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Techno–economic Viability of the Hybrid Solar (PV)-AC Utility Interfaced Power System for Rural India

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A hybrid solar Photovoltaic (PV)-AC utility interfaced power generating system has been developed for domestic use. The system consists of a photovoltaic array (installed on the structure of the roof), an intelligent power controller and an inverter with battery as an energy storage device. The system works in such a way that it utilises maximum power from the PV source, converts it into useful AC power for household critical loads. The variation in PV power is supplemented by a grid power source integrated with the PV source. The system finds wide application in rural sectors where the conventional source of supply has been restricted and further expansion of utility (grid) supply is not possible due to various technical and economic reasons. Thus it saves grid power and reduces the overburdening of power on grid lines. The technology of solar energy conversion into useful AC power through push-pull configured transistorised inverters involves the PWM strategy which produces a very near sine wave output with minimum THD, leading to a highly efficient system. The system has been designed for 300 W power supply for critical loads. The simulation for the generation of PWM pulses and the computation of THD value has been carried out. Performance of the system was tested under various abnormal conditions like grid failure, low or no sunshine conditions, etc. The system provides optimum use of solar PV power with environmental benefits.

Key words : *Intelligent Hybrid (PV-AC) System Controller (IHSC), Total Harmonic Distortion (THD), Pulse Width Modulation (PWM), Main Switching Signal (MSS), Polarity Control Signal (PCS), Veri-log Hardware Descriptive Language (VHDL), Field Programmable Gate Array (FPGA), Depth of Discharge (DOD), Watt (W), Hour (h)*

1.0 INTRODUCTION

India has a large area of land with an average solar energy of 3-5 kW/m^2 per day, being received over 300 clear days in a year. Even if 1% of this land is used to harness solar energy at an overall efficiency of 14%, as much as 400 x 10^9 kWh per year of electricity can be generated [1]. Several solar power plants ranging from 25 kW_p to 200 kW_p have been installed in our country. More than 1 million solar home lighting systems have been working for the last three years. This solar power supply can be used to provide lighting to villages.

2.0 SOLAR (PV)-AC UTILITY INTERFACED POWER CONVERTER SYSTEM

The PV power system, in general, is configured in two different ways [2,4,6,7] **:**

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- Stand alone autonomous and grid interfaced PV-AC hybrid system
- Grid (utility) inter-tie system

The stand alone PV system is bulky as it requires a larger size of PV panels and energy storage device (e.g. battery) even for a small load where as a grid inter-tie system does not involve energy storage devices and becomes less costly as compared to the stand alone system, but it can not provide power in case of grid failure beyond sun hours. The surplus PV energy during day hours is supplied to the grid and taken back from it as and when needed beyond sun hours. Moreover, it also requires a sophisticated and costly inverter circuitry to synchronise with grid supply.

The stand alone utility interfaced hybrid solar (PV)-AC system falls in between the two and is a better choice in many respects [3]. In this system, grid power is integrated with PV as a supplementary source which ensures the supply of power to load under all varying conditions like grid failure, low or no sun insolation and the changing demand of loads at the user's end. The important advantage of the solar PV-AC utility interfaced power system is that it can also work as a stand alone PV system at places where grid power is not available. The existing grid coupled emergency power pack is not facilitating them to meet their energy requirements in a cost-effective way.

An attempt has been made to design and develop a prototype sample to examine the technical feasibility and economic viability of its use in rural sectors of the country. This system decreases the day time load power dependency on the utility grid and thus conserves energy. Further, this system focuses on the overlooked fact that the existing grid coupled emergency power pack available in the range of 300 W to 1 kW having battery as storage device, draws a considerable amount of electricity from the grid supply for its regular normal operation, leading to a significant enhancement of the monthly/ annual electricity bill of the consumer. The grid coupled energy power back (battery inverter) requires more than 10 hours to charge the battery and make it ready for delivering continuous power to loads upto 4 hours.

The solar power conversion technology involves three steps namely: solar energy conversion into electrical power, power conditioning and load management. In the proposed study, the solar energy is converted into DC power and supplemented by the other backup sources i.e. the grid or battery source integrated with the PV source and fed to the inverter to produce approximated PWM sine wave output across the load. The intelligent controller monitors the load power requirement and switches on the critical loads on priority basis to match with input power. The schematic diagram of the system is shown in Fig. 1.

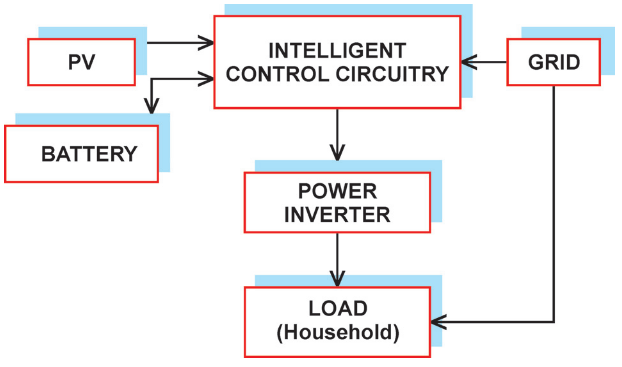

FIG. 1 SCHEMATIC DIAGRAM OF SOLAR (PV)-AC UTILITY INTERFACED POWER

3.0 SYSTEM MODEL

The system model consists of the PV panel, intelligent controller, inverter, battery and the power module configured in push-pull topology as shown in Fig. 2.

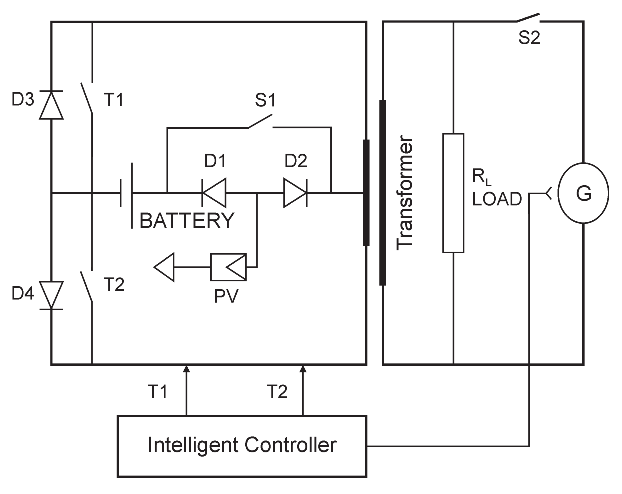

FIG. 2 POWER MODULE OF THE SOLAR (PV)-AC GRID CONNECTED POWER CONVERTER SYSTEM

The bipolar transistor, a self commutating device has been used as a switching device in the power module of the circuit [5].

The PWM switching pattern of AC output waveform is followed as per the sequence given below:

$$V_0 = + K_T \times V_{dc} \text{ (when } T_1 \text{ is on, } T_2 \text{ is off)} \quad (1)$$

$$= 0 \text{ (Transition } + V_{dc} \text{ to } - V_{dc}) \quad (2)$$

$$= - K_T \times V_{dc} \text{ (when } T_2 \text{ is on, } T_1 \text{ is off)} \quad (3)$$

Where, V_{dc} is the input DC voltage and V_0 is the output PWM AC voltage and K_T is a scaling factor which is decided by the turn ratio of Transformer.

4.0 CONTROL STRATEGY

The PWM pulses for N number per half cycle (Fig. 3) produces AC waveform (approximated to sine wave). This is governed by the following expression:

$$\text{Pulse width } (Pi) = K\left(\frac{180}{2N}\right) x 2 \Big[\quad (4)$$

Where, i = 1......... N (number of PWM pulses per half cycle) and

K = Voltage regulating factor (0 – 1).

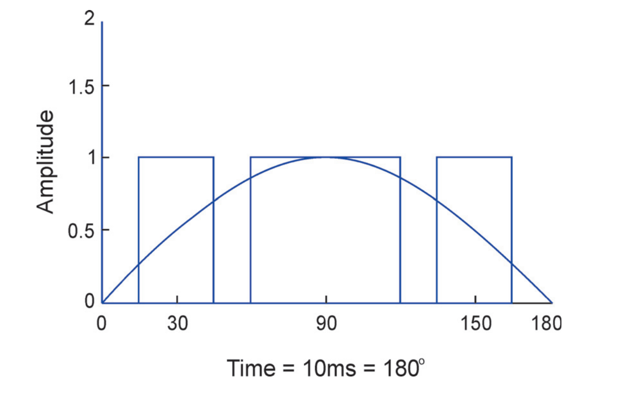

FIG. 3 PWM WAVE FORM AVERAGING TO A SINE WAVE FOR ONE HALF CYCLE (50 HZ)

The pulse width as well as notch width are computed by MATLAB software and are depicted in Table 1.

TABLE 1

PULSE WIDTH AND NOTCH WIDTH LOOK UP TABLE

Notch Width	Pulse Width
T_1 = 0.8330 ms	P_1 = 1.667 ms
T_2 = 0.8333 ms	P_2 = 2.217 ms
T_3 = 1.950 ms	P_3 = 1.667 ms
T_4 = 0.8333 ms	

PWM waveform generation is done through a computer program written in VHDL Code and its hardware implementation is done through Xilinx based FPGA Spartan 3E kit (Fig. 4).

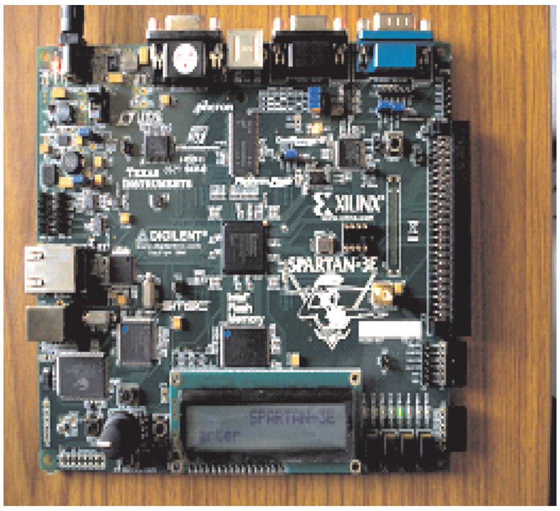

FIG. 4 FPGA SPARTAN 3E BOARD

The control drive PWM pulses are alternatively fed to transistors T_1 and T_2 of the inverter power module of circuit to produce positive and negative polarity of PWM AC voltage waveform (Fig. 5).

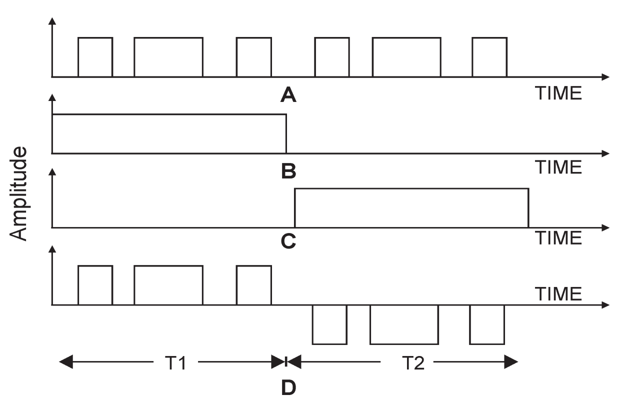

FIG. 5 (A) PWM MSS (B) AND (C) PCS WAVEFORMS (D) PWM AC WAVEFORM

5.0 INTELLIGENT HYBRID (PV-AC) SYSTEM CONTROLLER

The intelligent hybrid (PV-AC) system controller integrates the PV source with grid supply. One additional solar module of the same voltage rating (known as reference module) is used for checking the availability and magnitude of power. The voltage across the PV module changes with the change in load current and sun radiation. PV source voltage is maintained between 60% to 80% of its rated capacity. The low priority loads are switched over and put on the AC grid till the remaining high priority loads connected with the PV system match with the total available PV power. Thus the power, as required by critical loads of a rural house are met through integration of PV sources with grid power.

6.0 DESIGN OF SYSTEM COMPONENTS

The model design has been carried out for load requirement (300 W maximum) of a sample house which includes:

- Two 60 W fans
- Two CFL lamps rated for 23 W
- One 100 W TV

The PV and battery size are calculated from the energy balance equation.

(A) PV size

Load power $P_{TL} = (P_{PV} \times H) / f$ (5)

where,

H (sun hour) = 6.2 h

f (safety factor) = 1.5

$$P_{TL} = \sum_{6AM}^{6PM} P_L \text{ (sum of loads)} \times h \quad (6)$$

Where, h is working load hours.

Using the above equations (5) and (6):

P_{PV} = 1.5 x [(300 W x 6 h) / 6.2 h]

= 435 W

No of PV module (N) = 435 / 75 W_p

= 6 modules (7)

(B) Battery sizes

Battery AH = [Critical load (Wh) / Battery voltage] x DOD (8)

= 1800 Wh / 6 h = 150 Ah

= 4 x 33 Ah

Autonomy (Back up Period) =

(Power Stored / Load power) x DOD (9)

= (1800 Wh / 300 W) x 0.5 = 3 h

(Here, battery voltage = 12V and DOD = 50%)

7.0 GRID POWER SAVING

The grid power saving has been computed over a period of one year. The load power sharing as observed over the period of one year for a fixed monthly load of 54 kWh (300 W x 6 h/day x 30 days) is depicted in Table 2.

TABLE 2

GRID POWER SAVING AND PV CONTRIBUTION (IN %)

Month	Power from PV (kWh)	Power from grid (kWh)	PV contribution in %
Jan	30	24	56
Feb	36	18	66
March	42	12	78
April	45	09	83
May	42	12	78
June	36	18	66
July	30	24	56
Aug	30	24	56
Sept	30	24	56
Oct	33	21	61
Nov	36	18	66
Dec	30	24	66

From Table 2, average grid power saving has been achieved as 40%.

8.0 TECHNO-ECONOMIC ANALYSIS

To conduct a comparative techno-economic analysis of proposed 300 W solar (PV)-AC utility interfaced power converter system with commercially available conventional battery powered bi-directional inverter, life cycle cost analyses have been carried out.

The conventional battery inverter draws power from the AC grid for: (i) compensating the energy drawn from the battery during power shut down through boost/normal charging (ii) making up no load loss of the battery bank through trickle charging. The recharge of the battery takes place normally at the rate (C-10) of 10 hours.

A lead acid tubular battery of 150 Ah will require total maximum energy in a day of:

= 150 Ah x 12V = 1.8 kWh (10)

Therefore, monthly energy consumption will be:

= 1.8 kWh x 30 days = 54 kWh (11)

Hence, yearly consumption = 54 kWh x 12

= 648 kWh (12)

Life cycle cost analysis of the proposed solar converter with battery inverter has been reflected in Table 3.

TABLE 3

COST COMPARISON OF SOLAR (PV)-AC (LIFE CYCLE PERIOD OF 20 YEARS) WITH BATTERY INVERTER

Solar (PV) - AC module	**Battery Inverter**
Solar module (6 x 75W_p) Rs. 0.4 lakh	Not applicable
Battery one per 3 years Rs 0.6 lakh	Battery one per 3 years Rs 0.6 lakh
Grid power consumption 260 units @ Rs 6 for 20 years Rs 0.4 lakh	Grid power consumption 648 units @Rs 6 for 20 years Rs 0.8 lakh
Inverter Rs 0.06 lakh	Inverter Rs 0.06 lakh
Total Rs 1.46 lakh	Total Rs. 1.46 lakh

Note: The cost includes

1. Discount rate = 15 %
2. Inflation rate = 0.8
3. Life cycle of operation = 20 years

From Table 3, it has been observed that although the solar (PV)-AC utility interfaced power system is initially costly but after 20 years of its life cycle period, the system cost becomes comparable with the conventional battery inverter system. Further 50%–60% cost reduction is possible, if PV modules are purchased under subsidy or used as a building material in constructing roofs or walls of houses.

9.0 RESULTS AND DISCUSSION

(A) The simulated PWM waveform for N = 3 using Xilinx software has been shown in Fig. 6.

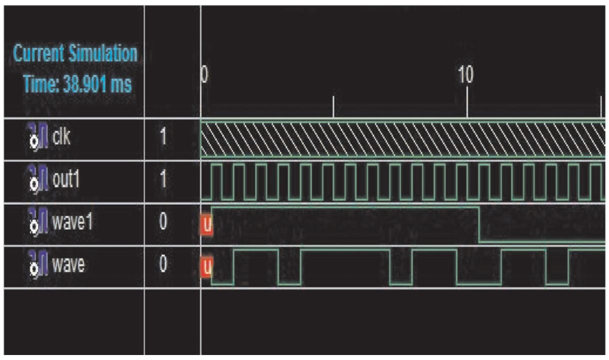

FIG. 6 SIMULATED PWM WAVEFORM FOR N (=3) PER HALF CYCLE

The circuit implementation has been done using the FPGA starter kit and tested on a prototype sample power module of a 300 W inverter. The oscilloscopic image of PWM control pulses and load wave form has been shown in Figs. 7 and 8 respectively.

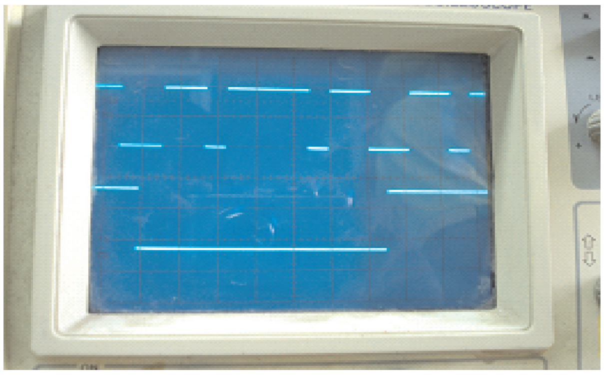

FIG. 7 PWM CONTROL PULSES

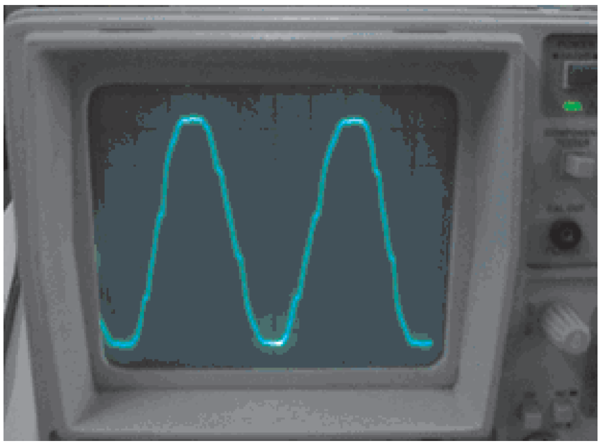

FIG. 8 LOAD WAVEFORM (220 V, 50 HZ)

(B) The THD computation of PWM waveform has been computed for N = 1 to 9 upto 15th harmonics content. The values are depicted in Table 4. From the table, it is observed that the THD value decreases with the increase in the number of PWM pulses per half cycle.

(C) Experimental data shows that 40% grid power has been saved. If the system is adopted by 0.375 million consumers which is only 15% of the total consumers, the total electricity saving could be around 36.3 million units during day time.

TABLE 4

THD COMPUTATION FOR DIFFERENT VALUES OF PWM PULSES (N) UPTO 15TH HARMONICS TERM

N \ n	n=3	n=5	n=7	n=9	n=11	n=13	n=15
N=1	0.3333	0.38873	0.41415	0.42879	0.43833	0.44502	0.44999
N=3	0.18196	0.42707	0.43599	0.56129	0.56204	0.56257	0.60122
N=5	0.035439	0.035909	0.15388	0.32554	0.33816	0.40516	0.4482
N=7	0.018487	0.018487	0.018487	0.019893	0.17297	0.30796	0.32895
N=9	0.011272	0.011275	0.011275	0.011275	0.011276	0.015853	0.018371

Note : 1 THD value is always less than 1

2 Where, N = PWM pulses per half cycle, n = number of odd harmonics

10.0 SUMMARY AND CONCLUSIONS

A small scale solar (PV)–AC utility interfaced power system has been developed to operate with the AC grid. The system consists of a photovoltaic array installed on the rooftop, a hybrid controller and inverter unit. The newly developed hybrid controller works in such a way that maximum available solar power is utilised and the remaining power is drawn from the AC grid to meet the total power requirement of rural houses. The battery used in the system provides necessary backup in the absence of PV power under low or no insulation period. The low Total Harmonic Distortion (THD) value (< 3%) of output waveform has resulted in low loss in the system due to elimination of lower order harmonics content leading to a highly efficient system. The system performance is well suited for operation even if grid failure exists for a prolonged period. The solar (PV)–AC system requires only 10 m^2 area (approximately) on the rooftop of houses thus avoiding the use of extra land. The system provides pollution free green power which is attractive and has a positive socioeconomic impact on society.

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