Modelling of Solar-Diesel Hybrid Power Plant

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Abstract. The article highlights the problems of distributed energy generation and focuses on solar-diesel hybrid power plant modelling and optimization. Designing power systems based on renewable energy sources includes a very relevant task of building mathematical models of such systems and their elements. The article presents an approach and definition of mathematical models describing photovoltaic-diesel (PV-D) hybrid power system elements used in decision making processes as a part of PV-D operation control. An overview of PV module output power, performance and temperature models is given. Along with the analysis of the specific fuel consumption dependencies on the operating power of the diesel generator, an example of diesel power plant unit commitment is shown.

1 INTRODUCTION

On the territory of the Russian Federation, there are large number of districts, where energy supply is distributed and normally is carried out by diesel power plants. Therewith isolated power systems are characterized by a number of problems:

- Outmoded generating equipment with high rate of specific fuel consumption.
- Negative environmental impact.
- High electricity generation costs.

According to [1], requirements for energy supply systems efficiency [2] are formulated as follows: the energy efficiency of power plants must be ensured “by implementing legal, organizational, scientific, industrial, technical and economic measures aimed at the efficient use of fuel and energy resources and integration of renewable energy sources in economic turnover”.

The implementation of several dozens of projects for the modernization of isolated power systems on the Far Eastern Federal District territory [4] showed that the construction of power stations combining diesel-driven generation and a power plant based on an unstable renewably energy source makes it possible to build energy complexes with good technical and economic characteristics. This is achieved by a decrease in specific fuel equivalent consumption per unit of generated electrical energy for the entire power plant [2] (henceforth specific consumption).

Getting lower specific consumption rate becomes possible when optimizing the design and operational characteristic of a hybrid power system, which requires verified mathematical models of its elements:

- a model of primary renewable energy source,

- a technical model (a description of specific technical solutions allowing to implement the power supply function),
- an economical model (an evaluation of technical and organizational solutions in economic (financial) indicators).

For the tasks of designing and controlling PV-D hybrid power systems, these mathematical models should also have contradictory properties: on the one hand, they should give the most accurate description of environmental conditions and technical features; on the other hand, to be fairly simple and clearly evident to use. Also, different groups of mathematical models are used to model the design and operation of PV-D systems. The purpose of the first ones is to calculate the steady-state operating modes of such systems (most commonly modeling hourly average performance indicators), the second ones are to be used for simulating instantaneous operating modes. An overview of methods for modeling steady-state PV-D hybrid power systems modes are presented below.

2 MATHEMATICAL MODELLING OF PV POWER PLANT

2.1 Solar PV module output power model

The output power P_{PV} of a single PV module is determined by its geometric dimensions, efficiency and solar irradiance incidence in one of two ways:

- the output power of a PV module depends on solar irradiance [5]:

$$P_{PV}(t) = P_{RPV} \cdot \left(\frac{G(t)}{G_{ref}} \right) \cdot \eta_{PV} \tag{1}$$

where P_{RPV} is PV module rated power (W); G is plane of array (POA) irradiance (W/m^2); G_{ref} is solar irradiance at reference conditions (usually set as 1000 W/m^2) ; η_{PV} denotes PV module efficiency.

- In [6] for calculating PV module output power an expression is used that takes its dimensions into account:

$$P_{PV}(t) = \eta_{PV} \cdot A \cdot G(t) \tag{2}$$

where A is a surface of a single PV module used in the system (m^2).

2.2 Evaluation of PV module efficiency

PV module efficiency is a value that depends on the environmental parameters, since ambient temperature affects the main electrical quantities, such as voltage and current of photovoltaic module. In [7] temperature impact on PV module efficiency is presented, where following nonlinear relationship is proposed:

$$\eta_{PV} = \eta_{ref}\left(1 - \beta_{ref} \cdot \left(T_c - T_{ref}\right) + \gamma \log_{10} G\right) \tag{3}$$

where η_{ref} is PV module efficiency at standard test conditions (STC); β_{ref} is dimensionless temperature coefficient; T_{ref} is reference temperature (K); T_c is PV cell temperature (K); γ is solar irradiance correction factor.

Solar irradiance correction factor usually reduces to zero, so that the expression is equated to following:

$$\eta_{PV} = \eta_{ref}\left(1 - \beta_{ref} \cdot \left(T_c - T_{ref}\right)\right) \tag{4}$$

Equation (4) is a traditional linear expression of PV module efficiency [8]. In recent studies this model is most commonly applied to describe the efficiency of a solar PV module [9, 10].

As it was stated in [11], the nonlinear PV module efficiency model is not appropriate, since the efficiency values are higher than those obtained experimentally in all cases. It is proposed to calculate the efficiency of PV module using the linear model.

The advantage of applying this model is that it has simple and easily accessible required parameters and can be used for various climatic conditions.

2.3 Temperature coefficient

The value of the temperature coefficient β is normally given by the manufacturer in PV module specifications. However, this value can be calculated using the following formula [12]:

$$\beta = \frac{1}{T_0 - T_{ref}} \tag{5}$$

where T_0 is material-dependent temperature at which the electrical efficiency of a PV module drops to zero [13].

2.4 PV cell temperature model

The correlations suggested in the literature usually express T_c as a function of the corresponding meteorological parameters, such as ambient temperature T_a, local wind speed V_w and POA solar irradiance G.

The simplest equation for the steady state operation mode relates T_c to the ambient temperature and solar irradiance as follows:

$$T_c = T_a + k \cdot G \tag{6}$$

where k is the Ross coefficient, which represents PV cell temperature increase with increasing irradiance.

Linear expression (6) is valid for no load operation and does not take the wind effect into consideration. The main difficulty of using it is to determine the Ross coefficient. Table 1 shows the values of k parameter for various PV modules mounting types.

Table 1. Empiric Ross Coefficients [14]

Mounting type	k, (K·м^2/W)
Free standing	0.021
Flat roof	0.026
Sloped roof (well cooled)	0.020
Sloped roof (not so well cooled)	0.034
Sloped roof (highly integrated, poorly ventilated)	0.056
Facade integrated (transparent PV cells)	0.046
Facade integrated (opaque PV cells)	0.054

The most common way to determine PV cell temperature is to use normal operating cell temperature (NOCT). The PV cell temperature depends on the ambient temperature T_a and irradiance G and can be described by following equation [15]:

$$T_c = T_a + \left(NOCT - 20\right) \cdot \frac{G}{800} \tag{7}$$

For taking the wind speed effects into account two models are utilized. They consider wind convection of free standing PV arrays for wind speeds greater than 0 m/s [16]:

$$T_c = T_a + \left(\frac{0.25}{5.7 + 3.8V_f} \right) \cdot G \tag{8}$$

$$T_c = T_a + \left(\frac{0.32}{8.91 + 2.0V_f} \right) \cdot G \tag{9}$$

where V_f is free flow wind speed upwind of the PV array, which can be calculated as $V_f = \frac{V_w + 0.5}{0.68}$ .and V_w .is the wind speed at the PV array installation geographical point

Equations (8) and (9) can be used only for a case of PV arrays mounted on free standing frames.

However, this limitation may be eliminated by using the Ross coefficient, which would consider PV modules mounting type. Thus, (9) is transformed into the following:

$$T_c = T_a + \omega \cdot \left(\frac{0.32}{8.91 + 2.0V_f} \right) \cdot G \tag{10}$$

Table 2 shows the values of ω dimensionless empiric coefficient.

Another model includes the wind speed [17]:

$$T_c = T_a + \frac{(\tau\alpha) \cdot G_t}{U_0 + U_1 V} \tag{11}$$

where V is the wind speed, τ and α are optical transmission coefficient and absorption coefficient respectively, U_0 is a coefficient describing irradiance effect on the PV module temperature, while U_0 describes the cooling by the wind. These coefficients are determined according to the location.

The following model uses empirical coefficients considering PV module types and its mounting methods. The suggested values of the empirical coefficients *a* and *b* are summarized in Table 3 [18].

The PV cell temperature model has the following form [18]:

$$T_c = T_a + G \cdot \exp(a + bV) \tag{12}$$

In one of the latest studies the following temperature model has been derived [19]:

Table 2. ω Empiric Coefficient Values [16]

Mounting type	ω
Free standing	1.0
Flat roof	1.2
Sloped roof	1.8
Facade integrated	2.4

Table 3. a,b Coefficients Values

PV module type	Mounting type	*a*	*b*
Glass/cell/glass	Free standing	-3.47	-0.059
Glass/cell/glass	Rooftop	-2.98	-0.047
Glass/cell/polymer	Free standing	-3.56	-0.075
Glass/cell/polymer	Integrated	-2.81	-0.046
Polymer/film/steel	Free standing	-3.58	-0.113

$$T_c = \frac{U_L T_a + \left[(\tau\alpha) - \eta_{stc}\left(1 - \beta T_{ref}\right)\left(1 + \gamma_{Pmp} \cdot \ln\left(\frac{G_g}{G_0}\right)\right)\right] \cdot G_g}{U_L + \eta_{stc}\beta\left(1 + \gamma_{Pmp} \cdot \ln\left(\frac{G_g}{G_0}\right)\right) \cdot G_g} \tag{13}$$

where U_L is the heat loss coefficient; G_g is solar irradiance at the PV array installation geographical point, η_{stc} and β are the module efficiency and the temperature coefficient, respectively, at STC; γ_{Pmp} is a dimensionless coefficient which is between 0.03 and 0.12 for single crystalline silicon.

The heat loss coefficient U_L is calculated as follows:

$$U_L = U_{L0} + U_{L1} \cdot V \tag{14}$$

where U_{L0} and U_{L1} are coefficients considering heat losses by convection and radiation, which are calculated for a specific location.

The above models were tested; the results are summarized in table 4 [19].

Table 4. Experimental Comparison of PV Cell Temperature Models

PV cell temperature model	R^2 (%)	RMSE (˚C)
(7)	93.97	3.85
(8)	98.30	1.24
(9)	98.47	1.22
(11)	98.61	1.27
(12)	97.44	2.03
(13)	98.77	1.13

It can be concluded from the Table IV that these models have satisfactory accuracy and can be applied to determine the PV cell temperature. The results show that the inclusion of the wind parameter makes PV module temperature calculations more accurate.

3 MATHEMATICAL MODELLING OF DIESEL POWER PLANT

The simplest approach to describing a diesel power plant (DPP) is to represent it as a voltage source [20]. The disadvantage of this approach, undoubtedly, is the representation of the DPP as an equivalent power source, which is equal to the sum of the installed capacities of all diesel-engine generators installed at the DPP.

From the design perspective, under this approach, the determining criterion for choosing a diesel generator is the maximum peak of load curve, i.e. the DPP output power must not be lower than the total peak load [21].

The restrictions on minimal $P_{DPP}^{\min}$ and maximum $P_{DPP}^{\max}$ operating power of the DPP are also considered:

$$P_{DPP}^{\min} \le P_{DPP}\left(t\right) \le P_{DPP}^{\max} \tag{15}$$

In this case, the DPP operating power is determined on the basis of the system power balance equation:

$$P_{DPP}\left(t\right) = P_{load}\left(t\right) - P_{PV}\left(t\right) \tag{16}$$

where $P_{load}\left(t\right)$ is hourly average power consumption (kW).

In case of diesel generators reduction in DPP it is not possible to determine the values of the specific fuel consumption of individual diesel generators due to differences in their individual energy characteristics. For a more accurate modeling of the specific fuel consumption, it is necessary to consider the typical sizes and the number of diesel generators installed at the DPP, as well as their load conditions and wear.

It is known [22] that in order to ensure stable and reliable operation of diesel generators, it is necessary to distribute active power between them in proportion to their nominal power.

Optimal loading of diesel generators is provided on the basis of individual dependences of specific fuel consumption on the diesel generator operating power (Figure 1).

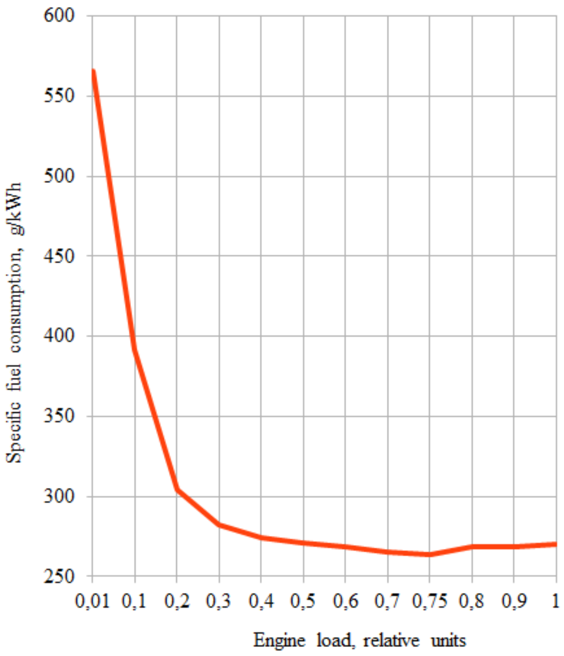

Figure 1. Typical dependence of specific fuel consumption on the diesel generator operating power.

The analysis of the dependences of the specific fuel consumption on the diesel generator operating power shows that the optimum work load of diesel generator units (DGU) of DPPs is provided by maximizing the specific load:

$$P_{DGU}^{sp} = {P_{DGU}(t)}\Big/{P_{DGU}^{nom}} \to \max \tag{17}$$

The condition mentioned above is obviously fulfilled at a specific load closest to 1, i.e. while diesel generators operate with an output power close to the nominal value.

In addition, an important feature of modern DPP control systems is the implementation of an equal specific load distribution:

$$P_{DGU1}^{sp} = \ldots = P_{DGUn}^{sp} = P_{DPP}^{sp} \tag{18}$$

For unit commitment a matrix of variants is drawn up to provide the maximum operating power of DPP. Table 5 lists an example of unit commitment variants for DPP consisting of 3 diesel generators.

In accordance with (17), one should select a variant with

$$\begin{aligned} &P_{DPP}^{sp} = {P_{DPP}^{\max.op}}\Big/{P_{load}(t)} \to \max \\ &P_{DPP}^{sp} \le 1. \end{aligned} \tag{19}$$

Additionally, it is recommended to consider the operating hours of each diesel generator engine.

Table 5. Unit Commitment Example for Providing The Maximum Operating Power of The DPP.

Load variant	DGU 1	DGU 2	DGU 3	The maximum operating power of the DPP $P_{DPP}^{max.op}$
1	1	0	0	P_{DGU1}^{nom}
2	0	1	0	P_{DGU2}^{nom}
3	0	0	1	P_{DGU3}^{nom}
4	1	1	0	$P_{DGU1}^{nom}+P_{DGU2}^{nom}$
5	1	0	1	$P_{DGU1}^{nom}+P_{DGU3}^{nom}$
6	0	1	1	$P_{DGU2}^{nom}+P_{DGU3}^{nom}$
7	1	1	1	$P_{DGU1}^{nom}+P_{DGU2}^{nom}+P_{DGU3}^{nom}$

4 CONCLUSIONS

Justification of photovoltaic-diesel hybrid power systems parameters is carried out by modeling operating mode of such systems for various configurations and equipment parameters. The variety of existing approaches to modeling the steady-state operation modes of PV-D system elements leads to the need to analyze their advantages and disadvantages and the possibility of using them in real project activities. In this regard, the article provides an overview and a brief description of simple and easy-to-use mathematical models, the accuracy of which is quite high

5 ACKNOWLEDGMENT

The investigation was carried out within the framework of the project “Development of decision-making software for controlling the operation of a solar-diesel hybrid power system, considering short-term solar radiation forecast” with the support of a grant from NRU "MPEI" for implementation of scientific research programs "Energy", "Electronics, Radio Engineering and IT", and “Industry 4.0, Technologies for Industry and Robotics in 2020-2022”.

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