International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 8, August - 2014

Performance Analysis of Photovoltaic Assisted Electric Vehicle

Scott Crawford, *IEEE student member*, Ziyad Salameh, *IEEE Life Senior Member*
Department of Electrical and Computer Engineering
University of Massachusetts Lowell
Lowell, MA, USA

***Abstract*-- Each day people leave their electric cars parked during peak sun hours. If a photovoltaic battery charging system was implemented in electric vehicles, these cars could be harnessing free energy from the sun. In a world where environmental consciousness is ever increasing, as well as the price of gasoline, there is a crucial need for clean free energy.**

This paper explores the design, installation and performance evaluation of a photovoltaic (PV) system to assists the electric car harnessing the free solar energy. The entire system includes a properly sized solar panel, maximum power point tracker (MPPT) and a step-up voltage regulator to match the electric vehicle's battery voltage. The largest design constraint is amount of area that is present to mount the PV panels.

Since there is a finite amount of area to place PV panels on an EV and the amount of area the PV panels cover is directly proportional to the output power, there is a demand for more efficient PV panels.

Considering that the operating environment of the vehicle will be subject to vibration and a rugged environment, a traditional rigid glass PV panel can't be used, but rather, a flexible thin film PV panel to avoid the inevitable risk of shattering.

***Key words*—PV panel, MPPT, Electric vehicle, battery, converter**

IJERT

I. INTRODUCTION

As implied in its name, a PV assisted electric vehicle harnesses energy from the sun and converts it to kinetic energy that propels the car. PV panels provide a means of harnessing solar energy and converting it to electrical power. This is a perfect fit for the electric vehicle which runs on batteries. By implementing PV technology, a high voltage battery charger was designed and installed in a preexisting electric car. From a system prospective, the PV assisted electric vehicle (EV) is nothing more than a battery charger with added intelligence. With so many environmental scenarios that can exist in nature, the control circuitry of the charger must be robust enough to provide adequate performance of the energy transformation. Beginning at the PV panel and ending at the battery, intelligent circuitry must be carefully implemented to maintain the integrity of the overall system.

The system begins with the sun's rays as an input to the system. In order to determine how intense the sun's rays are, a figure of merit named irradiance can be calculated. The irradiance is the amount of power in Watts over a given area in meters squared. As clouds obscure the sun's rays from directly reaching the earth's surface, energy is lost to the rays diffusing in the clouds which lower the irradiance. Likewise, the position of the sun in the sky also has an effect of the amount of irradiance produced. When the sun is at high noon and the PV panel is perfectly flat, the sun is directly overhead forming a normal angle with the PV panel. When the PV panel is normal or perpendicular to the sun's rays, the maximum amount of irradiance is produced

As the irradiance of the sun gets greater, the amount current will increase for a given load [1].

There are several algorithms that can aid the tracking of the maximum power point. All of the algorithms monitor the instantaneous power produced by the PV panel and calculate the derivative of the power over time, compare an instantaneous power level to a previous power level in time or a similar tracking scheme [2-6]. Some types of maximum power point tracking algorithms are the perturbation and observation method, incremental conductance and power slope method.

The maximum power point tracked is implemented in the form of a control circuit. The control can be made either with digital logic circuitry, analog circuitry or by writing software that is programmed into a PIC (programmable integrated circuit). Regardless of the topology of the control circuitry, the control signal feeds a device that regulates the output voltage of the PV panel. The voltage is regulated such that it is always being steered to the PV panel voltage that produces the maximum power output given the environmental conditions

Because the batteries of the EV that are to be powered by the PV panel require a voltage other than the nominal output voltage of the PV panel, the output of the PV panels need to be stepped up . This voltage conversion is done with an efficient switching regulator that can make the power transformation. The switching regulator utilizes a combination of an inductor, capacitor, diode and FET switch to transfer the energy in a manner that steps up the voltage. The output voltage of the switching regulator, regardless of its topology, is determined by the pulse repetition rate and duty cycle of the control pulse that triggers the FET.

By integrating the control signal produced by the maximum power point tracker and a switching regulator, a

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

very efficient means of power conversion can take place in a photovoltaic system. The maximum power point control voltage can be manipulated to accurately and efficiently control the switching regulator to achieve the maximum output power of the PV panel as well as perform a voltage transformation matches the needs of a particular load. It is especially important to pair a switching regulator with a maximum power point tracker control to get as much output power from the relatively inefficient PV panel as possible. The power diagram (Fig. 1) shows the PV assisted system installed on one of the electric cars owns by the Center for Electric car and Renewable Energy at UMass-Lowell, the design was optimized according to the electrical and mechanical aspects of the electric car.

This paper provides an in depth description of the design and analysis of this PV power battery charger. Each portion of the power system is explored and explained in detail. From the initial design phase to integrating the final physical product, the necessary calculations and measured data are evaluated and explored in full.

II. System Construction

A. PV Panels and their selection

The roof and hood must be dimensioned. Based on the EV dimensions, the maximum physical size of the PV panel(s) can be determined. The flexible (or "rollable") PV panels are generally less efficient than the conventional rigid glass panels but the ruggedness of the flexible panels is paramount to a robust design [7].

The more efficient the PV panel, the greater the output power per unit area. Unfortunately, PV panels are well known to be inefficient devices. Based on the given area of the hood and roof of the electric car, a 62W on the roof and a 30W PV panel on the hood made by Global Solar were chosen to be mounted to the electric vehicle fig. 2.

The combined maximum output power of 92W. based on a load pull of the two PV panels, the nominal rated voltage at the maximum power point is about 17.5V.

At this nominal voltage, the panel can provide a combined maximum of 4.6A.The I-V and P-V characteristics of the panels are shown in fig. 3

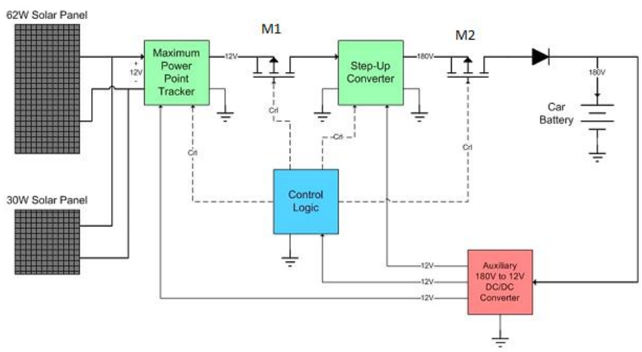

Fig. 1 Power Diagram of the PV Assisted EV

Fig. 2 Electric car with PV panels on the roof and the hood

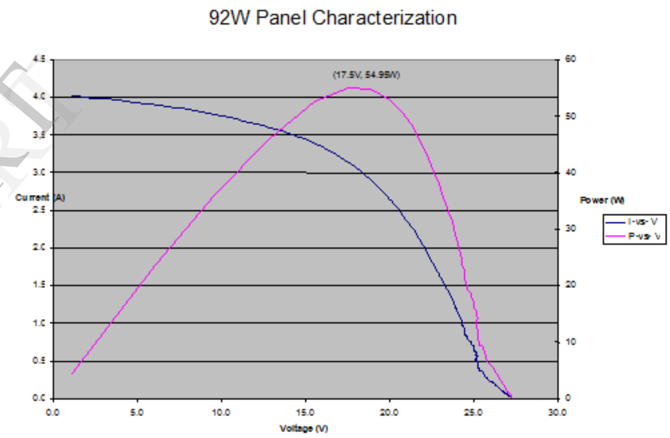

Fig. 3 Combined 30W and 62W PV Panel Characterization

B. Maximum power point tracker design

A maximum power point tracker (MPPT) acts as a dynamic load that will automatically steer the output voltage of the PV panel to the voltage that corresponds with the maximum power point .The way that the MPPT is able to find the maximum power point is by monitoring the PV panel output voltage and current over time.

The circuits for MPPT are studies in references [2-6].

C. Step-up regulator design

To match the output voltage of the MPPT and the Battery voltage a step up regulator was designed. The way that a step-up regulator works is by exchanging energy between an inductor to a capacitor [8].

D. Control logic circuit

Because the step up regulator requires a minimum voltage input of 10 volts to produce the specified output of 180V, a comparator is used to control MOSFET M1and turned it on if

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

the voltage output off the MPPT is more than 10v, otherwise it is off.

As a measure of precaution, a comparator (with hysteresis) driven FET switch was also implemented. The comparator monitors the output voltage of the boost regulator with a voltage divider circuit, once the output voltage gets up to 180V, the M2 is triggered to close. As current flows to charge the battery, the output voltage of the boost regulator will begin to drop. As mentioned above, the boost regulator does not like its output voltage to get too low; so as an added measure of safety, the comparator opens M2 when the boost regulator output gets down to 150V. Since the switch is now open, the boost regulator can start increasing the output voltage again until it hits 180V. This process then repeats indefinitely.

E. Output protection diode

The final stage of the power path is the series output diode. It is the most simple stage but also one of the most important. The diodes (D6) purpose is to prevent the battery from back biasing the entire circuit which would destroy the functionality of the circuit. When the battery voltage is less than the voltage produced by the circuit, the diode is forward biased and allows current to flow to the battery and charge it. However, if the battery voltage ever gets greater than the output of the circuit, the diode will be reverse biased and will prohibit the flow of current from the battery into the output of the circuit.

F. Powering the control circuitry

Now that the functionality and design of the battery charger has been defined, there is still one last portion that has yet to be mentioned: powering the control circuitry. Since this design is being integrated into an electric car, there exists a step down regulator that produces 12V from the 180V battery and powers all of the EV electronics.

III. EXPERIMENTAL RESULTS

The data was taken over a range of weather conditions from blue sky to cloudy. The electric vehicle that houses the PV charger is located in the Pinanski parking lot which gets a great amount of sun coverage from the morning to afternoon. All of the data was taken in the parking lot with the DAQ. As expected, it was found that the performance of the PV charger is proportional to how cloudy the weather is.

TABLE I MEASURED DATA OF PV CHARGER OVER VARYING WEATHER CONDITIONS

			Average Values per 1 Hour Data Collection Period						
Date	Weather Condition	Irradiance (W/m²)	Vin (V)	Iin (A)	Pin (W)	Vout (V)	Iout (A)	Pout (W)	Converter Efficiency
4/3/10	Sunny	903	10.097	4.715	47.613	145.573	0.278	40.488	85.04%
4/4/10	Scattered Clouds	876	9.659	4.096	39.681	147.804	0.198	29.374	74.03%
4/5/10	Scattered Clouds	525	9.573	2.749	26.664	148.395	0.102	15.210	57.04%
4/10/10	Cloudy	289	12.479	1.204	14.973	122.051	0.075	7.898	52.75%
4/11/10	Cloudy	310	12.558	1.981	24.790	123.429	0.103	10.959	44.21%

There were 5 one hour sets of data taken where the input/output voltage and current were recorded. Over the course of the data collection the computer display shows the input/output voltage and current as they change with the solar conditions. As the sun gets brighter, it can be noted that the input voltage and current adjust to achieve maximum power output and the output current pulses become larger and more frequent. Fig. 4 depicts a typical waveform of the output current pulses in sunny weather. It can also be noticed that as the sun gets brighter, the more frequent the output voltage spikes are. A data acquisition system was designed to record the voltage, the current and the power.

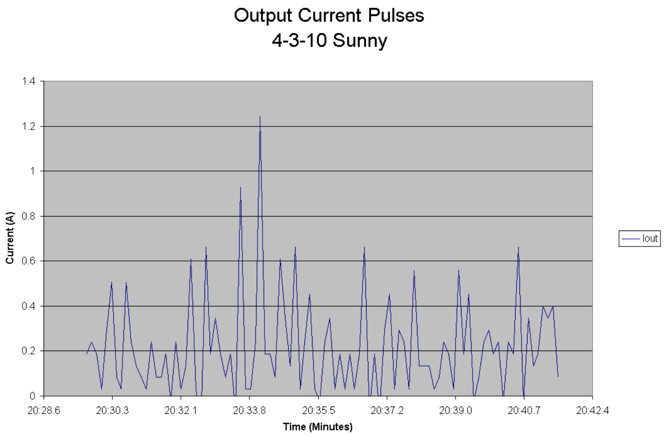

Fig. 4 Output Current Pulses -vs- Time

Based on the power and irradiance data that was collected several other characteristics of the system can be calculated. Two interesting calculations that can be made are the measured PV panel efficiency and the contribution of the additional distance that the PV charger can produce. These two figures of merit are excellent to consider when determining if this project is practical or not.

By taking the measured output power of the converter and dividing the product of the measured irradiance, the sine of the pyrometer tilt angle and PV panel area, the energy conversion efficiency of the PV panel can be determined. Given an absolutely ideal situation of the manufactures rated output power and a specified irradiance of 1000W/m², an absolute best case figure of 5.6% efficient is calculated (see Table 2). As a maximum PV panel efficiency, the system is not off to a good start. Based on measured data, an average efficiency of approximately 4.5% over 4 days with varying weather conditions was calculated using (1).

$$\eta = P_{OUT} / (E_{IRRAD} \sin(\theta) * A) \quad (1)$$

TABLE II PV PANEL EFFICIENCY

Date	Tilt Angle (θ)	Area (m²)	Irradiance (W/m²)	Pout (W)	Efficiency
4/3/2010	43	1.633	903	47.613	4.73%
4/4/2010	43	1.633	876	39.681	4.07%
4/5/2010	43	1.633	525	26.664	4.56%
4/10/2010	43	1.633	289	14.973	4.65%
4/11/2010	43	1.633	310	24.79	7.18%
Rated	90	1.633	1000	92	5.63%

By knowing the output power of the PV charger, the length of charging time and the "power mileage", the amount of distance added by the PV charger can be calculated with (2) and the results can be seen in Table 3. This calculation assumes a "power mileage" of 5 miles per kilowatt hour which is approximately the value for the electric car based on

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

average data collected by Professor Salameh over the last 17 years driving the same car.. Using (2), an absolute maximum amount of miles gained with exactly 92W of output power produced by the PV panels and a 100% efficient power converter over an 8 hour charging period of 1000W/m² irradiance, 3.68 miles would be gained; of course that is in the ideal world. The greatest amount of additional miles was produced on the sunny day, being 0.202 miles over the time period of the one hour of data collection. Table 3 shows the amount of miles gained over the five days of data collection for the one hour time period as well as an eight hour time period which would represent a day's worth of charging.

$$dist = (P_{OUT} / 1000W/m^2) * 8h * 5mi/(kWh) \quad (2)$$

TABLE III DISTANCE GAINED BY PV CHARGER

Date	Power Mileage (mi/kWh)	Charge Time (h)	Pout (W)	Distance (mi)
4/3/2010	5	1	40.488	0.202
4/4/2010	5	1	29.374	0.147
4/5/2010	5	1	15.21	0.076
4/10/2010	5	1	7.898	0.039
4/11/2010	5	1	10.959	0.055
Ideal	5	1	92	0.460
4/3/2010	5	8	40.488	1.620
4/4/2010	5	8	29.374	1.175
4/5/2010	5	8	15.21	0.608
4/10/2010	5	8	7.898	0.316
4/11/2010	5	8	10.959	0.438
Ideal	5	8	92	3.680

IV. DISCUSSIONS

The data that was recorded is as expected and believable. As the weather conditions change from a sunny day to a cloudy day, the amount of output power produced decreases based on the decreasing irradiance. It is especially interesting to analyze the data taken with scattered clouds and note the change in input and output power as the irradiance varies.

Another thing to consider is that the PV panels are mounted flat on the hood and roof of the car. In order to achieve the maximum output power of the panels, they must be tilted to an angle normal to the sun's rays. Given that fact, the output power of the panels will never reach the full 92W unless the sun is directly overhead.

Unfortunately the mileage isn't much, but it is still free energy. Another thing to consider is how important it is for the PV panel efficiency to be improved. The most limiting factor of this system is by far the PV panel efficiency. Table 4 shows how increasing PV panel efficiency translates into additional distance based on an average irradiance and average "power mileage" over the course of an eight hour charging time period. These calculations are based on (3). Given the significant effect the PV panel efficiency has on the additional mileage, it would be extremely beneficial to the new thin-film processes to be optimized to yield higher efficiency.

$$dist = ((\eta * E_{IRRAD} * A)/ 1000W/m^2) * 8h * 5mi/(kWh) \quad (3)$$

TABLE IV DISTANCE GAINED BY PV PANELS WITH INCREASED PV PANEL EFFICIENCY

Area (m²)	Irradiance (W/m²)	Charging Time (h)	Power Mileage (mi/kWh)	PV Panel Efficiency	Added Distance (mi)
1.633	850	8	5	5%	2.78
				10%	5.55
				20%	11.10
				30%	16.66
				40%	22.21

V. CONCLUSION

The form factor of the flexible PV panels is certainly a great addition to the electric car. A conventional glass PV panel would never survive the rugged environment an EV can be exposed to. Glass PV panels are simply too brittle to survive the shock, vibration as well as impact of debris falling on the car. The advent of the thin film flexible PV panel has been a major step forward in preserving the mechanical integrity of the PV panel.

A problem with the flexible PV panels is that the electrical performance pales in comparison to the traditional glass PV panels. The thin film technology is relatively new and improvements in the performance are expected. However as the PV charger design stands, the performance is surprisingly good at higher levels of irradiance.

Given the very small amount of charge current that can be produced by the PV charger, the charging an 180V EV battery is not the best application. In a perfect world with no clouds and no electrical power losses, a 92W PV panel array can only provide 511mA of charge current at 180V of output voltage. This figure is not taking into account the efficiency of the power converters, the efficiency of the PV panels and the weather conditions.

As a system, the PV charger is able to produce 180V pulses that deliver charge current to the battery. On a sunny day the efficiency of the power conversion reaches as high as 85%. Putting things into perspective, commercial DC/DC converters typically have an efficiency of 80-92%. From a power converter point of view, an efficiency of 85% is a promising figure of merit for a first attempt.

REFERENCE

[1] Green, M. A., 1982, Solar Cells, Prentice Hall, Englewood Cliffs, NJ.
[2] G. Howe, Z. Salameh, "Solar Powered Battery Charge Controller", Proceedings of Annual Meeting of the American Solar Energy Conference, April 22-28 1993, Washington, DC.
[3] P.Batcheller, and; Z.Salameh "Microprocessor Controlled Maximum Power Point Tracker for Photovoltaic Systems"Proceedings of Annual Meeting of the American Solar Energy Conference, April 22-28 1993, Washington, DC.
[4] P. Buasri, and; Z. Salameh, "A Maximum Power Point Tracker for a Wind/PV/Fuel Cell DistributedGeneration Power Syste" IASTED, PES October 24-26 2005, Marina del Ray, CA.
[5] D. Taylor,and Z; Salameh, "Step-Up Maximum Power Point Tracker for Photovoltaic Arrays"Solar Energy January 1990, Volume 44, Number 1, Page 65-69.
[6] F. Dagher, W.; Lynch, Wand Z. Salameh, "Step-Down Maximum Power Point Tracker for Photovoltaics", Solar Energy, 1991, Volume 46, Number 5.
[7] Hwang, Dr. Hong-Sik; Kresge, Lee and Cheng, Dr. Ning Flexible Thin-Film Technology: A Novel Metallization Paste Renewable Energy World International January/February 2009, Volume 12.

IJERT

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

[8] Rashid, Muhammad H. 2004. Power Electronics: Circuits, Devices and Applications Third Edition. Pearson Prentice Hall, New Jersey, pp.190-194.
[9] Appleyard, David, Utility-Scale Thin-Film: Three New Plants in Germany Total Almost 50MW Renewable Energy World International January/February 2009, Volume 12, Issue 1.
[10] Ghannam, Moustafa Y.; Abouelsaood, Ahmed A.; Alomar, Abdulazeez S. andPoortmans, Jef, Analysis of thin-film silicon solar cells with plasma textured front surface and multi-layer porous silicon back reflector Solar Energy Materials and Solar Cells Volume 94, Issue 5, May 2010, Pages 850-856.
[11] Nishiwaki, S; Satoh, T; Hashimoto, Y; Shimakawa, S; Negami, T. and Wada, T.Preparation of $Cu(In,Ga)Se_2$ Thin-Films From Cu-Se/In-Ga-Se Precursors for High Efficiency Solar Cells Solar Energy Materials and Solar CellsVolume 67, Issue 1-4, March 2001, Pages 217-223.
[12] Sera, Dezso; Teodorescu, Remus; Hantschel, Jochen and KnolMichael Optimized Maximum Power Point Tracker for Fast ChangingConditions IEEE Transactions on Industrial ElectronicsVolume 55, Number 7, July 2008, Pages 2629-2637.
[13] Bhat, Akshay Single IC Forms Precision Triangular-Wave GeneratorEDN MagazineApril 8, 2010, Pages 46-50.

IJERT

(This work is licensed under a Creative Commons Attribution 4.0 International License.)