Implementation of a grid-tied emergency back-up power supply for medium and low power applications

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Article Info	ABSTRACT
	Emergency back-up power supply units are necessary in case of grid power shortage, considerably poor regulation and costly establishment of a power system facility. In this regard, power electronic converters based systems emerge as consistent, properly controlled and inexpensive electrical energy providers. This paper presents an implemented design of a grid-tied emergency back-up power supply for medium and low power applications. There are a rectifier-link boost derived DC-DC battery charging circuit and a 4-switch push-pull power inverter (DC-AC) circuit, which are controlled by pulse width modulation (PWM) signals. A changeover relay based transfer switch controls the power flow towards the utility loads. During off-grid situations, loads are fed power by the proposed system and during on-grid situations, battery is charged by an AC-link rectifier-fed boost converter. Charging phenomenon of the battery is controlled by a relay switched protection circuit. Laboratory experiments are carried out extensively for different loads. Power quality assessments along with back-up durations are recorded and analyzed. In addition, a cost allocation affirms the economic feasibility of the proposed framework in case of reasonable consumer applications. The test-bed results corroborate the reliability of the research work.

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1. INTRODUCTION

Modern power system architecture integrates with sustainable and definitive power electronic converters consisted of effectual circuit structures and stable operational characteristics. These converters are generally realized and configured as switching networks with active and passive switching modules, power transfer devices and circuit constituents like resistor, capacitor, inductor etcetera. The infrastructure comprises control loops which feed switching signals to the converter circuit. These switching converters based power generation and distribution models can work in both grid-connected and islanded modes. In any case, these converters can perform as alternatives to the traditional power generation and distribution networks. Many regions across the world fall victim to grid power shortage, frequent distribution failure, very poorly regulated supply, glitches in the constituent power sub-stations and expensive infrastructure. In the events of grid power unavailability, emergency utility loads (also known as critical loads) can be supplied power by these uninterruptible and continual power sources. Thereby, practitioners and researchers indulge themselves in designing and implementing power electronic converters of different topologies and architectures for ensuring effective supply of electrical energy to consumers. Moreover, these converter networks are deployed in developing efficient renewable energy sources enabled power systems and scalable microgrids, as reported in [1-4]. These microgrid

technologies extend the horizon of clean and unwavering electrical energy generation and supply incorporating the cutting edge premises of power electronics.

In this article, a medium and low power utility back-up system is presented, which is developed using power electronics and control devices and methodologies. The system design, equivalent mathematical models of the switching converter circuits and obtained PLECS simulation results of the system are reported in [5]. The proposed research design consists of a battery-sourced 4-switch push-pull inverter circuit. This power inverter unit feeds energy to the consumer end when the mains supply is unavailable. A DC-DC boost converter charges the battery. The grid connection of the designed framework is substantiated through the rectifier-link source end of the battery charger. An electrical isolation at the input terminal of the battery charger is implicated, which steps-down the grid voltage (230 V r.m.s. to 12 V r.m.s.) and the converter produces a suitable voltage level (24 V DC) to charge the battery. In this proposed system, the charger maintains a charging voltage twice the nominal battery voltage.

The switching operation of the DC-DC boost converter is controlled by high frequency (40 kHz) PWM signals. The switching frequency is maintained as such to reduce the current ripples, size of the filter components and switching device conduction losses. The converter operates in continuous conduction mode (CCM), which means the average inductor current is always greater than the ripple component and the current does not go negative during the entire cycle of operation. A 4-switch push-pull inverter offering a high current driving ability is used as the energy feeder in case of grid power failure. Snubber components connected at the switching devices reduce overall $\frac{dv}{dt}$ effects during circuit operation. At load end a 50 Hz center-tapped step-up transformer is located to generate suitable range of utility voltage and provide galvanic isolation between the power supply port and consumer port. Finally, an L-C low pass filter is designed at the load side. The inverter switches are controlled by two complementary fixed duty ratio PWM signals of the mains line frequency (50 Hz). During on-grid condition, the loads and the battery are fed power by the grid and the charger, respectively. During off-grid condition, the customized power supply system delivers power to the loads. The power transfer switching from grid to the customized power supply system is automatic and instantaneous, which means no humane involvement is required and no considerable delay is compromised. For this transfer application, a changeover relay with a switch operating rate of 3-5 ms is employed here. There is a relay switching circuit to control the charging process of the battery. If the battery voltage is at its rated value (12 V), the charge controller disconnects the battery from the charger, and thus prevents the over-charging phenomenon.

There are a number of research works and associated experiments conducted to implement reliable power supply frameworks based on power electronic means, such as [6, 7]. In these works, innovative designs of power inverters are articulated. Moreover, a high gain switched-coupled-inductor-switched-capacitor step-up converter topology for practical applications is presented in [8]. In addition, several novel designs of DC-AC converters for industrial applications are reported in [9-26]. High sending-end power factor and reduced voltage and current THD are significant features of a efficient power system. The proposed system provides good sending-end power factor and low voltage and current THD values, as obtained from the laboratory assessments. Several power electronic systems reporting power factor improvement and THD reduction in case of non-linear loads are presented in [27-30].

In [5], a state averaging model of the battery charging circuit is derived and a Laplace domain transfer function is determined from the time domain model. Additionally, the inverter circuit is analyzed as a switching converter model in [5]. In this article, experimental test results of the proposed design are presented. A test-bed of different AC utility loads rated from 60 W to 250 W is configured for experiments. Sending-end power factor, input-output power quantities (voltage and current) with the associated THD values, utility back-up power durations and power efficiencies in accordance with load variations are evaluated. An overall cost estimation is presented as well.

From literature reviews, background study and state-of-the-art investigations, it can be implied that reliable and economically feasible power electronics based clean and alternative energy solutions are essential in modern power systems. In regard to this prospect, this article presents a grid-connected emergency back-up power system providing a cost-reasonable medium power architecture for frequent consumer and industrial applications. The framework proposes custom engineered PWM signal generation circuits, power inverter circuit and relay based switching circuits. The proposed design is simpler and more cost-effective than those reported in [9-26] with a potential efficiency merit. The in-depth experimental validations affirm the applicability and major contributions of the proposed research work.

The remnant of the manuscript is organized as follows. Section 2. presents the overview of the pro-

posed design including the power transfer switching operation, relay switching circuit function and PWM generation circuits manifestation. Section 3. documents the practical design considerations and laboratory based experimental assessments of the framework. Section 4. concludes the article.

2. OVERVIEW OF THE PROPOSED DESIGN

The design of the developed grid-tied emergency back-up power supply system for medium and low power applications is reported in [5], which is presented here by Figure 1. The description of the system layout is documented in [5]. Nevertheless, a brief overview of the implemented design and its functionalities is articulated in this particular section.
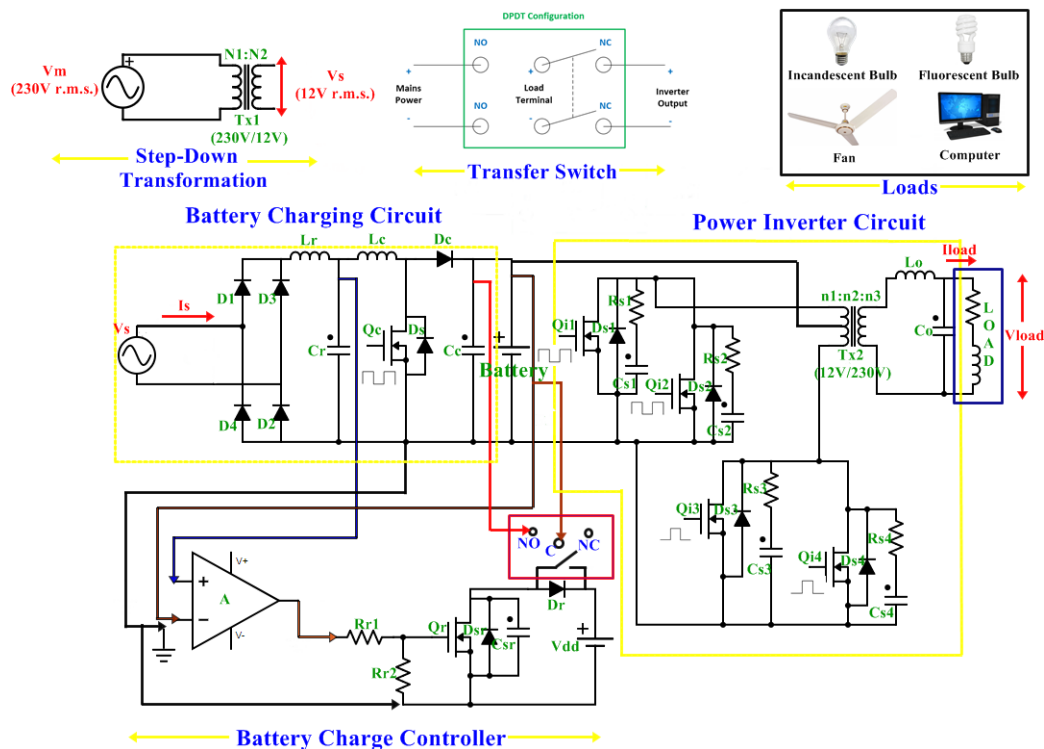

Figure 1. Layout of the proposed back-up power system [5]

2.1. Power transfer switching operation

The transfer switching operation from the mains line to the customized power circuit in case of grid power failure is implemented by a changeover relay following a double pole double throw (DPDT) switching structure. The switching operation is configured as follows.

- Direct connection relay R_{c1} connects the mains power line to the utility load terminal.
- Circuit-to-load connection relay R_{c2} bridges the inverter circuit output port with the utility load terminal.
- R_{c1} and R_{c2} get activated alternatively.
- Generally a relay has two switching terminals and one moving pole to shift position from one terminal to another. In this DPDT relay, the normally closed (NC) terminal or R_{c2} is connected to the inverter output and the normally open (NO) or R_{c1} is connected to the grid. Any utility load is realized by the moving pole.
- In the de-energized state (mains power is absent), the load is connected to NC and conversely, in the energized state (mains power is present), the load gets automatically connected to NO.

2.2. Relay switching circuit operation

An intelligible relay switching circuit is designed to control the connectivity of the battery to its charger. Therefore, this relay switched circuit unit determines the charging operation and provides protection against over-charge and over-voltage states for the battery. The relay switching operation is configured in the following manner.

− If the battery voltage is at or above its rated nominal value, the switching circuit disconnects the charger from the battery.
− Charger connection relay R_{cc}, is basically a single pole double throw (SPDT) relay switching circuit which connects the battery to the charger.
− Battery charge controller consists of a comparator circuit, in which the reference voltage V_{rf}, kept at 12 V, is fed from the rectifier and it is connected to a non-inverted port, whereas the battery voltage V_B is connected to an inverted port of an operational amplifier (op-amp).
− The difference voltage V_δ is $V_{rf} - V_B$. The work process in op-amp happens to be: the comparator output voltage V_{cmp} is $-V_{sat} = V- = 0V$, if $V_\delta < 0$ and is $+V_{sat} = V+ = 12V$, if $V_\delta > 0$; here V_{sat} is the saturation voltage.
− The comparator is followed by a relay switching circuit, as presented in Figure 1, of which the input is the comparator output voltage. Here NO terminal is connected to the charger, NC terminal is open and the moving pole C is connected to the battery.
− When $V_{cmp} = 0V$, there is no current flowing through the switching relay and the battery is disconnected from the charger. When $V_{cmp} = 12V$, a current flows through the relay and the battery is connected to the charger.

2.3. Switch control PWM signal generation

The switching operations of the DC-DC boost converter and push-pull inverter are executed by fixed duty ratio (0.5) PWM signals of 40 kHz and 50 Hz, respectively. Analog integrated chip (IC) SG3525A is used to generate the associated PWM signals. These PWM signals are fed into the gate terminals of the switching devies. Technical features, operational principles and connection diagrams of SG3525A are reported in details in [31]. In regard to maintain the trade-off between switching loss and conduction loss of a switching device, 40 kHz switching frequency is optimized in this work for controlling boost converter. In case of the push-pull inverter, both of the complementary 50 Hz pulses are used to control the switching operations of the inverter legs, leg1: $Q_{i1} - Q_{i2}$ and leg2: $Q_{i3} - Q_{i4}$. Here 50 Hz pulses are required irrespective of conduction and switching losses, since the inverter ought to generate power quantities at the grid fundamental frequency. For biasing the PWM generation circuits, the battery voltage is used. Figures 2 and 3 present the circuit schematics for 40 kHz and 50 Hz PWM signal generation, respectively. To evaluate the performance of the developed system, different types of utility loads with different power ratings are fed power by the inverter circuit. A critical load such as a personal computer unit (HD display+CPU) is also tested to ascertain the emergency back-up power supply capability of the proposed framework.
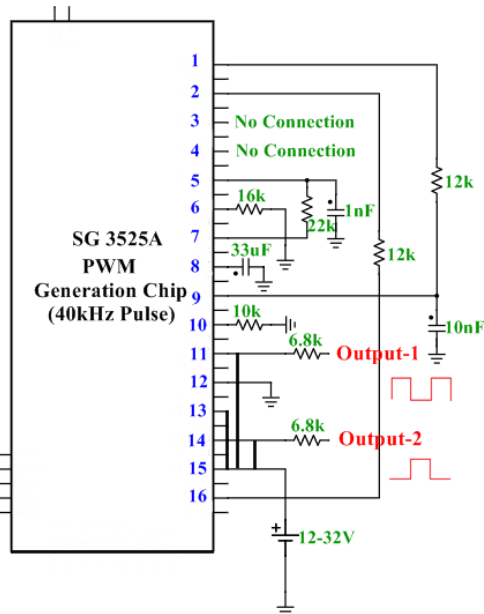

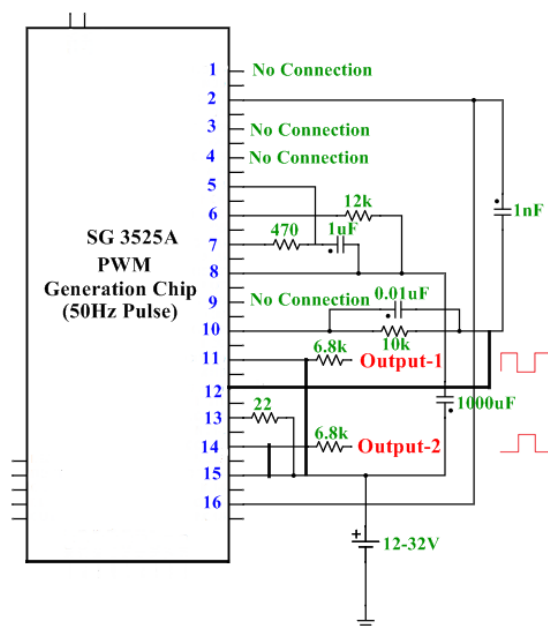Figure 2. Circuit schematic for 40 kHz PWM signal generation using SG3525A [5]

Figure 3. Circuit schematic for 50 Hz PWM signal generation using SG3525A [5]

3. EXPERIMENTAL RESULTS AND ANALYSIS

In this article, a simple yet efficient and cost-effective emergency back-up power system for regular medium and low power consumer applications is reported. Laboratory tests are conducted to ratify the validation of the articulated design for practical user applications. The test-bed containing various utility loads with different power ratings are experimented. The waveforms of power quantities are observed in digital oscilloscopes. For measurement purposes, digital multimeter, LCR meter, THD meter, watt meter and power factor meter are utilized. Table 1 shows the specifications of the developed system components. 60 W - 250 W different types of utility loads are used for the experimental evaluations. The components' notations follow the terms as presented in Figure 1.

Table 1. Specifications of the system components to develop the laboratory prototype

Components' Notations	Specifications
T_{x1}	230 V - 12 V, 300 W, 50 Hz iron core step-down transformer with a turns ratio of $N_1 : N_2 = 38 : 2$
$D_1 - D_4, D_s, D_c, D_{s1} - D_{s4}, D_{sr} \& D_r$	GP60-005 power diodes
L_r	0.1 mH, rectifier output filter inductance (made on a powder core)
C_r	500 μF, rectifier output filter capacitance (25 V electrolytic capacitor)
L_c	0.95 mH, boost converter input inductance (made on a powder core)
C_c	47 μF, boost converter output capacitance (50 V electrolytic capacitor)
$Q_c, Q_{i1} - Q_{i4} \& Q_r$	IRFZ44N n-channel enhancement type MOSFET with an absolute maximum on-resistance, R_{on}=17.5 mΩ and maximum drain current, $I_D = 49A$
Battery	12 V (rated nominal voltage), 7.5 A-h (capacity) and 9 V (cut-off voltage), Uniross UPS battery
$R_{s1} - R_{s4}$	225 Ω, snubber resistance (2 W resistor)
$C_{s1} - C_{s4} \& C_{sr}$	10 nF, snubber capacitance (ceramic capacitor, part number 103)
T_{x2}	12 V - 230 V, 400 W, 50 Hz iron core step-up transformer with a center-tapped primary side and a turns ratio of $n_1 : n_2 : n_3 = 2 : 2 : 38$
L_o	21.2 mH, inverter output filter inductance (made on a powder core)
C_o	470 μF, inverter output filter capacitance (250 V electrolytic capacitor)
A	LM324, op-amp with the biasing voltage of $V_+ = 12V$ and $V_- = 0V$
$R_{r1} \& R_{r2}$	1 kΩ and 12 kΩ respectively, resistances in the input terminal of the battery charge controller circuit (2 W resistor)
V_{dd}	12 V, biasing voltage of the relay switching circuit
C, NO & NC	common, normally open and normally closed terminals of a 250 V, 20 A, SPDT electromechanical relay
Transfer Switch	250 V, 30 A, 3 ms (transfer rate) electromechanical relay

However, the detailed PLECS simulation results and associated analysis are reported in [5]. In this article, Figure 4 presents a device under test (DUT) model of the system. There is a cooling fan of 12 V bias voltage attached to the prototype to annihilate the heat of the circuit components. Every electrical switching module in the circuit is associated with heat sinks. To evaluate the efficacy, certain power quality measures are taken into consideration. The sending-end power factor can be defined as follows.

$$PF_s = \frac{P_R}{S_A} = \frac{V_\phi I_\phi cos\alpha}{V_\phi I_\phi} = cos\alpha \tag{1}$$

Here P_R is the real power (W), S_A is the apparent power (VA), α is the angle between voltage, V_ϕ and current, I_ϕ. Low power factor means significant power loss, therefore it is rudimentary to maintain a high sending-end power factor during operations of a power utility system. In addition, harmonic distortions are determined to calculate the losses and observe irregularities in the waveforms due to unwanted harmonic contents in voltage and current measurements. Due to presence of harmonics and sub-harmonics, distorted voltage and current signals are fed into utility loads and the overall operation becomes degraded. The total harmonic distortion (THD) values (%) of respective current and voltage signals are measured as follows.

$$I_H = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + I_6^2 + \cdots}}{I_1} \times 100\% \tag{2}$$

$$V_H = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + V_6^2 + \cdots}}{V_1} \times 100\% \tag{3}$$

Here any power quantity can be represented by L (= V and I). L_1 is the fundamental or base frequency (50 Hz) component, L_2, L_3, L_4, L_5,... are the 2nd, 3rd, 4th, 5th,... order harmonic components, respectively.

Figures 5 and 6 present the obtained 40 kHz and 50 Hz PWM signals with fixed 50 % duty ratio, respectively. These switching signals are outcomes of SG3525A. The switching frequencies of these two generated PWM signals are measured as 43.1256 kHz and 51.169 Hz, respectively; which are very close to the desired values. In the design, few voltage conversion stages are present to employ correct quantities for most optimized power transformations. Table 2 manifests the voltages at different stages of the system.
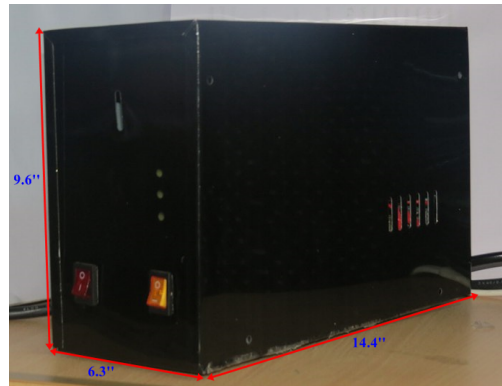

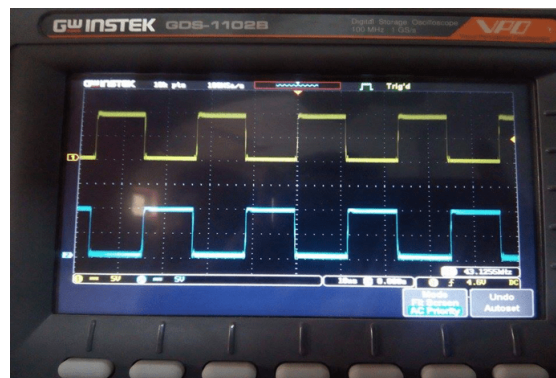Figure 4. A DUT model of the proposed design for laboratory assessments

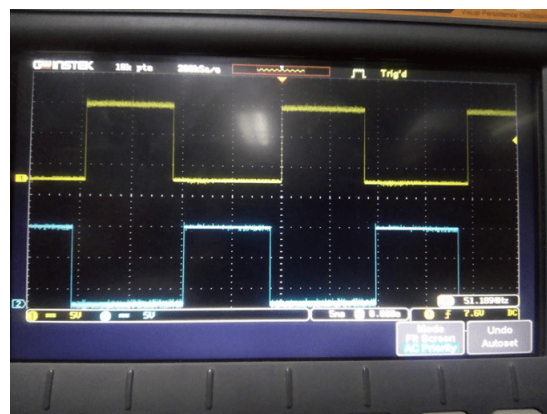Figure 5. Generated 40 kHz switching PWM pulses

Figure 6. 50 Hz switching PWM pulses in oscilloscope

Table 2. Voltage levels at different stages

Stage	Value (V)
Mains Line (grid)	230 (r.m.s.)
Step-Down Transformer Output	12.1 (r.m.s.)
Rectifier Output	12.5
Boost Converter Output	23.9
Battery	12
Inverter Output (no-load)	228.8 (r.m.s.)

60 W - 250 W utility loads are supplied power by the developed system. A personal desktop computer acts as a 250 W critical load while assessing the emergency back-up power supply performance and its reliability for consumer usage. Figure 7 presents the output voltage waveforms for 60 W and 100 W loads, whereas Figure 8 presents 132 W and 192 W load voltages, respectively.
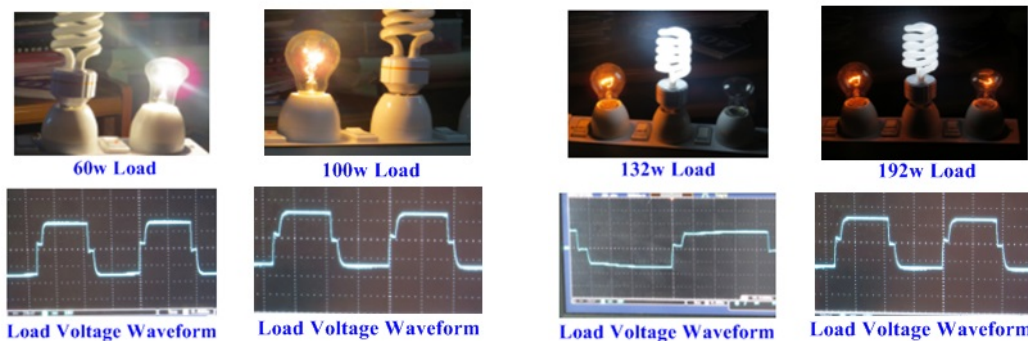

Figure 7. Inverter output voltages for 60 W and 100 W loads respectively

Figure 8. Inverter output voltages for 132 W and 192 W loads respectively

An elaborated performance inspection is carried out considering power factor, voltage and current harmonic distortions, output voltage, back-up duration and power efficiency yielding to load variations. Table 3 presents the overall performance evaluation of the implemented system for different loads. Here for a fluorescent and incandescent bulb the maximum utility is considered to be its full brightness level to approximately 80 % of the full brightness level and for a fan is considered to be its full rated speed to 80 % of the full rated speed. The brightness level is estimated roughly on the basis of a 25 - 30 year old viewer's eyesight comfort level in night-time and the speed of a fan is determined using a speedometer. At the no-load condition the inverter output voltage (r.m.s.) is 228.8 V with an operating frequency of 50.2 Hz. Table 3 presents the changes in load voltage values with respect to loads with different power ratings. The minimum utility load tested here is a 60 W incandescent bulb and the maximum utility load tested here is a 250 W desktop computer. For each load, instantaneous transfer switching (from mains power to inverter power) feature is tested during off-grid condition. The back-up power durations for different loads are considerable and after 10 minutes of back-up supply, inverter input current and power efficiency for each load are measured.

From Table 3, it can be observed that the inverter output voltage THD values (≈18.3 %) do not change with load variations, whereas the load current THD values (minimum ≈17.8 % and maximum ≈19.1 %) change with load variations. From Figures 7 and 8, it is observed that the load voltages are in the form of modified square wave of a fundamental frequency of approximately 50 Hz. From the changes in inverter output voltages during load variations, it can be concluded that the inverter with loaded conditions works like a current source inverter (CSI) and requires a feedback control loop to keep the output voltage constant. For a fixed reference load current, a closed-loop control is essential that can be in continuous or discrete mode of operation; since no specific loop update time is required in the design. For a power control implication, a multi-loop control happens to be required in which voltage control is going to be the outer loop and current control is going to be the inner loop receiving commands to track from the outer voltage control loop. However, these control prospects are in the future scope of this research design.

The experimental sending-end power factor of the proposed system is close to 0.9 with a mains line

current THD of around 25 %, which is considerably significant in case of low line power loss. The system power efficiency is subject to load variations. The maximum and minimum power efficiencies are close to 92 % and 75 %, respectively.

The observed back-up times for different loads underscore the reliability of this system as an emergency power supply especially in the regions, which are victims to frequent power outage and poor voltage regulation. A computer is supported for a time period of 13 minutes, whereas low loads like 60 W and 100 W incandescent bulbs are provided power back-ups for more than 1 hour durations. Thereby, it can be implied that the proposed system can be a potential solution to consumer UPS devices.

The cost effectiveness is one of the most prominent features of the presented research work. The overall cost estimation is enumerated in Table 4. It can be observed that the proposed system can be implemented incurring an expense below 30 $, which is significant in case of regular and reasonable consumer applications.

Table 3. Performance evaluation of the DUT for different loads with sending-end power factor $PF_s = 0.89$, mains current THD $I_{mH} = 25.3(\%)$, no-load inverter voltage $V_{NL} = 228.8V$ (r.m.s.) and operating frequency $f_{op} = 50.2Hz$

Load Type (Quantity)	Load Power Rating (W)	Inverter Output Voltage in Full Load State V_L (V)	Power Back-Up Duration for Maximum Utility t_b (Minutes)	Inverter Input Port Current I_{inp} (A) [measured after 10 minutes of power back-up]	Power Efficiency $\eta_P(\%)$ [measured after 10 minutes of power back-up]	Inverter Output Voltage THD $V_{LH}(\%)$	Load Current THD $I_{LH}(\%)$
Incandescent Bulb (1)	60	208	86	4.9	91.8	18.3	17.8
Incandescent Bulb (1)	100	185	72	8.7	86.2	18.3	17.8
Incandescent Bulb (1) + Fluorescent Bulb (1)	132	166	58	11.8	83.9	18.3	18.0
Incandescent Bulb (2) + Fluorescent Bulb (1)	192	144	49	20.3	79.8	18.3	18.3
Ceiling Fan (1)	120	171	53	10.7	84.1	18.3	18.5
CPU+Display unit (1)	250	127	13	29.9	74.6	18.3	19.1

Table 4. Cost allocation of the developed prototype

Subsystem	Expenditure ($)
Battery	7.67
Charger & its Controller	5.95
Inverter & its Controller	11.26
Relay & Switching Circuit	3.64
Total	28.52

4. CONCLUSION

Efficient and cost effective power electronic switching converters based emergency back-up power supply systems are significant alternatives to poorly regulated and expensive grid power networks, especially in the regions which face frequent grid power outages. In this article, design and practical considerations in regard to implementation of a grid-tied emergency utility back-up for medium and low power consumer usage are presented. A 4-switch push-pull inverter circuit is developed to support loads alternatively with the mains power line. Modified square wave voltage signals are generated at the grid fundamental frequency by the back-up unit. The inverter is sourced by an energy storage device (battery), which is charged by a rectifier-fed PWM signal switched boost converter. A DPDT configured changeover relay makes the instantaneous

transfer operation between the grid and the customized power supply system. Over-voltage and over-heat protection schemes are provided for the battery through an SPDT relay switching circuit, which controls the charging operation. Control units to generate switching PWM signals of respected frequencies are developed in this work.

A laboratory prototype is developed to assess the performance for different loads. The performance evaluations and overall cost estimations corroborate the reliability and economic feasibility of the proposed design for potential consumer applications. A more compact and high power sine wave generating power system with feedback control feature is a future scope of this work.

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