A Steady-State Model of the Photovoltaic System in EMTP

H. I. Cho, S. M. Yeo, C. H. Kim, V. Terzija, Z. M. Radojević

Abstract--**This paper presents a steady-state model of a grid-connected photovoltaic (PV) system using Electromagnetic Transient Program (EMTP) MODELS. Recently the PV system has been introduced in power systems. The previous PV generation was used only to supply small loads or for home use. Nowadays, installations of grid-connected PV systems are increasing due to several advantages compared to standalone PV systems. Depending on the characteristics of the PV system and the power quality issues of connecting PV systems to the grid, a detailed and integrated analysis of grid connection is necessary. Through modeling, we should be able to determine the potential energy benefit and analyze the power quality of grid-connected PV systems. The steady-state analysis is necessary to analyze the distribution system with PV systems in transient conditions. PV generators or PV arrays are formed by combinations of parallel and series connections of PV modules. The evaluation and modeling of PV systems are performed with data from real PV modules in EMTP/ATPDRAW MODELS. Results of the modeling and PV characteristics are described.**

Keywords: **ATPDRAW, EMTP, grid-connected system, modeling, MODELS, photovoltaic array, PV system,**

I. INTRODUCTION

GLOBAL warming and environmental pollution are worldwide concerns. Renewable energy can reduce environmental problems and delay fossil fuel depletion. Therefore needs of renewable energy have been increased [1].

A variety of distributed generation methods have been introduced to the power system. Solar energy, wind energy, and fuel cells are three energy sources emphasized by researchers.

Historically, the most important applications of PV systems have been outer space PV systems and standalone systems in areas with poor or absent electricity supply from the public grid. Recently, the installation of grid-connected PV systems is increasing due to several advantages over standalone PV systems. Grid-connected PV generation is being considered to improve the electric power supply. Grid-connected PV systems are becoming more economically practical as the cost of PV components has decreased in recent years, especially the average cost of PV modules and inverters. Technical issues associated with inverters and interconnections of PV systems to the grid have been addressed by manufacturers, and today's generation of inverters have enhanced reliability and reduced size. Solar energy is produced during the middle of the day, adding value to the electricity produced [2]. Cost savings can be realized by reducing peak demand at the generating facility [3].

Due to the increase in power quality problems when PV systems are connected to the grid, shading problems, installation and other potential problems require analysis of the PV system design parameters. Computerized tools to determine the potential energy benefits and to analyze grid-connected PV systems are needed. The popularization of PV systems has led to the development of tools to estimate the output energy characteristics of new systems, and models based on parametric analysis have been used for this purpose, mostly because of their simplicity [4].

PV system analysis, which includes system and field condition analysis, can be done with a transient phenomenon analysis program for the electric power system. We describe the entire simulation process. It covers from the modeling of the solar module to the comparison with data of the practical PV system in the field and that of the modeled PV system [1]. EMTP/ATPDRAW has been used as the simulation tool.

II. EMTP/MODELS

In order to develop a PV system, it needs to be either tested in a laboratory based power system model or to be simulated with the fault data usually obtained from EMTP. In fact, EMTP simulations provide good understanding of both relay performance and power system dynamics during transient conditions, revealing malfunctions in protective schemes [5]. The recently introduced EMTP MODELS simulation language makes it possible to control the interaction between the power system and protective system operations. It is a symbolic and general-purpose description language. The MODELS is supported by a set of simulation tools for studying time-variant systems. The MODELS language provides a format which

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focuses on the description of the structure of a model and on the function of its elements. The description of a model is intended to be self-documenting, and can therefore be used both as the description document used for representing the system and as the data used in the actual simulation.

The MODELS calculates the monitoring and controllability parameters of the power system as well as some other algebraic and relational operations for programming. The MODELS has the user describe the power system by describing the physical constants and/or the functional subsystems of the target systems. This paper presents a technique for the modeling of a power system. All the procedures for the simulation of a PV system are in an EMTP formatted file [6]-[7].

III. THE PV SYSTEM

A. Grid-connected PV systems

Grid-connected PV systems are starting to play a role in PV applications. These systems supply the electricity transformed from solar energy directly to a grid. The PV system is composed of a PV generator, an inverter, and AC loads. An example system is shown in the schematic block diagram of the grid-connected PV system in Fig. 1. The PV generator is an array of PV modules which convert solar electricity to DC electricity. The inverter is needed to convert DC into AC electricity. AC loads are electrical appliances [2].

If the sun illuminates PV modules, and the DC electricity produced by PV modules is converted to AC power by the inverter. This AC power first supplies the system's AC requirements, then outputs some or all of the remaining energy produced to the grid. At night, power is supplied by the utility grid. The batteries used in the standalone PV applications are replaced by electricity from the utility grid in grid-connected systems, resulting in cost and maintenance reduction. If necessary, batteries can be used as they are in standalone systems [2].

B. The Solar cell

A simple equivalent circuit is illustrated in Fig. 2. The solar cell is a current source in parallel with a diode. The output of the current source is proportional to the light falling on the cell. The diode determines the I-V characteristics of the cell. The diode ideality factor (n) has a value between one and two. The value of n=1 is used for the ideal diode. A series resistance (Rs) was included, but not a parallel resistance. The parallel resistance is very large and the effect is very small so this term is neglected to simplify the electrical model. [8]-[10].

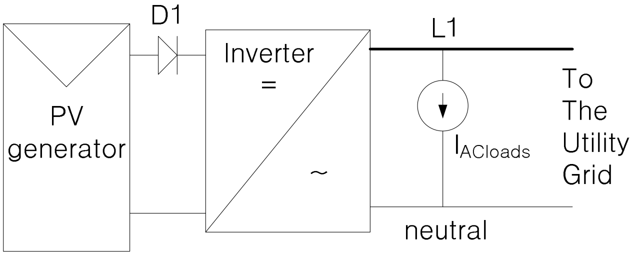

Fig. 1. Schematic block diagram of the grid-connected PV system.

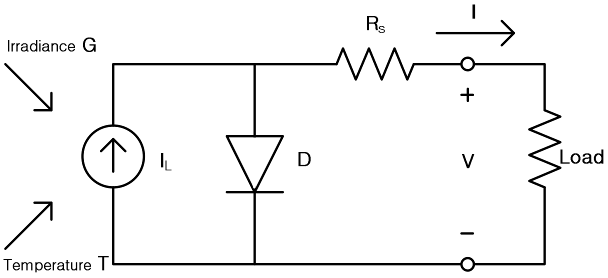

Fig. 2. The equivalent circuit of the solar cell.

C. The PV array

Solar cells comprise the PV module, and PV modules comprise the PV generator. Single solar cells have a limited potential to supply power at power voltage levels, because the open circuit voltage is independent of the solar cell area and is limited by the semiconductor properties. It is necessary to connect solar cells in series in order to scale up the voltage produced by a PV generator [2]-[4]. PV generators are formed by combinations of parallel and series connections of solar cells or by parallel and series connections of PV modules. The first case is for outer-space applications. In terrestrial applications, arrays are formed by connecting PV modules, each consisting of a number of series-connected solar cells and bypass diodes [8]-[11].

D. Modeling the PV array

A DC source has been used instead of the PV array in EMTP/ATPDRAW, because there is no PV array model in EMTP. For this reason, we propose a PV array model using EMTP/MODELS.

In the most general case, a PV generator is made up of several standard PV modules combined in a $N_{sG} \times N_{pG}$ series-parallel matrix. Scaling rules are required to connect the characteristic of the PV plant or generator to individual PV module characteristics.

The PV array is considered with the following I(V) parameters:

- Short-circuit current: I_{scM}
- Open-circuit voltage: V_{ocM}
- Maximum power: P_{maxM}
- MPP current: I_{mM}

- MPP voltage: V_{Mm}
- Thermal potential: V_T
- Temperature of the cell: T_{cell}
- Operating temperature of the cell under standard conditions, 25℃: T_r
- Temperature coefficients for the short-circuit current and open-circuit voltage
- Boltzmann's constant: $k=1.380622 \times 10^{-23}$ [J/K^{-1}]
- Quantity of electric charge: $q = 1.60 \times 10^{-19}$ [C]

The I(V) characteristic of the generator scales as:

$$I_G = N_{pG} I_M \tag{1}$$

$$V_G = N_{sG} V_M \tag{2}$$

where, subscript M stands for module and G for the PV generator.

For an arbitrary value of the irradiance and the temperature, the short-circuit current is given by:

$$I_{scM} = \frac{I_{scMr}}{1000} G + \left(\frac{dI_{scM}}{dT} \right) \left(T_{cell} - T_r \right) \tag{3}$$

and the open-circuit voltage can be written as:

$$V_{ocM} = V_{ocMr} + \left(\frac{\partial V_{ocM}}{\partial T} \right) \left(T_{cell} - T_r \right) + V_T \ln \frac{I_{scM}}{I_{scMr}} \tag{4}$$

where, I_{scMr} and V_{ocMr} are the short-circuit current and open-circuit voltage under standard test conditions(AM = 1.5G, Irradiance G = 1000 W/m^2, Cell temperature T_{cell} = 25 °C).

The thermal potential V_T is defined as,

$$V_T = k(T_{cell} + 273)/q \tag{5}$$

The v_{oc} can be calculated from the data for a single solar cell.

$$v_{oc} = \frac{V_{ocM}}{N_s n V_T} \tag{6}$$

The Fill factor (FF) is defined as the ratio between the maximum power P_{max} and the product of I_{sc} and V_{oc}. The fill factor indicates how far the product $I_{sc} \cdot V_{oc}$ is from the power delivered by the solar cell. The FF can be approximated by a practical relationship, assuming an ideal solar cell as follows

$$FF_0 = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{1 + v_{oc}} \tag{7}$$

The series resistance is computed from the value of the power density per unit area at the maximum power point.

$$R_{sG} = \frac{N_{sG}}{N_{pG}} \left(\frac{V_{ocM}}{I_{scM}} - \frac{P_{\max M}}{FF_{0M} I^2_{scM}} \right) \tag{8}$$

Equation (9) shows the I(V) characteristics of the PV array. The value of the diode factor, n, used in this paper is estimated as 1.402 by curve fitting.

$$I_G = N_{pG} I_{scM} - \frac{N_{pG} I_{scM}}{e^{\frac{V_{ocM}}{nN_s V_T}}} \left(e^{\frac{V_G + I_G R_{sM} \frac{N_{sG}}{N_{pG}}}{nN_s N_{sG} V_T}} - 1 \right) \tag{9}$$

In the same way as the coordinates of the maximum power point were calculated for a single solar cell or module, they can be calculated for a PV generator of arbitrary series-parallel size.

$$I_{mG} = N_{pG} \left(I_{mMr} \frac{G}{G_r} + \left(\frac{dI_{scM}}{dT} \right) \left(T_{cell} - T \right) \right) \tag{10}$$

According to the scaling rule, the module current at maximum power is,

$$I_{mM} = \frac{I_{mG}}{N_{pG}} \tag{11}$$

$$V_{mG} = N_{sG} \Bigg(\begin{matrix} N_s V_T \ln \left(1 + \frac{I_{scM} - I_{mM}}{I_{scM}} \left(e^{\frac{V_{ocM}}{N_s V_T}} - 1 \right) \right) \Bigg) \\ - I_{mM} R_{sM} \end{matrix} \Bigg) \tag{12}$$

These equations describe the I(V) characteristics of the PV array.

IV. THE PRACTICAL PV ARRAY MODEL

All of the constants in the above equations can be chosen by examining the manufacturer's ratings for the PV array and the published or measured I-V curves for the PV array. The Hyundai HiS-M182SF module, a typical 182W PV module, was chosen for modeling. The module has 54 series-connected multi-crystalline cells. The key specifications are shown in Table I and Fig. 3[12].

TABLE I
PARAMETERS FOR THE HYUNDAI HIS-M182SF[12]

Parameters	
Nominal output (P_{max})	182 W
Warranted minimum power	176.5 W
Voltage at P_{max} (V_{pm})	25.9 V
Current at P_{max} (I_{pm})	7.06 A
Open-circuit voltage (V_{oc})	32.7 V
Short-circuit current (I_{sc})	7.80 A
Temperature coefficient of V_{oc}	-0.32 %/K
Temperature coefficient of I_{sc}	0.056 %/K
No. of cells & connections	54 in series

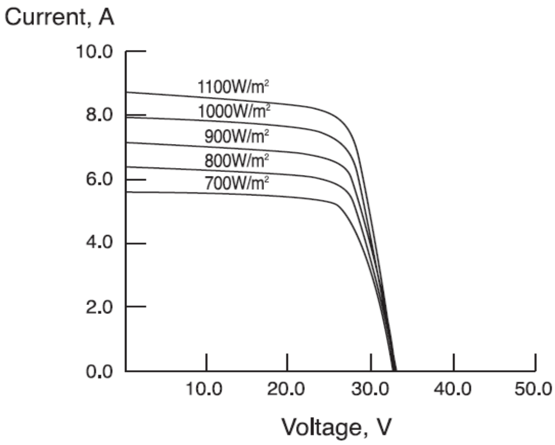

Fig. 3. The I(V) characteristic of Hyundai HiS-M182SF[12].

V. MODELING OF THE PV SYSTEM USING EMTP/MODELS

A. *Model of the PV module using EMTP/MODELS*

The model was evaluated using EMTP/MODELS. The current I is calculated utilizing the above parameters and the variables voltage, irradiation, and temperature.

For verification of the model, its characteristics were compared to the characteristics of a module with real data shown in Table I and Fig. 3. The PV module is combined in a 54 series cell string and calculated in a 1×1 series-parallel module matrix. Fig. 4 shows the I(V) characteristic of the PV module under several irradiance values simulated with EMTP/MODELS. The I(V) curves shown in Fig. 4 are calculated in (9), and show perfect matching with the manufacturer's curves in Fig. 3. As can be seen in Fig. 4, the I(V) curves are proportional to the irradiance. The exponential term in (9) has been simulated by a diode in saturation, and the short-circuit current has been simulated by constant current data at 7.80 A.

The power of the PV module is shown in Fig. 5. The maximum power is 182 W at standard reference conditions AM1.5G and 1000 W/m^2. The power output characteristic of the PV module is a function of the irradiance and the temperature. This curve is nonlinear and is controlled by the irradiance and the temperature. In order to deliver maximum power, it is necessary to calculate the maximum power point. Equations (10) and (12) are evaluated with the values in Table I.

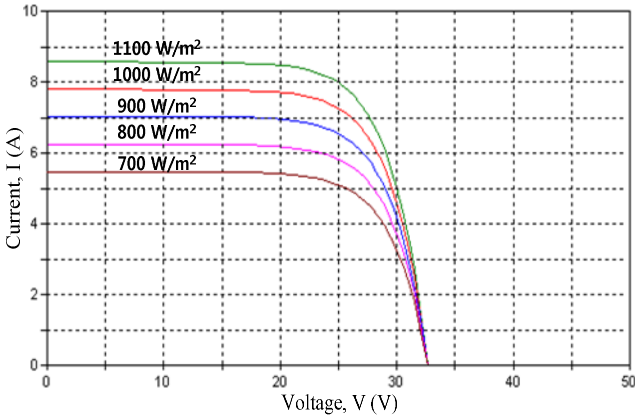

Fig. 4. The I(V) characteristic of the PV module at various irradiances simulated with EMTP/MODELS.

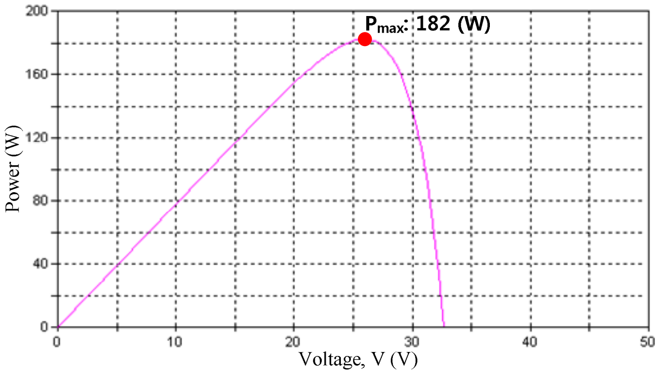

Fig. 5. The power of the PV module simulated with EMTP/MODELS..

Fig. 6 shows the values calculated in (3) and (4). As can be seen in (3) and Table I, the short-circuit current is proportional to the irradiance and has a small temperature coefficient. Similarly, the open-circuit voltage from (4) has a negative temperature coefficient and is determined by the logarithm of the irradiance [2].

In Fig. 7, the voltage at the maximum power point occurs at the high irradiance value. It is mitigated by the temperature coefficient. The temperature coefficient causes a decrease in voltage at higher irradiances due to the resulting higher cell temperature [2].

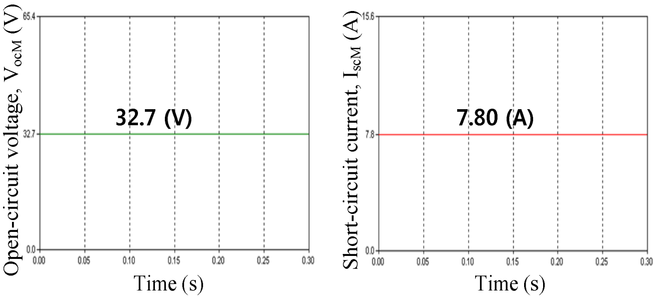

Fig. 6. The open-circuit voltage V_{ocM} and the short-circuit current I_{scM} simulated with EMTP/MODELS.

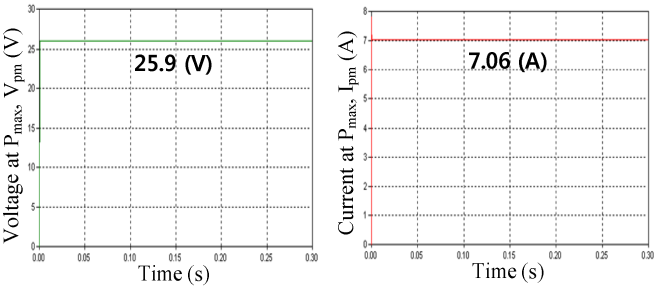

Fig. 7. The voltage V_{pm} and the current I_{pm} at P_{max} simulated with EMTP/MODELS

The open-circuit voltage is defined at the intersection of the I(V) curve with the voltage axis. From (4), it can be seen that the value of the open-circuit voltage is determined logarithmically by the I_{scM}/I_{scMr} ratio. This means that at constant temperature, the value of the open-circuit voltage scale varies logarithmically with the short-circuit current, which in turn scales linearly with the irradiance, resulting in a logarithmic dependence of the open-circuit voltage on the irradiance [2].

B. *Model of the PV array using EMTP/MODELS*

The PV array is composed of 25 strings in parallel, each string consisting of 260 PV modules in series. The total power installed is 1.2 MW. The PV system assembles solar cells to meet the output power requirement.

The result of the I(V) characteristic for the PV array is plotted in Fig. 8. It is matched to the single PV module with the voltage and currents scaled up according to the scaling rules. The short-circuit current is 2028 A (from 260 times 7.80 A in the single module). The open-circuit voltage is 817.5 V, and is scaled up 25 times.

It can be seen that the maximum power output of the PV array is 1.2 MW in Fig. 9. It describes a 182 W PV module of a 260×25 series-parallel matrix.

The coordinates of the maximum power point of the PV array are shown in Fig. 10. They increase proportionally to the series-parallel size. The voltage at the maximum power point is 647.5 V, and the current at the maximum power point is 1856.8. This result corresponds to the calculated value from (10) and (12).

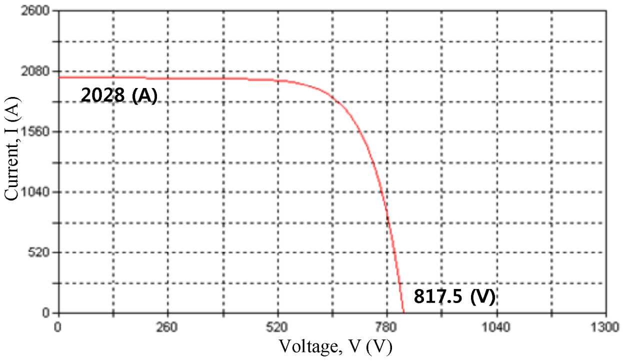

Fig. 8. The I(V) characteristic of the PV array at the standard conditions simulated with EMTP/MODELS.

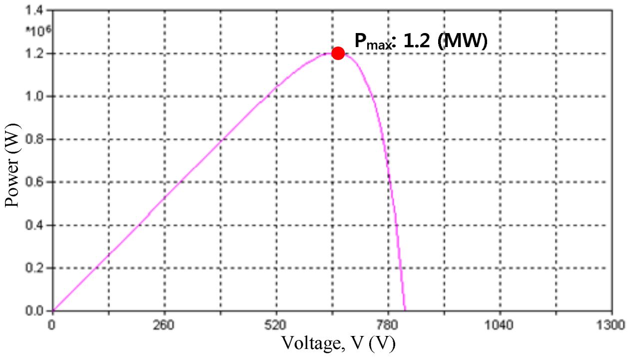

Fig. 9. The power of the PV array simulated with EMTP/MODELS.

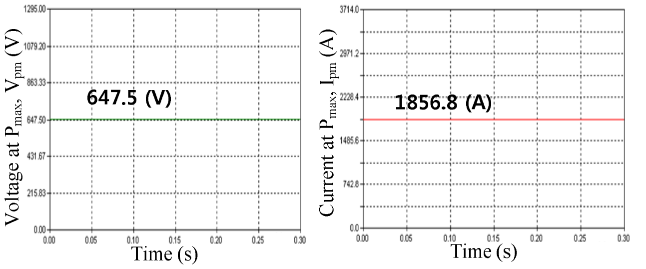

Fig. 10. The voltage V_{pm} and the current I_{pm} at the P_{max} of the PV array simulated with EMTP/MODELS.

C. *The PV system simulated in EMTP/ATPDRAW*

Fig. 11 shows a diagram of the test system used in this paper. As seen in the left side of Fig. 11, the PV array is modeled using EMTP/MODELS and TACS voltage sources. The saturation transformer is connected with the grid in parallel. The three phase inverter is simulated with six switches and The MODELS converts DC to AC voltage. The MODELS controls the amplitude and frequency of the AC power in the inverter.

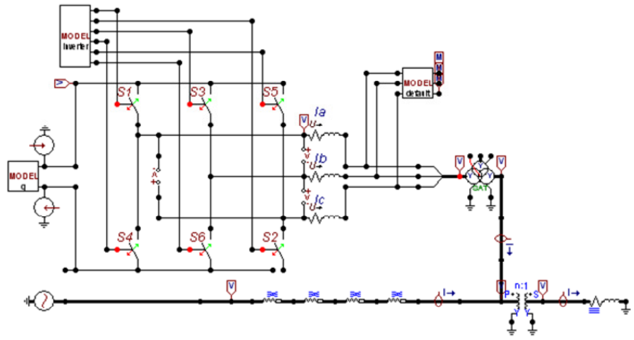

Fig. 11. Grid-connected PV system simulated with EMTP/MODELS.

VI. CONCLUSION

In this paper we proposed a PV array electrical model using EMTP/MODELS for a typical 182W PV module. The model matches real module data. We analyzed the I(V) characteristics at various irradiance levels, the power output, the coordinates of the maximum power point, the short-circuit current, and the open-circuit voltage of the PV module and the PV array. The proposed model of the PV array can be conveniently input when the irradiance, the temperature, the electrical characteristics of the PV module, and the number of modules are known. This model can be used to analyze the characteristics and problems of grid-connected PV systems. This steady-state model also can be utilized to a variety of simulation models. Most of all, it can be applied to both slow and fast transient simulations. The transients analysis of the grid-connected PV system will be addressed in the future work.

VII. ACKNOWLEDGEMENT

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VIII. REFERENCES

[1] M. W. Park, B. T. Kim, and I. K. Yu, "A novel simulation method for PV power generation systems using real weather conditions," *IEEE International Symposium*, vol. 1, pp. 526-530, Jun. 2001.

[2] L. Castañer, S. Silvestre, "Modelling Photovoltaic Systems Using PSpice," John Wiley & Sons Ltd, 2002.

[3] G. C. Pyo, H. W. Kang, S. I. Moon, "A new operation method for grid-connected PV system considering voltage regulation in distribution system,*" IEEE Power and Energy Society General Meeting*, pp. 1-7, Jul. 2008.

[4] P.S. Pimentel, H. Matsukawa, T. Oozeki, T. Tomori, K. Kurokawa, "PV system integrated evaluation software," in *Proc.* 2002 *IEEE Photovoltaic Specialists Conf.*, pp. 1638-1647.

[5] K. M. Silva, W. L. A. Neves, and B. A. Souza, "EMTP Applied to Evaluate Three-Terminal Line Distance Protection Schemes," presented at IPST'07 in Lyon, France.

[6] C. H. Kim, M. H. Lee, R. K. Aggarwal, and A. T. Johns, "Educational Use of EMTP MODELS for the Study of a Distance Relaying Algorithm for Protecting Transmission Lines," *IEEE Trans. Power System*, vol. 15 pp. 9-15, Feb. 2000.

[7] L. Dube, "MODELS IN ATP: LANGUAGE MANUAL," Aug. 1995. Available: http://www.eeug.org/files/secret/MODELS.

[8] G. Walker, "Evaluating mppt converter topologies using a matlab PV model," Journal of Electrical & Electronics Engineering, Australia, vol. 21, no.1, pp. 49-56, 2001.

[9] O. Akihiro, "Design and simulation of photovoltaic water pumping system," Thesis, California Polytechnic State University, 2005.

[10] R. Faranda, S. Leva, V. Maugeri, "MPPT techniques for PV Systems: energetic and cost comparison," *IEEE Power and Energy Society General Meeting*, pp. 1-6, Jul. 2008.

[11] H. I. Cho, S. M. Yeo, C. H. Kim, "A Study on Analysis of Solar Cell Characteristics using EMTP," in Proc. 2008 The Korean Institute of Electrical Engineers summer Conf., Korea, Jun. 2008.

[12] Available: http://www.hyundai-elec.com.