Analysis of the energy flow in photovoltaic systems

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This article defines the fundamental structure of the remote area power system (RAPS) - grid off system: energy source, equipment for energy storage and energy appliances. Each structure member is mathematically defined. These elements can work together as a part of RAPS.

Key words: *renewable energy system, remote area power system, RAPS, energy flow*

Introduction

RAPS has been connected to the power distribution network in last recent years. Those are solar power plants, wind generators and small hydro or biomass energy sources. Generated electrical energy is then consumed by various customer appliances, connected to the power distribution system [1, 9, 10, 13].

In the case of RAPS, there is an energy source and a few appliances. Since the production and consumption of electricity can be realized in different time periods [5, 7, 9, 12, 13], it is necessary to use temporary electricity storage device, preferably rechargeable batteries [2, 3, 4]. If the island systems must run in continuos operation, it is necessary to define both parameters of elements and operation rules to control the system [6, 8, 11].

Key elements of the RAPS

The term - renewable energy sources (RES) defines energy source, based on the generation of the required form of energy and not burning fossil fuels. Omission of fossil fuels in the energy systems has a lot of positive attributes. In particular, main goals are energy generation in selected form and contribution to reduction of greenhouse gases.

To ensure RAPS operation, it must have basic structure of these elements: a source of energy, short or long-term energy storage and power appliances.

Unlike huge energy generation systems with both small and large appliances, the RAPS can work only in condition of these existing elements: energy source – accumulator – power appliances.

Electrical energy sources

There can be various types of energy sources in RAPS:

Small-sized RAPS systems: photovoltaic panels, small wind generator, small water generator, etc.

Medium-sized RAPS systems: smaller set of photovoltaic panels, a smaller set of wind generators, small hydroelectric generators, tidal stream generator, etc.

Large island systems: a large set of photovoltaic panels, a large set of wind generators, small hydroelectric generators, biomass generator, wave powered generator, tidal stream generator, etc.

Each of these sources produces electrical energy, depending on the available form of energy. For example, photovoltaic panels generate electricity only during the day, if the sun shines. The wind generator can produce electricity during day and by night, if the wind blows. Small hydroelectric generator works, but if there is enough water in the dam, which is specific for each hydropower plant. It can work in two modes: all-day long if there is enough water, or only in limited mode during defined time period. Hydroelectric power plan can be started and stopped at different times of the day or night.

Wave powered generator can be used only in coastal areas and in condition of appropriate wave size. Obviously, the size of waves depends on the wind strength. Wind situation can be not only stable (during monsoons, the mistrals), but also unstable, depending on storm activity in the area.

The use of low and high tides depends on the site location, since tide height differs in various locations on Earth. Although the tide is cyclical and stable, its the maximum and minimum change across time period during the day and night.

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Burning biomass generates energy from production of sufficient quantities of biomass. This source, like other generators using heat, starts its operation with some delay after start and finishes its operation with some delay after shut-down. The effectiveness of this resource is higher during continuous operation and when energy consumption is uniformly distributed.

Production of renewable energy source is dependent on the level of solar radiation in the current region. This is a direct dependence, since energy source generates energy from solar radiation. However, there can be also an indirect dependency, because the use of wind, water and biomass, depend on sunlight radiation level. Therefore it is possible to use renewable energy sources only in case of favorable weather conditions. Water resources and biomass can be used as needed, but providing enough water or biomass for required electricity generation.

Since the operation renewable energy sources can be continuous or randomly interrupted, it is necessary to evaluate the amount of generated electricity W_{GENER} as a flow of produced energy based on periodic measurements:

$$W_{GENER} = \sum_{i=0}^{n} W_i = \sum_{i=0}^{n} U_i I_i \Delta t \quad [J] \qquad (1)$$

where W_{GENER} is produced electrical energy, produced during time period (usually 1 day, U_i is electric voltage during time interval Δt, I_i is electric current during time interval Δt and n is a number of time intervals.

Due to possible dynamic weather changes, it's suitable to periodically repeat the measurement of generated electricity in minute-intervals. For day and night - 24 hours, it corresponds to 1440 minute measurements.

To determine the parameters of the technical solution, it's necessary to know the peak value $W_{GENERPEAK}$ of produced electricity, which is the maximum value, that the system can achieve in favorable meteorological conditions.

Next, very important value, is a mean value of generated energy during time period $n\Delta t$. .

$$W_{GENERMEAN} = \frac{W_{GENER}}{n\Delta t} \quad [J] \qquad (2)$$

This value gives the amount of energy generated and uniformly distributed over a period of time - 24 hours.

Short-term energy storages

The main task of energy storage in RAPS is balancing the disproportion among electricity production and consumption.

Disproportions arise from nature of RAPS. Electric generation is limited by weather situation, but consumption is determined by the use of electrical appliances. To ensure system operation, mean amount of produced energy $W_{GENERMEAN}$ must be higher than mean amount of consumed energy $W_{CONSUMMEAN}$:

$$W_{GENERMEAN} \geq W_{CONSUMMEAN} \quad [J] \qquad (3)$$

This inequality ensures that the generated energy is partly consumed and partly stored in batteries. The ratio between consumption and storage changes continually. If energy production is reduced due to adverse weather conditions, energy consumption must be covered from reserves in batteries.

The issue of storing electricity in batteries is affected by other factors such as batteries efficiency, decreasing of battery capacity over time, with the temperature and the type of operation, etc.

Energy appliances

RAPS can provide family house with electric energy. According to energy consumption of appliances, a specific profile for electricity consumption of the household is created.

Some appliances are turned on all day and night, in continuous or non-continuous mode. Typical examples of continuously running appliances are: clocks, appliances in stand-by mode like TV, cookers, etc., but also periodically switched appliances (refrigerators, freezer, etc.). Other electrical appliances can be switched on and off as needed, which is a matter of chance. For example, turning on the TV depends on either on meteorological situation, or working shifts. Some example appliances are shown in Fig. 1. Example of total energy consumption is shown in Fig. 2.

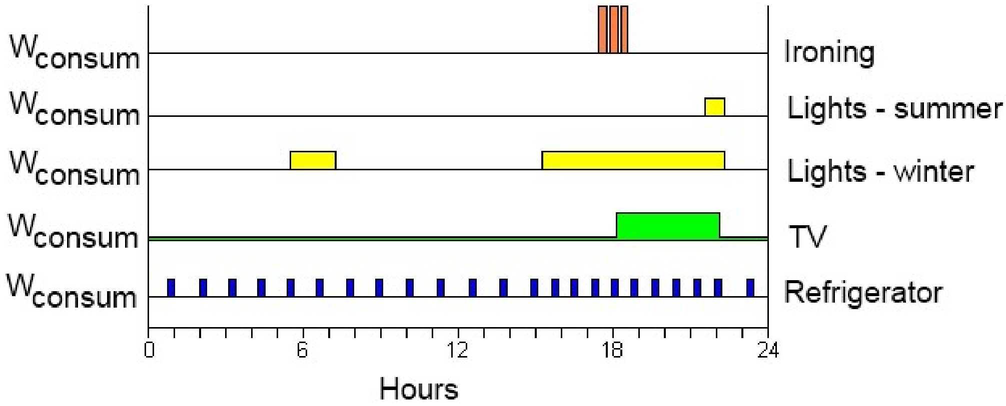

Fig. 1. Example appliances in household and their consumption.

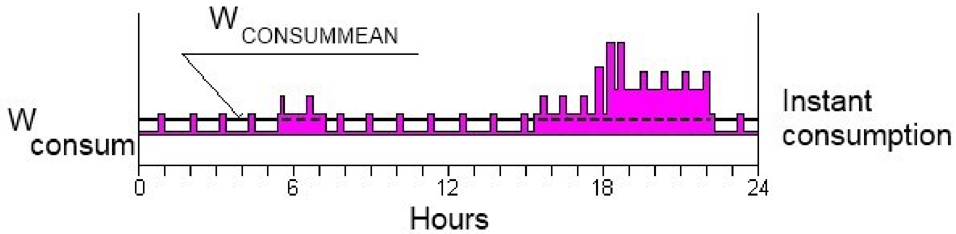

Fig. 2. Total energy consumption during the day.

Figures Fig. 1 and Fig. 2 show power consumption during the working day. Consumption changes during these time periods:

From 11 PM to 5 AM all residents sleep. Then, TV is in continuous low-power mode and refrigerator turns on periodically.

From 5 to 8 AM clock both TV and refrigerator run. During winter period, people sometimes turn on either chandeliers or lights. In the summer it isn't necessary to turn them on, because the amount of sunlight is sufficient. Residents leave to work and school.

From 8 AM to 3 PM all residents are either at school or work. Energy consumption is similar to that at night.

From 3 to 11 PM people return at home, they use refrigerator and lights more frequently. They turn on chandeliers, keeping them on in winter at all times. In summer, they turn them on only after 9 PM, when the sun goes down. Somebody watch TV and iron, others may use other energy appliances. At this time, energy consumption can be at maximum level.

Evaluation of the total consumption is expressed as the sum of all partial consumptions. Each sub-consumption is at different time intervals, which comes not only regularly, but often also randomly. Consumption is determined by the type of appliance – for example, TV's consumption is lower than iron's:

$$W_{CONSUM} = \sum_{k=1}^{s}\sum_{i=1}^{n} W_{ki} = \sum_{k=1}^{s}\sum_{i=1}^{n} U_{ki} I_{ki} \Delta t \quad [\mathrm{J}] \qquad (4)$$

where

W_{CONSUM} is energy consumption during defined time period (usually 1 day),
U_{ki} is input voltage of k-th appliance during i-th time interval Δt,
I_{ki} is input current of k-th appliance during i-th time interval Δt,
s is number of appliances,
n is number of time intervals.

The variable $W_{CONSUMPEAK}$ is peak value of W_{CONSUM}. It's maximum value of energy consumption, which RAPS must meet.

It's also necessary to define $W_{CONSUMMEAN}$ - mean value of W_{CONSUM} during the time period $n\Delta t$. This value is usually 24 hours.

$$W_{CONSUMMEAN} = \frac{W_{CONSUM}}{n\Delta t} \quad [J] \tag{5}$$

This value defines amount of energy consumption, uniformly distributed over the time period (24 hours). This approach to the problem's solution helps not only to design RAPS, but also divide system into parts according defined requirements.

General condition of RAPS operation

The RAPS system, consisting of elements generating electricity, energy storage and set of appliances, can work under the condition according to equation (3) - the value of generated electricity must be equal or greater than the value of the consumed energy.

Since the RAPS has three parts, its operation is expressed as follows:

$$W_{GENER} \geq W_{ACCUM} \geq W_{CONSUM} \quad [J] \tag{6}$$

where

W_{GENER} is value of generated energy during defined time period,
W_{ACCUM} is value of accumulated energy during defined time period,
W_{CONSUM} is value of consumed energy during defined time period.

Extending the equation (3) and expressing basic operation to the equation (6), is caused by the necessity to express the fact, that efficiency of stored energy is less than 100 %, like in other devices. This situation is shown in Fig. 3.

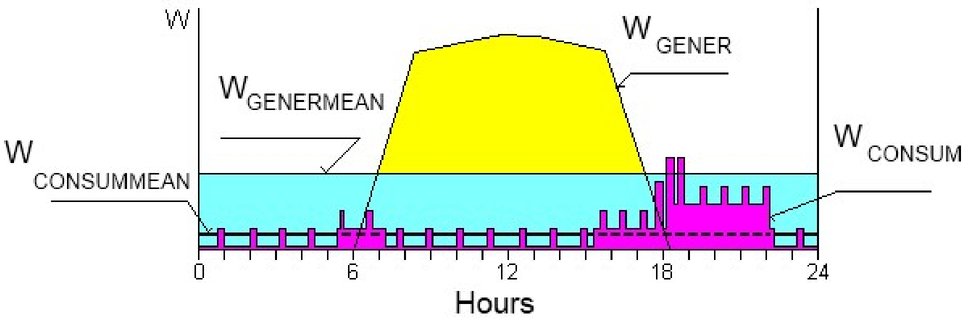

Fig. 3. Example of RAPS operation.

Setting the ratio of production and consumption is a complex task, affected by various events and factors. Technical equipment has certain efficiency, changing and decreasing over the time. Designing RAPS is also dependent on both objective factors, such as geographic location, weather conditions at this site and subjective factors, which are defined by a RAPS owner.

Conclusion

RAPS can be built either with connection (on-grid system) or without connection to power distribution network (off-grid system).

Current proposal is limited with many objective and subjective conditions. These conditions must be respected in the design, in order to achieve the efficient usability of the system.

To achieve continuous operation of RAPS, it's necessary to introduce some organizational rules. These rules will ensure that energy requirements will be met during energy availability and minimized during energy unavailability.

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