International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-8 Issue-2, July 2019

WECS fed Off-Board EV Battery Charger using Single Stage Converter

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Abstract*: *Wind energy conversion system fed EV battery charging system using single phase bridgeless cuk converter is proposed in this paper. PMSG is employed in the WECS to convert the mechanical energy into electrical ac power. In standalone wind energy conversion systems, two stage ac-dc & dc-dc converters are employed to obtain the desired output. The bridgeless cuk converter employed in the proposed charger is a single stage converter which acts as rectifier as well as dc-dc converter. The bridgeless cuk converter converts the ac voltage generated from PMSG into a desired dc voltage for charging the battery of an electric vehicle. Thus, an intermediate stage of power conversion is reduced in the proposed system. Also, a simple output voltage controller is employed in the proposed system to charge the electric vehicle battery with constant voltage irrespective of the wind speed. The proposed off-board EV battery charger is simulated in Simulink environment of MATLAB software and the results obtained are furnished in this paper. The experimental investigation has been carried out in the developed laboratory prototype of the EV battery charging system and the obtained results are furnished in this paper.

Index Terms*: *Off-board EV Battery Charger, Wind Energy Conversion System, Bridgeless Cuk Converter.

I. INTRODUCTION

The growing stress on the fast depleting conventional sources has led to severe environmental hazards and also led to the depletion of fossil fuels. Also owing to the extensive use of these fossil fuels, carbon dioxide emission has increased which in turn eventually leads to global warming or "green house effect" [1]. This paves the research to shift towards the renewable sources of energy in transport sector [2]. Among various renewable energy sources, PV array and wind energy (WE) are the promising sources. As wind energy is available round the clock, this energy is preferable in the Electric Vehicle (EV) battery charging applications. Due to the intermittent nature of wind energy, power electronic interface needed in this system to obtain the desired output.

Conventional wind energy conversion system (WECS) based EV battery charger is a two stage system which employs an rectifier to convert the generated ac voltage from Permanent Magnet Synchronous Generator (PMSG) to a dc voltage and a dc-dc converter for stepping down or stepping up the dc voltage to obtain the desired output voltage [3]. These converters have more semiconductor devices which eventually increases the conduction loss. Nowadays, research has been focused towards the single stage bridgeless ac-dc converters, due to the primary reason being that, these converters contain less number of semi-conductor devices. Also, the bridgeless converter decreases the conduction losses, improves the efficiency and saves cost. According to recent research, several bridgeless converters have been put forward for the power density improvement and for reduction of noise emission. Among the several bridgeless topologies, the bridgeless boost converter has the disadvantage of high inrush current and high electromagnetic emissions [4]. The bridgeless buck converter increases the total harmonic distortion (THD) and reduces the power factor (PF) [5-6]. Another bridgeless sepic converter topology is presented in [7-8] has relatively high output current ripple.

To eradicate these drawbacks, bridgeless cuk converter (BCC) have been developed which has the advantages of low ripple in the input current and low electromagnetic interference (EMI) when operated in discontinuous conduction mode (DCM) [9-10]. DCM operation provides almost unity PF and low THD in the input current. Thus, a BCC, which operates in step-down mode, is used as EV battery charger in this paper.

II. PROPOSED EV BATTERY CHARGER

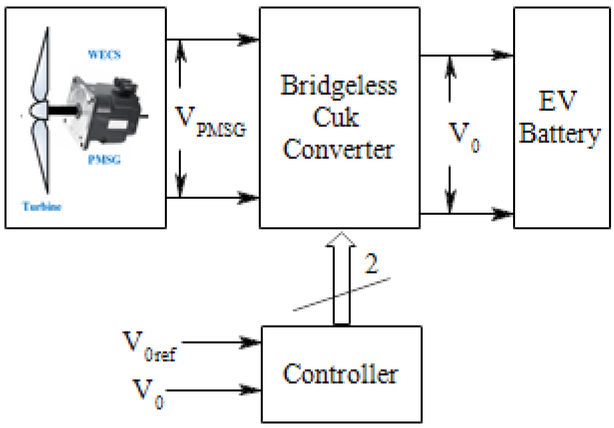

Fig. 1. The proposed EV battery charger configuration

The arrangement of the proposed EV battery charger shown in Fig. 1 consists of a PMSG based WECS, a bridgeless Cuk converter, controller and EV battery.

Revised Manuscript Received on 30 July 2019.
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WECS converts the wind energy into ac power with the help of PMSG which in turn is fed to the bridgeless cuk converter for providing required step down dc voltage to charge EV battery. The controller ensures the constant output voltage irrespective of the wind speed for constant voltage charging of EV battery by generating appropriate gate pulses to the switches of bridgeless cuk converter.

III. DESIGN OF EV BATTERY CHARGER

The design and operation of each block shown in Fig.1 were described in detail in the following sub-sections.

PMSG based WECS

WECS consists of a wind turbine (WT) which converts the wind energy to mechanical torque. Torque input is provided to PMSG to obtain the desired output power. The WT generated power, P_m and the torque produced, T_m is given by equations (1) & (2) respectively as follows [11]:

$$P_m = C_p \lambda \frac{1}{2} \rho A V_W^3 \tag{1}$$

$$T_m = \frac{P_m}{\omega_m} \tag{2}$$

where, A is the area of WT (m^2),
V_W is the speed of wind (m/s),
C_p is the power coefficient of WT (maximum is 0.59 as per Betz law),
ρ is the air density (1.225Kg/m^3),
λ is the tip speed ratio which is expressed as

$$\lambda = \frac{\omega_m R}{V_W} \tag{3}$$

R is radius of WT (m),
ω_m is the rotor angular speed (rad/s) and is expressed as

$$\omega_m = \frac{2\pi N}{60} \tag{4}$$

N is the rotor speed (RPM)

A. Bridgeless Cuk Converter

Fig. 2 shows the circuit diagram of BCC [12]. This topology has two cuk converters integrated into a single circuit, each conducting for Positive half cycle (PHC) and negative half cycle (NHC) of the input ac voltage, V_{PMSG}. It consists of 2 power MOSFET switches, S_1 & S_2, 4 diodes, D_p, D_n, D_1 & D_2, 4 inductors, L_1, L_2, L_{01} & L_{02} and 3 capacitors, C_1, C_2 & C_0.

During PHC, the first cuk converter conducts, wherein the components, L_1, S_1, C_1, L_{01}, D_1 and D_p are active. During NHC, the second cuk coverter conducts and the components L_2, S_2, C_2, L_{02}, D_2 and D_n are active.

The diode, D_p conducts during the entire PHC switching period. The current flowing through C_2 and L_{02} are almost negligible and thus the capacitor voltage, V_{C2} is equal to the output voltage. During PHC, the current through inductor, L_2 is the negative current through the body diode of S_2. Thus, the return current is shared by the input diode D_p and body diode of S_2. This operation repeats in the NHC with the continuous conduction of the diode D_n and body diode of S_1.

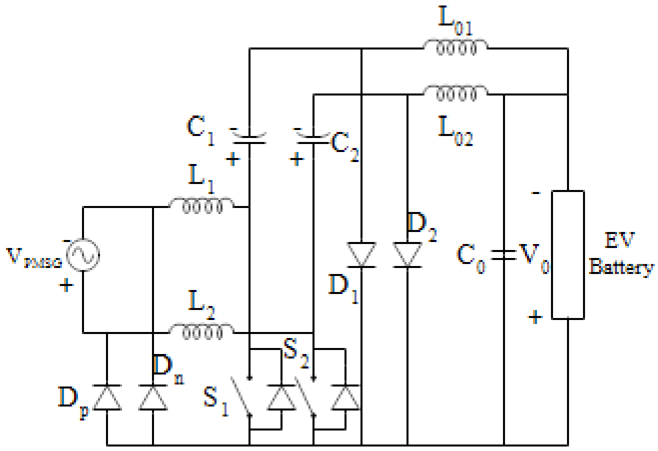


Fig. 2. Schematic Diagram Of The BCC

The voltage conversion ratio, M of the BCC is given by [12]

$$M = \frac{V_0}{V_{PMSG}} \tag{5}$$

Where, V_0 is the output dc voltage & V_{PMSG} is the input ac voltage of the cuk converter
Minimum value of dimensionless conduction parameter, $K_{e\text{-}crit\_min}$ is given by

$$K_{e\text{-}crit\_min} = \frac{1}{2(M+1)^2} \tag{6}$$

where, $K_e = 0.9 K_{e\text{-}crit\_min}$ (7)

The BCC operates in DCM for $K_e < K_{e\text{-}crit\_min}$ and the duty cycle is calculated using

$$\delta_1 = M\sqrt{2K_e} \tag{8}$$

The inductors are designed such that it satisfies the condition below.

$$\delta_1^2 = \frac{2L_e}{R_e T_s} \tag{9}$$

Where, $R_e = \frac{V_{PMSG}^2}{P_0}$ and $\frac{1}{L_e} = \frac{1}{L_1} + \frac{1}{L_{01}}$

The capacitors, C_1 & C_2 values are calculated based on inductor values (wherein $L_1 = L_2$ and $L_{01} = L_{02} = L_0$) such that, during DCM operation, the resonant frequency, f_r is given by

$$f_r = \frac{1}{2\pi\sqrt{C_1(L_1 + L_{01})}} \tag{10}$$

The output capacitor is designed considering maximum of 2% ripple in output voltage, ΔV_0 as per the following equation.

$$C_0 = \frac{V_0}{\omega R_L \Delta V_0} \tag{11}$$

Where, R_L is the load resistance

B. Controller

As the wind speed is intermittent in nature, a simple output voltage PI controller is employed in the proposed system for generating the gate pulses to the switches of bridgeless cuk converter to charge the battery of an EV continuously with the constant output voltage.

The gate pulses to the switch S_2 is 180° phase shifted from that of the switch S_1 which makes the control circuitry simple.

IV. SIMULATION STUDIES AND RESULTS

The proposed system is simulated in the Simulink environment of MATLAB software. The proposed system is constructed using wind turbine model, PMSG, Lithium Ion battery available in the simulink library. The Bridgeless cuk converter and controller are developed using power mosfet switches, diodes, inductors, capacitors, PWM generator, PI controller, logic gates and comparator available in simpowersystem blockset of simulink library as shown in Fig. 3. The dynamic response of the proposed system was investigated in 3 modes viz. mode 1, mode 2 and mode 3 for the wind speed of 12, 8 and 10 m/s respectively. Depending on the wind speed, PMSG generates the output voltage, V_{PMSG} and current, I_{PMSG} of 53.02 V& 4.37 A in mode 1, 46.87 V & 4.401 A in mode 2 and 49.53 V & 4.568 A in mode 3 respectively and fed to the BCC as shown in Fig. 4. The ac voltage, V_{PMSG} of BCC is converted to dc voltage and bucked to a constant voltage of 27.54 V in all the modes to charge the EV battery is shown in Fig. 4. Fig. 5 shows the THD in the input voltage & current of 1.74 % and 2.18 % respectively. The waveforms of EV battery SOC, EV battery voltage & current presented in Fig. 6 shows that the EV battery is charged continuously with the battery voltage, V_{batt} of 22.4 V and battery current, I_{batt} of 9.76 A irrespective of the wind speed. Also, increase in SOC of EV battery and negative current indicates that the charging of EV battery has taken place in all the three modes irrespective of the wind speed. Fig. 7 shows that the input inductor currents, I_{L1} and I_{L2} are out of phase by 180° and the output inductor currents, I_{L01} and I_{L02} are also out of phase by 180° contributing to the input and output current ripple cancellation respectively.

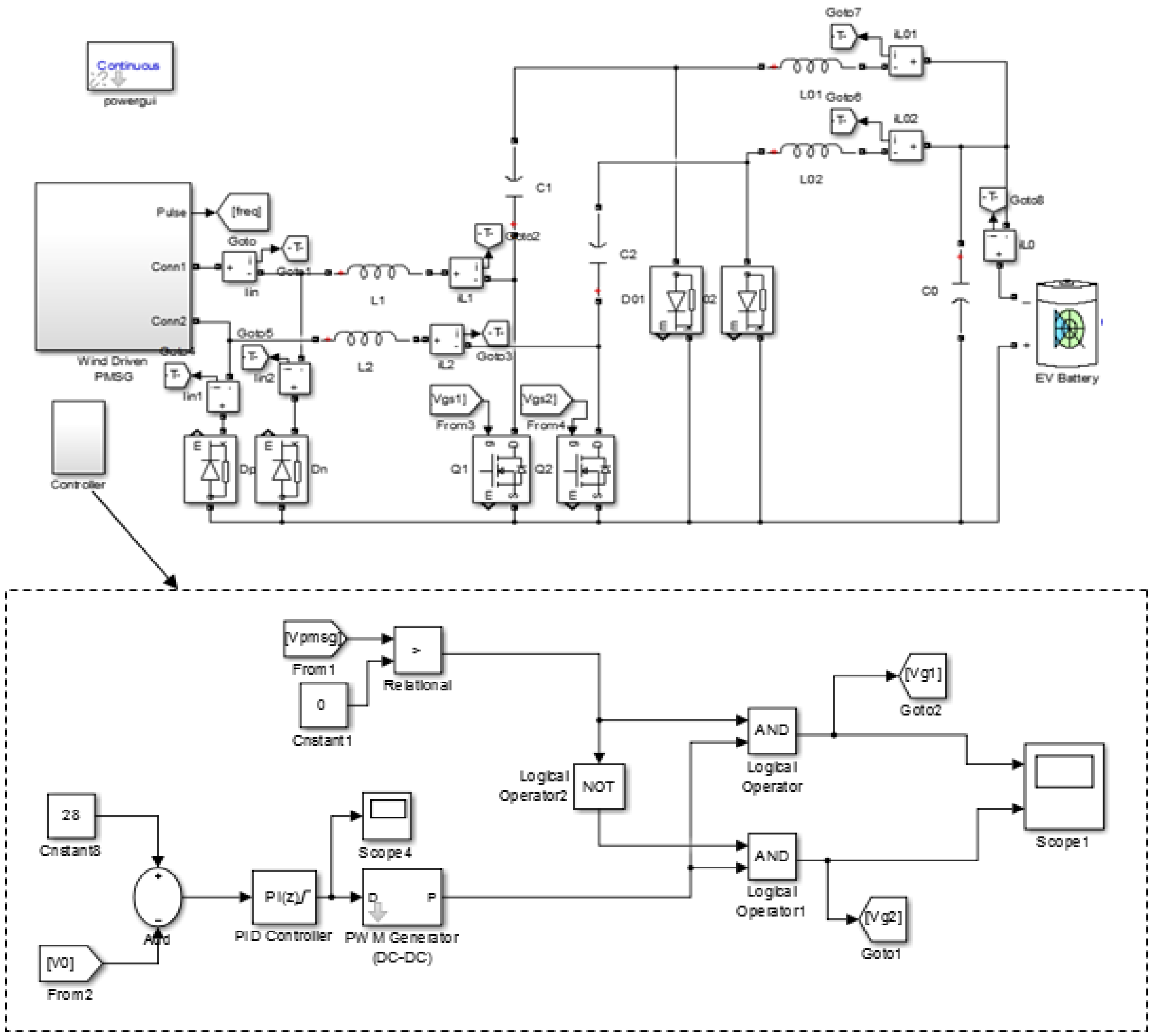


Fig. 3. Simulation Model Of EV Battery Charger

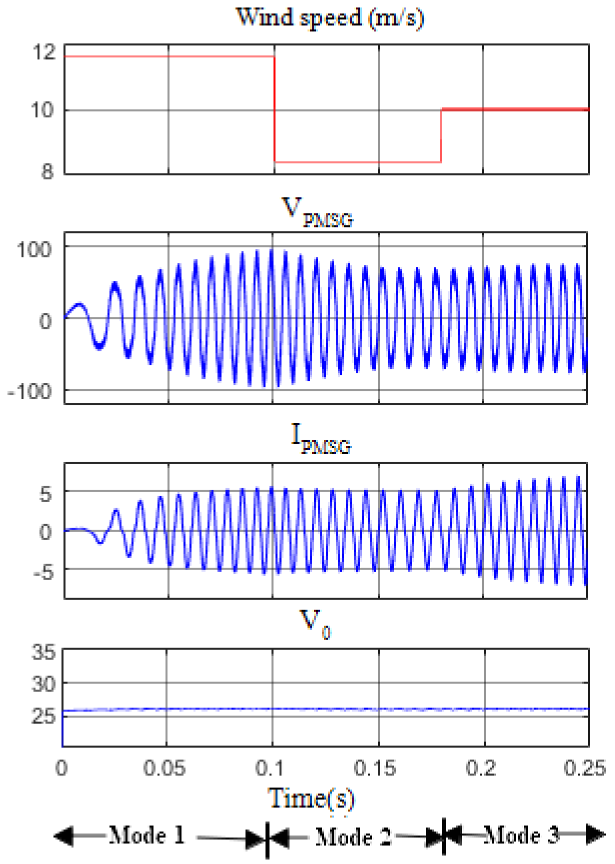


Fig. 4. Simulation Results Of Wind Speed, BCC Input Voltage And Current

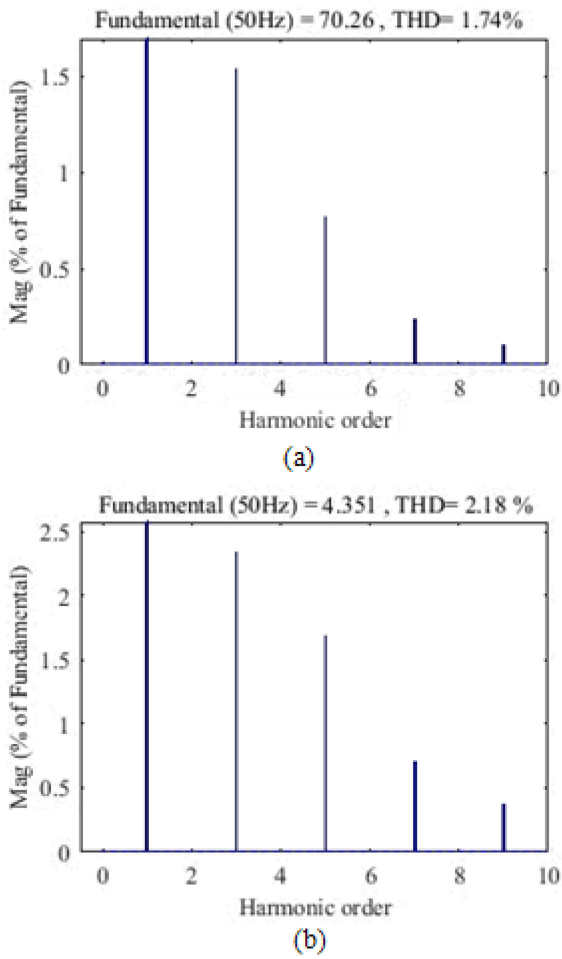


Fig. 5. Harmonic Spectrum Of (A) Input Voltage And (B) Input Current

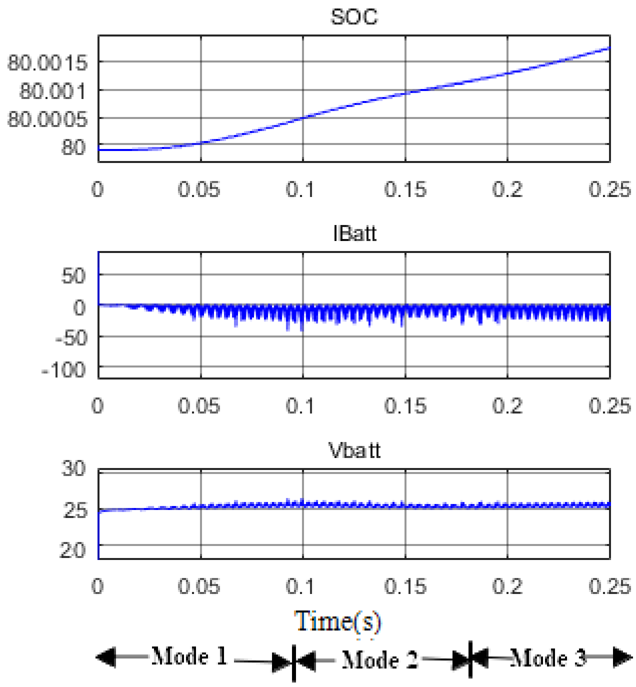


Fig. 6. Waveforms Of Output Voltage, SOC Of EV Battery, EV Battery Voltage & Current

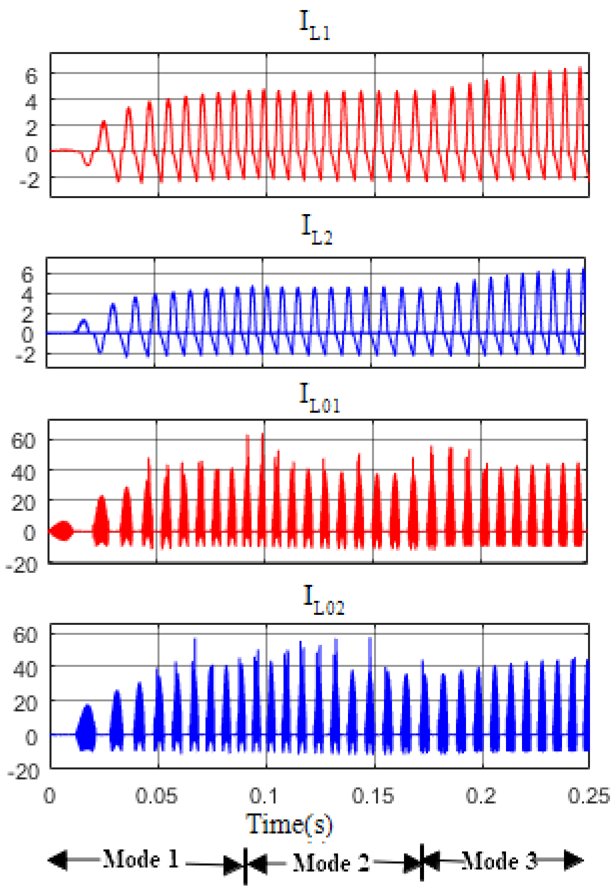


Fig. 7. Simulation Results Of Inductor Currents Of Bridgeless Cuk Converter

Retrieval Number: B3735078219/19©BEIESP
DOI: 10.35940/ijrte.B3735.078219
Journal Website: www.ijrte.org

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-8 Issue-2, July 2019

V. EXPERIMENTAL INVESTIGATION

A 250 W hardware prototype of the proposed system was fabricated and tested in the laboratory. The prototype was tested with single phase ac supply with auto transformer as the input power source. MOSFET IRF540 (100 V, 28 A), Diode RHRP30120 (1200V, 30 A), inductors of 1mH/20A and capacitors of 1000 µF/250V and 600 µF/150 V are used to fabricate bridgeless cuk converter. The experimental investigation is carried out in Hardware-in-loop methodology using OPAL-RT Real time simulator OP4500. The gate pulses with switching frequency of 50 kHz are generated in OPAL-RT and fed to the MOSFET switches using IR2130 driver circuit.

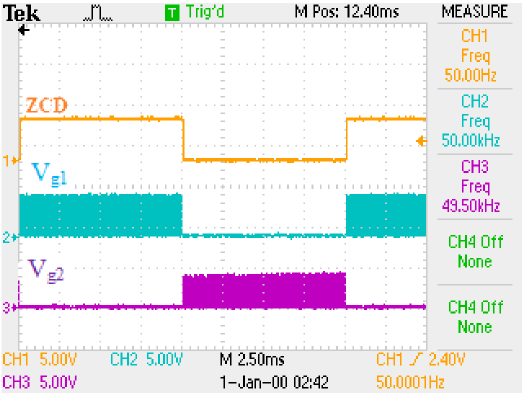
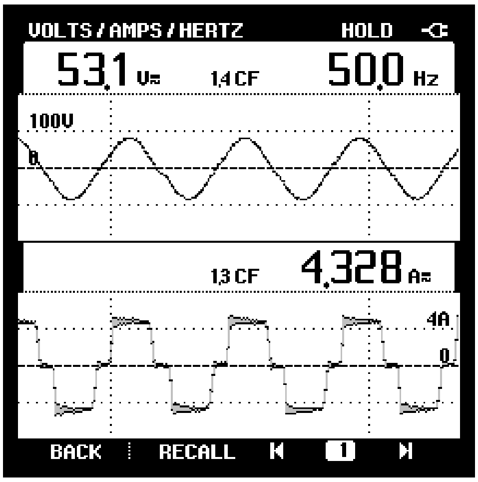
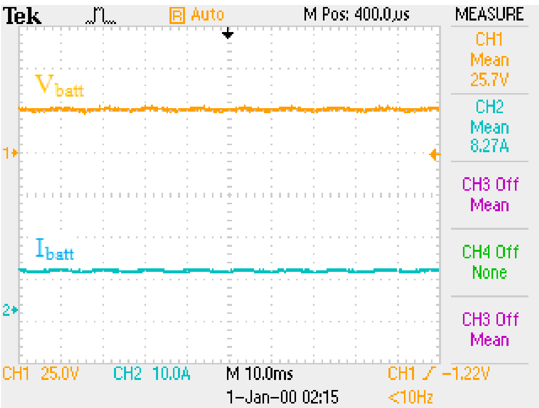


Fig. 8. Experimental Results Of ZCD And Gate Pulses V_{g1} & V_{g2}

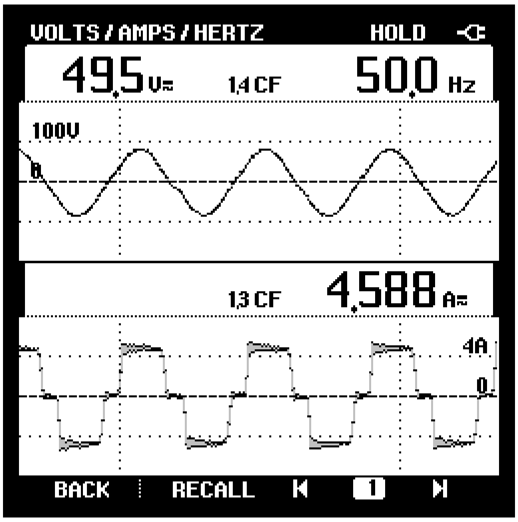


(a)

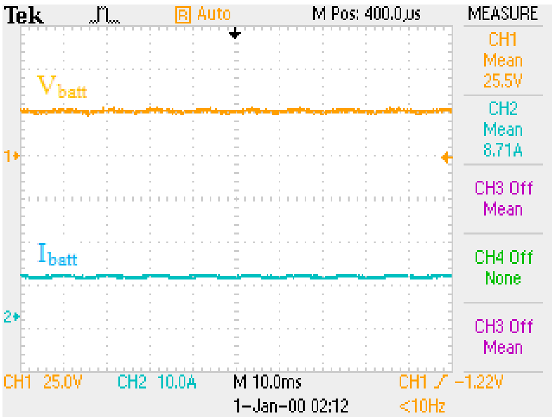


(b)

Fig. 9. At Wind Speed Of 12m/S, Experimental Results Of (A) Input And (B) Battery

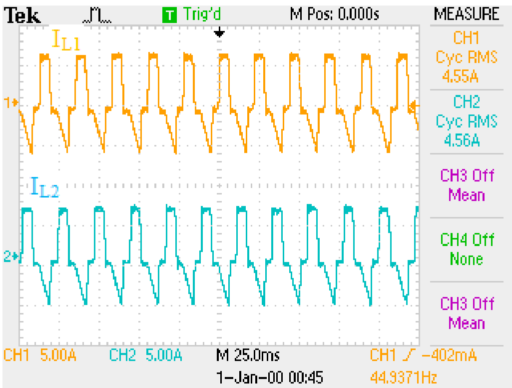


(a)

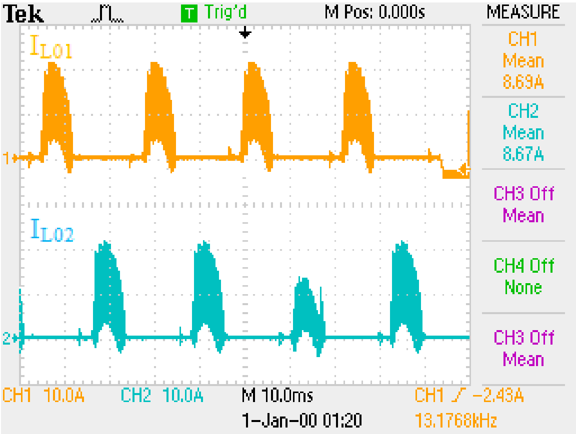


(b)

Fig. 10. At Wind Speed Of 10m/S, Experimental Results Of (A) Input And (B) Battery



(a)



(b)

Fig. 11. Experimental Results Of (A) Input Inductor Currents And (B) Output Inductor Currents

VI. CONCLUSION

In this paper, an off-board EV battery charging system fed from WECS is proposed. The flexibility of the proposed system to charge the EV battery constantly irrespective of the wind speed is presented in this paper. The EV battery charger is designed and simulated in Simulink environment of the MATLAB software and the hardware prototype of the proposed system is fabricated and tested in laboratory and the results are furnished for the two different wind speed. Correlation between the experimental and simulation results emphasize the efficacy of the charger proposed.

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Sujitha N. was born in Chennai, India in 1988. She received her B.E. degree in ECE from Shri Andal Alagar College of Engineering, Anna University, Chennai, Tamil Nadu, India in 2009 and M.E. degree in PED from Jeppiaar Engineering College, Anna University, Chennai, Tamil Nadu, India in 2013. She is currently pursuing her Ph.D. degree in EEE in VIT, Chennai, Tamil Nadu, India. Her field of interest includes Power electronic converters, Renewable Energy system and Electric Vehicle battery charging applications.

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