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Intelligent Off-Grid Photovoltaic Supply Systems

Prashant Kumar Soori, Parthasarathy L., Masami Okano, and Awet Mana

***Abstract*—**Off-grid Photovoltaic (PV) systems are empowering technology in underdeveloped countries like Ethiopia where many people live far away from the modern world. Where there is relatively low energy consumption, providing energy from grid systems is not commercially cost-effective. As a result, significant people groups worldwide stay without access to electricity. One remote village in northern Ethiopia was selected by the United Nations for a pilot project to improve its living conditions. As part of this comprehensive project, an intelligent charge controller circuit for Off-grid PV systems was designed for the clinic in that village. In this paper, design aspects of an intelligent charge controller unit and its load driver circuits are discussed for an efficient utilization of PV-based supply systems.

***Keywords*—**Compact Fluorescent Lamp (CFL), Fluorescent Lamp, Intelligent Charge Controller Unit (ICCU), Light Emitting Diode (LED), Photovoltaic (PV).

I. Introduction

SOLAR energy is a very large, inexhaustible source of energy. The power from the sun available on the earth is approximately 1.8×10^{11} Mega Watts (MW), which is many thousands of times larger than the present consumption rate of all commercial energy sources on the earth [5]. Thus, in principle, *solar energy* could supply all the present and future energy needs of the world on a continuing basis.

In spite of a high initial cost, PV systems are being used increasingly to supply electricity for many applications requiring small amounts of power. Practical studies show that it is more economical to install a stand-alone PV system instead of an overhead transmission line to a village using a load of 10 Kilowatts (KW), if the village is more than 40 kilometers (Kms) from the grid line [5].

Korero, a remote village in northern Ethiopia, is totally isolated from the modern world. Grid extension to this village would be very expensive because of its relatively low energy consumption and the high cost of connecting distant households to a grid. Off-grid PV supply systems are very often the most economic solution to provide required electricity to important sectors such as clinics and evening schools [2]. Presented in this paper is a stand-alone solar PV supply system to cover the basic electricity demands of the village clinic.

Photovoltaic systems are solar energy systems that produce electricity directly from sunlight. PV systems provide clean, reliable energy without consuming fossil fuels. They are much safer and more environment friendly than conventional sources of energy production.

The availability of solar energy varies because of the day-night cycle and seasonally, because of the earth's orbit around the sun. Consequently, the energy collected when the sun is shining must be stored for use in periods when it is unavailable. Thus there is need for energy storage in a stand-alone off-grid PV system. As the energy storage device batteries are used; they play a major role in PV systems [2], [3]. System loads can be powered from the batteries during the day or night, continuously or intermittently, regardless of weather conditions. Unfortunately, experience has shown that in stand-alone PV systems, batteries appear to be the *weakest point* of the system since their life expectancy is considerably lower than that of all other PV system components [2]. The main requirements to be met by a storage battery for a stand-alone PV system are:

- An ability to withstand several charge/ discharge cycles.
- A low self-discharge rate.
- Little or no need for maintenance.

Overcharge of the battery results in corrosion, loss of electrolytes and active materials from the plates, causing reduction in battery life. The repeated failure of the battery to reach a fully charged state leads to stratification of electrolytes [4]. Hence there is a need for an intelligent, diagnostic charge controller circuit to increase energy storage and battery life. Discussed here are the remedial measures to enhance the life of a storage battery and the effective, automatic use of such PV systems.

Fig. 1 is a schematic representation of the proposed stand-alone PV systems for the clinic in Korero village of Ethiopia.

Prashant Kumar Soori, Dean, is with Mekelle Institute of Technology P.O.Box: 1663, Mekelle, Ethiopia (phone: 00251-911-404994; fax: 00251-344-409988; e-mail: pksoori@ yahoo.com).

Parthasarathy L. is with Department of Electrical Power Technology, Defence Engineering College, Ethiopia (e-mail: partha2005@yahoo.com).

Masami Okano is with Department of Electrical Engineering, Mekelle Institute of Technology, P.O.Box: 1632, Mekelle, Ethiopia is a senior volunteer from Japan International Cooperation Agency (JICA) Ethiopia (e-mail: bx06447@yahoo.co.jp).

Awet Mana is with Department of Electrical Engineering, Mekelle Institute of Technology, Mekelle, Ethiopia.

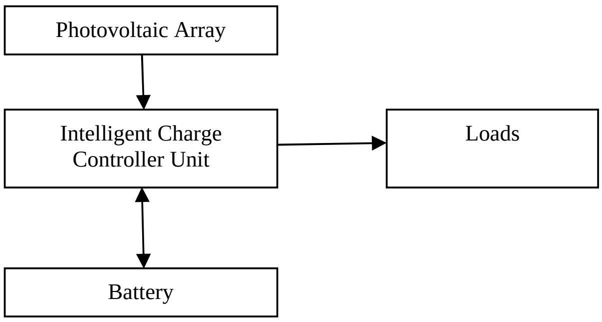

Fig. 1 Schematic of a stand-alone PV system

II. Proposed System

Although PV systems can be used without charge controllers, it needs to be stated that in planning the long-term operation of a stand-alone PV system, overcharge and deep discharge of the battery *must* be avoided. Fig. 2 shows the detailed block schematics of the proposed system. The proposed system was designed and tested for a period of ten months at Mekelle Institute of Technology, Ethiopia. Its design aspects are outlined and discussed below.

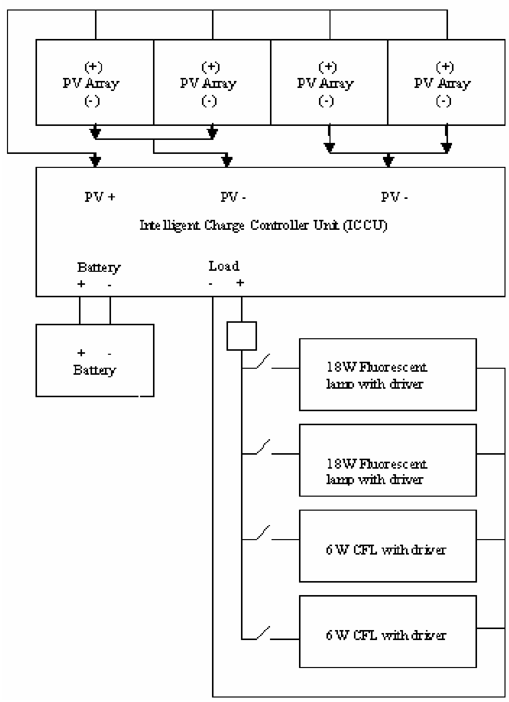

Fig. 2 Detailed block schematics of the proposed system

III. Design Aspects of an Intelligent Charge Controller Unit (ICCU)

The charge controller unit is the link between the PV array, the battery and the load. It prevents both overcharging and deep discharging of the battery. Fig. 3 is the detailed block schematic of an intelligent charge controller unit (ICCU) of the proposed PV supply systems. The designed charge controller has the following features:

- Battery Overcharge Protection Circuit.
- Battery Deep Discharge Protection Circuit.
- System Condition Indication Unit.
- Reverse Polarity Protection Circuit.
- Self Protection Unit.
- Charge Current Monitoring Circuit.

A. Battery Overcharge Protection Circuit

Whenever the battery voltage exceeds 14.5 Volts (V), it changes to a trickle mode of charging; meanwhile the system state Light Emitting Diode (LED) will glow [1]. In Fig. 3, LED1 gives the indication. If the battery voltage is between 13.5V and 14.5V, the duty-ratio of the charging circuit is decreased to control the charging rate of the battery. This state is indicated by LED2. The set voltage depends on the type of Lead Acid battery used [1]. This mode of automatic adjustment of duty-ratio control will protect the battery from overcharging. A battery in a good voltage range is indicated by LED3.

B. Battery Deep Discharge Protection Circuit

A battery deep discharge protection circuit is mandatory for a long service life of the battery. When the battery voltage decreases and approaches 11.5V, a warning signal LED4 will glow indicating that the deep discharge condition is approaching. Load disconnection can be performed by the user according to load priorities. If the battery voltage falls below 10.8V all the loads will be automatically shut down and LED5 will give a low battery indication [1]. This automatic control enhances the life of the battery. The set voltage can be varied according to the type of battery employed.

C. Reverse Polarity Protection Circuit

It should be noted that occasionally the user may not be able to properly connect the PV module cable to the battery. If the user reverses the battery polarity by mistake, the circuit will not work. If the reverse polarity connection of the battery continues, it disconnects the entire load and gives a visual indication until the polarity of the battery connection is corrected.

D. Charge Current Monitoring Circuit

Charge monitoring is achieved by sensing the real-time charging current flowing from the PV to the battery through the charge current monitoring circuit. In the absence of this current, the respective charging indicator LED does not glow even though the voltage of the PV module is available. This mode of real-time charging optimizes the collection of solar energy and helps the user to utilize the PV energy effectively.

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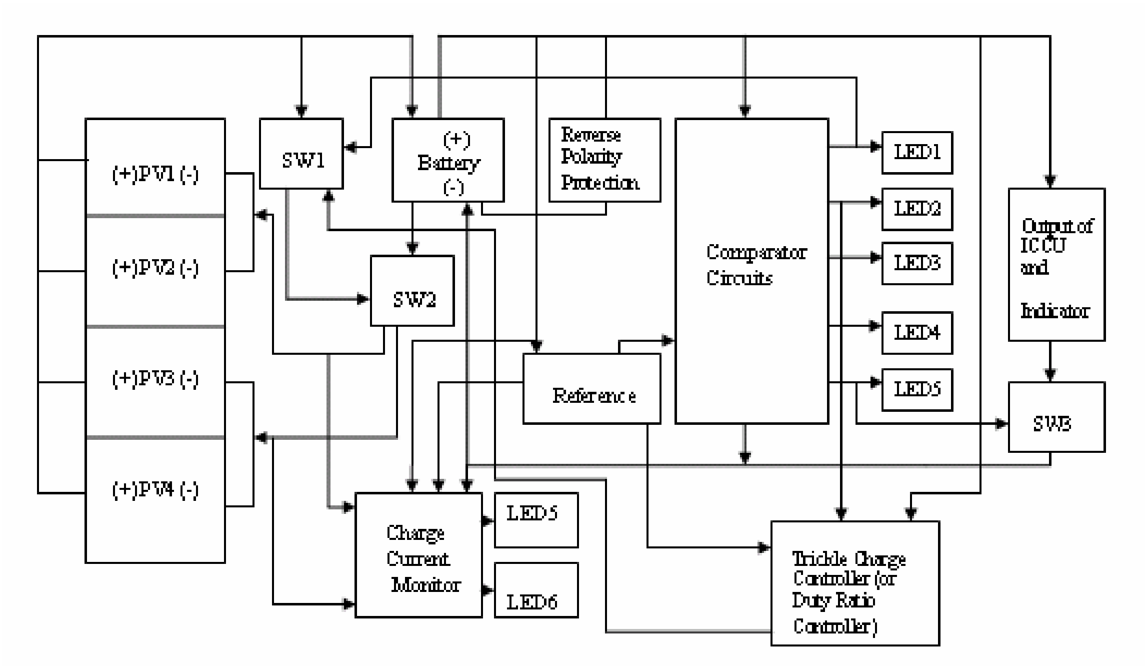

Fig. 3 Detailed block schematic of an intelligent charge controller unit

IV. System Specifications

The tests were carried out with the following system specifications.

A. *The PV module*

53W, 17.5V, 3.05A, 5.6Kg
Number of Modules: Four
Mounting: Roof mounted

B. *Battery*

Low Maintenance Lead Acid (LMLA) battery: 12V, 150Ampere-hour (Ah) with three-day autonomy.

C. *Load*

Load1: Two 18W fluorescent lamps with reflectors and cases, hung from the ceiling in two rooms - designed to operate eight-hours a day.
Load2: Two 6W CFL with reflectors and cases for lighting two small rooms designed to operate eight-hours a day.
Total Connected Load: 48W.

V. System Sizing

A. Battery Sizing

AC average daily load= x=48W

Inverter Efficiency=n= 0.85

DC System Voltage= V=12V
Number of hours of operation per day=y=8

Average Ampere-hour (Ah) per day $= \frac{xy}{Vn} = 37.65$
Days of autonomy=3

Required battery capacity= 37.65×Days of autonomy=112.94Ah
Battery proposed= 150Ah, 12V.
Depth of Discharge of the battery per day= 25.1%.

B. PV Sizing

Effective sun-hours per day=4.5
Average Ah per day supplied by the battery=37.65
Battery efficiency=0.8 [6]
Array peak amperes required=

$$\frac{\text{Average Ah per day supplied by the battery}}{(\text{Battery efficiency})(\text{Effective sun} - \text{hours per day})}$$

=10.46A
Peak amperes per module=3.05A
Number of modules required in parallel=

$$= \frac{\textit{Array peak amperes required}}{\textit{Peak amperes per module}} = 4$$

Conversion Efficiency=0.6 [6]
Power Rating of each module= (10.46/4/0.6) 12= 52.3W
Proposed PV module rating=53W

VI. Design Aspects of Load Driver Units

A. Design of Converter System for 18W Fluorescent Lamp Drive Circuit

The input to the load is derived from the output of an intelligent charge controller unit. Fig. 4 shows the schematic of the system employed to drive the load. It uses a push-pull circuit with suitable feedback to generate the high frequency AC required by the load. The principle of electronic ballast depends on a saturable ferrite-core transformer and the design of a capacitor-based, harmonic filter circuit. This designed converter system is simple, low cost, and easily maintainable.

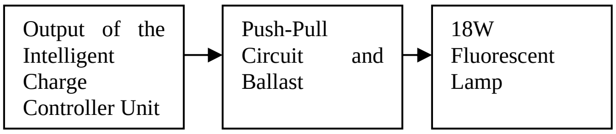

Fig. 4 Block schematic of the 18W fluorescent lamp drive circuit

B. Design of Converter System for 6W CFL Drive Circuit

The block schematic of the 6W CFL drive circuit is shown in Fig. 5.

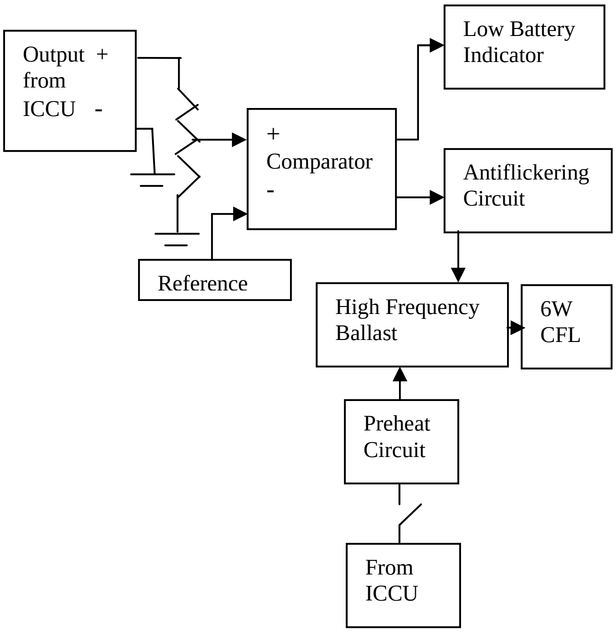

Fig. 5 Block schematic of the 6W CFL drive circuit

Its design aspects are outlined and discussed below.

- Battery Deep Discharge Protection Circuit.
- Anti-flickering Circuit.
- Electronic Ballast.
- Preheat Circuit.

The *battery deep discharge protection circuit* disconnects the load from the output of the charge controller unit whenever the input voltage falls below a set voltage [6]. The output of this circuit also provides the input low indication and drives an *anti-flickering circuit* that isolates the load from the charge controller [6].

An *electronic ballast* provides the required high frequency power supply for a CFL. A CFL requires high voltage in the secondary winding of the high frequency transformer before the ionization begins, and high current in the primary winding after ionization. The criticality of the design is based on a saturable ferrite core relaxation oscillator and the design of a capacitor-based harmonic filter circuit.

The *preheat circuit* is designed to reduce the ionization voltage required for a CFL; a low ionization voltage avoids the blackening of the CFL and enhances its life. The circuit allows current to flow through the filament of the CFL for a short time prior to the illumination of the CFL. The time interval can be fixed as per the specifications of the CFL manufacturer.

VII. Test Results

The system was successfully designed and tested over a period of ten months.

Fig. 6 shows the battery charging voltage, measured at the terminals, and the time in the day during a winter season when the loads were not switched on. It was observed that the battery voltage and the battery current both rise as the battery receives bulk charging to replace the energy dissipated by the previous night's load.

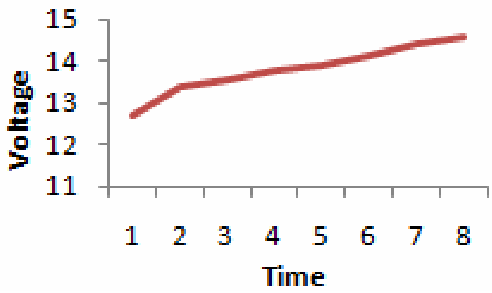

Fig. 6 Battery voltage measured at one-hour interval while charging

The system was also tested with a fully charged battery isolated from PV array for three consecutive days. The test was conducted when the loads were on for eight uninterrupted hours daily. Fig. 7 shows the battery voltage, measured at the terminals, and the times on day one, two and three respectively. On the first day the battery voltage dropped from 13.7V to 12.58V when the loads were on for eight hours. On the second day, when the loads were switched on, battery voltage was 12.56V initially; after eight hours it dropped to 12.47V. On the third day, the initial voltage was 12.46V; after eight hours of load it dropped to 12.41V.

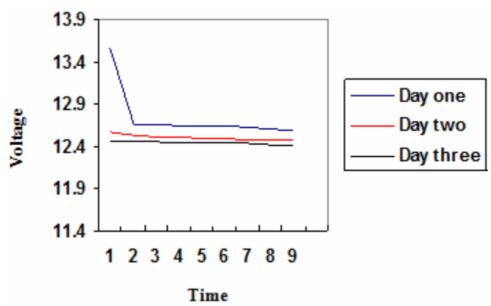

Fig. 7 Battery voltage on three consecutive days of use with the PV array disconnected

The deep discharge protection circuit of the intelligent charge controller unit worked efficiently when the battery voltage fell below 10.8V; it disconnected all the loads. Visual indication of the system helps the user to switch on or off the load as per the load priorities.

The overcharge cut-off circuit of the intelligent charge controller unit worked efficiently when the battery terminal voltage exceeded 14.5V. This circuit increases battery life.

The reverse polarity protection circuit of the intelligent charge controller unit prevented any damage from an accidental reverse polarity connection of the battery.

The charge current monitoring circuit of the intelligent charge controller unit helps to avoid losses in the collection of PV energy.

A push-pull circuit with suitable feedback generated the required high frequency AC for the 18W fluorescent lamp. It is a low cost system.

The battery deep discharge protection circuit of the 6W CFL drive unit disconnected the load when the input voltage was less than 10.8V.

An electronic ballast of the 6W CFL drive unit designed to operate at 50 KHz has an efficiency of approximately 85%.

Fig. 8 (a) shows the waveforms of Gate to Source voltage (V_{GS}) of the power Metal Oxide Semiconductor Field Effect Transistor (MOSFET) and the current in the primary winding of the high frequency transformer and (b) shows the waveforms of V_{GS} and the secondary output voltage of the transformer.

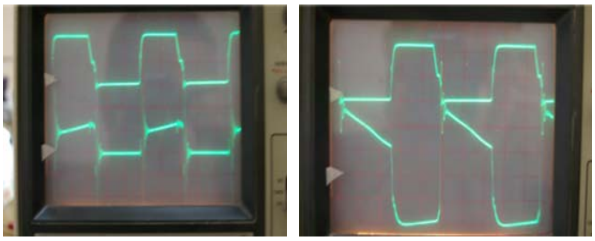

Fig. 8 a) V_{GS} and primary current of the transformer
b) V_{GS} and the secondary output voltage of the transformer.

Fig. 9 (a) shows the waveforms of V_{GS} and the capacitor output and (b) shows the waveforms of V_{GS} and the secondary current of the transformer.

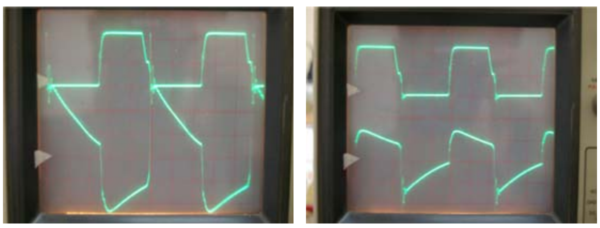

Fig. 9 a) V_{GS} and capacitor output of the transformer
b) V_{GS} and the secondary current of the transformer.

The capacitor-based harmonic filter circuit in the ballast allows preheat current to flow through the filament of a CFL at the time of switching on the light. This drastically reduces the ionization voltage required for the CFL and avoids blackening of a CFL. A preheat circuit enhances the life of a CFL.

VIII. Conclusion

The charge controller unit and its load driver circuits were designed, tested and verified over a period of ten months.

It is a very simple, easily maintainable, highly efficient and low cost system which can be used in a clinic, evening schools and many other applications in third world applications.

References

[1] Prashant Kumar Soori, L.Parthasarathy, Masami Okano, Leake Enquay, Kifleberhane Zemalecot, and Gebrehiwot Abraha, “Automated charge controller for off-grid photovoltaic lighting system,” presented at the 2007 5th Int. Conf. Industrial automation, Montréal, Québec, CANADA.

[2] Antonio Luque, and Steven Hegedus, “Handbook of photovoltaic science and engineering,” West Sussex: Wiley, 2005, ch. 17.

[3] Bogdan S.Borowy, and Ziyed M.Salameh, “Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system,” *IEEE Transl. Energy conversion*, vol. 11, June 1996, pp. 367-373.

[4] H.P.Garg, and J.Prakash, “Solar energy fundamentals and applications,” 1st revised ed, Tata McGraw-Hill, 2002, pp. 403-404.

[5] S.P.Sukhatme, “Solar energy principles of thermal collection and storage,” 2nd ed. New Delhi: Tata McGraw-Hill, 2002, pp. 22-23.

[6] *Photovoltaics Design and Installation Manual*, Solar Energy International, New Society, 2004.

[7] Soori Prashant Kumar, Wondimu W/G, and Tademe Asfaw, “Photovoltaic domestic lighting system for rural areas,” presented at the 2003 1st CEETE Conf., Ethiopia.

[8] S.Saha, and V.P.Sundarsingh, “Novel grid-connected photovoltaic inverter,” *IEE Proc.Gener. Transm. Distrib.* vol. 143, no. 2, pp. 219-224, March 1996.

[9] L.Salvaderi, and G.B.Martini, “An international perspective on the future of power generation and transmission worldwide: The Italian case,” *IEEE Trans. Energy Conversion*, vol. 7, no. 1, pp. 83,March 1992.

[10] Badrul H.Chowdhury, “Optimizing the integration of photovoltaic systems with electric utilities,” *IEEE Trans. Energy Conversion*, vol. 7, no. 1, pp. 72-78, March 1992.