30% of energy is lost during its transportation.

People in different countries solve this problem by utilizing renewable energy sources and the modern computer equipment. Particular attention to development and creation of "hybrid systems" is paid in the USA and Japan. Comprehensive promotion of renewable energy in energy sector has been the key element of the European energy and environmental policies for many years now.

One of the efficient and common methods for generating heat is conversion of solar radiation directly into heat or electrical energy. In order to do so, passive helio-systems with solar vacuum collectors are used, where heated water is stored in a capacitive hydraulic accumulator [2]. These are the simplest systems that do not require additional power mains, are easy in installation and operation. They are ideally suitable for private residences, summer cottages and temporary facilities. A disadvantage of such systems is that the maximum consumption during a day or a year is in antiphase to solar activity. Therefore, a problem of accumulating solar energy arises, which leads to an increased cost of heat-generating units. Moreover, during summer periods, there is also a problem of presence of excessive amount of hot water, which in absence of a process for excess heat dissipation leads to overheating of the helio-collector. Utilization of such a system in urban conditions requires availability of significant area and additional heat source.

Today, heat pumps are commonly used throughout the world. In developed countries, number of used heat pumps is counted by millions of units. In Japan and the USA, heat pumps of "air-air" type became popular as of late. In Europe, heat pumps of "water-water" type are popular. Heat pumps operate efficiently when heating medium is supplied at temperature of up to +55 ^{o}C. Heat generating system based on a heat pump is environmentally friendly because it does not burn organic fuels and provides no emissions into the atmosphere. A heat pump is characterised by a quite high economic efficiency. Electric power transformation ratio is 3-6, i.e. 1 kW·h of consumed electric power is transformed into 3-6 kW·h of heat. A heat pump operates efficiently under temperature up to -25 ^{o}C. Due to climate change, such temperatures occur extremely rare.

An important factor of heat pumps utilization in comparison with traditional systems is their high level of safety due to absence of natural gas boilers and pipelines.

Electrical energy source for a heat pump may be either a power mains or renewable electrical power sources. In urban conditions, this function is performed by a solar power station. Solar power station is simple in design and does not require significant operating costs. Solar panels located on the roof connect to existing AC mains of industrial frequency through an inverter. An inverter synchronises panels operation with the mains and ensures protection in case of emergency operating modes.

Undoubtedly, the above examples of energy-efficient technologies utilization require significant economic investment. Therefore, the area of application of such equipment should be considered based on a thorough technical and economic reasoning.

Research objective is improving energy-efficiency of public utility units.

Model for research

For household needs of the house (for example, a student dormitory) 600 persons requires 15 m^3 of hot water each day. Consumption of hot water is quite inconsistent and in some cases has unpredictable nature (Fig. 1).

Moreover, the maximum consumption coincides with the maximum capacity of the solar power station.

Water consumption throughout the day is uneven. It was experimentally established that the minimum consumption is 0.5 m^3, and the maximum is 5 m^3. The amount of heat required for heating water to temperature +55^{o}C is calculated according to the formula:

$$W = cm\frac{(t_2 - t_1)}{3.600} = 4.183 \cdot 15 \cdot \frac{(55-15)}{3.600} = 697.17 \cdot \text{ kW}\cdot\text{h}, \quad (1)$$

where: c – specific heat of water (c=4,183 J/kg·degree); m – water weight, kg; t_2 – heated water temperature, ^{o}C; t_1 – cold water temperature, ^{o}C;

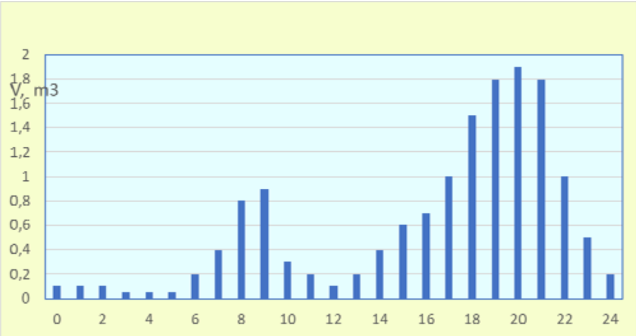

Fig. 1. Daily schedule of hot water supply

For hot water supply needs, a heat-generating unit based on a heat pump fed by a rooftop solar power station is proposed. In parallel to a solar power station, an industrial power mains is connected. Functional installation diagram is shown on Fig. 2. Solar panels transform solar energy into electrical energy and supply it through the inverter to the heat pump. An inverter synchronises solar power station operation with the mains and ensures protection of solar panels and other equipment in case of emergency operating modes. Since hot water consumption is erratic in its nature, the heated water is stored in a buffer storage tank, from where the circulation pump supplies it to the consumer. Heat accumulator may be made in three options [2]:

- Capacitive, which uses the heat capacity of the substance being heated (water);
- Accumulators operating on the phase transition of the heat-accumulating material and using latent heat, which is used during melting or solidification of the substance;
- Chemical and photochemical accumulators that are based on the release or absorption of heat during reversible chemical and photochemical reactions.

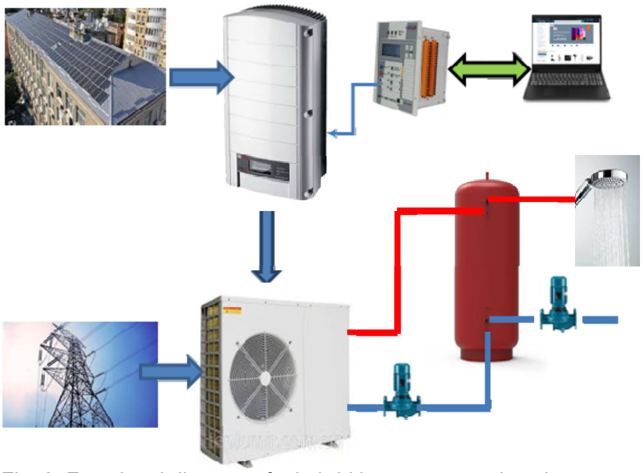

Fig. 2. Functional diagram of a hybrid hot water supply unit

For the proposed heat-generating unit, the two first types of accumulators are recommended. The first type is the cheapest and the most simple. Therefore, using methods of imitation modelling and taking into account the schedule of hot water supply, we calculated the required volume of the buffer capacity of the hydraulic accumulator (7 m^3 in this case). Reasoning for such a volume of buffer capacity is based on the hypothesis that the amount of water left from the previous day or renewed during the night should be sufficient for the consumer morning needs up to 12:00.

For heating water for hot water supply, we propose using heat pump AIR - FREON - WATER Mitsubishi Electric PUNZ-SHW230YKA2, with heat capacity of 45 kW. Taking into account SCOP energy efficiency ratio of 3.65, the consumed daily quantity of electric power will be 191 kW·h. Operation duration is 4.25 hours.

The unit operation is controlled by a control unit (Fig. 3) based on a microprocessor [1]. Different sensors are connected to the control unit, which allow monitoring the following:

- The quantity of produced electric power:
- Electricity flows;
- Weather conditions;
- The quantity of produced heat power:
- Quantity and schedule of hot water consumption.

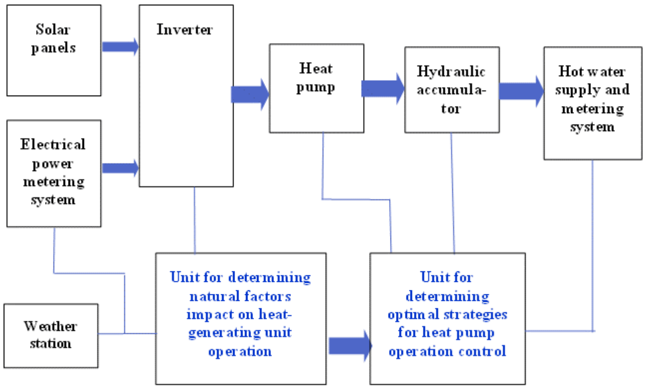

Fig. 3. Control unit based on a microprocessor

Operation efficiency of a solar energy-generating unit depends on the area of solar panels and the quantity of solar radiation. The lowest efficiency is observed during winter period. Moreover, performance is also affected by diffused radiation. Thus, in circumstances of full snow blanket during a month, the aggregate radiation is increased by 27% in comparison with a snowless winter [1].

In general, the quantity of produced electric power depends on the following physical values:

$$W = f\left(q,\ z,\ T\right), \quad (2)$$

where: q is the insolation or average value of overall solar radiation that earth's surface receives depending on the geographical latitude and the location of a solar power station; z is the coefficient that takes into account weather conditions (availability of cloud cover); T is the temperature.

Rated generation (W_1) of electric power is calculated based on the following dependence:

$$W_1 = q \cdot S, \quad (3)$$

where: S is the area of solar panels of the solar power station.

The overall quantity of produced electric energy throughout the month is calculated according to the formula:

$$W_2 = k \cdot P \cdot W_1 \cdot t_s \,, \tag{4}$$

where: *k* is the coefficient that takes into account losses, k=0.5 for summer period, k=0.7 for winter period; t_s is the number of operating hours of the solar power station during the month; *P=1000 W/m*^{2} is the quantity of solar radiation that earth's surface receives under standard conditions.

The calculations results and their analysis

Calculated data of monthly generation of electric power with 350 m2 area of solar panels are presented in Table 1.

Table 1 - Estimated values of electrical energy generation

Month	q, kW·h/m^2	τ, hours	W_1,kW·h	W_{PMT},kW·h
January	1.32	63	0.84	0.84
February	2.01	86	1.29	1.29
March	3.41	141	2.18	2.18
April	4.93	198	3.15	3.15
May	6.16	263	3.94	3.94
June	6.75	306	4.32	4.32
July	6.86	346	4.39	4.39
August	6.24	324	3.99	3.99
September	5.15	242	3.29	3.29
October	3.72	169	2.38	2.38
November	2.32	76	1.48	1.48
December	1.51	54	0.97	0.97
Total	-	-	-	-

The research conducted by us demonstrated that real values of efficiency of the solar power station (Fig. 4) are somewhat lower than the estimated by approximately 10-15% as a result of the following energy losses:

- Near shading (2.5-3.5%);
- IAM factor on global (1.8-2.1%);
- Soiling loss factor (0.9-1.3%);
- PV loss due to temperature (2.5-3.2%);
- Shadings-Electrical Loss (1.3-1.6%);
- Light induced degradation (1.3-1.6%);
- Mismatch loss, modules and string (0.9-1.3%);
- Inverter loss during operation (1.4-1.9%);

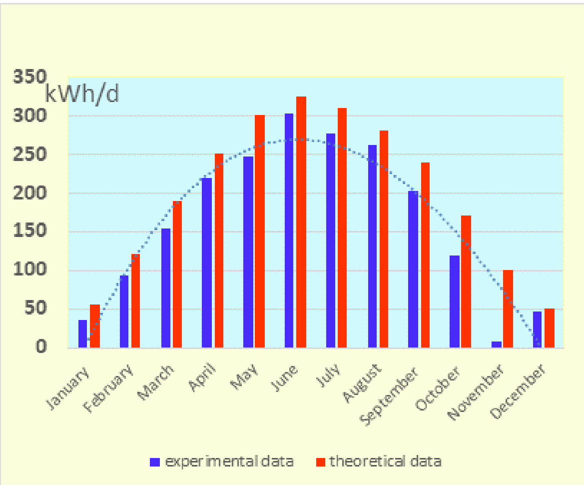

Fig. 4. Efficiency of solar power station depending on the time of season

Having conducted mathematical processing of experimental data, we obtain dependency of quantity of produced electric power from the time of year.

$$W(d) = 364 \cdot d_2 + 12 \cdot d + 14 \,, \tag{5}$$

where: *d* - certain day of the year.

In order to use this function for estimating the efficiency of solar power station in dependency with temperature changes and other climate factors, we propose using some adjusting coefficients. In this case, dependency (5) will look like this:

$$W(d) = k_k \cdot k_{x(d+1)} \cdot k_{t(d+1)} \cdot \left(364 \cdot d^2 + 12 \cdot d + 14\right). \tag{6}$$

where: k_k is the coefficient of adjustment to the current day; $k_{x(d+1)}$ is the coefficient of the effect of cloud cover change on the next day; $k_{t(d+1)}$ is the coefficient of temperature change on the next day.

Hot water supply system operation is controlled by a microprocessor system based on neural network [5] that allows utilizing solar panels capacity at a maximum level in the most efficient way, to calculate and adjust in real-time mode amount of consumed hot water, take into consideration weather forecast for the next day and to utilize possibility of heat pump operation during night-time under reduced tariff conditions.

The research was conducted in order to determine the costs of the energy sources depending on the technological parameters of hot water supply system. Based on experimental data, the first neural network was developed, which takes into account impact of natural factors on technological parameters of water supply (Fig. 5). Throughout the year, experimental data are stored in the storage. Based on those data, the second neural network is generated, which is designed for creation of a heat pump control algorithm.

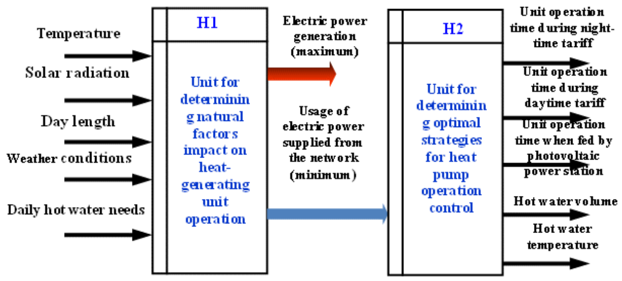

Fig. 5. Neural networks for hot water supply system and energy consumption

We propose considering the maximum profit from hot water supply as an efficiency criterion of a hot water supply system:

$$\Pi = \sum_{Я=1}^{5} (C_Я - C_x) N_Я + C_g E_g - C_e E_e \rightarrow \max \tag{7}$$

where: $C_Я$, C_x, C_g, C_e - the cost of a m3 of hot and cold water, electrical power generated by solar power station, and the electrical power from the industrial mains, UAH; $N_Я$ - the volume of hot water supply, m^3; E_g - the quantity of produced electric energy supplied into the industrial mains, kW·h; E_e - the quantity of consumed electrical energy from the industrial mains, kW·h.

The efficiency of neural network operation was evaluated via Statistica 6.0 software. This procedure was carried out in three stages:

- training stage;
- control stage;
- testing stage.

The best results were obtained with multi-layer perceptron network structure. Statistica 6.0 software via "Network Designer" window allows for additional neural network training. The above allowed to reduce the training error margin to 3%, and control error margin to 2,2%.

Obtained accuracy meets the technological requirements and allows to conclude on the correctness of the hypothesis on the usage of hybrid hot water supply unit. (Fig. 6).

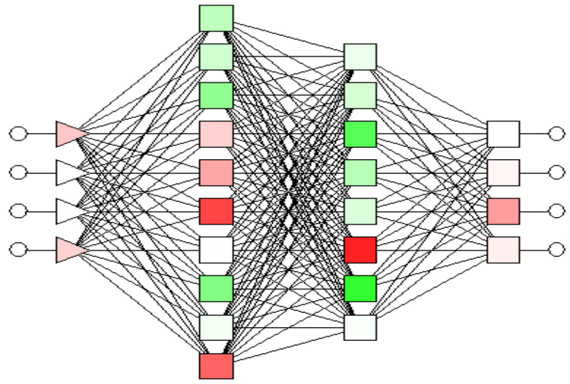

Fig. 6. Neural network architecture NN1 for assessing consumption of electrical energy by the hybrid hot water supply unit.

For neural network training stage, each continuous function of n variables given in a unit cube of n-dimensional space can be represented as [4]:

$$f(x) = \sum_{q=1}^{2n+1} h_q \left[\sum_{p=1}^{n} \phi_q^p (x_p) \right] \quad (8)$$

where: *f(x)* is a quality function; $h_q(x)$ are continious functions of input parameters change, that form the quality function; ϕ_q^p (x_p) is the function that does not depend on function $h_q(x)$, and is formed from the input parameters.

Utilization of a neural network in hot water supply control systems allows for continuous and flexible adjustment of control strategy based on accumulated databases in order to achieve high energy efficiency level. This process is carried out with the so-called "follow-up training" of the network (Fig. 7).

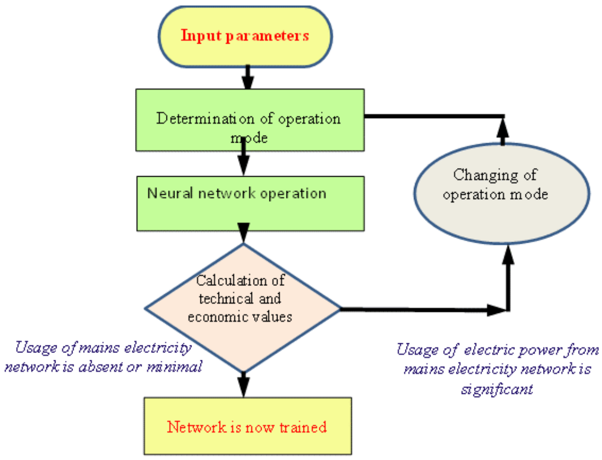

Fig. 6. Neural network learning process illustration

Conclusion

For "training" of the neural network NN1 we used the results of the research carried out at the National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine Based on the data received, we have conducted the technical and economic assessment of hybrid hot water supply system operation.

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