Optimizing Production of Electric Energy from Renewable Sources by Differential Evolution

[1]Oriol Costa Garrido, [2]Gorazd Štumberger, [2]Jože Voršič

[1]Taller de Fred, s.l., Santa Rita,nº23, Sant Fost de Campsentelles, 08105 Barcelona, Spain

[2]University of Maribor, Faculty of Electrical Engineering and Computer Science
Smetanova 17, 2000 Maribor, Slovenia
phone:+386 2 220 7075, fax:+386 2 220 7272, e-mail: **Gorazd.Stumberger.@uni-mb.si**

Abstract. This work deals with a general procedure for optimizing operational diagrams of electric energy production units that use alternative energy sources. The goal of optimization is to supply given load at minimal use of conventional energy sources. In order to perform the optimization, simplified mathematical models of different production units that use alternative energy sources are introduced. These units are based on solar cells, wind turbines, fuel cells and electrolysis. The optimization is performed for given weather forecasting and forecasted load diagram by the Differential Evolution, which is a stochastic search algorithm.

Key words: renewable energy, electric energy, operational diagrams, optimization, differential evolution

1. Introduction

This work deals with an electric energy production system based on renewable energy sources. The primary electric energy production units in discussed system are photovoltaic and wind turbine based. Production of electric energy in these units strongly depends on weather conditions, i.e. solar irradiation and wind speed. These units can produce electric energy only if weather conditions are appropriate. On the other hand, the electric energy cannot be directly accumulated, which means that production of electric energy must fit load demands at any time. Thus, weather dependent production of electric energy in photovoltaic and wind turbine based devices on the one hand and required balance between production and consumption on the other hand, force use to introduce some kind of energy storage device into discussed system. In the given case, this is actually a set of devices composed of a hydrogen production unit, hydrogen tank and fuel cell unit. When power produced in the photovoltaic and wind turbine devices is higher than consumption, the rest of energy after supplying costumers is used for hydrogen production. The hydrogen is stored in the hydrogen tank. The fuel cell unit uses this hydrogen for production of electric energy when consumption is higher than production in photovoltaic and wind turbine units.

This work presents a general procedure used for optimizing operational diagrams of hydrogen production unit and fuel cell unit in the cases when characteristics of all devices in the discussed electric energy production system, its geographic position, day in the year, weather forecasting and forecasted load diagram, are known. The operational diagrams are determined by a stochastic search algorithm called Differential Evolution [1], considering bounds of all devices in the system. The optimization objective is to supply given load with electric energy from the discussed system at minimal possible use of electric energy delivered from the gird.

The optimization algorithm requires models of all units present in the discussed system in the form of mathematical expressions or look-up tables. The look-up tables are preferred in optimization algorithms. The unit (device) manufacturer can provide us with them. They are compact and require only modest computation effort. On the contrary, the models given in the form of mathematical expressions normally require more computation effort and are less compact than look-up tables. They describe processes and balances in individual units and devices that already exist or are at the design stage. Detailed descriptions of all models used in optimization procedure presented in this work are given in [2]-[5].

The optimization of operational diagrams is performed for the given time interval of observation, which is divided into 15 minutes long discrete intervals. Thus, the solar irradiation, wind speed, load diagram, production of electric energy in individual units and their operational diagrams are available only as average values given for 15 minutes long discrete time intervals over the entire interval of observation. The obtained optimization results are presented at the end of the paper.

2. Models

This section deals with calculation of solar irradiation and wind power. It describes input-output relations in models of different units (devices) given in [2], which are an indispensable part of optimization procedure. These models can be given in the form mathematical expressions or in the form of look-up tables obtained from the device manufacturer.

2.1 Solar irradiation

According to [6] and [7], the total extraterrestrial irradiation I_{tot} in the time interval of observation $t\in[t_0, t_0+\Delta t]$ is given by (1):

$$I_{tot} = \int_{t_0}^{t_0+\Delta t} I_0 \; e(t) \sin\alpha \; dt \tag{1}$$

where *e(t)* denotes the orbital eccentricity, I_0 is the solar constant while α is the solar altitude angle. The orbital eccentricity *e(t)* is expressed in (2) as a function of the day number in given year *n*.

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

The total terrestrial irradiation on a tilted surface I_{tt} is expressed by (3):

$$I_{tt} = R_b B + R_d D + R_r (B + D) \tag{3}$$

where R_b, R_d and R_r are the beam, diffuse and reflected irradiation tilted factor, respectively. The diffuse irradiation on a horizontal surface *D* and the beam irradiation on a horizontal surface *B* are given by (4) and (5):

$$D = G\,(1 - 1.13\, K_T) \tag{4}$$

$$B = G - D \tag{5}$$

where K_T is the clearness index while G=K_T I_{tot} is the global irradiation received on a horizontal surface at the site of observation. The factors R_d, R_r and R_b are given by expressions (6) to (8):

$$R_d = \cos^2\left(\frac{\beta}{2}\right) \tag{6}$$

$$R_r = \rho \sin^2\left(\frac{\beta}{2}\right) \tag{7}$$

$$R_b = \frac{\cos(L-\beta)\cos(\delta_s)\sin(h_{sr}) + h_{sr}\sin(L-\beta)\sin(\delta_s)}{\cos(L)\cos(\delta_s)\sin(h_{sr}|_{\alpha=0}) + h_{sr}|_{\alpha=0}\sin(L)\sin(\delta_s)} \tag{8}$$

where β is the surface tilt angle, ρ is the diffuse reflectance, *L* is the latitude, δ_s is the declination of the sun (9), while h_{sr} is the sunrise hour angle (10).

$$\delta_s = 23.45\,\frac{\pi}{180}\sin\left(2\pi\,\frac{284+n}{365}\right) \tag{9}$$

$$|h_{sr}| = \min\left\{\left|h_{ss}|_{(\alpha=0)}\right| \quad , \quad \left|h_{ss}|_{(i=90^o)}\right|\right\} \tag{10}$$

where h_{ss} is the sunset hour angle while *i* is the incidence angle. For a tilted surface expression (11) can be written:

$$\begin{aligned}&\text{In Winter: } \left|h_{ss}|_{(\alpha=0)}\right| = \left|h_{sr}|_{(\alpha=0)}\right| = \arccos(-\tan L \tan\delta_s)\\ &\text{In Summer: } \left|h_{ss}|_{(i=90^o)}\right| = \left|h_{sr}|_{(i=90^o)}\right| = \arccos(-\tan(L-\beta)\tan\delta_s)\end{aligned} \tag{14}$$

The incidence angle *i* for a south facing tilted surface and the solar altitude angle α are expressed in implicit ways by (12) and (13):

$$\cos(i) = \sin(L-\beta)\sin(\delta_s) + \cos(L-\beta)\cos(\delta_s)\cos(h_s) \tag{12}$$

$$\sin(\alpha) = \sin(L)\sin(\delta_s) + \cos(L)\cos(\delta_s)\cos(h_s) \tag{13}$$

The expressions presented in this subsection are used for calculation of terrestrial and extraterrestrial solar irradiation distribution during the day *n*. The impact of the weather is accounted for by the clearness index K_T.

2.2 Wind power

According to [7], the output power P_w of an aero generator is given by (14):

$$P_w = 0.6\, C_w\, \frac{\rho A V_\infty^3}{2} \tag{14}$$

where C_w is the efficiency factor, ρ is the air density, *A* is the swept aero generator area, while V_∞ is the free-stream wind speed. Considering that *D* denotes the aero generator diameter, the swept area *A* can be expressed by (15).

$$A = \pi\,\frac{D^2}{4} \tag{15}$$

The energy W_w produced by an aero generator in the time interval $t\in[t_1, t_2]$ can be expressed by (16),

$$W_w = \int_{t_1}^{t_2} P_w \; dt \tag{16}$$

while the average power P_{wa} produced in this time interval is given by (17).

$$P_{wa} = \frac{W_w}{t_2 - t_2} = \frac{1}{t_2 - t_2}\int_{t_1}^{t_2} P_w \; dt \tag{17}$$

The average power produced with the aero generator in each 15 minutes long discrete time interval is required in optimization procedure. It is normally calculated for given weather forecasting before the optimization starts. Number of 15 minutes long discrete intervals depends on the length of entire interval of observation.

2.3 Models of individual units and relations among them

The discussed system consists of a photovoltaic electric energy production unit, wind turbine or aero generator based electric energy production unit, hydrogen production unit, hydrogen tank and fuel cell based electric energy production unit. System inputs are terrestrial solar irradiation that reaches tilted surface of the photovoltaic system, wind turbine input power and load diagram. They are given for 15 minutes long discrete time intervals over the entire interval of observation. The solar irradiation and wind turbine power are calculated as described in subsections 2.1 and 2.2 for given geographic position, day in the year and weather forecast.

Input for the photovoltaic unit model is the solar irradiation that reaches tilted surface of the photovoltaic system while its output is the output power on the terminals of DC/AC converter. It is supposed that the solar cells and DC/AC converter operate tracing the maximal power point. Input for the wind turbine unit model is the average wind power (17) while its output is DC/AC converter output power. Power above the load demand is used for hydrogen production. Input for the hydrogen production unit is the available power while its output is volume of hydrogen produced in 15 minutes long discrete time intervals. Input for the hydrogen tank is the difference between volume of hydrogen produced in the hydrogen production unit and volume of hydrogen spent in the fuel cell unit. Output of the hydrogen tank model is volume of hydrogen in the tank. Finally, input for the fuel cell unit model is volume of the hydrogen spent in 15 minutes interval, while its output is the AC output power on the DC/AC converter terminals.

The optimization objective is to find optimal operational diagrams of hydrogen production unit and fuel cell unit in order to supply given load at minimal use of electric energy from the grid. It is performed for a set of 15 minutes long discrete time intervals over the entire interval of observation. This means the for 24 hours long interval of observation inputs and outputs of all units in the system are given as average values in 96 (24 times 4) 15 minutes long discrete intervals. The optimization results show us when and how much of electric energy produced in photovoltaic and wind turbine units should be spent for the hydrogen production and when and how much of this hydrogen should be spent for production of electric energy in fuel cell unit.

3. Objective function

Differential Evolution is an evolutionary strategy. It performs optimization by simulating evolution in the nature. Optimization starts by generating initial population members. The best offspring of actual generation form the next generation. Each new population member inherits properties of his parents. The population size is constant while the objective function evaluates quality of each individual in the population. Only the best members survive. In this way, the best properties inherit from generation to generation, leading to the population members with the best properties at the end of optimization.

In the given case, the operational diagrams of hydrogen production unit and fuel cell unit are to be determined by the optimization for 24 hours long interval of observation. Considering 15 minutes long discrete time intervals, both of them are given in 96 points. In the sense of Differential Evolution, each population member is a vector consisting of 192 elements, 96 for the hydrogen production unit operational diagram and the other 96 for the fuel cell unit operational diagram. In order to determine both operational diagrams by Differential Evolution an objective function q is defined by (18):

$$q = \mathbf{e}^T \mathbf{e} \tag{18}$$

where $\mathbf{e}$ is the vector of differences between produced power and the load demanded power given in 96 point for 24 hours. It is defined by (19):

$$\mathbf{e} = \left(\mathbf{P}_{wind} + \mathbf{P}_{solar} - \mathbf{P}_{hydrogen} + \mathbf{P}_{fuel\ cell} - \mathbf{P}_{load} \right) \frac{1}{P_{inst}} \tag{19}$$

where P_{inst} is the total installed power of photovoltaic unit, wind turbine unit and fuel cell unit. Powers produced in the wind turbine unit, photovoltaic unit and fuel cell unit are given with vectors $\mathbf{P}_{wind}$, $\mathbf{P}_{solar}$, and $\mathbf{P}_{fuel\ cell}$, respectively. Vectors $\mathbf{P}_{hydrogen}$ and $\mathbf{P}_{load}$ denote power spent in the hydrogen production unit and power delivered to the load. All vectors are given in 96 points for 24 hours. Eight penalties are used to direct the optimization process.

4. Results

Figures 1 and 2 show optimized operational diagrams of the entire system. Graphs in figure 1 are arranged in a matrix form. Graph (1,1) shows power exchange with the grid. Graphs (1,2) and (1,3) show power produced in photovoltaic and wind turbine units. Graph (2,1) shows power used for hydrogen production, while graph (2,2) shows power produced in fuel cell unit. Volume of the hydrogen in the tank is shown with graph (2,3). Figure 2 show the load diagram and power produced with our system.

5. Conclusion

This work presents a general approach to optimization of electric energy production based on renewable energy sources. The discussed system of energy production units consists of solar cells unit, wind turbine unit, hydrogen production unit, hydrogen tank and fuel cells stack based production unit. The aim of optimization is to supply given load with electric energy at minimal use of electric energy delivered from the grid, which is normally produced with the conventional energy sources. The Differential Evolution, which is a stochastic search algorithm, is used to perform the optimization. The optimization requires models of all aforementioned production units, geographic position of discussed system, date and time interval of observation, weather forecasting and load diagram forecasting. The power produced with the solar cell unit depends on geographic position, time and date of observation and weather conditions, while power produced with the wind turbine unit depends only on the weather conditions. The optimization results are operational diagrams of the hydrogen production unit and fuel cell unit. They give us information when and how much of electric energy produced with the solar cell and wind turbine units should be used for hydrogen production and when and how much of this hydrogen should be used for production of electric energy with the fuel cell unit.

References

[1] Kenneth V. Price, Rainer M. Storn, Jouni A. Lampinen, *Differential Evolution*, Springer, 2005.

[2] Oriol Costa Garrido, *Optimizing daily operational diagrams of electric energy production units that use alternative energy sources in order to minimize use of conventional energy sources,* Escola Tecnica Superior d' Enginyeria Industrial de Barcelona, Barcelona, Spain, Master's thesis, 2006.

[3] Antonius R. Burgers, *New Metallisation Patterns and Analysis of light Trapping for Silicon Solar Cells*, Ph.D thesis, Universiteit Utrecht, 2005

[4] Ph.M.Kanarev, *The foundations of Physchemistry of micro world-New theory of low voltage Process of Water Electrolysis*, The Second Edition Internet Version, 2003 [http://guns.connect.fi/innoplaza/energy/story/Kanarev/book/1103.html]

[5] J.M. Corrêa, F.A. Farret, L.N. Canha, M.G. Simoes, *An*

Electrochemical-Based Fuel Cell Model Suitable for Electrical Engineering Automation Approach, [http://egweb.mines.edu/msimoes/journal_papers/Correa_Farret_Canha_Simoes.pdf].

[6] J. F.Kreider, F. Kreith, *Principles of Solar Engineering,* McGraw-Hill, 1978.

[7] *The irradiation data-1998,* [http://solar.anu.edu.au/Sun/Irrad/Irradiation.html]

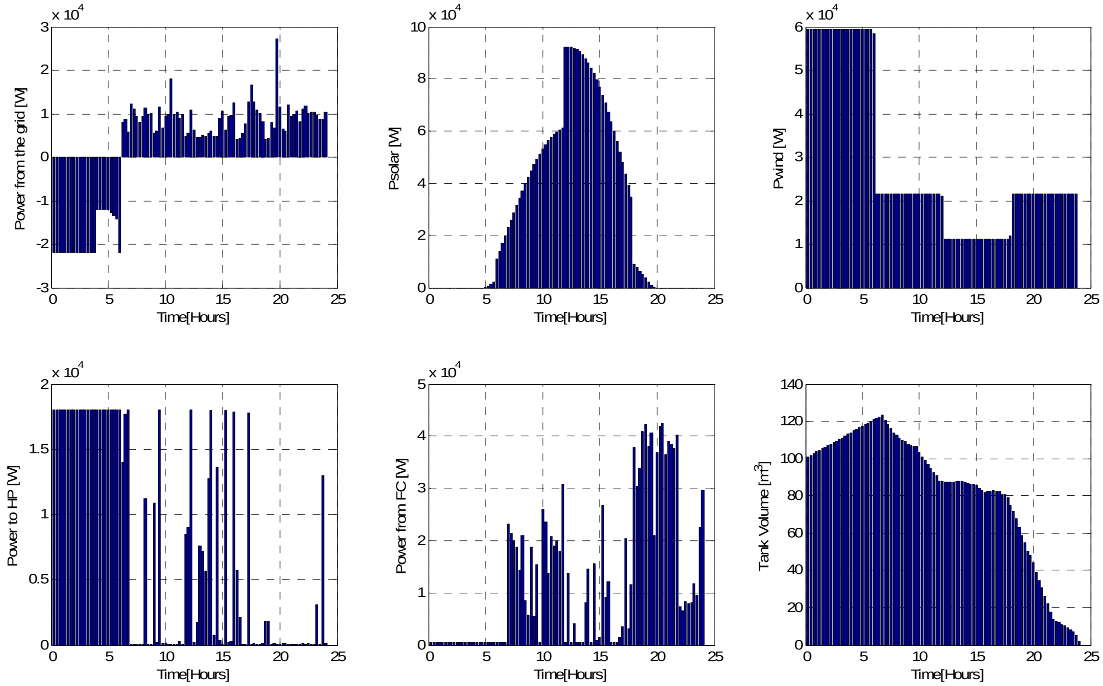

Figure 1: Power from the grid, solar cell unit output power, aero generator output power, hydrogen production unit input power, fuel cell unit output power and hydrogen tank level for 24 hours optimization.

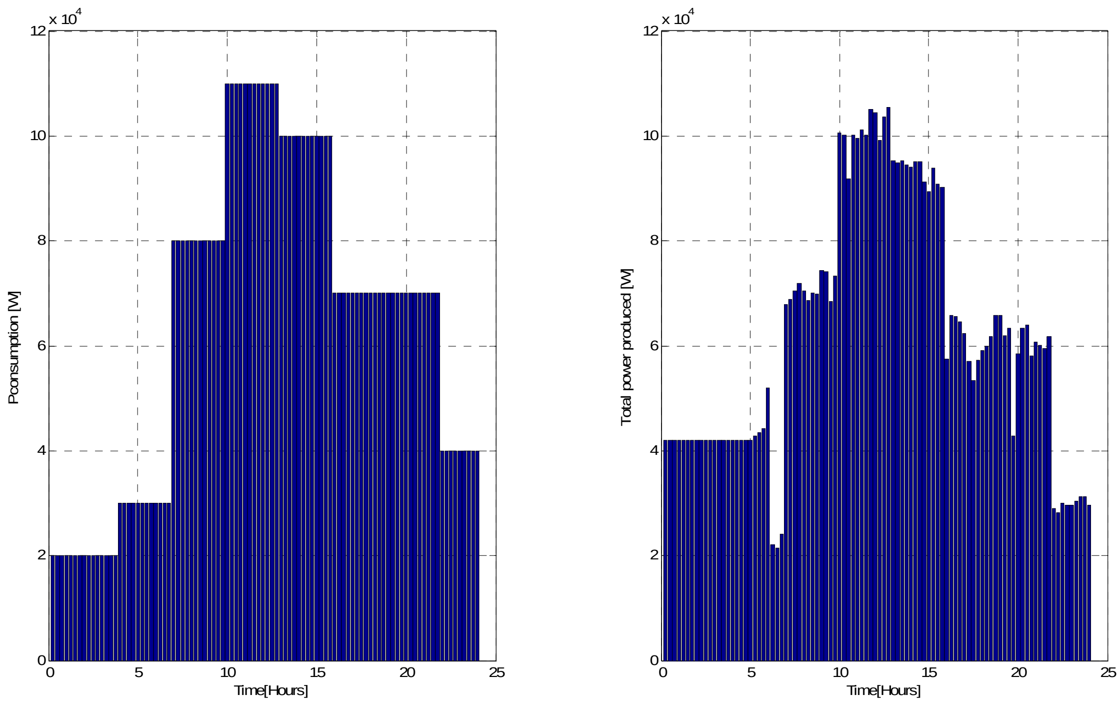

Figure 2: Load diagram and power produced given for 24 hours optimization.