Electric Bike Photovoltaic Charging Station (PV-CS): Experimental Design for Electrical Fault Investigations

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ELECTRIC BIKE PHOTOVOLTAIC CHARGING STATION (PV_CS): EXPERIMENTAL DESIGN FOR ELECTRICAL FAULT INVESTIGATIONS

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Abstract

Electric Vehicles (EV) have gained interest over the past decade. Accordingly, to support EV technology installation of charging stations are required. A Photovoltaic Charging Station (PV_CS) can generate clean electricity from the sun for charging electric bikes but as can be exposed to harsh weather conditions and faults, which can result in deviations of system characteristics from their normal operating conditions. Reliability of these charging stations is extremely important for supplying adequate charge to EVs, and therefore it must be maintained at all times. This paper presents a systematic approach to electrical reliability issues for PV_CS, by establishing an experimental test bed, which will ultimately allow the examination of a number of electrical faults scenarios that can occur in PV_CS systems. The design and installation of the PV_CS system, as well as assembly of different measurement sensors are presented to distinguish the electrical and thermal characteristics of each signature fault. Through this work, PV_CS charging stations will have the embedded capability of specifying when a fault is occurring and where the fault is occurring, thus reducing maintenance costs and downtime of the PV charging system.

Background

With the rising prices of fuels and the trends encouraged by the Kyoto protocol for reducing the level of global emissions, there has been a focus on integration of renewable energy resources for electricity generation [1]. In line with these commitments, Ireland has set a target of powering 10% of all vehicles on the road via electricity by 2020 [2] with the roll out of Electric Vehicles (EV) in progress [3]. EV is an alternative to the conventional vehicle, as this energy storage technology has zero emissions at the usage point [4] and when using PV has zero emissions at the generating point. There are various types of EVs available to the end users. One of which is part of the Dublin Bike Scheme is the *Pedelec* bike assisted by an electric motor, powered by a rechargeable battery, commonly known as the electric bike or EBike [5-7]. EBikes offer a viable solution over standard bikes and private vehicles, as they require less effort with the overall journey times of city routes similar to standard car transport, specifically when considering traffic congestion [8]. Although EVs have the advantage of mechanical simplicity, the limited battery charge and the lack of charging points, make their travel range limited [9]. In order to embrace the technological advancements in this field, Ireland must ensure that the infrastructure is there to meet the influx of this new technology. Electricity Supply Board (ESB) Ecars has already committed to support the electrification of transport fleet, by employing electric charging stations on the national level; such as home charge points, public charge points and fast charge points [10].

One such method to address this is through the use of photovoltaic (PV) panels which are becoming a prominent energy source for renewable electricity generation [11]. PV panels use mainly semiconductors to convert incident sunlight directly into electricity [11], and can be harnessed in PV_CS [12-14] to generate GHG emission free electricity. In off-grid PV_CS applications 100% of the required electricity is generated from solar energy [13]. The size of these off-grid PV_CS determines the number of batteries they can service. Since the batteries fitted in EBikes require less amount of energy when compared with larger capacity electric vehicles, off-grid PV_CS can be the feasible choice. Hence, the stand-alone charging units can be utilised in a similar fashion to solar mobile phone charging stations [14].

Introduction

Current research to advance performance and improve efficiency in PV_CS systems can be divided into four main streams (A-D) and is presented in Figure 1, where section A is PV and system components; B is controller components; C is battery storage and D is the electric vehicles. This paper concentrates on section A which is made up of two major components; PV module and system components called Balance of System (BoS). Throughout their life span, PV and conductors in PV_CS systems can be exposed to various environmental and functional stresses; such as harsh weather conditions, electrical faults and potential interferences prior or during the operation. Hence, a fault can be defined as a contingency situation, where system deviates from its nominal state. Faults can be classified based on location and structure [15, 16]. According to Davarifar, some of the typical anomalies in PV/BoS can be classified as following; bridging faults, open circuit faults, mismatch faults (partial and full shading), snow, soldering, cracks, degradation and hotspots. These defects in PV systems may damage the PV module and/or cables and cause significant amount of energy loss. The appropriate protection of these components for guaranteeing reliability and performance of PV_CS system is necessary. Hence, protective device provides a form of insurance for high-cost electrical equipment ,which can reduce the extent and duration of an interruption, as well as reduce equipment damage or personal injury [17].

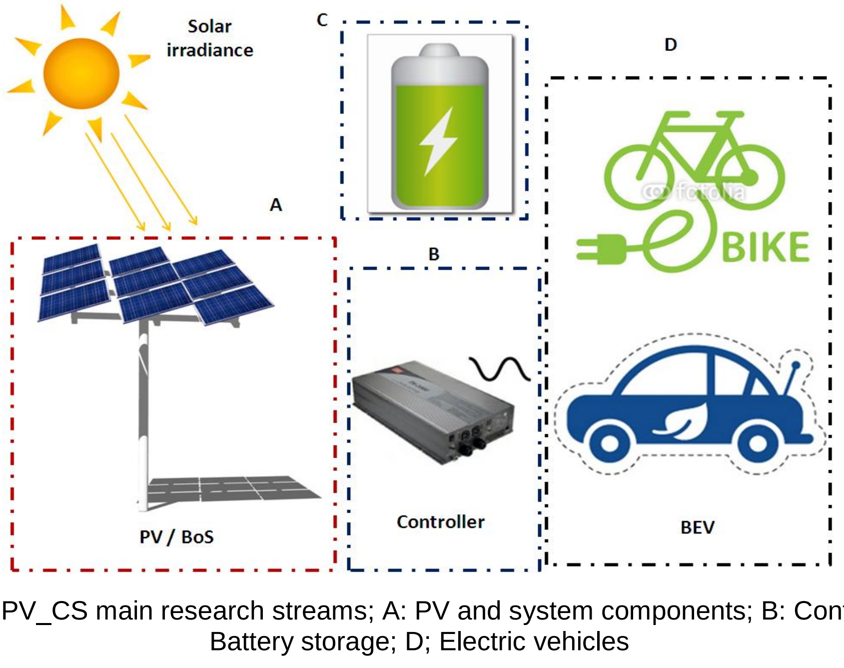

Figure 1: PV_CS main research streams; A: PV and system components; B: Controller; C: Battery storage; D; Electric vehicles

While resilience has a direct impact on PV_CS system performance, reliability and protection considerations in the PV field for small systems has not been investigated in depth [18]. Considerations for electrical hazards in PV have been dominated by higher DC voltage levels (greater than 120v DC) [19]. Voltage levels lower than 120v DC (Extra Low Voltage (ELV)), is generally ignored. [20]. Furthermore, the existing level of safety on Low Voltage (LV) level (between 120-1500 V), for PV protection is not sophisticated. According to standard IEC and NFPA 70 article 69;2014, conventional fault detection and protection methods usually add overcurrent protection devices/fuses in series with PV components. There is also a ground fault protection device close to the inverter to protect against ground faults [21, 22]. However, since the PV module current is only increased marginally when going from operating to short circuit conditions, there might not be sufficient level of over-current value to trigger the fuse function. Therefore, overcurrent devices may not operate at this voltage level, which can lead to the hidden fault problem [23, 24]. The problem of unrefined protection in PV_CS i.e., since most of the standalone PV_CS systems utilise ELV and LV voltage range, may therefore lead to system underperformance and the loss of load.

The aim of this work is, to build a platform for an evaluation of the protection strategies that currently exist or potentially may prevail on both LV and ELV voltage spectrums of PV_CS systems. The main focus of this paper is the assessment of reliability in PV_CS systems. This is done by introducing a number of electrical fault scenarios on the system and observing the electrical and thermal characteristics behaviours, i.e., specific fault signatures in normal and abnormal conditions.

Photovoltaic Charging Station power requirements

The proposed experimental set-up is designed to imitate an off-grid stand-alone PV_CS charging station. This is where the users are provided with a slot to park and charge Ebikes during the day. The experiment utilises a silicon based PV module to supply the Ebike load. The specifications of the monocrystalline silicon module and the EBike under Standard Test Conditions (STC) are presented in Table 1. Hence, STC condition is a defined performance at incident sunlight of 1000 W/m² and cell temperature of 25°C [25].

Table 1: Source (PV) and Load (EBike) specifications [8, 26, 27]

*PV (SANYO (HIP-215NHE5)_*	*Ebike (Kalkhoff Agattu)*
Power max = 215 W	Motor = 36V/ 250 W
Short Circuit Current (Isc) = 5.61 A	Battery (Lithium ion) =15Ah
Open circuit Voltage (Voc) = 51.6 V	Battery Capacity = 469 Wh
Current at max power (Imp) = 5.13 A	Weight 23.9 kg
Voltage at max power (Vmp) = 42.0V	
Panel Efficiency = 17%	

As presented in Table 1, the EBike battery capacity is 469 Wh. Therefore, the first step was designated to load matching estimations. This was to assess, whether the maximum charge requirement could be supplied via this particular PV source.

An initial scenario was based on the assumption of having the output close to PV panel Pmax of 215 W where STC represents typical summer day weather conditions. Based on this, within 2 hours the PV_CS would be able to charge the battery to its maximum capacity.

A second scenario was based on an Irish overcast day and PV output was determined and is presented in Table 2. Voc, Isc, Pmax measurements were taken using a IM490 solar modular analyser device, irradiance (I) was measured using a Kipp and Zonen Pyranometer (CM-b6), area (A) was calculated and efficiency (η) was determined from the following equation,

$$\eta = \frac{P_{\max}}{IA} \qquad \textit{Eqn. 1}$$

Table 2: Measured PV output under overcast conditions

Sample No	Voc (V)	Isc (A)	Pmax (W)	Irradiance W/ M²	Area M²	(η) (%)
1	49.23	1.31	64.49	461.3	1.25	11.157
2	49.31	1.382	68.15	446	1.25	12.194
3	49.31	1.384	68.25	446	1.25	12.212
4	49.29	1.384	68.22	414.7	1.25	12.207
5	49.28	1.375	67.76	414.7	1.25	13.04
6	49.26	1.364	67.19	414.7	1.25	12.93
7	49.23	1.351	66.51	414.7	1.25	12.78
8	49.23	1.343	66.12	414.7	1.25	12.724
9	49.23	1.35	66.46	397.3	1.25	13.35
10	49.23	1.353	66.61	397.3	1.25	13.38

From Table 2, the average power output of this module was 67 W, only 31% of the STC value (215 W). Therefore to charge the battery to its maximum capacity, the EBike will need to be parked for approximately 7 hours, excluding other losses in the system. This required time is within the acceptable range, since the user can park during the working hours and collect the charged vehicle at the end of the working day.
According to O'Donoghue [8] the average journey time of Dublin Pedelec bike, is estimated to be 13 minutes therefore the average energy requirement for each journey was 54.17 Wh. When the Ebike battery is fully charged, i.e., since the maximum battery capacity of this Ebike is 469 Wh, the user can utilise the bike for 8 average journeys.
Therefore in summer this bike would only need 15 minutes to adequately charge for one average journey increasing to 48 minutes charging for overcast winter conditions.

Experimental procedure

To maintain charge throughout the required period, it is imperative that the system is reliable and there are no undetected faults. The investigation of system electrical reliability can be undertaken by comparing normal and faulty state operating conditions. To accomplish this goal, a detailed design and instrumentation for evaluation and monitoring of electrical and thermal characteristics, was undertaken. The schematic of this PV_CS system design is illustrated in Figure 2. In order to observe both the steady state and fault behaviours, an array of the most applicable variables were identified such as current (A), voltage (V), temperature (T) and irradiance (W/M²).

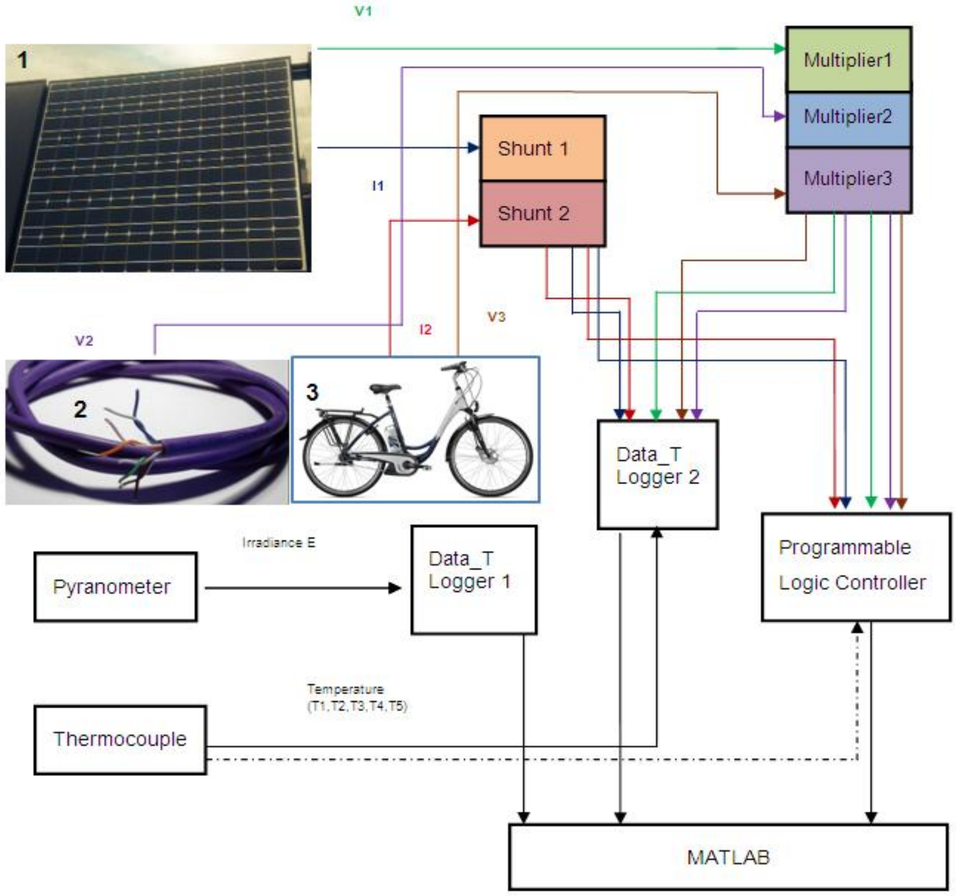

Figure 2: PV_CS (1-PV, 2-Cabling and 3-EBike) measurement sensors and logging devices

The PV_CS system has been divided into three main pillars; source (PV), conductor (cables) and load (EBike) labelled 1-3 in Figure 2. The PV panel was mounted on the roof of Dublin

Institute of Technology, Kevin Street at the latitude angle of 53 degrees. Solar irradiance was measured by a Kipp and Zonen pyranometer. Ambient temperature (T1), temperature at the back of the PV panel (T2), PV cabling temperature (T3), conductor cables (T4) and load temperature (T5) were recorded using calibrated T-type thermocouples. These data were captured at a rate of 1 second, via a DeltaT data logger.

Two shunts were used to record current, where I1 and I2 represent PV current as well as load current values. Power from the panel was wired through the conductor to create the desired voltage for the rest of the system and service the Ebike. Hence, in the diagram: V1 measured via multiplier 1 represents PV voltage; V2 measured via multiplier 2 corresponds to the voltage of the running cable between PV and the load and; V3 measured via multiplier 3 is associated with voltage at the load side. All current and voltage values were acquired by data logger2 at the rate of 1 second. However, in order to distinguish the variations and the likely distortions in the captured signals, data acquisition for fault studies in ELV typically demand a faster sampling rate.

As the result, an alternative method for capturing all current and voltage values was employed using a Programmable Logic Controller (PLC). The PLC model used was a Mitsubishi FX2N, which was programmed at a sampling rate of 10 milli-second. Hence, loggers would now capture all the detected current and voltage values at both slow (1 second) and fast (10 milli-second) sampling rates. Further to this data was transferred to MATLAB to be used as reference tables. These tables correspond to ideal reference test points, where the PV_CS operates in a normal steady state condition

Fault Detection Investigation

In order to work through the fault behaviours of this system, the following scenario was investigated where a PV_CS user, parks their Ebike with the aim to collect the vehicle fully charged after 2 hrs on a bright sunny day (similar conditions to STC). However, in the event of hidden faults on the system prior or during the charging activity, the system will malfunction. Fault categories are presented in Table 3. In the worst case situation, the system may stop charging and the user returns to find the EBike not sufficiently charged for the homeward journey. This phenomenon can arise for two fault conditions in PV_CS outlined in Table 3. Short Circuit (S/C) and Open Circuit (O/C) when considering the PV cell can lead to effectively very small to no power.

As a result, in order to assess the level of reliability and compare the performance under the faulty conditions, PV_CS test system was exposed to the diversity of these fault categories as summarized in Table 3.

Table 3: Fault categories on PV_CS system

Fault ID	Fault Type	Fault Location b
F1	S/C (Short-Circuit)	PV Cable
F2	O/C (Open-Circuit)	PV Cable
F3	S/C (Short-Circuit)	Load Cable
F4	O/C (Open-Circuit)	Load Cable
F5	P-S/C(Partial Short-Circuit)	Load
F6	P-O/C(Partial Open-Circuit)	Load

Furthermore, these defects were introduced at different locations on the system. As it can be seen in Figure 3, i.e, circuit design of PV for PLC logger, F1 and F2 emerged on the PV side, whereas F3 and F4 took place on the cable side. Finally, F5 and F6 appeared on the load side of the rig.

These preceding faults are all colour coded in the below diagram. Red represents S/C (full/partial) and alternatively blue suggest the O/C (full/partial) conditions

Please note: in Figure 3; electrical protection components such as; fuse, switches and breakers, were excluded from this system design. Ohmic choice of resistors and the load obliged for fine instrumentation considerations. This was to match with the Ebike load, as well as to tune to the acceptable voltage and current range of sensors.

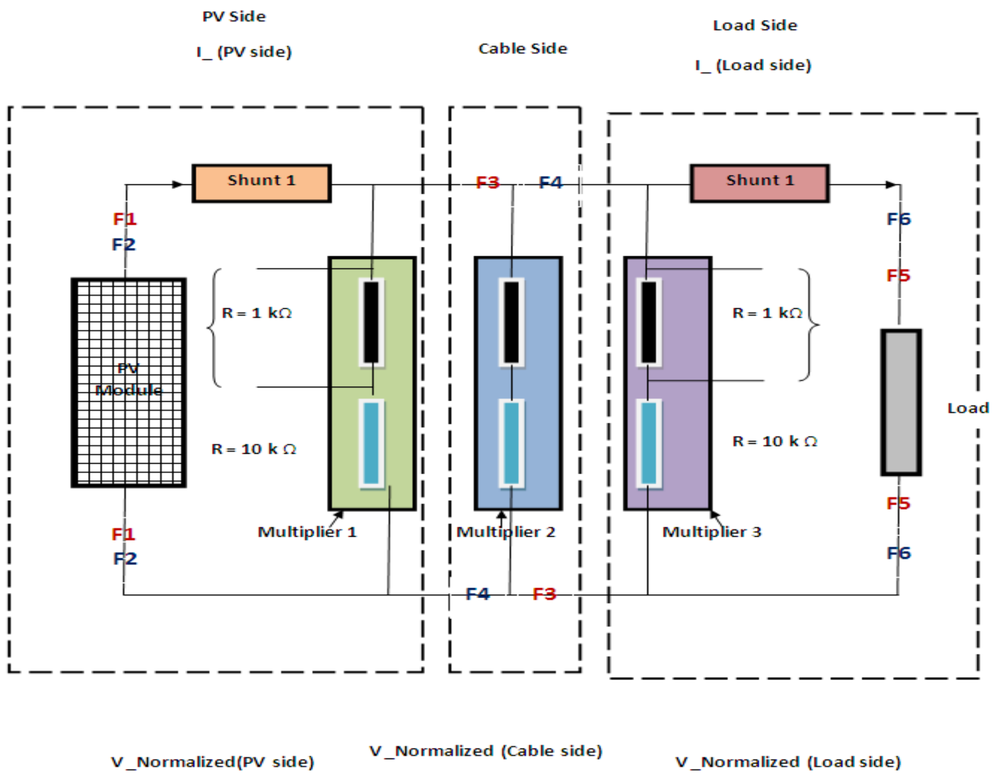

Figure 3: Circuit design of PV for PLC logger

The obtained data from each fault scenario was populated in distinct tables. These tables will now form the backbone of future analysis where the signature electrical and thermal fault characteristics will be determined by utilising these tables.

Conclusion

In order to investigate the effect of electrical faults on the reliability of PV_SC systems, along with consequence of these defects on EBike battery performance, an experimental rig was set up. This experimental platform facilitated studies of the PV_CS system and essentially allowed the behaviours of standalone off-grid charging stations in both steady state and faulty conditions to be mimicked. In the steady system, a PV panel generated electricity and, the power generated by the PV could be used to charge of Ebike battery. The preliminary instrumentation and calibrations were conducted in normal steady state test conditions as well as both S/C and O/C faults, as these would allow obtaining sets of electrical and thermal measurement characteristics. These data were captured with both fast and slow sampling methods, by means of dedicated data loggers. Captured data will be assessed, and the correlation between measured parameters will allow detection of signature fault characteristics. Dependent on the specific location and fault signature, these datasets will be utilised to minimise system downtime and reduce maintenance cost.

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