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BATTERY MANAGEMENT SYSTEM BASED ON SYNCHRONOUS NON-INVERTING BUCK-BOOST DC-DC CONVERTER

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ABSTRACT

Battery and load management on a stand-alone electric generator from renewable energy sources manages the process of battery charging and discharging. This study discusses design, simulation and implementation of Synchronous Non-Inverting Buck-Boost (SNIBB) using four-switch H-bridge to control current and voltage of multi-stage charging lead acid battery. When the voltage is under 2.4 V/cell, the charging current of battery is kept constant using constant-current (CC) mode, then the voltage is kept constant on constant-voltage (CV) mode until the charging current reaches 5% and it is switched to float-charge mode with set point voltage 2.25 V/cell. Controlling battery charging/discharging and load is using two switches with the parameters, such as power electric source, battery capacity, and load. The implementation of the design is using microcontroller ATMega 16 with PI controller. As on CV and CC mode, SNIBB circuit is able to keep voltage and current appropriate to the set point with the changes of input voltage. On CC mode, when the set point of current is increased, the charging time is faster. The result shows that the battery management designed is able to control charging and discharging the battery to the load.

Keywords: synchronous non-inverting buck-boost, multi stage charging lead acid battery, PI controller, battery and load management system.

1. INTRODUCTION

Nowadays utilization of renewable energy power sources to supply the load is very popular among us. Usually, such kind of energy required storage devices to maintain its power [1]. Electrical energy from renewable energy in a standalone power station is stored to the battery and requires charging and discharging control technique in order to prolong the battery life. Some battery charger products have been develop charging technique to the battery. However they still use conventional method. Reference [2] develops battery managements system based on pulse charging method. This method is not efficient to prolong the battery life. Reference [3] just focusing on the state of charge of battery without considering charging management. Reference [4-5] only manage some power sources to the system without considering charging control to the battery.

Therefore, to prolong battery life state of charge condition and battery charge and discharge current have to predict precisely. Through battery and load management sets the switch configuration of the charging and discharging process of batteries to avoid over-charged and over-discharged batteries. This study designed the simulation and implementation of Synchronous Non-Inverting Buck-Boost (SNIBB) SNIBB circuit for battery charging and load management. The test is performed on simulation and implementation using ATMega16 microcontroller as PWM signal generator and processor of output current and voltage error according to the set-point. It is used PI-controller with different proportional and integral constants for the CC and CV battery charging modes.

2. BATTERY CHARGING MANAGEMENT

A. Overall proposed system

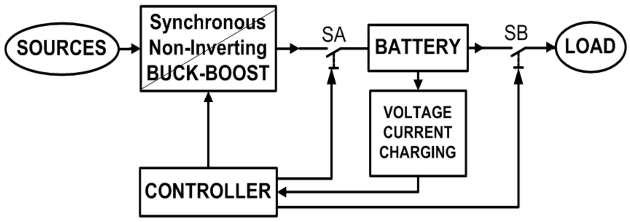

Figure-1. Battery charging and load management.

Figure-1 shows overall battery control system. The SNIBB circuit controls the voltage and output current according to the lead-acid battery charging mode that uses multi-stage charging. The controller processes the feedback error signal and the battery charging current with the set-point voltage and current according to the charging mode of the battery to set the PWM signal of the SNIBB circuit.

The battery charging and load management controls SA and SB switches with battery charging, load, and source charging parameters. The system works independently, using a single phase uncontrolled inverter connected to the load. Inverter input voltage is kept constant by SNIBB circuit.

B. Multi-stage charging battery lead-acid

Figure-2 shows multi stage charging for lead acid battery. Multi-stage charging lead-acid batteries uses three modes, those are, bulk-charge, absorption charge, and float charge. Bulk charge mode (A) uses the constant-current mode. Battery charging current is kept constant 1A or 10% of capacity 10Ah until 70% or 2.4V/cell. In absorption charge mode (B), battery charging voltage is kept constant 2.4V/cell, while charging current slowly decreases. When the battery charging current is 5% of battery capacity, charging mode switches to float-charge (C). The charging

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voltage is kept constant at 2.25 V/cell until charging current is 1%. Float charge compensates for self-discharge of battery and keeps life-time of battery, so battery stays 100% maximum until used.

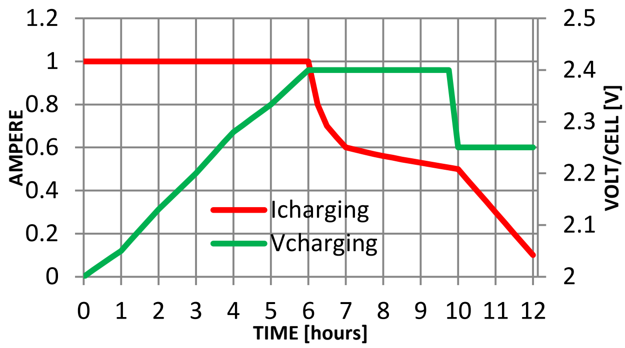


Figure-2. Multi-stage charging lead-acid battery [2].

C. Synchronous non-inverting buck-boost (SNIBB)

The SNIBB circuit as shown in Figure-3 decreases and increases the input voltage and current according to the set-point on the multi-stage charging of the battery. SNIBB is a combination of buck and boost circuit using four switches with H-bridge configuration. S1 and S2 are buck switches that work alternately with the ignition signal set by buck PWM. S3 and S4 are boost switches with the ignition signal set by boost PWM. S2 and S4 replace the buck and boost diodes [7].

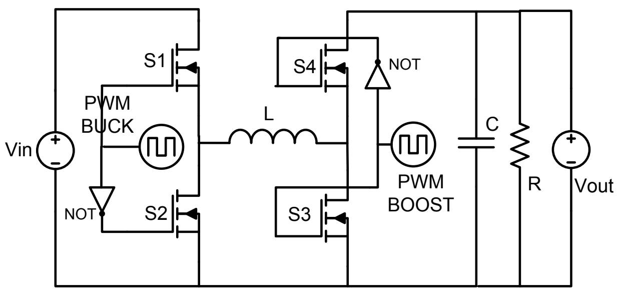
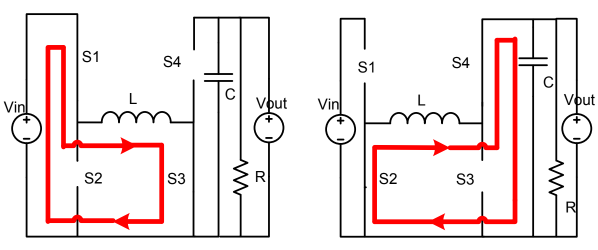


Figure-3. SNIBB circuit.



(a) (b)

Figure-4. SNIBB circuit analysis; (a) when switches close (b) when switches open.

Figure-4(a) shows the analysis of enclosed switch SNIBB where S1 and S3 are ON, while the synchronous switches S2 and S4 are OFF, so the current charges the inductor.

$$V_{in} = L\frac{di}{T_{on}} \tag{1}$$

Open switch analysis as in Figure-4 (b) where S1 and S3 are OFF, both synchronous switches S2 and S4 are ON. So that the current stored in the inductor supplies the load.

$$L\,di = V_{out} \cdot T_{off} \tag{2}$$

By substituting the equation on the switch closed and open analysis, it is obtained the SNIBB circuit output voltage equation is as follows: [3].

$$Vo_{ut} = \frac{V_{in} \cdot D}{(1-D)} \tag{3}$$

where, D is the duty-cycle and T is the period of the ignition signal.

3. SIMULATION AND IMPLEMENTATION

A. SNIBB design circuit

Table-1 shows The SNIBB circuit parameters. Meanwhile, all parameters supporting this circuit are calculated by using equation 4-7.

Table-1. SNIBB circuit parameters.

Parameters	Value
Output voltage	15 V
Minimum input voltage (MIN)	0.5 V
Maximum input voltage (MAX)	300 V
Load current	4.5 A (max)
Output current deviation	10% (450 mA)
Output voltage deviation	0.4% (0.06V)
Switching frequency	10 kHz

Firstly, it is calculated duty-cycle as equation 3 with two parameters of the largest and smallest input voltage [8].

$$D_1 = \frac{V_o}{V_o + V_{i-min}} = \frac{15}{15+0.5} = 0.967\ (Vin\ MIN) \tag{4}$$

$$D_2 = \frac{Vo}{Vo + V_{i-max}} = \frac{15}{15+300} = 0.0476\ (Vin\ MAX) \tag{5}$$

$$L = \frac{V_{i-max} \cdot D_2}{f.\Delta I} = \frac{300\ .0{,}0476}{10.10^3.0.45} = 3.17\ mH\ (L\ max) \tag{6}$$

$$C = \frac{Io.D_1}{f.\Delta Vo} = \frac{4.5\ .0{,}967}{10.10^3\ .\ 0.06} = 7.25\ mF\ (C\ max) \tag{7}$$

The calculation of inductor value is chosen 3 mH when the input voltage is maximum. The value of the capacitor considers the value of the components on the market, selected capacitor 7700 µF [9].

VOL. 13, NO. 8, APRIL 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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B. PI controller design

Two different PI-controller parameters are used to adjust the voltage (CV) and current (CC). The search of the variable of controller is obtained by trial-error tuning as seen in Table-2.

Table-2. SNIBB PI-controller parameters.

Mode	Kp	Ki
CV	0.006	3
CC	0.06	9

C. Design of battery and load management configuration

The configuration of the two SA and SB switches is as shown in Figure-1. These switches will regulate charging and discharging the battery with the conditions as listed in Table-3.

Table-3. Battery charging and load management configuration.

Mode	Condition					Action
	SA	SB	Source	Battery	Load	
A	OFF	OFF	OFF	OFF	OFF	-
B	OFF	ON	OFF	ON	ON	*Dicharging*
C	ON	OFF	ON	ON	OFF	*Charging*
D	ON	ON	ON	ON	ON	Parallel

D. Simulation design

It is designed the simulation with parameters according to SNIBB circuit design as shown in Figure-5. In charging controller set the charging mode of lead-acid battery, CC or CV mode.

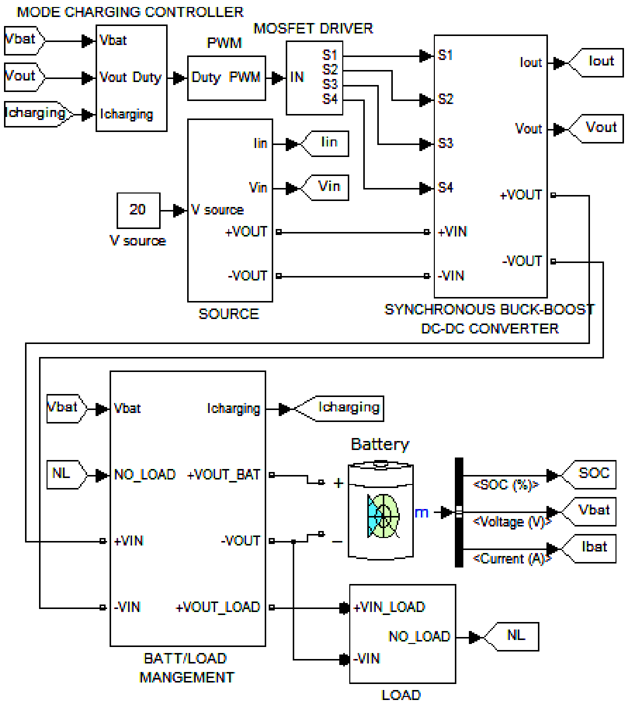

Figure-5. Simulation design.

When battery charging voltage is below 12.1 V, it applies CV mode. The CC set point is set to 1 A, while the PI-controller feedback signal from I charging battery with Kp value is 0.06 and Ki is 9. Set-point CV is 13.1V and maximum battery voltage is 13.06 V. The feedback signal of the PI-controller from Vout which the value of Kp is 0.006 and Ki is 3.

The controlled duty-cycle signal from the charging controller mode is then converted to a PWM signal with a 10 kHz saw-tooth carrier signal frequency. The MOSFETs driver regulates the synchronization of four SNIBB MOSFETs, where S1 and S3 receive PWM signals, while S2 and S4 receive inverse signal of PWM signals. The SNIBB circuit regulates the voltage and output current according to the charging mode. It is used four MOSFETs with H-bridge configuration. Battery and load management regulates charging and discharging batteries and loads with configurations as shown in Table-3.

E. Implementation design

Figure-6 shows hardware implementation of proposed battery management system, Table-4 shows components use for this circuit. The SNIBB circuit implementation design uses four IRFP460 MOSFETs with H-bridge configuration, and is controlled by two IR211 buck and boost MOSFET drivers. Both MOSFETs receive PWM input signal from microcontroller ATMega16. Microcontroller reads SNIBB output voltage and current with 10-bit Analog to Digital Converter (ADC) function.

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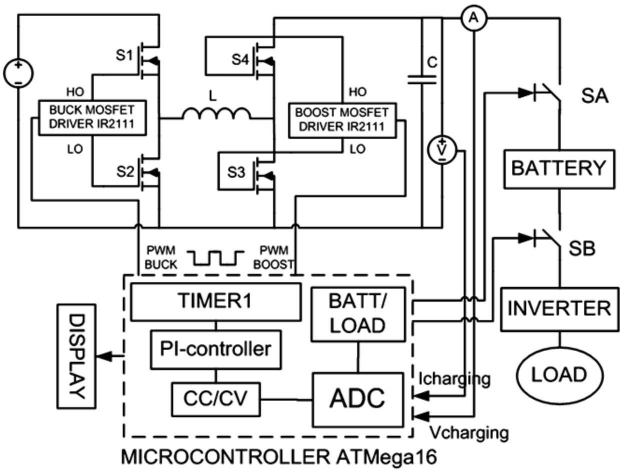

Figure-6. Implementation design.

The voltage sensor uses a voltage divider circuit with 33 kΩ and 6 kΩ resistors. The current sensor uses a voltage drop across a series mounted resistor at a load of 1 Ω with a power capacity of 20 W, so that the maximum current passed is 4.47 A.

Voltage and current are read as reference charging mode CC/CV batteries. PI-controller for CC processes the error signal between charging current and set-point current with Kp 0.006 and Ki 9. On the other hand, CV processes the signal error between charging voltage and set-point voltage charging with Kp 0.06 and Ki 3.

The controlled duty-cycle signal is converted to a 10-bit binary unit in timer1. Using two timer1 functions, OCR1A with PORTD.5 as output of PWM buck signal. The PWM boost signal uses the OCR1B function with PORTD.4 as the output.

The microcontroller controls two SA and SB switches by reading the voltage and charging current of the battery. According to the configuration as shown in Table-3, the 1 phase inverter increases and converts DC signal into AC signal on the load side. Maximum load power is 300 W. Table 4 shows a list of components and implementation of SNIBB circuit design as battery and load management is shown in Figure-7.

4. SIMULATION AND IMPLEMENTATION RESULT

A. Open loop of SNIBB circuit testing

Figure-8 shows the open-loop test of the SNIBB circuit compares the output voltage calculation with the output voltage of SNIBB's open-loop simulation and implementation. Based on the duty-cycle change that varies from 10% until 90% with input voltage 10 V.

Table-4. SNIBB circuit components.

Components	Value
MOSFET IRFP460	600V/20A
MOSFET Driver IR2111	600V
Inductor	2.96 mH
Capacitor	7700uF
Resistor (Voltage sensor)	33kΩ
Resistor (Current sensor)	1Ω / 20W
Microcontroller	ATMega16
1 phase Inverter	300W

Figure-7. Implementation system.

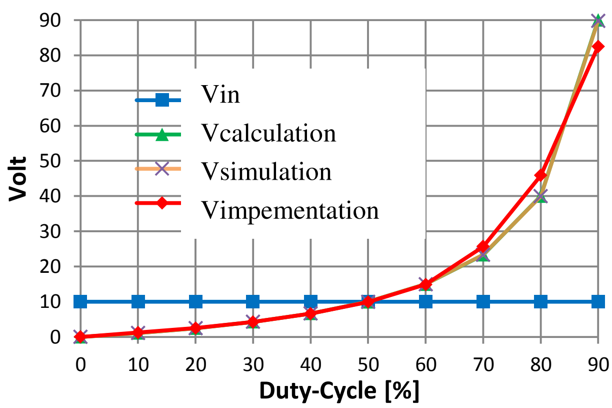

Figure-8. The comparison between open loop calculation, simulation and implementation.

The open-loop test of SNIBB circuit's output voltage is simulated and the result calculation approximately equals to the small error. Testing the implementation by calculating the magnitude of output voltage error when duty-cycle 80% and 90% for maximum error is 15%. From the CV simulation testing above, the SNIBB circuit is able to maintain the output voltage according to the set-point value 15 V. When the input voltage is below 15 V, the SNIBB circuit works in boost mode. When the input voltage is above set-point, the SNIBB circuit works in buck mode. Testing of CV implementation with set-point 15 V. The input voltage varies from 1 V to 30 V, and vice versa.

B. Constant voltage testing

Figure-9 shows simulation results for CV simulation. Constant-voltage maintains the output voltage according to set-point value, for testing the CV simulation with set-point output voltage 15 V. While the input voltage rises from 7 V to 22 V. Setting PI-controller with Kp value 0.006 and Ki 3. CV testing is done without load for output voltage output read by oscilloscope as shown in Figure-10. The result of CV of SNIBB circuit implementation is able to keep output voltage according to set-point value

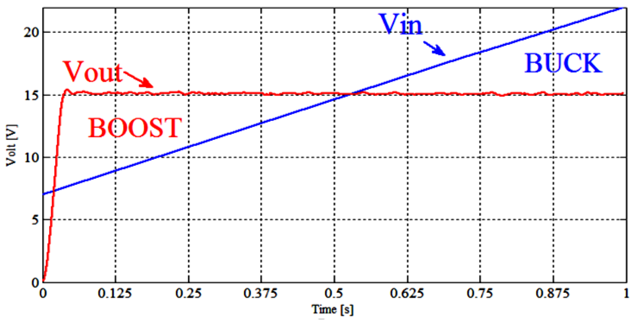

Figure-9. CV simulation with the changes of input voltage.

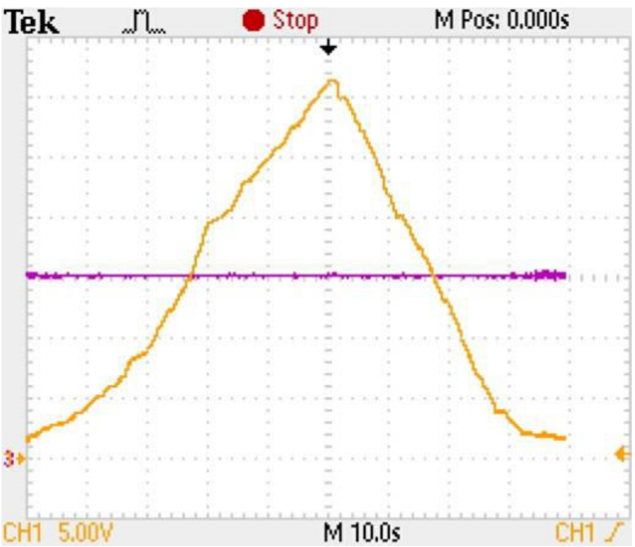

Figure-10. CV implementation testing.

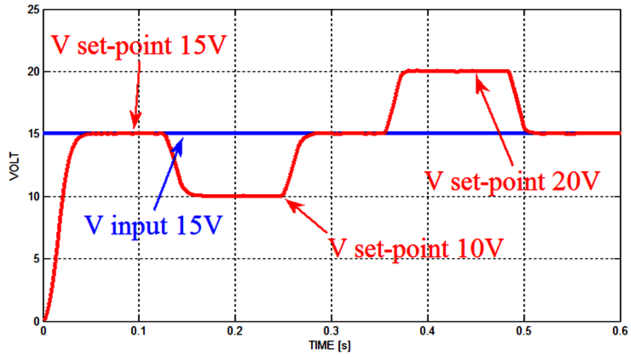

Figure-11. The output voltage of CV simulation with set-point changed.

Figure-11 shows CV testing with changes of set-point of output voltage 15 V, 10 V, and 20 V with input voltage 15V. SNIBB circuit and controller are able to respond to change in output voltage sets. The implementation testing is shown in Figure-12. The SNIBB circuit is able to respond to changes in output voltage sets

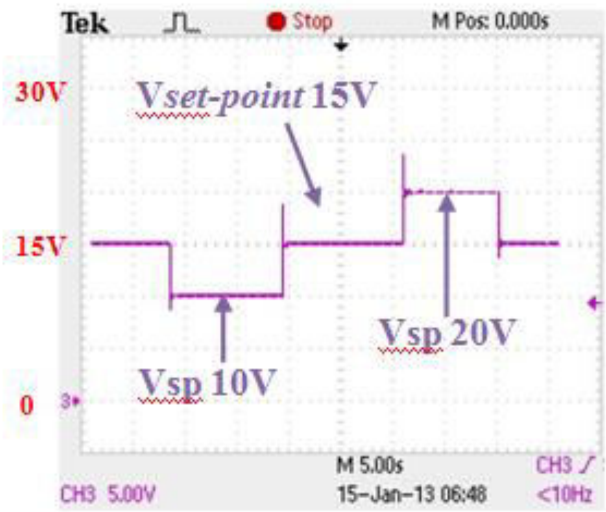

Figure-12. CV implementation testing with the changes of set point.

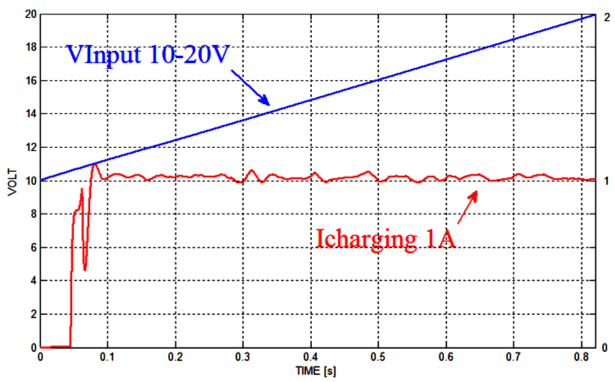

Figure-13. CC simulation with the changes of input voltage.

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C. Constant-current testing

CC testing is done with set-point charging current 1A as shown in Figure-13. Battery lead-acid 5 Ah with SOC 50%, while the input voltage rises from 10 V to 20 V. The PI-controller constant for Kp is 0.06 and Ki is 9. CC simulation test is able to keep the charging current according to set-point 1 A with the change of input voltage. The charging current rises up by 0.04 s (A), because the SNIBB charging voltage rises up to the voltage above the battery voltage. In the battery charging process, charging voltage must be above battery voltage. When the charging current and voltage crawls up for 0.04 s (B) there is a discharging process of the capacitor with a capacity of 7700uF, after which the charging current rises again towards the set-point value. Figure-14 shows implementation result of CC is read by oscilloscope with time/div 10 s. From this Figure it can be observed that proposed system ables to manage the current 1 A contantly.

The charging current is read from the Rsense current sensor which is mounted in series with the load. Parameter read is voltage drop resistor 1Ω/20W and range channel 2 is 0.5 V/div. The proportional and integral constants of the microcontroller are the same as the simulations. From the results of CC testing is able to keep the charging current according to set-point 1A. CC simulation testing with set-point changes is shown in Figure-15. The SNIBB circuit is able to respond to charging current set-point changes, which are 1 A, 0.5 A, and 1.5 A with time settling 0.04s to achieve steady-state. Testing of CC implementation with set-point changes is shown in Figure-16 with load of 5 Ah lead-acid battery. The SNIBB circuit is capable of responding to the changing of charging current set-points, 1 A, 0.5 A, and 1.5 A.

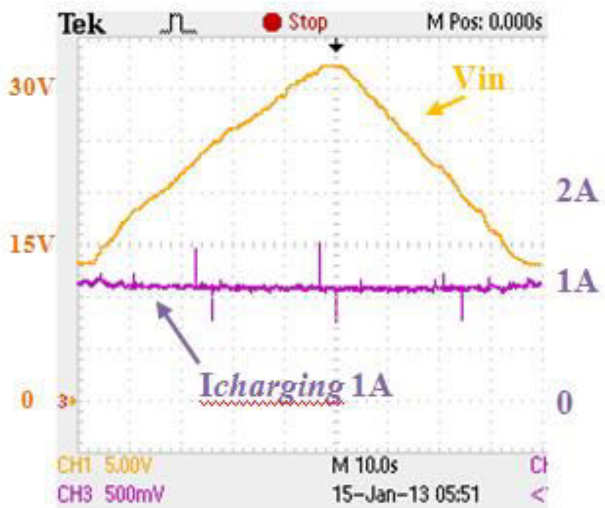

Figure-14. CC implementation with the changes of input voltage.

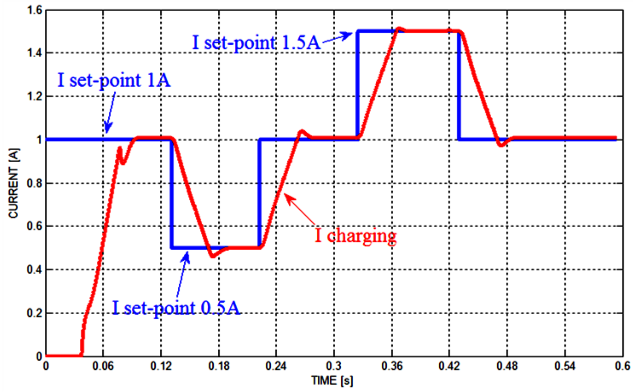

Figure-15. CC simulation testing with the changes of charging current set point.

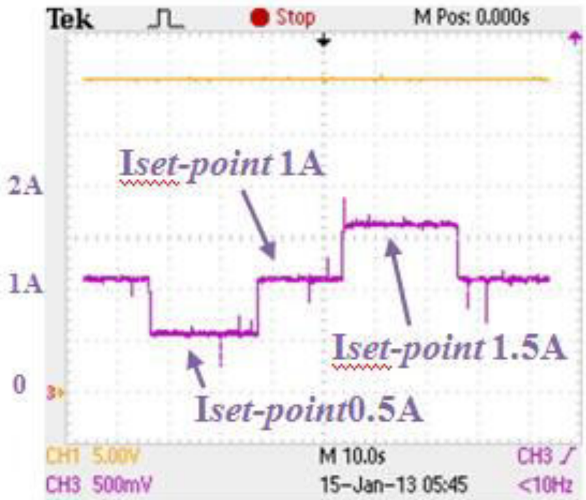

Figure-16. CC implementation testing with the changes of current set-point.

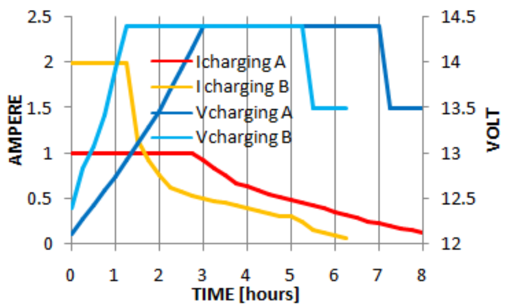

Figure-17. The implementation of battery charging with current set point 1 A and 2 A

D. Battery charging testing

Multi-stage charging lead-acid battery testing is done with battery capacity 5 Ah. The lead-acid battery charging mode uses CC and CV modes. Testing is done, both simulation and implementation. Figure-18 shows simulation results for lead acid battery charging.

VOL. 13, NO. 8, APRIL 2018 ISSN 1819-6608
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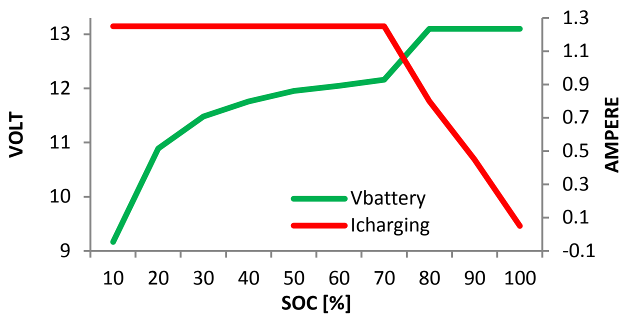

Figure-18. Lead-acid battery charging simulation testing.

The testing of lead-acid battery charging is based on SOC battery. CC is used when SOC is below 70%. The charging current is kept constant at 1.25A or 25% of battery capacity, while the battery voltage rises to 12.16 V. In CV mode, the set-point charging voltage is set 13.1 V. The voltage is kept constant while the charging current decreases. When the battery is near maximum, the charging current drops to be 0.05 A.

Figure-18 is testing of the implementation of 12V/5Ah lead-acid battery charging is done with two sets of CC current points, those are 1 A and 2 A. When charging A for set-point CC 1A (Icharging A) or 20% of capacity battery (5Ah). The charging voltage (Vcharging A) rises from 12.11 V when the SOC battery is 10% [6] to 14.4V for 3 hours of charging. After that, it uses CV mode at 14.4V for 4 hours. When charging current is 0.25 A, it uses float-charge with charging voltage set-point of 13.5 V.

When set-point charging current 2A (Icharging B) or 40% of battery capacity. The battery charging voltage (Vcharging B) rises from 12.4 V to 14.4 V for 75 minutes. After that CV 14.4V mode is used for 4 hours, while the float-charge mode when the charging current is 0.25A. The increase of set-point charging current in CC mode will speed up battery charging time.

E. Battery and load management testing

Figure-19 shows the battery charging and load management uses two SA and SB switches with configurations as shown in Table-3. Here are the results of implementation testing. Condition A is when both switches OFF, while condition B is when charging mode battery with float-charge CV 13.5 V and current 0.61 A. Condition C is when the SNIBB circuit is parallel to the battery and 13 W load, while Icharging read is 0.82 A. I load value cannot be displayed due to conversion constraint from current to voltage reading of oscilloscope. The digital ampere meter reading is 1.02 A, so the battery discharging current is 0.2 A. When the battery-load source is parallel, the charging current rises. The condition D is discharging the battery to the load. V*load* value drops close to the nominal voltage of the battery when the maximum is 12.2 V, with a discharging battery current 1.09 A. The system is able to regulate the charging-discharging process of batteries and parallel between battery-load and sources.

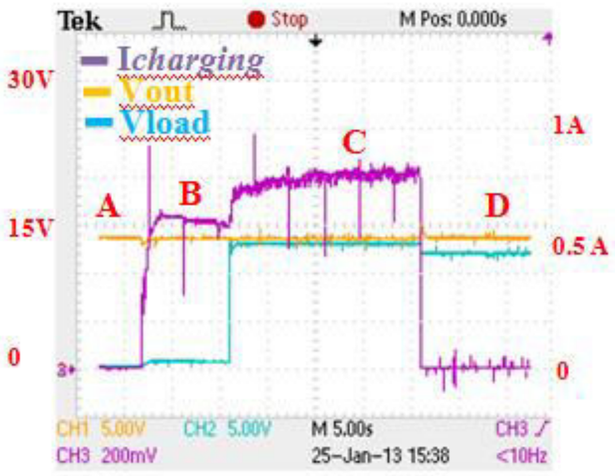

Figure-19. Charging battery and load management testing.

CONCLUSIONS

The SNIBB circuit uses four MOSFETs with H-bridge configurations and works synchronously. In lead-acid battery charging management with multi-stage charging, the circuit is able to keep the voltage or output current appropriate to the charging mode (CC/CV) with the change of input and set-point voltage. When the CC charging current set-point is increased, the battery charge time is faster. Battery and load management uses two switches capable of adjusting charging and discharging of batteries. The SNIBB circuit can be maximized for bidirectional converters on stand-alone generators with batteries and MPPT or regenerative breaking of electric cars.

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