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J. Kamala, K. Santhosh

Efficient Energy Management System for Solar Energy

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Original scientific paper

Solar power is the major renewable energy source opted by developing countries as stand-alone / Grid enabled system. Industries and educational institutions are opting for solar energy to combat power crisis. This paper proposes knowledge based, self configurable, smart controller to efficiently use solar energy according to load, under frequent grid failure environment. It is enabled with fault identification and isolation. Extension to higher power capacity is easily achieved with plug and play mechanism. Proposed control architecture is implemented using Field Programmable Gate Array (FPGA), that supports modular level implementation with well defined interfaces for each sub-system. It can be used with low power as well as high power photo-voltaic system. Efficiency of the proposed architecture is demonstrated for the photo-voltaic system installed in educational institution.

Key words: Field Programmable Gate Array, Photo-voltaic system, Pulse width modulation, Stand alone system.

Sustav za efikasno upravljanje solarnom energijom. Solarna energija spada među glavne obnovljive izvore energije odabrana od strane zemalja u razvoju kao samostalnih izvora ili umrežene s ostalim izvorima. Industrija i edukacijske institucije predlažu solarnu energiju u borbi protiv energetske krize. U ovome radu predstavljen je samokonfigurabilan regulator za efikasno korištenje solarne energije s obzirom na opterećenje i česte promjene u mreži. To je omogućeno uz identifikaciju kvara. Ekstenzija na visoke snage jednostavno se postiže sa uređajem koji se može odmah koristiti. Regulator je implementiran koristeći programirljive logičke sklopove (FPGA) koji podržavaju modularnu implementaciju svake razine sa sučeljem prema svakom podsustavu. Predloženi sustav može biti korišten za niske snage kao i za visoke snage kod fotonaponskih sustava. Efikasnost predložene arhitekture testirana je na fotonaponskom sustavu postavljenom na edukacijskoj instituciji.

Ključne riječi: programirljivi logički sklopovi, fotonaponski sustav, pulsno-širinska modulacija, samostalni sustav

1 INTRODUCTION

Recent applications of high power PV (Photo-Voltaic) system utilize advanced techniques such as Distributed Maximum Power Point Tracking (MPPT), converter per panel and multi-level converters [1]. Distributed MPPT exhibits more losses due to mismatch in different PV modules. Module Integrated Converters (MIC) [2] are developed to reduce these losses. They are used to integrate PV system with Grid, future energy delivery, dc link etc [3-6]. Multi-level converters/inverters are preferred for improved power quality [7] with lower harmonic distortion [8-9]. Design of multi-level system controller is complex and high-end hardware is required to generate multiple switching pulses [10-11]. Necessary high frequency switching signals of these systems are generated by CMOS implementation of controller [12-13]. Very Large Scale Integrated (VLSI) circuit technology provides optimum solution to the design issues of modular integrated / multi-level converters.

Efficient energy management is another prime requirement of photo-voltaic system. Adika and Lingfeng proposed load scheduling algorithm for efficient energy consumption. Simulation results of this algorithm shows savings in energy cost of 9.43% and pricing of 10.92%. [14]. Zigbee and PLC based smart Home Management System is designed to schedule the home appliances usage according to energy generation and consumption. [15]. Demand response program is developed to save money by reducing reverse flow in the energy production and consumption centre [16]. Existing literatures discuss energy management system for domestic purpose.

This paper proposes new smart control architecture for modular multi-level photo-voltaic system, which supports wide load variation under frequent grid failure environment. PV module control signals are generated considering efficient energy management scheme. Controller is designed to use solar power for the following purposes with fault detection and isolation.

- Battery charging

- Supply peak load
- Connect with AC grid

It supports plug and play mechanism. System capacity can be easily extended by including new solar panels without affecting existing modules. Modular implementation of the architecture enables faster fault identification and isolation. Figure 1 shows the interfacing signals of proposed controller.

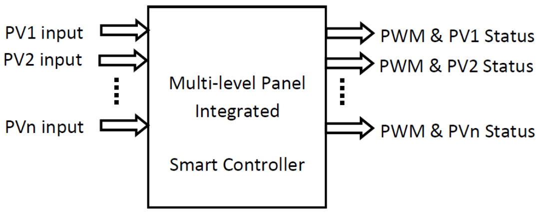

Fig. 1. Modular Multi-level controller interface

Smart controller capable of processing more inputs and generating control signals is mandatory for multi-level PV system. Suitable choice for this controller implementation is FPGA that supports parallel and pipe-lined architecture for faster execution of algorithms [17-20].

Section 2 discusses about operating modes of proposed photo-voltaic system. Result oriented research can be enhanced by installing FPGA based modular multi-level PV system in educational institution. Section 3 explains the implementation of the proposed system in educational institution as case study. Control signals of different operating modes are validated by simulation results in section 4. Section 5 provides the hardware utilization and timing parameters of the proposed controller. Section 6 concludes with features and future extension of the proposed work.

2 SMART PHOTO-VOLTAIC SYSTEM

Proposed controller uses single processor to generate control signals required for PV module and energy management. It uses minimum number of switching devices for various applications of PV system like battery charging, supply peak load / AC grid. Full bridge inverter [21-26] topology is chosen for the architecture. Schematic of proposed switching module for single stage is shown in figure 2. Fast switching relays like Phoenix contact DPDT MR 12VDC/21-21, could be used for switches SW1-SW5. Seamless operation is achieved using soft start routine and initializing the relay before its switching delay of 7ms. Power MOSFET device (Metal Oxide Semiconductor Field Effect Transistor) IRFP150PN is used for transistors Q1-Q4.

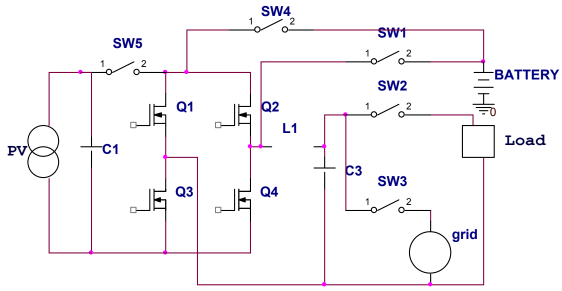

Fig. 2. Proposed Single Stage Switching Module

Table 1. Operating modes of proposed system

Source	Operation	Control signals
Solar Power	Battery charging	SW1, SW5, PWM for Q2
Solar Power	Supply AC load	SW2, SW5, Sine PWM for Q1-Q4
Solar Power	Supply AC grid	SW3,SW5, Grid synchronized Sine PWM for Q1-Q4
Battery power	Supply AC load	SW2, SW4,Sine PWM for Q1-Q4

Solar power is utilized to supply load as shown in figure 3. Photo-voltaic cell is connected to load through full bridge inverter and filter. Transistors Q1-Q4 are applied with sine PWM control signals generated by the controller.

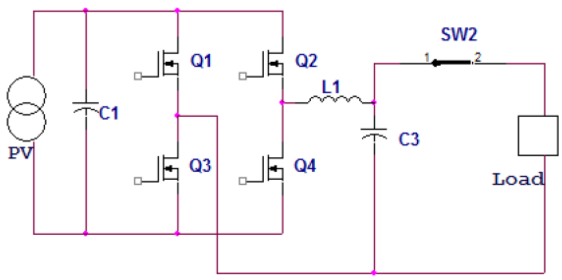

Fig. 3. Solar power supplying load

With no load and battery charged condition, solar power is interfaced with grid as shown in figure 4. Grid synchronized sine PWM signals are generated for the transistors Q1-Q4.

With the availability of solar power and no load condition, battery charging is achieved as shown in fig. 5. PWM based battery charging [27-28] is used to generate control

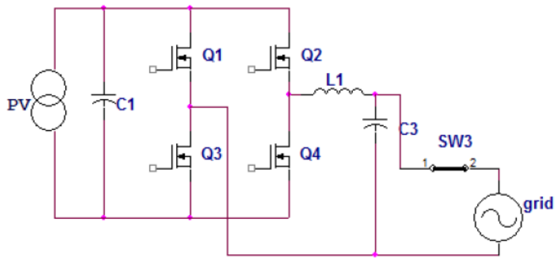

Fig. 4. Solar power interfaced with grid

signals, which activate switch sw1 and transistor Q2.

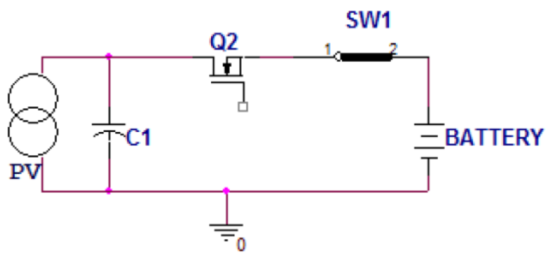

Fig. 5. Battery Charging mode

To meet load requirements during evening hours, battery is used to supply load as shown in fig. 6.

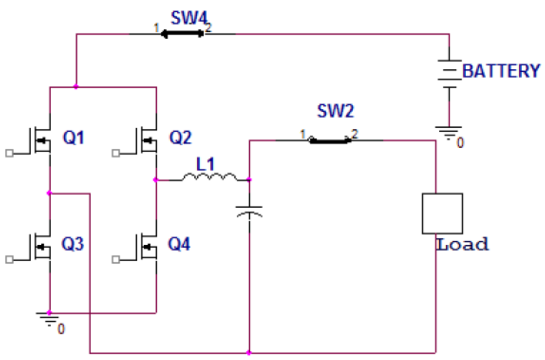

Fig. 6. Battery supplies load in the absence of solar power

Interface signals of proposed controller of single stage photovoltaic system is shown in figure 7. Solar panel voltage, current, battery voltage and load current are the input signals for controller action. Analog to digital converter ADC0808 converts these analog signals into 8-bit digital signal. Eight input channels of ADC can be utilized by two PV stages. Control signals required for ADC (ALE, SOC, EOC, OE), switches (SW1-SW5), and transistors (Q1-Q4) are generated by controller. Status of each PV module is also indicated by an output signal. Grid synchronization input is common for all PV modules. Input signal 'mode' decides the operating mode of controller. Two photovoltaic modules need maximum 35 Input / Output pins for the controller.

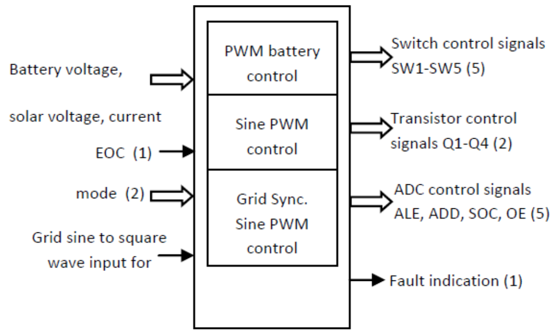

Fig. 7. Interface signals of smart controller for single stage PV system

Virtex 6 FPGA device XC6VLX240T-1FFG1156 [29] is chosen for smart controller implementation. It has 600 input/output pins and capable of processing signals derived from 33 photo-voltaic modules simultaneously. It can be efficiently utilized for multi-level photo-voltaic system as shown in figure 8.

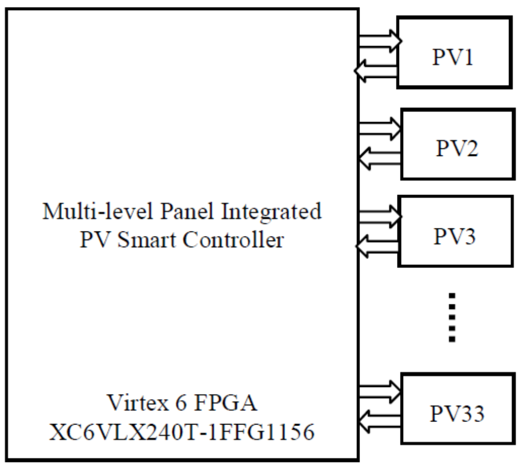

Fig. 8. Multi-level Modular Panel Integrated Smart Controller

Control signals of this architecture are suitable for all standard power electronics converter/inverter modules. Battery charging control is similar to converter control. It can be used with any type of DC-DC converter [30] configurations, namely cascade [31], module integrated, panel integrated, per panel converter [32] architectures. Control signal generation of each module is independent of others. Therefore mixed combinations of converter and inverter operating modes can be chosen for power configuration of Building integrated PV system [33-34]. Module Integrated converters configuration of inverters [35-36] can be implemented with inverter mode of controller.

3 CASE STUDY : MODULAR MULTI-LEVEL PHOTO-VOLTAIC SYSTEM

Efficient solar power utilization is mandatory for developing countries, where frequent grid failure is common phenomenon. This paper proposes FPGA based smart controller for energy management of solar powered computer laboratory in academia. FPGA based multi-level photo-voltaic system in academia assists research in the following fields:

- Advanced and complex MPPT algorithm development using FPGA
- Design and analysis of charge controller, converter and inverter topologies
- Controller design for efficient energy management
- Development of multi-level photo-voltaic system.

Consider a laboratory with 30 computers and lighting, and it is operational for 3 hours in forenoon and afternoon. In the average 9 sunshine hours/day, peak load period is 6 hours. At peak load, solar power is completely utilized for laboratory; otherwise it is used for battery charging or Department lighting. During week end holidays and vacation periods, solar power is tied with AC grid. Proposed controller of this paper efficiently utilize the solar power for either one of the four cases namely Laboratory power, Department lighting, Battery charging or feeding grid as given in table 2 and shown in fig. 9. This solar power utilization is more suitable for regions of dry weather like South India.

Battery back-up is provided for ten computers and lab lighting for three hours, to conduct part time classes in evening hours. Battery charging is enabled with five solar panels. Operation of controller is defined in four operating modes as given in table 3. In mode 00, once the battery is charged, solar power is connected to load or grid according to requirements.

Modular multi-level implementation of control architecture is chosen for 5KWp photo-voltaic system. Each PV module of 500Wp is chosen and it can be varied according

Table 2. Utilization of Solar power

Sunshine hour - 7.30 AM to 5.30 PM; Working hour – 8.30AM – 5.30PM		
Day	*Period*	*Load*
Working day	7.30-8.30 am	Battery charging / Grid
	8.30-9.30 am	Battery charging / Department lighting
	9.30am-12.30pm	Computer lab
	12.30-1.30pm	Battery charging / Department lighting
	1.30-4.30 pm	Computer lab
	4.30-5.30 pm	Battery charging/ Department lighting
Holidays	7.30 am to 5.30 pm	Battery charging/ Grid

Table 3. Operating modes and Load

Function	**Operating mode**	**Load**
Battery charging	00	Battery
Solar power to peak load/ load	01	30 Computers / Department lighting
Solar power to grid	10	AC grid
Battery to load	11	10 Computers/ Lab lighting

to the requirement. Capacity of PV modules can be increased by adding solar cells in series / parallel. Overall system block diagram is shown in fig. 10. It has advantages such as better utilization of solar power, extension to higher power without affecting existing modules, greater safety in installation and maintenance with cost effective solution. Control signals of all modules are generated in synchronization with single FPGA clock. Therefore best synchronization among modules is achieved.

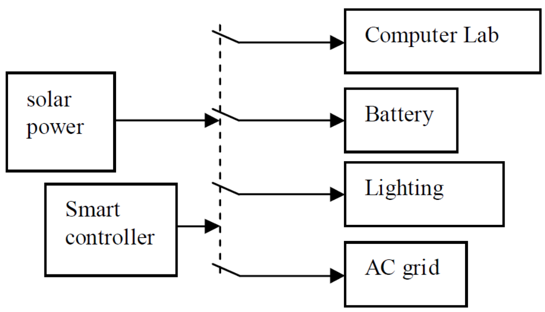

Fig. 9. Solar power utilization

4 SMART CONTROLLER MODULE SIMULATION

Major functional modules of the controller are battery charge controller, sine PWM controller and Grid synchronized PWM controller.

According to the operating mode, one of the controllers is activated. State flow model of controller is shown in fig. 11. Independent operating mode for each module enables configurations of different types of multi-level power configurations [37-38]. Under faulty condition, all control signals are deactivated and switches are off. Controller operating modes are simulated in Xilinx ISE 12.2 simulation platform.

4.1 Battery Charge Controller

It is activated by mode 00 and senses battery voltage, to find state of charge. If it is not charged, battery charging algorithm is executed to generate PWM signal for transistor Q2, and control signals SW5 and SW1. Once battery is charged, sine PWM / grid synchronized PWM controller is activated according to load requirement. Input and output signals of this controller are shown in fig. 12. Simulation results of this controller are shown in fig. 13 with PWM signal of 50% duty cycle. Duty cycle of PWM signal is varied by choosing proper count value. Fault is indicated, if battery voltage remains constant for a longer time, while charging.

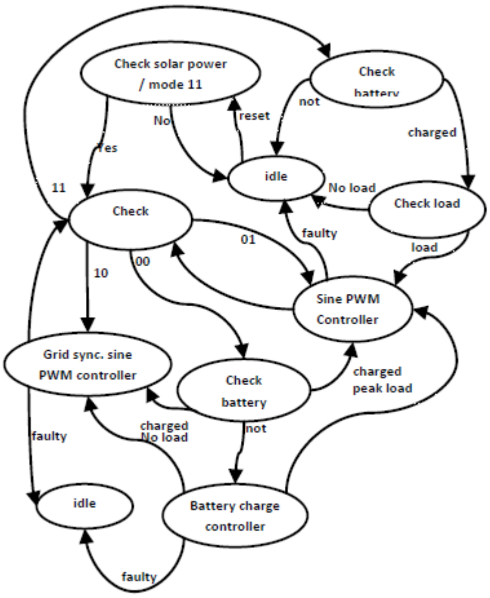

Fig. 11. State Flow Model of proposed controller

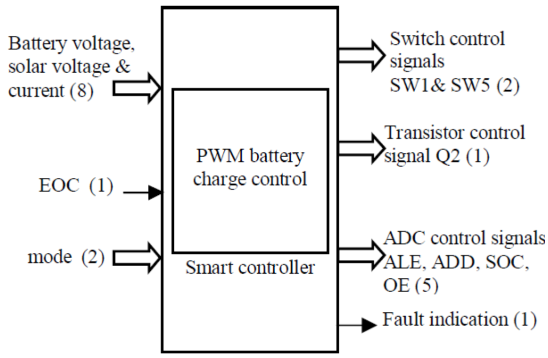

Fig. 12. Battery charge controller interface

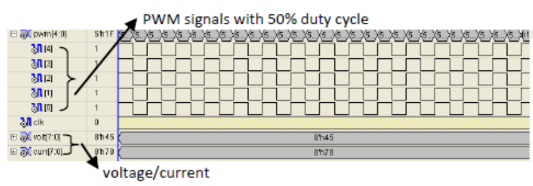

Fig. 13. PWM signal output for five stages

4.2 Sine PWM Controller

Sine PWM signal is generated using sine look up table with triangular wave carrier signal. Frequency of sine PWM is varied by changing count used for signal generation. It is activated in mode 01 and mode 11. Interface

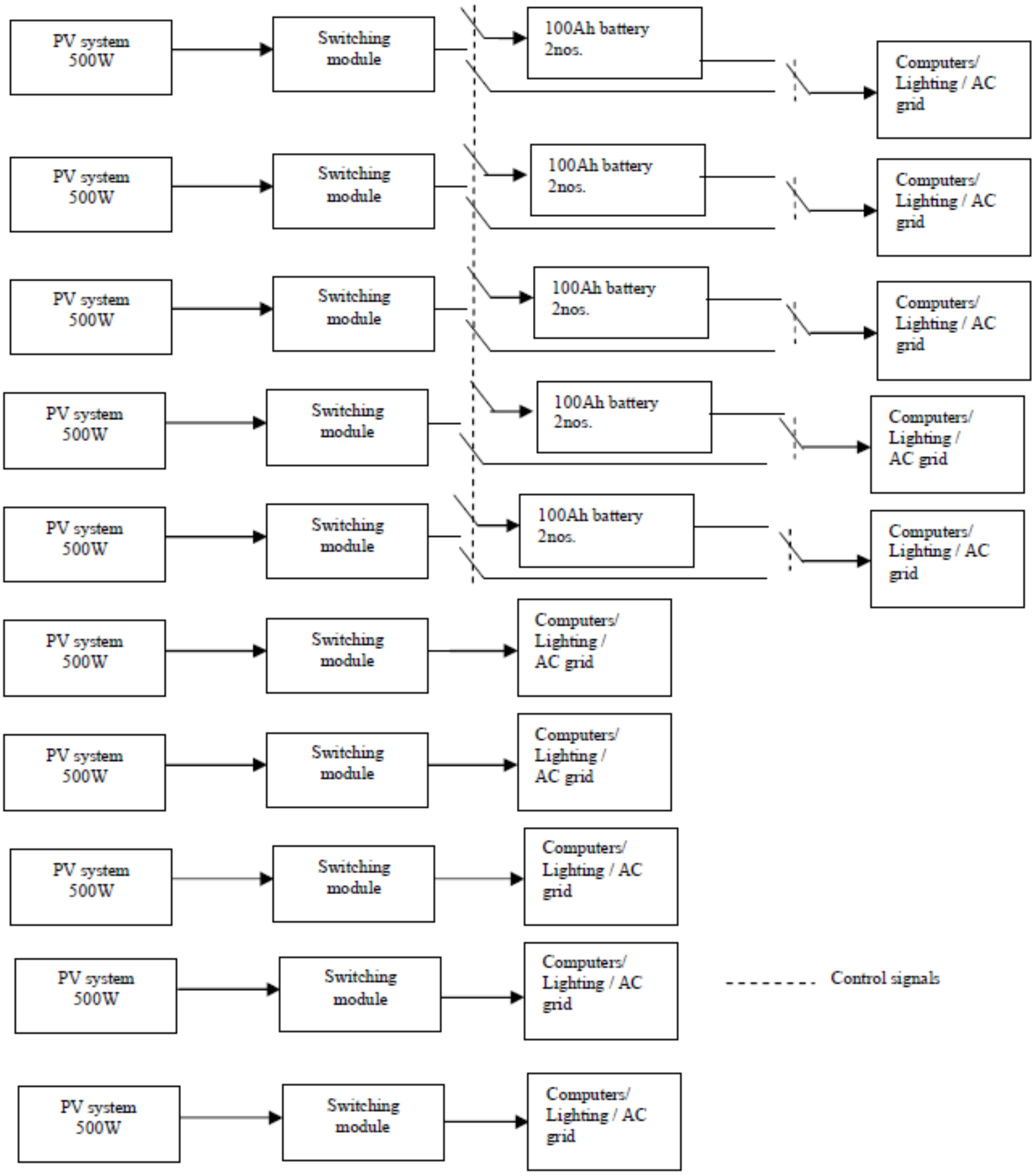

Fig. 10. Multi-level Modular Panel Integrated Photo-voltaic system

signals of this mode are shown in fig. 14. Sine PWM signal generation is shown in fig. 15. Over current is indicated by fault indication.

4.3 Grid Synchronized PWM Generator

It is activated manually by mode 10 or automatically after battery charging at no load. Interface signals of this controller are shown in figure 16. Grid output is scaled down by step down transformer and it is converted into square wave. Rising edge of square wave is used to generate sine PWM signal in synchronization with grid. Sine PWM wave is generated in synchronization with rising edge of square wave as shown in fig. 17. Grid failure is indicated by fault and all switches are opened to tackle islanding condition.

4.4 Mode 11

This mode is used to supply load from battery during non sunshine hours. If battery is charged, sine PWM controller is activated. Switches SW2 and SW4 are activated

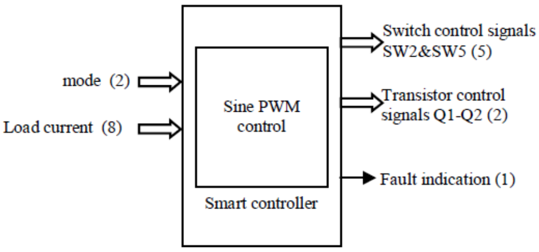

Fig. 14. Sine PWM control interface

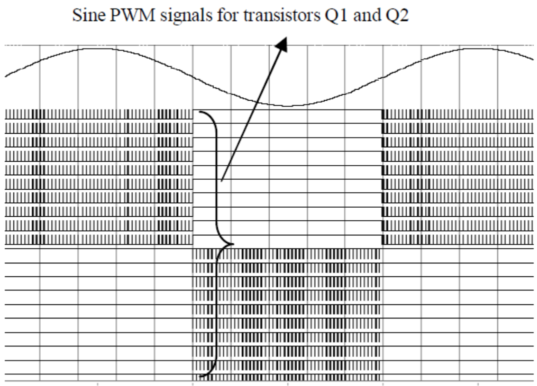

Fig. 15. Sine PWM generation for 10 stages

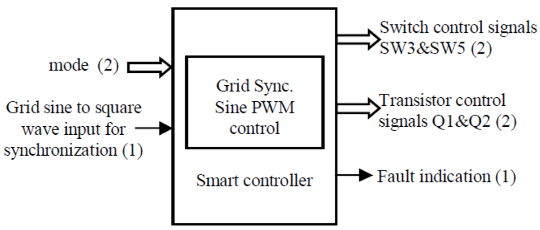

Fig. 16. Grid synchronized sine PWM controller interface

and others operations are similar to mode 01.

Fault in any of the module is detected by comparing voltage and current values at various stages with its limiting values. Higher current exceeding the limit is indicated as fault, corresponding control signals are de-activated as shown in figure 18. Simulation results show, fault in stage 1. Switches of stage 1 are off with zero output in the corresponding signals.

5 EXPERIMENTAL RESULTS AND IMPLEMENTATION

Single stage prototype model is developed using Spartan 3E FPGA. Oscilloscope captured signals of inverter

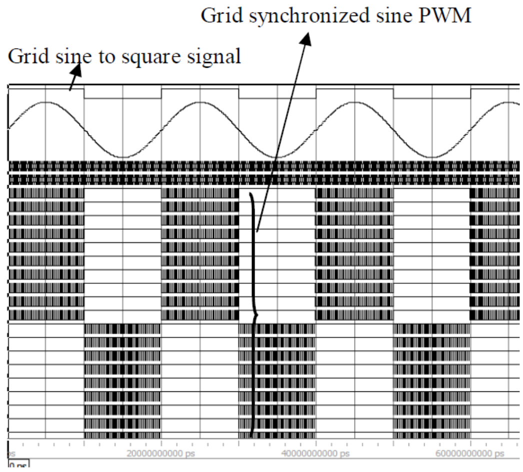

Fig. 17. Grid synchronized PWM signal generation

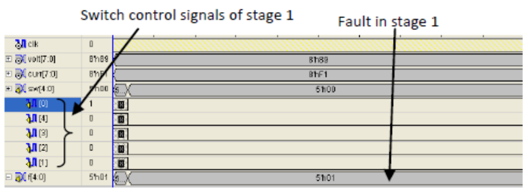

Fig. 18. Fault in stage 1

output and PWM signal for battery charging are shown in fig. 19 and fig. 20. Peak to peak amplitude of inverter output is 24V. Control signal generation is independent of the capacity of PV module. Therefore solar panel of 100 Wp with 12V, 42Ah sealed lead acid battery is used to generate various control signals. Experimental set-up is shown in fig. 21.

Virtex 6 FPGA device XC6VLX240T-1FFG1156 is chosen for this modular multi-level controller implementation. Major functional modules and their interconnectivity of the proposed controller are shown in fig. 22.

ML605 evaluation kit with the FPGA is shown in fig. 23. Implementation of proposed controller architecture utilizes maximum 37% of hardware. Logic utilization of the hardware and timing issues provided by synthesis report are given in table 4.

6 CONCLUSION AND FUTURE WORK

Efficient energy management system for modular multi-level photo-voltaic system is implemented using FPGA. Major contribution of this work is in the generation of control signals of multiple PV modules considering efficient energy management scheme. Proposed multi-level

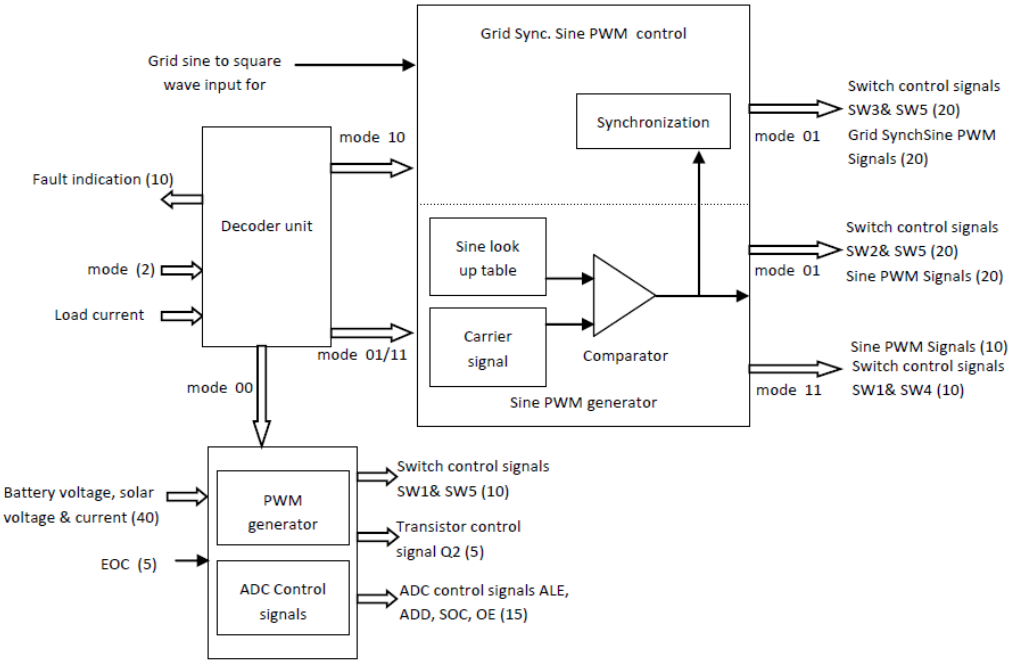

Fig. 22. Functional blocks of proposed controller

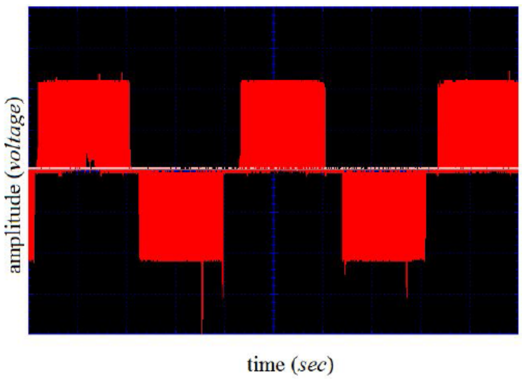

Fig. 19. Output of Full Bridge Inverter

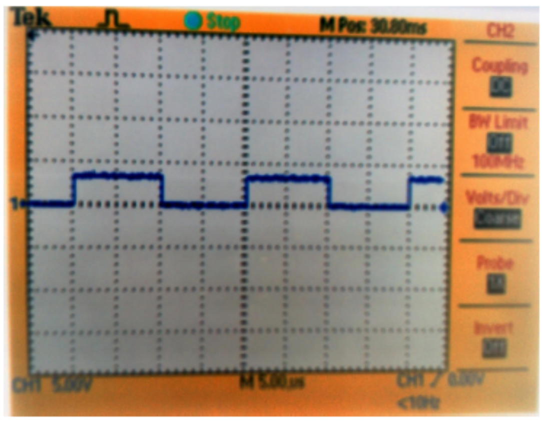

Fig. 20. PWM Signal for battery charger

PV controller includes the functionalities of energy management system. Implementation of this proposed architecture using micro-processor / controller or digital signal processor is limited by its fewer inputs / outputs. FPGA supports more input / output signals synchronized with all modules. PV System capacity can be extended easily without affecting existing working modules.

Performance of smart controller is illustrated for the photo-voltaic system suitable for educational institution with varying load condition. Input/output requirements and control signals of various operating modes are discussed. Simple algorithms such as PWM based charger and sine PWM generator are selected for the controller. Switching module of this research work uses less numbers of transistors. Industries develop cutting edge technological solutions in the field of solar energy, by supporting this type of research in academia.

Efficiency of this system is same as that of conventional

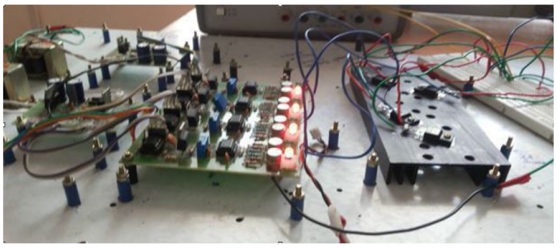

Fig. 21. Experimental setup

Table 4. Logic Utilization

Logic Cells	Utilization
slice registers	0% (281/301440)
slice LUTs	0% (671/150720)
fully used LUT-FF pairs	37% (260/702)
Bonded IOBs	15%(95/600)
Timing Analysis Minimum period 9.602ns; Maximum frequency 104MHz Set-up time 3.186ns; Hold time 0.84ns	

Fig. 23. Virtex 6 FPGA XC6VLX240T-1FFG1156

systems. This work can further be extended by developing complex MPPT algorithms [39-41] for charger and inverter to improve the efficiency. Various MPPT based control algorithms can be developed, considering different source and load combinations. Electronic storage of characteristics of all modules in standard format facilitates easier controller design and its configuratio1 [42-43]. Automatic change over to various operating modes eliminates manual operation.

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Kamala J. received her B.E. degree in Electronics and Communication Engineering from Madurai Kamaraj University in 1989, M.E. degree in VLSI Design from Bharathidasan University, in 2002 and Ph.D from Anna University, Chennai, India in 2011. She is currently working as Assistant Professor in the Department of Electronics and Communication Engineering, Anna University, Chennai, India. Her research includes VLSI implementation, Power Electronics, Solar power controllers and Smart sensors.

Santhosh K. received his BE degree in Electronics and Communication Engineering from Anna University, Tirunelveli, and ME degree in VLSI design from Anna University Chennai in 2011 and 2014 respectively. He is currently working as an Assistant professor at IIET Chennai. His research area includes Power Electronics and VLSI RF circuits.

AUTHORS' ADDRESSES

J. Kamala Ph.D, Assistant Professor, Dece,
College of Engineering Guindy,
Anna University, Chennai,
TAMIL NADU - 600025, India.
email : jkamalaa@annauniv.edu, jkamalaa06@gmail.com
K. Santhosh, M.E., Dece,
College of Engineering Guindy,
Anna University, Chennai,
TAMIL NADU - 600025,India.
email : lksanthosh00@gmail.com

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