Finite State Machine Model of photovoltaic panel

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This paper deals with a mathematical model of a photovoltaic panel, based on finite state machine, which directly supplies a constant resistive load without inverter cooperation. The model’s correctness is evaluated through the comparison of simulated values and real measured data.

Mathematical model of a PV cell

The equivalent circuit of solar cell based on Shockley equation is shown on Fig. 1. This model consists from a current source, a diode, a shunt resistance $R_s$ and a series resistance $R_h$, which represents an internal resistance of the cell. In this paper, it is considered that the solar cell is loaded by known resistive load.

![Fig. 1. Equivalent model of a photovoltaic cell with resistive load](image)

Current-voltage characteristic (I-V curve) of a solar cell is a nonlinear function, therefore its mathematical model is also nonlinear and it is necessary to use iterative methods (e.g., Newton’s iterative method) to solve the model. We can solve the nonlinear system using Newton-Raphson iterative method:

$$f(U, I) = (I - f(I, U))$$

As it can be seen on Fig. 2, the I-V curve has no local extremes. Therefore, gradient based methods, like Newton-Raphson, are unable to find the solution of such an equation. This can be solved by modifying the original equation to a quadratic form. This alternated equation has the same solution as the original function, but now the solution is located in a local minimum of the function (Fig. 2).

![Fig. 2. The quadratic form of I-V curve](image)

The quadratic form is

$$f(U, I) = (I - f(I, U))^2$$

and its first derivation is

$$f(U, I) = 2(I - f(I, U))$$

Equation (3) changes all negative values to positive ones (Fig. 2) and so the function can be solved using the Newton-Raphson iterative method. After knowing the solution — the value of diode voltage $U_D$ — it is possible to calculate the values of all other variables.

Equations (2) and (3), as well as equations from [1], were used to create a model of PV panel in software tool Ptolemy II [2] (Fig. 3). In order to implement its mathematical description, a FSM model was created (Fig. 4).

![Fig. 3. Model of a PV panel created in Ptolemy II](image)

![Fig. 4. FSM diagram in the model of PV panel](image)

Verification of created simulation model

To verify the results of introduced simulation model, a measurement of the current-voltage characteristic of a small PV installation consisting of two series-connected photovoltaic panels were done. One panel consists of two parallel branches of 60 series-connected cells.

All parameters relevant to the measurement were applied to the created FSM model of PV panel (Fig. 4), with respect to the real interconnections of measured PV installation. The main parameters influencing the generated output were a value of ambient temperature ($T = 23\,\text{°C}$), a value of solar irradiance $G = 0.78\,\text{kHz/m}^2$ and panel parameters taken from data sheet provided by the manufacturer of used panels. The created simulation model was used to calculate current-voltage characteristic as well as power characteristic of measured PV installation.

Both measured and simulated characteristics were compared. Fig. 6a shows the comparison of measured and simulated current-voltage characteristics and Fig. 6b shows the same comparison for power characteristics. As it can be seen from both figures, there is a very good correlation between simulated and measured data.

![Fig. 6. The comparison of simulated and measured values](image)

Conclusion

This paper describes a nonlinear mathematical model of PV panel consisting of series-parallel connected PV modules. As a calculation method a finite state machine model was used. Advantage of such a model is that one model can be used for the mathematical description of different modes of operation. Presented model is just the introduction of a simulation attitude that will be used for the creation of more complex model of a distribution network with distributed generation.

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References