Energy storage device as a part of electric energy production system based on renewable energy sources

Sebastijan Seme, Gorazd Štumberger, Jože Voršič

University of Maribor, Faculty of Electrical Engineering and Computer Science
Smetanova 17, 2000 Maribor, Slovenia
phone: +386 2 220 7179, fax: +386 2 220 5481, e-mail: sebastijan.seme@uni-mb.si

Abstract. This work deals whit an energy storage device as a part of electric energy production system based on renewable energy sources. The system supplies given load with known load diagram. Operational diagrams of individual units in the system are determined in an optimization procedure. The optimization goal is to supply given load with minimal use of conventional energy delivered from electric grid. Optimization is performed by a stochastic search algorithm called Differential Evolution for the system consisting of a solar power plant, wind turbine unit and flow battery connected to the load and to the electric grid. The optimization input data are given weather forecasting and forecasted load diagram.

Key words: renewable energy, electric energy, energy storage system, optimization, differential evolution

1. Introduction

This work deals with an electric energy production system based on renewable energy sources installed at the University of Maribor, Faculty of electrical engineering and computer sciences. The electric energy production units in discussed system are photovoltaic power plant and wind turbine. A flow battery VRB is used for energy storage, while total consumption of the Power Systems laboratory represents the load.

The photovoltaic power plant and wind turbine power plant produce electric energy according to the available solar irradiation and wind speed, which are given by geographic location and weather condition. In this way produced electric energy can be spent for supply of the load or for supply of the energy storage system.

In order to minimize use of electric energy delivered from electric grid operational diagrams of individual units in the system are determined by optimization. The optimization procedure [1] requires models of all devices in the system. They are described in [2]-[7]. The required input data for optimization are geographic location of the discussed system, time interval of observation, forecasted load diagram and weather forecast. The operational diagrams are determined by Differential Evolution [1]. It is an evolutionary strategy which can be describe as a stochastic search algorithm. Electric energy from renewable energy sources is produced whenever these sources are available. Thus, the optimization result is operational diagram of the energy storage system.

In the given case, the optimization procedure is performed for 24 one hour long discrete time intervals. This means that all variables used in the optimization procedure like solar irradiation, wind speed, forecasted load diagram, operational diagrams of all individual units in the discussed system as well as results presented at the end of this work are given in aforementioned one hour long discrete time interval for 24 hours.

2. Models

This section deals with calculation of solar irradiation and wind power. It describes input-output relations in models of different units given in [2]. The flow battery which is used as an energy storage system is described as well. Models of aforementioned units are needed in optimization procedure. They can be given in the form mathematical expressions or in the form of look-up tables.

2.1 Solar Irradiation

The total extraterrestrial irradiation G_{tot} is the total beam irradiation outside the Earth's atmosphere. In the time interval of observation $t \in [t_o, t_o+\Delta t]$ it is described by (1):

$$G_{tot} = \int_{t_0}^{t_0+\Delta t} G_{sc} e(t) \sin \alpha_s dt \quad (1)$$

$$e(t) = 1 + 0.034 \cos\left(\frac{2\pi n}{365}\right) \quad (2)$$

where G_{sc} denotes the solar constant ($G_{sc} = 1367\ \mathrm{W/m^2}$), $e(t)$ is the orbital eccentricity (2), n is the day number counted from first of January.

α_s is the solar altitude angle which can be calculated using equation (3):

$$\sin\alpha_s = \sin\delta\sin L + \cos\delta\cos L\cos\omega \qquad (3)$$

where L, δ and ω are the latitude, declination of the sun and the solar hour angle respectively. The declination of the sun δ (4) is the angle between the sun's rays and the zenith direction at noon on the Earth's equator.

$$\delta = 23.45\sin\left(\frac{360}{365}(284+n)\right) \qquad (4)$$

The total irradiation on the inclined surface G_t results from the sum of direct irradiation, the isotropic sky diffuse irradiation and also the ground reflection proportion with the reflection coefficient ρ, is given by (5):

$$G_t = (G_h - G_{dh})F_{surface-facing} + G_{dh}F_{surface-sky} + G_h F_{surface-ground}\,\rho \qquad (5)$$

where $F_{\text{surface-facing}}$, $F_{\text{surface-sky}}$ and $F_{\text{surface-ground}}$ are the beam, diffuse and reflected irradiation tilted factors, respectively. The irradiation on the horizontal surface is called global irradiation (G_h) and is given by (6):

$$G_h = G_{bh} + G_{dh} \qquad (6)$$

where G_{bh} is the beam irradiation. The direct G_{dh} irradiation on the horizontal surface (7) is supplied in many meteorological data records as measured hourly values:

$$G_{dh} = G_h(1 - 1.13K_t) \qquad (7)$$

where K_t is the clearness index, while $G_h = K_t G_{tot}$. The factors $F_{\text{surface-facing}}$, $F_{\text{surface-sky}}$ and $F_{\text{surface-ground}}$ are given by expressions (8) to (10):

$$F_{s-f} = \frac{\cos(L-\beta)\cos(\delta)\sin(\omega_{sr}) + \omega_{sr}\sin(L-\beta)\sin(\delta)}{\cos(L)\cos(\delta)\sin(\omega_{sr}(\alpha=0)) + \omega_{sr}(\alpha=0)\sin(L)\sin(\delta)} \qquad (8)$$

$$F_{surface-sky} = \frac{1+\cos\beta}{2} \qquad (9)$$

$$F_{surface-ground} = \frac{1-\cos\beta}{2} \qquad (10)$$

where β is the surface tilt angle. The solar hour angle ω_{sr} is given by (11):

$$|\omega_{sr}| = \min\left\{|\omega_s(\alpha=0)|, |\omega_s(i=90^0)|\right\} \qquad (11)$$

where ω_s is the sunset hour angle, while i is the incidence angle. For a tilted surface expression (12) – In Winter and (13) – In Summer can be written:

$$|\omega_s(\alpha=0)| = \arccos(-\tan L\tan\delta) \qquad (12)$$

$$|\omega_s(i=90^0)| = \arccos(-\tan(L-\beta)\tan\delta) \qquad (13)$$

The incidence angle i for a south facing tilt surface is expressed in implicit way by (14).

$$\cos i = \sin\delta\sin(L-\beta) + \cos\delta\cos(L-\beta)\cos\omega \qquad (14)$$

The expressions presented in this subsection are used to calculate time dependent distribution of extraterrestrial solar irradiation and total irradiation on the inclined surface during the day n.

2.2 Solar power plant model

Solar irradiation is necessary for calculation of electric energy produced in the photovoltaic unit. This energy depends on the solar irradiation normal to the surface of solar cells. Distribution of the total solar irradiation that reaches solar cell surface in individual one hour long discrete time intervals during the day of observation is described in subsection 2.1. Production of electric energy by photovoltaic power plant depends on the solar irradiation that reaches surface of solar cells, total surface of solar cells and efficiency of the inverter. In the model it is supposed that the maximal power point tracking of the solar cells is achieved by the correct control of the inverter.

2.3 Wind power

Model of a wind turbine can be extracted from an air stream which can produce mechanical energy that may be transformed into other forms of energy. In a real system, in addition to the energy extracted, energy losses also occur because of the rotational motion of the fluid that is imparted by the blades and frictional drag. To determine the maximal possible output of a wind turbine, we shall assume that:

- blades operate without frictional drag,
- a well-defined slipstream separates the flow passing through the actuator from that outside the actuator disk,
- the static pressures inside and outside the slipstream tube far ahead of and behind the rotor are equal to the undisturbed free-stream static pressure,
- the thrust loading is uniform over the actuator disk and

- no rotation is imparted to the flow by the actuator.

The instantaneous power output of an aero generator is given by (15):

$$P_w = 0.6 C_w \frac{\rho A V_\infty^3}{2} \quad (15)$$

where C_w is the efficiency factor, while ρ is the air density and V_∞ is the free stream wind speed. A is the swept aero generator area and can be expressed by (16):

$$A = \pi \frac{D^2}{4} \quad (16)$$

where D denotes the aero generator diameter. The energy W_w produced by an aero generator in the time interval $t \in [t_1, t_2]$ can be expressed by (17),

$$W_w = \int_{t_1}^{t_2} P_w dt \quad (17)$$

while the average power P_{wa} produced in this time interval is given by (18).

$$P_{wa} = \frac{W_w}{t_1 - t_2} = \frac{1}{t_1 - t_2} \int_{t_1}^{t_2} P_w dt \quad (18)$$

The average power produced by the aero generator in each one hour long discrete time interval is required in optimization procedure. It is normally calculated for given weather forecasting before the optimization starts. Number of one hour long discrete intervals depends on the length of entire interval of observation.

2.4 VRB energy storage system

In order to minimize need for electric energy delivered form electric grid the system of devices for electric energy production based on renewable energy sources is completed by an energy storage system. The energy storage system discussed in this case is Vanadium Redox Battery – Energy Storage System (VRB-ESS). It is based on the vanadium redox regenerative fuel cell that converts chemical energy into electrical energy. Energy is stored chemically in different ionic forms of vanadium. The principle of the VRB is show in Fig. 1. It consists of two electrolyte tanks, containing active vanadium species in different oxidation states [8] (positive: $V^{4+}/V^{5+}+e^-$ redox couple, negative: $V^{3+}+e^-/V^{2+}$ redox couple).

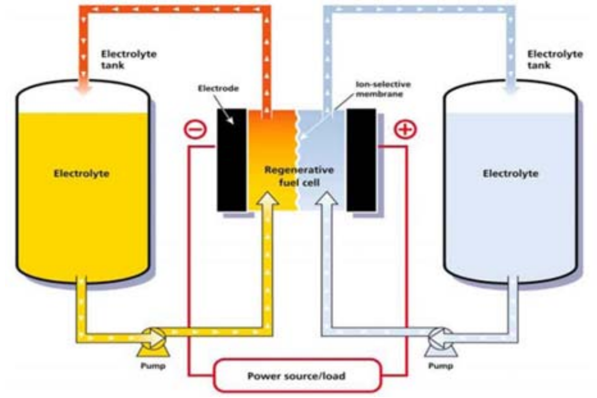

Figure 1: Concept of the VRB-EES.

The VRB-ESS employs vanadium ions in both half-cell electrolytes. Therefore, cross-contamination of ions through the membrane separator has no permanent effect on the battery capacity, as is the case in redox flow batteries employing different metal species in the positive and negative half-cells. The vanadium half-cell solutions can even be remixed bringing the system back to its original state. No degradation from repeated deep charges and discharges are known. The theoretical charge/discharge window of 1:1 (practically 1.8:1) allowing off-peak charging for on-peak dispatch.

The VRB-ESS model is given in the form of an energy reservoir (integrator) with efficiency, limited storage capacity and limited charging and discharging power corresponding to the efficiency, capacity and power of the VRB. The changes between charging and discharging modes are considered as instantaneous. Like in all other models of the system one hour long discrete time intervals are used.

The optimization goal is to find operational diagram of the VRB in such a way that the use of energy delivered from the electric grid is minimized. The optimization is performed for 24 one hour long discrete time intervals. By the optimization determined operational diagram of the VRB show when and how much of the energy produced from renewable energy sources should be used to charge the VRB and when the stored energy should used to supply the load.

3. Differential Evolution

Differential Evolution is one of stochastic search algorithms. It is an evolutionary strategy and which performs optimization by simulating evolution in the nature.

In a population of potential solutions within an n – dimensional search space, a fixed number of vectors are randomly initialized, then evolved over time to explore search space and to locate the minimum of the objective function. At each iteration, called generation, new vectors are generated by the combination of vectors randomly chosen from the current population (mutation). The out coming vectors are then mixed with a predetermined target vector. This operation is called recombination and produces the trial vector. Finally, the trial vector is accepted for the next generation if and only if it yields a reduction in the value of the objective function. This last operator is referred to as a selection.

In the given case, the operational diagram of VRB unit is to be determined by the optimization for 24 hours long interval of observation. The goal of optimization is to minimize value of the objective function q, which is defined by (19).

$$q = \mathbf{e}^T \mathbf{e} \qquad (19)$$

The objective function represents the sum of squared differences between consumption and production of electric energy **e** in each 1 hour interval. **e** is defined by (20):

$$\mathbf{e} = \left(\mathbf{P}_{SOLAR} + \mathbf{P}_{WIND} - \mathbf{P}_{VRB} - \mathbf{P}_{LOAD}\right)\frac{1}{\mathbf{P}_{inst}} \qquad (20)$$

where P_{inst} is the total installed power of photovoltaic unit, wind turbine unit and VRB unit. Vectors P_{SOLAR} and P_{WIND} represent power produced in the solar cells power plant and wind turbines power plant, respectively. Each element of these two vectors represents average power produced in one hour long discrete time interval. Similarly, vector P_{VRB} represents the power of VRB unit in each one hour long discrete time interval. This vector is to be determined by the Differential Evolution in order to minimize value of the objective function, which means to minimize need for electric energy from the grid.

4. Results

All results presented are given for the system installed at the University of Maribor. It consists of a photovoltaic power plan whit rated power of 7.5 kW, a VRB storage system whit capacity of 10 kWh and rated power 3.3 kW, and the load with maximal power of 4.1 kW.

Figs. 2 and 3 show optimized operational diagrams of individual units in the discussed systems determined for two different cases. Fig. 2 shows results for the case when electric energy produced from renewable sources is in the same range as consumption while Fig. 3 shows results for the case when consumption is higher than production of electric energy from renewable energy sources.

Fig. 2.a and b show power produced in photovoltaic and wind turbine units. The power produced by the VRB storage system shows Fig 2.c. The power delivered from the grid is shown in Fig. 2.d while Figs. 2.e and f show total power produced in the discussed system and load diagram. Results shown in Fig. 3 are presented in the same way.

5. Conclusion

This work deals with the system of devices for production of electric energy from renewable energy sources installed at the University of Maribor. The system consists of photovoltaic unit, a wind turbine unit, VRB based energy storage system and load. The goal of this work is to determine operational diagrams of individual units in the system by optimization in order to minimize use of electric energy from the grid.

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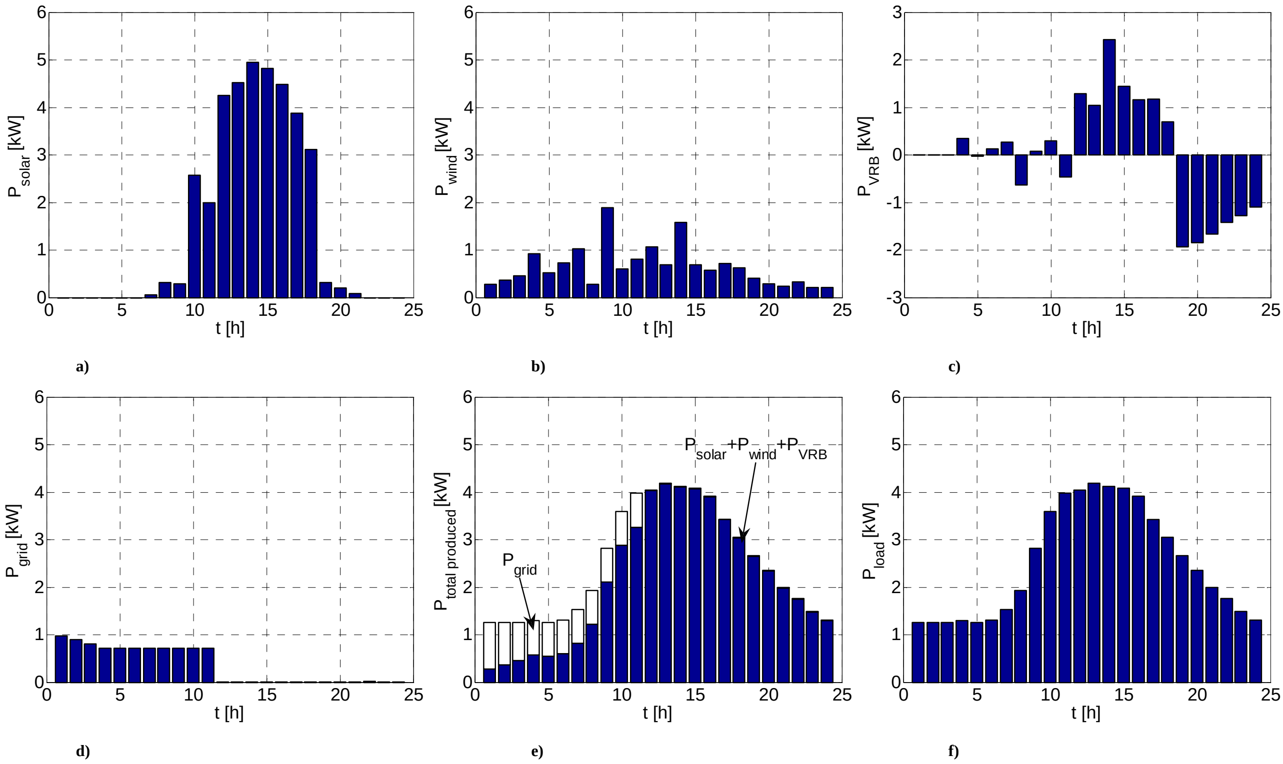

Figure 2: Power from the photovoltaic unit a), power from the aero generator b), power from the VRB unit c), power from the grid d), total power produced in the system e), and load diagram f).

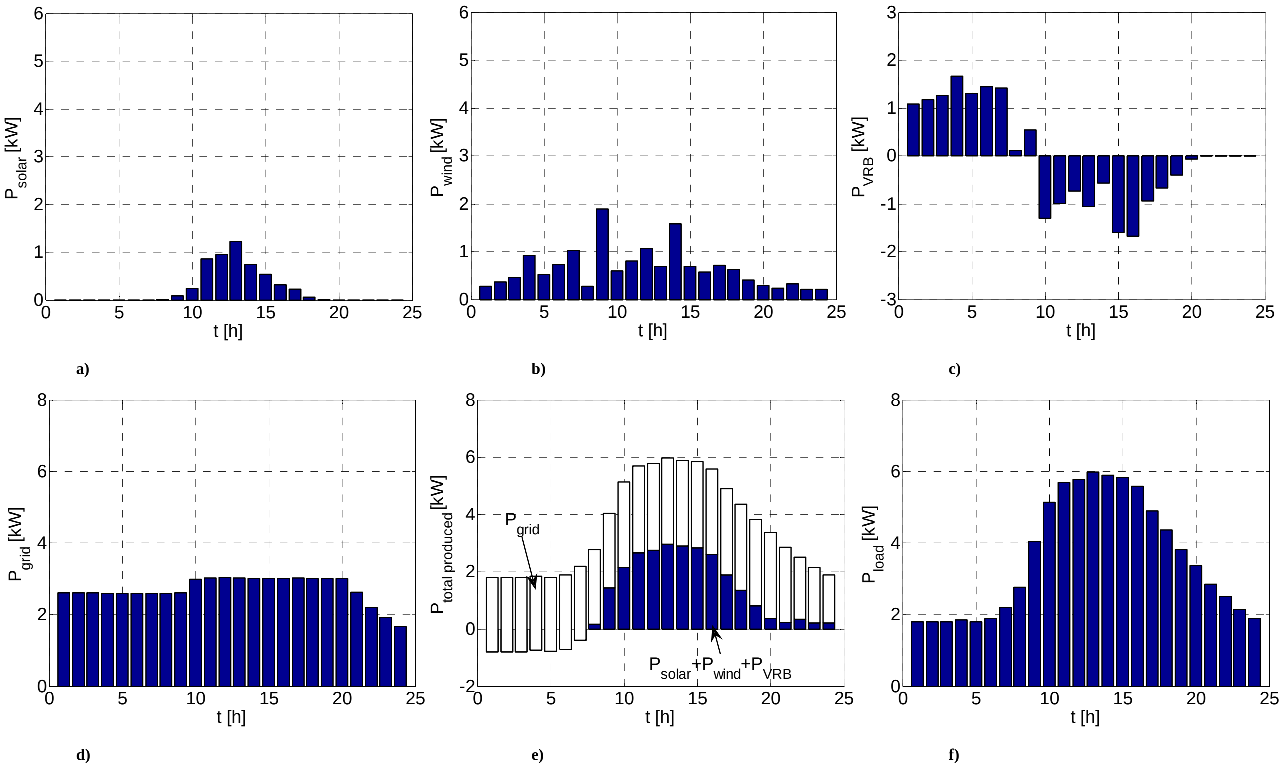

Figure 3: Power from the photovoltaic unit a), power from the aero generator b), power from the VRB unit c), power from the grid d), total power produced in the system e), and load diagram f).