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The role of bypass diodes in the failure of solar battery charging stations in Thailand

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Abstract

This paper focuses on the failure of bypass diodes in solar battery charging stations (SBCS) in Thailand. The Thai government has installed over 1000 SBCS in unelectrified villages to be used to charge 12-V batteries for household lights and small appliances. The unnecessary inclusion of bypass diodes in these systems created an unexpected failure mode when villagers misconnected their batteries with reverse polarity. In a survey of 31 stations, 18 stations were disabled by burnt-out bypass diodes. The electrical engineering theory of this failure mode is analyzed. In addition, we discuss how the bypass diode failures have been compounded by lack of end-user feedback to the implementing agencies. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Photovoltaics; Rural electrification; Bypass diode; Solar battery charging stations; Project evaluation

1. Introduction

Though less popular worldwide than household scale solar home systems, in the past decade solar battery charging stations (SBCS) have emerged as an option for basic rural electricity services in several countries. SBCS have been installed in Morocco, India, Brazil, Bangladesh, South Africa, as well as Thailand [1]. In contrast to solar home systems, which are installed in individual households, SBCS are located centrally in the village. System users must bring their batteries to the station to be charged during the daylight hours and return to collect them in the

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evening. Until the potential for alternative electricity generation, millions of rural villagers who owned 12-V batteries would take them to be charged by the grid or a diesel generator. SBCS can potentially decrease this inconvenience by providing a central location in a village for charging these batteries. By using sunlight, SBCS also avoid the expense and environmental drawbacks of fossil fuel consumption for battery charging.

This paper highlights the problems that have occurred when basic feedback about the systems' performance was not incorporated into the ongoing project design or maintenance programs for the systems. For end user participation in similar projects see Ref. [2–4]. Specifically, we find that failure to follow up on system performance to learn from system failures has resulted in the propagation of a serious design flaw, namely the inappropriate inclusion of a bypass diode in many of the systems. The bypass diode in these systems is not only unnecessary, but has been the source of a dominant failure mode. The incorporation of this bypass diode has been responsible for the frequent deterioration of these systems and initiated a feeling of dissatisfaction with the systems by the end users. These findings about the SBCS are reinforced by the work of Kirtikara [5] and Khuanmuang [6] who performed analysis on over 400 photovoltaic water pumping stations in Thailand which have been implemented in government programs of a similar nature to the SBCS programs. Their findings suggest that hardware failures were frequently caused by social factors or misuse of the systems by end users through ignorance of how the system was designed to be operated.

One advantage of SBCS over the solar home systems is that the station is located in a public area, rather than split up inside individual homes and so problems of misuse can be identified early on. In addition, in comparison to solar home systems, it is argued that a smaller total investment in photovoltaics can serve a given customer base because villagers can share battery charging station channels. A significant disadvantage of these systems is their common-access characteristic, which presents a challenge with coordination and allocation of battery charging rights and responsibilities. There is also the added inconvenience and risks to the villagers of having to move their batteries to and from the station each time they require charging.

2. Solar battery charging stations in Thailand

The Thai government has used solar powered electricity generating systems as a component of their rural electrification scheme for the remotest villages throughout the country over the last 10 yr. So far, over 1000 villages have received electric power from these SBCS, allowing thousands of villagers the potential to access electric power to run lights and for limited use of other electrical appliances such as tape players and small televisions [7–10] (Fig. 1).

In Thailand two government agencies, the Department of Energy Development and Promotion (DEDP) and the Department of Public Works (DPW) have installed SBCS in approximately 1000 villages. Eighty per cent of these have been installed by

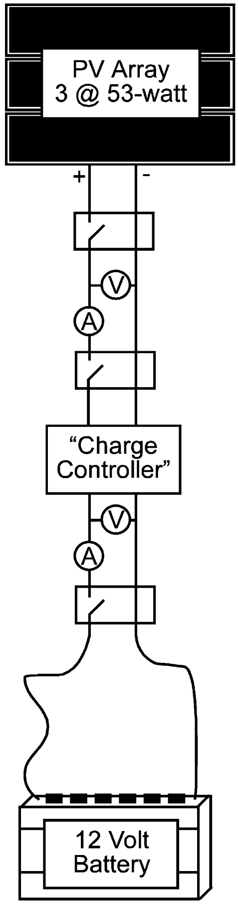

Fig. 1. One of five identical channels of a typical battery charging station installed by the DPW. Each channel is powered by three 53-W-peak modules in parallel. Source: [11].

the DPW, although their stations have smaller arrays (600 w-peak) than the DEDP installations (3000 w-peak). The equipment cost of installation of the systems is completely subsidized by the Thai government. The villagers are only responsible for providing labor to prepare the site for the station building and the array. For DEDP systems, villagers are required to set up committees to collect charging fees to cover system maintenance and to create a fund in order for new batteries to be purchased for public events. Villagers are also expected to look after the system and provide regular maintenance during its operational life.

Over the last decade, millions of US dollars in foreign exchange have been invested to purchase component parts (PV modules, electronics) in these installations. In addition, millions of baht have been used in the planning, design and construction stages of these installations. There has, however, been no comprehensive evaluation of these systems' performance so far. One isolated case of study of a station in Huay Dua Village in Central Thailand found several problems with the system. These included: lower than expected power output from photovoltaic modules due to shading; poor electrical connections; the use of inefficient incandescent light bulbs instead of fluorescent lamps, resulting in deep discharge of batteries; long wait times for system repairs; inadequate information available in the purchase of energy efficient appliances; and fear from some villagers of the photovoltaic switchboard [11]. Our research suggests that the failures of these government programs are not because renewable energy technologies are inherently weak. Rather, many of the failures are the consequence of easily avoidable technical flaws and deficient feedback incentives in maintenance arrangements for the systems.

3. Field monitoring and feedback

It is ironic that many published papers and reports concerning renewable energy programs for rural development explicitly call for evaluation and monitoring of projects as an essential component in program sustainability [3,12]. Yet in a search of 25 energy journals which revealed 121 articles on renewable energy and rural development from 1995 through 1999, only five explicitly included case studies of how projects perform in the field [12–17]). In this light, it appears that the focus of monitoring system performance in the field must again be stressed as a method to enhance the potential for overall system sustainability.

In our study, the field performance of 31 SBCS was investigated in three missions between 1998 and 1999 (see Table 1). Eighteen of these stations were installed by the DEDP, while 13 were installed by the DPW. The average age of these stations was 2 yr. We documented the performance of the stations, as well as carried out a simple survey of end user experience and satisfaction with the system. The sample of stations visited was selected from a set of systems that DPW and DEDP officials felt were most likely to be functioning, as well as from several field trips with private industry technicians, local government staff and individual explorations. Thus, this sample is likely to under report problems with SBCS because known non-functioning stations were not included in our investigations.

In our survey sample of 31 stations, 18 of them (58%) had problems with disabled channels caused by the failure of bypass diodes. The diode problem was sometimes accompanied by a telltale sign, that of melted module junction boxes. The problem occurred when end users connected their batteries to the charging system with

Table 1
Thai SBCS with bypass diode problems surveyed by authors

Problem	DEDP stations	DPW stations
PV channel failure caused by reverse polarity of bypass diodes	8 of the 18 DEDP stations visited showed channel failure,	10 of the 13 DPW stations visited showed channel failure

reversed polarity. This caused the bypass diodes, which are installed in the junction boxes at the back of each module, to short-circuit the battery. When this happened, the diodes carried currents vastly in excess of their rated capacity. In some cases, this short-circuit current created enough heat to melt the junction boxes or burn the module's electrical connections. The mechanism by which reverse polarity caused module damage is explored in more theoretical terms below.

A crucial element in the diode problem was lack of end user education. From the field mission investigations, it was clear that there was very little end user awareness about how to correctly operate the system. Adequate information was not generally given during the system installation and no regular follow up by government officials to reinforce the importance of operating the system correctly was actually provided. In many cases, the color coding of the wires from the charging board had been removed, making it difficult to determine which wire was positive or negative. Furthermore, during site visits it was frequently observed that villagers, rather than appointed station operators, would connect up the batteries themselves. For the smaller 6-V batteries which were frequently used, against the wishes of the government field staff, this group would also include the village children, who reasonably would have no knowledge of the importance of correctly connecting the battery for charging.

We focus much of the remainder of the paper on an investigation of the causes of the failure of the bypass diodes. The problem is interesting because photovoltaic modules are generally the most robust component in any solar electric system. Photovoltaic panels have no moving parts and are inherently immune from a variety of electrical faults including short circuits and reverse polarity. This fact is reflected in the expected lifetime of single or polycrystalline photovoltaic module of the type installed in Thailand's SBCS which is 20 yr [18]. The following section explores the theory of bypass diodes, and how the diodes failed in the case of the Thai SBCS.

4. Bypass diode use theory

Ignoring series and shunt resistance, a solar cell can be modeled as a limited current source in parallel with a forward biased diode [19]. The diode in this model is a consequence of the solar cell's p-n junction, and the limited current source is a consequence of the disassociation of electron-hole pairs created by incident photons within the built in field for the junction diode. A solar photovoltaic module is a collection solar cells wired in series (Fig. 2). A typical nominal 12-V module has 36 photovoltaic cells wired in series. When a single cell in a module is shaded, power is absorbed by the shaded cell [19]. In principle, it is possible to use a *bypass diode*, a normally reversed bias diode in parallel with the cell, to isolate the shaded cell to provide an alternate path for current to flow (see Fig. 3).

In practice with single crystal or polycrystalline cells it is not practical to put bypass diodes in parallel with each cell. Instead, protection is carried out at the module level (Fig. 4) protecting partially shaded modules that are wired in series. A

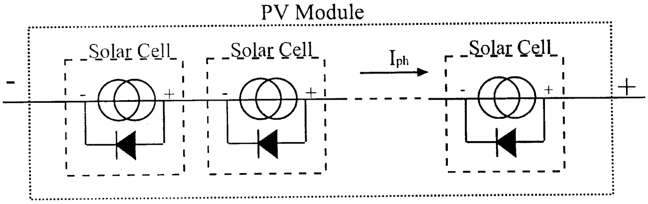

Fig. 2. Solar cells can be modeled as a limited current source in parallel with a forward biased diode. A module is a collection of these cells wired in series. The direction of current flow in the module from the photovoltaic effect is indicated by I_{ph}.

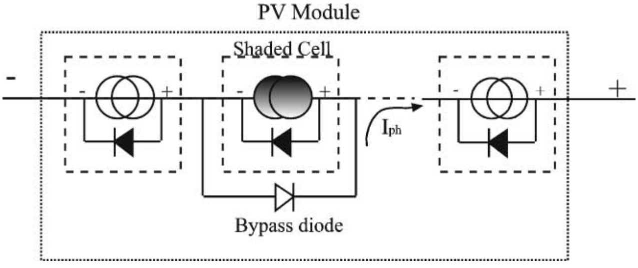

Fig. 3. PV module with a bypass diode parallel to a shaded cell.

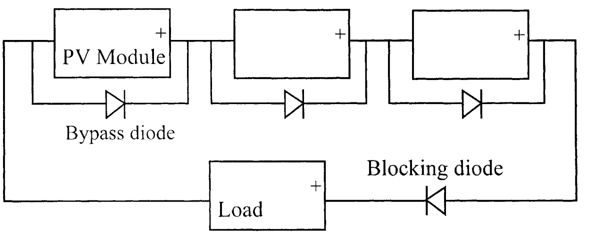

Fig. 4. Series wired modules with bypass diodes. The polarity and location of a blocking diode is also indicated.

blocking diode is sometimes used to prevent reverse current leakage from the battery through the modules at night.[1]

Bypass diodes across modules only make sense if modules are wired together in series, and are generally only used if the nominal voltage of the array exceeds 48 V [20]. When modules are wired in parallel, as is the case with the 12-V Thai SBCS, a bypass diode serves no purpose. Fig. 5 shows proper wiring for modules wired in parallel to form a low voltage array.

[1] This practice has largely been abandoned since with single or polycrystalline cells. Nighttime leakage current is negligible compared with the power lost through the diode during the day. Furthermore, many modern charge controllers generally open the connection with the module at night to eliminate any leakage current.

5. Bypass diodes in the Thai SBCS

Although bypass diodes served no apparent purpose in the 12-V SBCS, they were included in the design anyway (Fig. 6). This created a significant failure mode when combined with a condition that the engineers specifying the design of the system had not considered: that the users might connect the batteries backwards (Fig. 7). When battery polarity is reversed, the bypass diodes become forward biased and conduct the short-circuit current from the battery. In those cases where the battery state-of-charge was low enough (and thus battery impedance was high and battery voltage low), the diodes did not immediately blow open-circuit, but rather continued to conduct creating significant heat that ultimately burned or melted the junction boxes.

The cables connecting the SCBS to the battery have simple spring-loaded alligator clips for connecting to the battery posts, similar to those used in automotive jumper cables. There is nothing stopping end users from connecting their battery with reverse polarity, that is positive to negative rather than positive to positive.

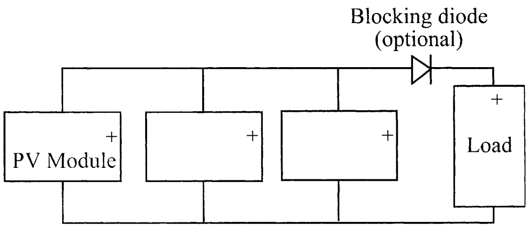

Fig. 5. Array composed of parallel modules. No bypass diodes are used in this case.

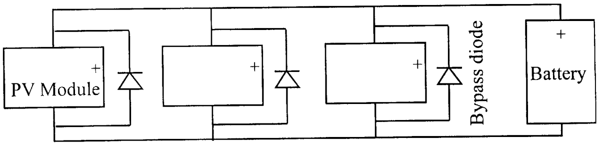

Fig. 6. Thai SBCS with unnecessary bypass diodes.

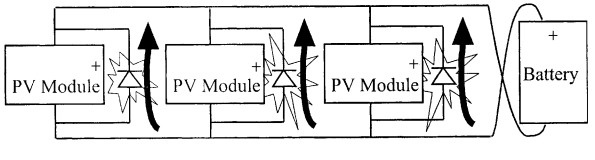

Fig. 7. The failure mechanism—when batteries are connected backwards, the bypass diodes become forward biased, conducting current limited only by the impedance of the battery, wires, and the voltage drop across the diode. If the battery is initially in a low state of charge, its voltage is low and internal resistance is high. In these cases the diode did not immediately blow open-circuit, but instead heats up, burning electrical contacts within the module and melting the junction box plastic.

6. Conclusion

The failure of over half of the SBCS in Thailand that have been studied illustrate the dangers of replicating a design that did not take the full range of user behaviors into account. It may be assumed that this problem would affect the majority of the SBCS in Thailand which have this system design, when installed in villages with low end user understanding about the systems. This suggests that a significantly high percentage of the installed systems in the country will be affected to varying degrees by this problem. Unfortunately, it is also likely that there are other significant factors that will compound this design fault to further lower the overall success rates of these systems.

The irony of this situation is that the modules in these systems were inherently reverse polarity protected and the incorporation of bypass diodes defeated this inherent protection. Designers of renewable energy systems and policy makers who promote renewables for rural development would do well to learn from the problems that have been identified in these Thai systems. The lessons here are manifold: keep the system design simple and do not add unnecessary components, avoid the temptation to replicate designs that have not been fully tested in the field and do not underestimate the ability of system users to use the systems in unexpected ways. This is especially true for SBCS that require frequent connection and disconnection of the batteries by the end users.

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