A Voltage Regulator Suitable for Renewable Energy System Applications

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***Abstract*: A DC-DC system is presented to compensate power and voltage fluctuations in supply grid. In order to reach this aim, the proposed system provides output voltage regulation and control of energy flow between a battery bank and the output DC bus in a simple structure. Therefore, this system is able to operate in various modes of operation, according to load needs and supply grid limitations. A general concept is formulated. Operating principle and theoretical analysis are described. Digital simulation and experimental results are included for different modes of operation, supporting the validity of the concept.**

I. INTRODUCTION

Battery energy storage in combination with converters has been widely presented in Literature in order to improve the system performance, in concern of power quality and voltage stability. A typical application is the Uninterruptible Power Supplies (UPS). These systems are standard solution when total outage or voltage sag compensation is required. The topology presented in [1] is an integrated DC UPS topology that combines battery charger and DC-DC converter. The battery charger stage is a buck converter and, when outage occurs, the battery supplies the load in a natural way through a diode connected between the battery and an output capacitor.

Over the past decades an interest is growing up about the exploration of renewable energies, such as wind and solar energy, for generation of electrical energy. However, the electric power generated is fluctuating, since the wind presents a random characteristic and the available solar energy depends on the weather conditions. An alternative is to store energy in a battery bank. A model of a wind/diesel system with battery storage bank is proposed in [2] to compensate for the power fluctuations due to the stochastic nature of the wind. In study described in [3] a shunt battery bank injects or absorbs the compensating power to eliminate the ac power component contained in Photovoltaic (PV) array output power.

Another growing application is the use of battery storage to limits at a maximum the power delivered by the supply grid. A bi-directional converter for battery energy storage connected with a utility grid operates at energy storage and peak cut modes [4]. The load-adaptive variable-speed generating system presented in [5] comprises two energy sources: an engine-driven alternator and a battery bank. When the energy from the alternator is insufficient to meet sudden increments in load demand, energy is pumped from the battery to the DC-link. When there is excess engine capacity, the battery energy is replenished.

In order to give an additional contribution in this area, this paper proposes a dc-dc converter in combination with battery energy storage in a simple structure. This system is suitable for applications in renewable energy system, since it presents the following features:

- Voltage regulation,
- Peak power leveling,
- Compensation for power fluctuations.

II. SYSTEM DESCRIPTION

The basic principle of the proposed system is shown in Fig. 1. Note that there are two power stages: DC-DC voltage regulator and battery energy storage.

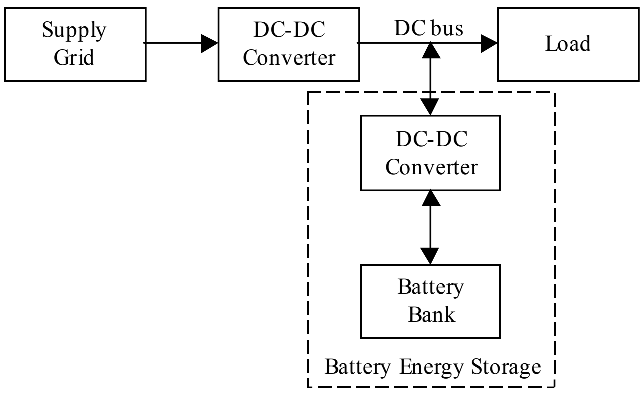


Fig. 1. Block diagram of a general voltage regulator with battery energy storage.

The voltage regulation is accomplished by means of a DC-DC converter, which lifts the supply grid voltage to a regulated output DC bus voltage.

Concerning the battery energy storage, this power stage stores the energy from the supply grid in the battery bank and injects the energy from the battery bank to output DC bus. Thus, compensation for power fluctuations and peak power leveling is obtained.

The proposed Voltage Regulator - Battery Energy Storage System (VR-BESS), shown in Fig. 2, includes these two power stages in a simple structure based on DC-DC bi-directional converter [6, 7]. The VR-BESS is composed of two switches, three diodes, two inductors, two capacitors and a battery bank. This system is connected to an uncontrolled DC grid (V_s).

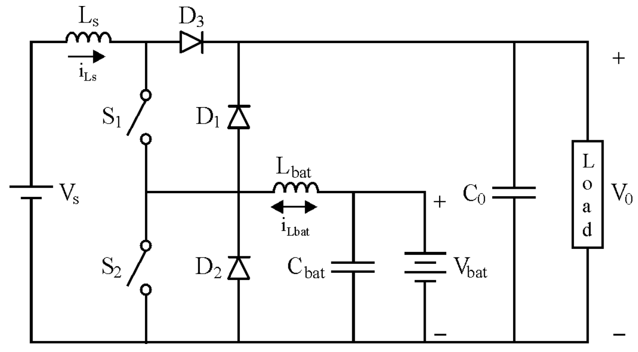


Fig. 2. Power circuit of the VR-BESS.

Switches S_1 and S_2 switching simultaneously, DC grid voltage Vs, inductor Ls, diode D_3, capacitor C_0 and the load form the voltage regulator.

For battery charging it is used the buck converter formed by DC grid voltage V_s, inductors L_s and L_{bat}, switch S_1, diode D_2, capacitor C_{bat} and the battery bank.

The boost converter formed by the battery bank, capacitors C_{bat} and C_0 inductor L_{bat}, switch S_2, diode D_1, and the load steps up battery voltage to output DC bus.

In the VR-BESS, energy flows in various paths. These can be differentiated into the following modes of operation:

- Mode 1 (Battery charge): Under normal operating conditions the DC grid is able to feed the load and charge battery bank.
- Mode 2 (Peak power leveling and compensation for power fluctuations): When the energy available in DC grid is not sufficient to supply the load, the battery bank supplements the energy required by load. A particular operation in this mode occurs when there is no available energy at DC grid. In this case the battery bank supplies full load current.

III. Principle of Operation

In continuous conduction mode the VR-BESS presents three operating stages for modes 1 and 2. Assuming that devices used in the circuit are ideal, these stages are as follows:

Mode 1

First stage $[0 - t_1]$: The switching period begins when the switches S_1 and S_2 are turned on. Diodes D_3 and D_2 are reversed biased. The voltage across the inductor L_s is $v_{Ls} = V_s$ and voltage across the inductor L_{bat} is $v_{Lbat} = -V_{bat}$. These voltages cause a linear increase in the inductor current i_{Ls} and a linear decrease in the inductor current i_{Lbat}.

Second stage $[t_1 - t_2]$: At t_1 the switch S_2 is turned off. Diode D_3 conducts the current i_{Ls} - i_{Lbat}. This results in a negative voltage $v_{Ls} = V_s - V_0$ across the inductor L_s and a positive voltage $v_{Lbat} = V_0 - V_{bat}$ across the inductor L_{bat}.

Third stage $[t_2 - t_3]$: This stage begins when the switch S_1 is turned off. The load receives all energy from the inductor L_s as well as from DC grid. Current i_{Lbat} continues to flow, now through the diode D_2, because of the inductive energy storage. The voltage across the inductor L_{bat} is $v_{Lbat} = -V_{bat}$.

Fig. 3 illustrates the equivalent circuit for each operating stage and Fig. 4 shows the theoretical waveforms of one switching cycle.

Mode 2

First stage $[0 - t_1]$: The switching period begins when the switches S_1 and S_2 are turned on. Diodes D_3 and D_1 are reversed biased, thus isolating the load. The DC grid supplies energy to the inductor L_s and the battery bank supplies energy to the inductor L_{bat}. The voltage across the inductors L_s and L_{bat} are $v_{Ls} = V_s$ and $v_{Lbat} = V_{bat}$, respectively. These voltages cause a linear increase in the inductor currents i_{Ls} and i_{Lbat}.

Second stage $[t_1 - t_2]$: When the switch S_1 is turned off at t_1 the diode D_3 conducts and DC grid and the inductor L_s feed the load. Meanwhile battery bank supplies the inductor L_{bat} through switch S_2.

Third stage $[t_2 - t_3]$: This stage begins when the switch S_2 is turned off. The load receives all energy from the inductors L_s and L_{bat} as well as from DC grid and the battery bank.

Fig. 5 illustrates the equivalent circuit for each operating stage and Fig. 6 shows the theoretical waveforms of one switching cycle.

IV. System Analysis

The analytical expressions describing the operation of the VR-BESS are presented.

The average output voltage V_0 and the average battery bank voltage V_{bat} can be obtained by the analytical study of the operating stages illustrated in Fig. 4 and 6.

In steady state, the integral of the inductor voltages v_{Ls} and v_{Lbat} over one time period must be zero.

Definitions:

- Switching time period: $T_s = t_3$

- Duty cycle 1: $$D_1 = \frac{t_1}{T_s} \qquad (1)$$

- Duty cycle 2: $$D_2 = \frac{t_2}{T_s} \qquad (2)$$

- $$\Delta D = \frac{t_2 - t_1}{T_s} \qquad (3)$$

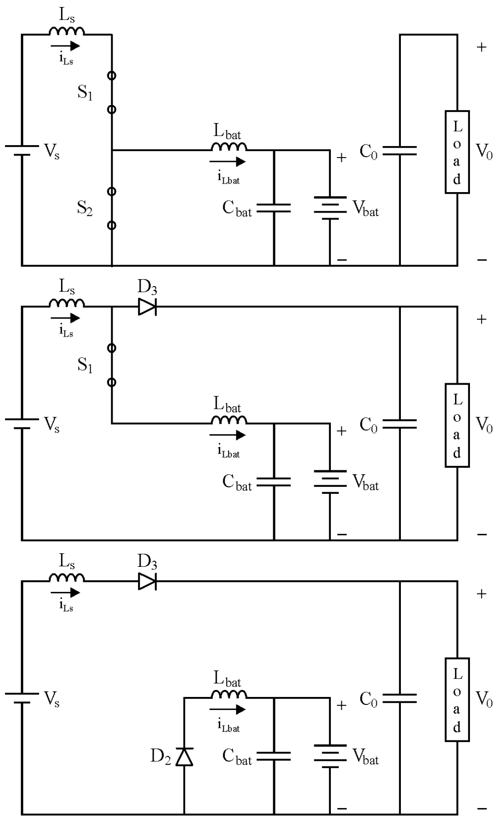


Fig. 3. Equivalent circuit for mode 1.

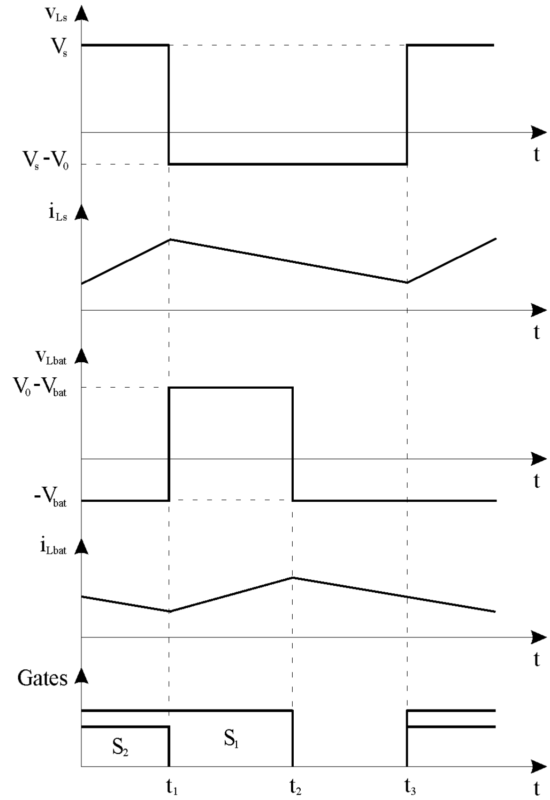


Fig. 4. Principal waveforms of VR-BESS for mode 1.

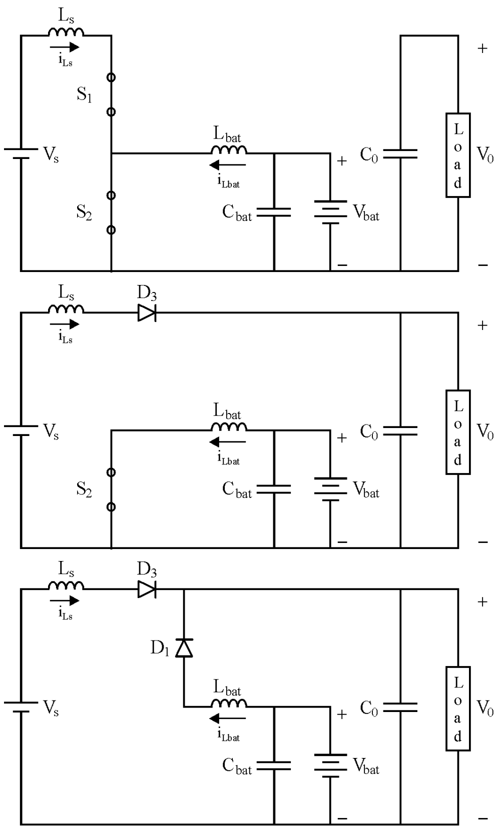


Fig. 5. Equivalent circuit for mode 2.

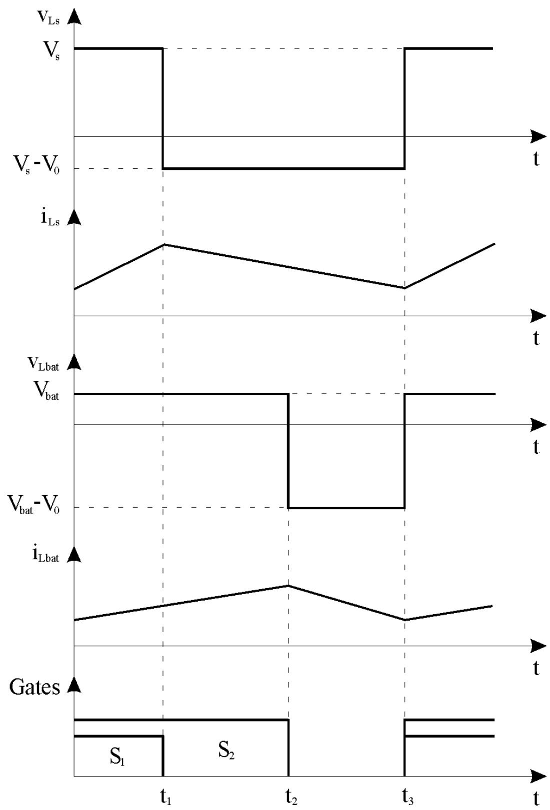


Fig. 6. Principal waveforms of VR-BESS for mode 2.

Mode 1

$$\int_0^{T_s} v_{Ls} dt = \int_0^{t_1} V_s dt + \int_{t_1}^{t_2} (V_s - V_0) dt + \int_{t_2}^{T_s} (V_s - V_0) dt = 0 \quad (4)$$

$$\int_0^{T_s} v_{Lbat} dt = \int_0^{t_1} - V_{bat} dt + \int_{t_1}^{t_2} (V_0 - V_{bat}) dt + \int_{t_2}^{T_s} - V_{bat} dt = 0 \quad (5)$$

Solving (4) and (5) it finds:

$$V_0 (T_s - t_1) = V_s T_s \quad (6)$$

$$V_{bat} T_s = V_0 (t_2 - t_1) \quad (7)$$

Dividing both sides by T_s and rearranging terms it finds:

$$\frac{V_0}{V_s} = \frac{1}{1 - D_1} \quad (8)$$

$$\frac{V_{bat}}{V_0} = \Delta D \quad (9)$$

It is important to observe from (8) that in mode 1 the system operates like a simple boost converter, with input voltage V_s and output voltage V_0, operating with duty cycle D_1. From (9) the system operates like a simple buck converter, with input voltage V_0 and output voltage V_{bat}, operating with duty cycle ΔD.

Mode 2

$$\int_0^{T_s} v_{Ls} dt = \int_0^{t_1} V_s dt + \int_{t_1}^{t_2} (V_s - V_0) dt + \int_{t_2}^{T_s} (V_s - V_0) dt = 0 \quad (10)$$

$$\int_0^{T_s} v_{Lbat} dt = \int_0^{t_1} V_{bat} dt + \int_{t_1}^{t_2} V_{bat} dt + \int_{t_2}^{T_s} (V_{bat} - V_0) dt = 0 \quad (11)$$

Solving (10) and (11) it finds:

$$V_0 (T_s - t_1) = V_s T_s \quad (12)$$

$$V_0 (T_s - t_2) = V_{bat} T_s \quad (13)$$

Dividing both sides by T_s and rearranging terms it finds:

$$\frac{V_0}{V_s} = \frac{1}{1 - D_1} \quad (14)$$

$$\frac{V_0}{V_{bat}} = \frac{1}{1 - D_2} \quad (15)$$

It can be seen from (14) and (15) that in mode 2 the system operates like two independent boost converters in parallel.

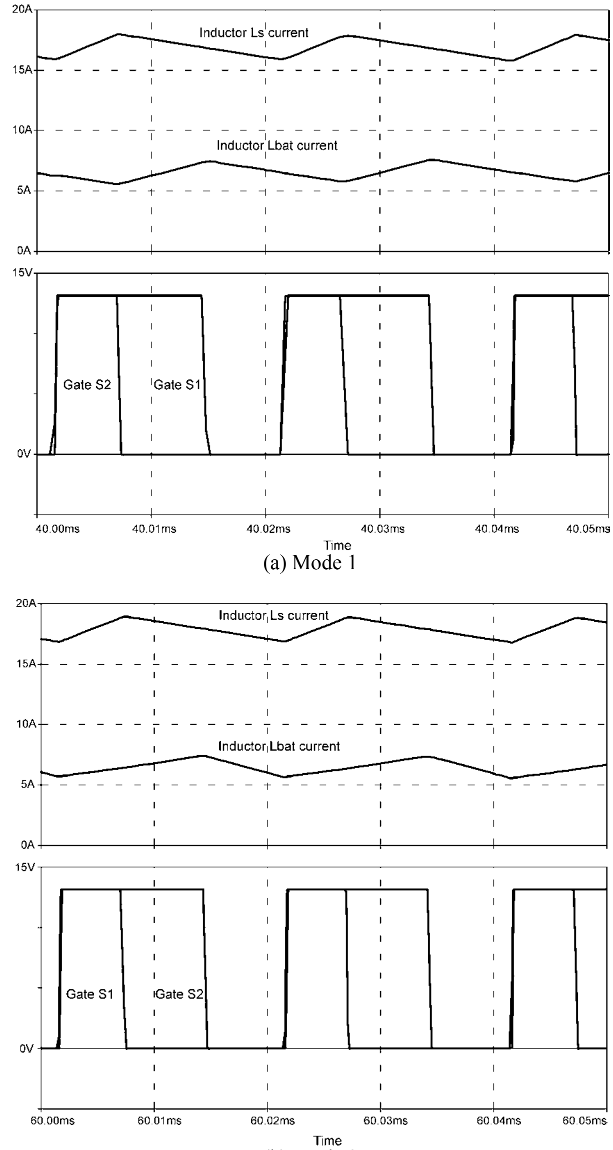
V. Simulation Results

In order to confirm the concept, the VR-BESS has been studied by simulation, using the parameters listed in Table 1.

TABLE 1
PARAMETERS OF SIMULATION

DC Grid voltage (V_s)	240 - 300 V
Battery bank voltage (V_{bat})	150 V
Output DC bus voltage (V_0)	400 V
Inductor L_s	700 μH
Inductor L_{bat}	1 mH
Capacitor C_{bat}	200 μF
Capacitor C_0	200 μF
Output Power (P_0)	4 - 6 kW
Maximum DC Grid Power (P_s)	5 kW
Switching frequency	50 kHz

Currents through inductors L_s and L_{bat} in modes 1 and 2 can be seen in Fig. 7.



(a) Mode 1

(b) Mode 2

Fig. 7. Simulation results: Inductors L_s and L_{bat} currents.

Fig. 8 shows a response of the VR-BESS to a step change in the load. At t = 45ms, the load resistor was reduced, generating an increase in the demand of power from 4 kW to 6 kW. It can be noted that the current though inductor L_{bat} has changed. Initially the battery bank has been charged. After the increase in the output power the battery bank supplements the energy required by load.

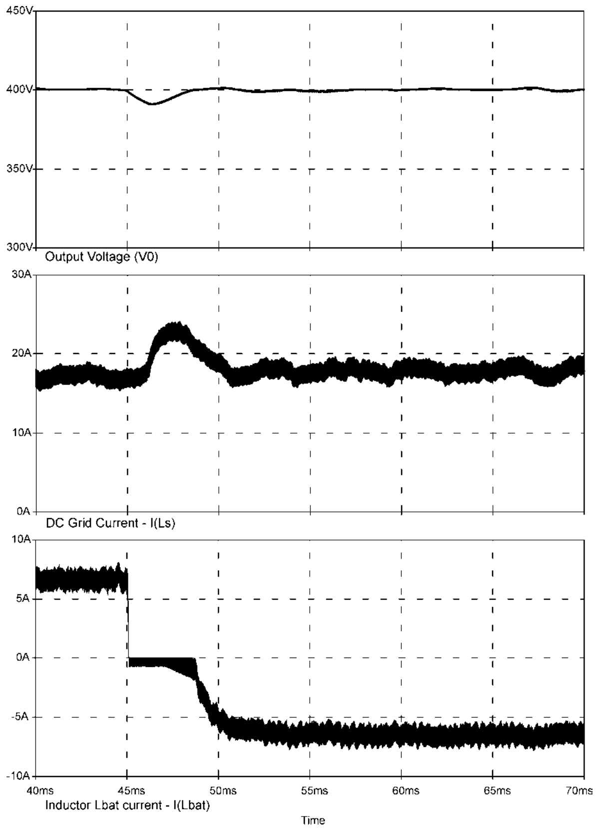


Fig. 8. Simulation results. Response to a step change in load.

Fig. 9 shows a response of the VR-BESS to a step change in the input DC grid voltage. At t = 90 ms, the DC grid voltage V_s was changed from 300 V to 240 V.

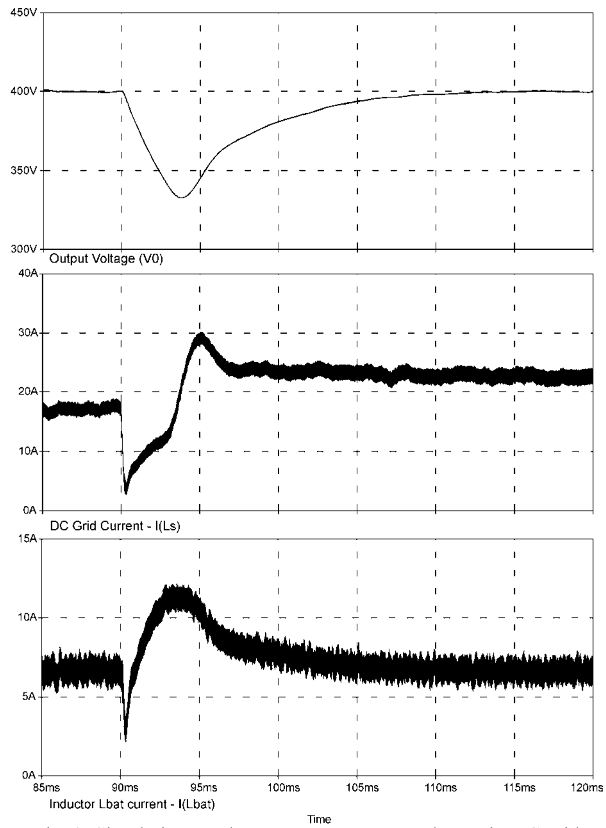


Fig. 9. Simulation results. Response to a step change in DC grid voltage.

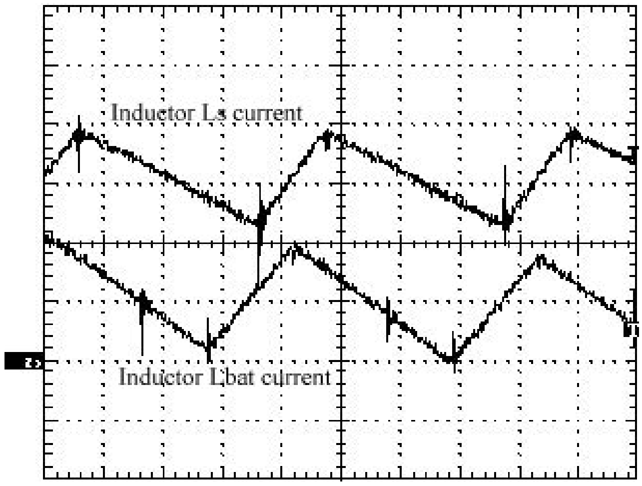
VI. Experimental Results

To verify the theoretical and simulated results of the proposed system, a prototype has been built and tested using the parameters listed in Table 2.

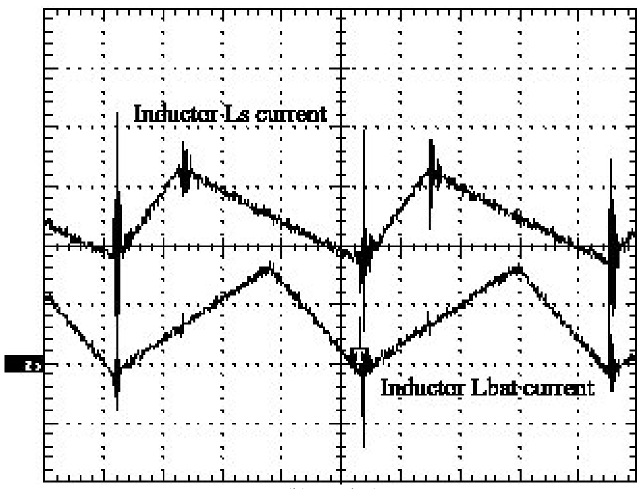
TABLE 2
PARAMETERS OF IMPLEMENTED PROTOTYPE

DC Grid voltage (V_s)	300 V
Battery bank voltage (V_{bat})	150 V
Output DC bus voltage (V_0)	400 V
Inductor L_s	1 mH
Inductor L_{bat}	1 mH
Capacitor C_{bat}	330 μF
Capacitor C_0	330 μF
Output Power (P_0)	1.5 kW
Switching frequency	50 kHz
Switches	IRFP 460
Diodes	MUR 1560

In Fig. 10 are shown the currents through inductors L_s and L_{bat} in modes 1 and 2.



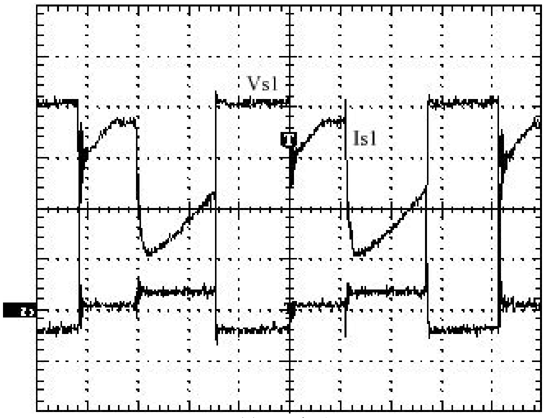
(a) Mode 1.



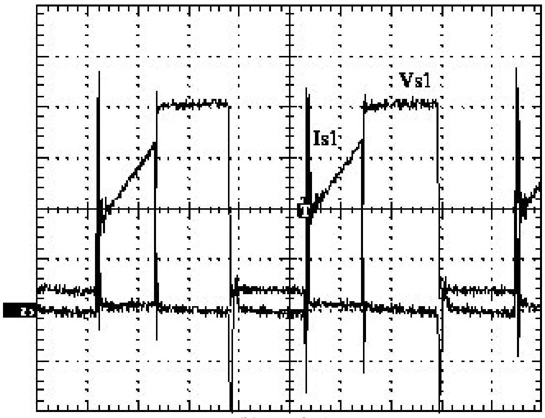
(b) Mode 2.

Fig. 10. Experimental results: Inductors L_s and L_{bat} currents. (2A/div, 5μs/div).

Figures 11 and 12 show voltage and current across the switch S_1 and voltage and current across the switch S_2, respectively.

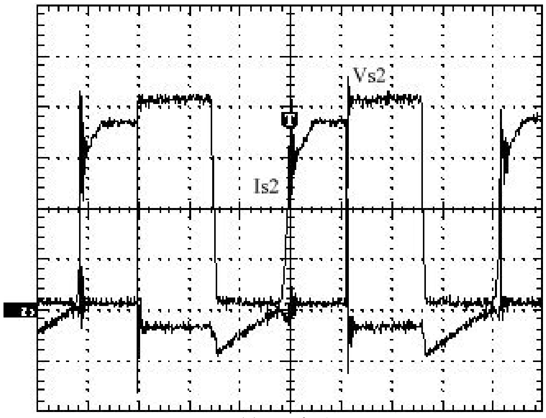


(a) Mode 1.

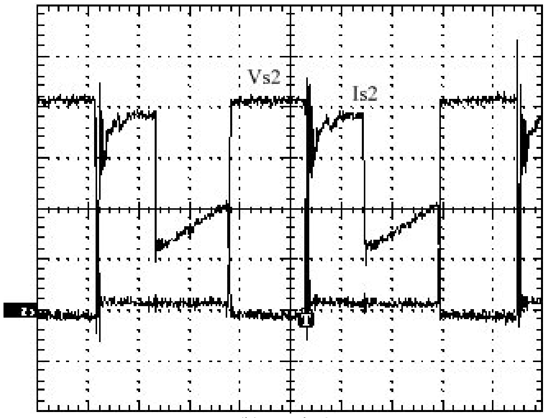


(b) Mode 2.

Fig. 11. Experimental results: Switch S_1 voltage and current. (2A/div, 100V/div, 5μs/div).



(a) Mode 1.



(b) Mode 2.

Fig. 12. Experimental results: Switch S_2 voltage and current. (2A/div, 100V/div, 5μs/div).

VII. CONCLUSION

This paper has been presented an analysis of system composed of a voltage regulator and a battery energy storage. Voltage regulation, peak power leveling and compensation for power fluctuations are realized by a simple structure. Due these features, the proposed system becomes adequate for applications in renewable energy system. For wind energy, the Voltage Regulator - Battery Energy Storage System (VR-BESS) can be connected to an uncontrolled rectifier. In the case of solar energy, the proposed system can be connected directly to a photovoltaic array.

Functionally, the proposed VR-BESS operates like a conventional boost converter to provide voltage regulation and to step up the battery bank voltage to output DC bus. For battery charging the VR-BESS operates like a conventional buck converter.

Mathematical expressions, digital simulations and experimental results for various modes of operation have been developed in order to describe the operation of the VR-BESS. The results validate the operational concept of the proposed system.

VIII. ACKNOWLEDGMENTS

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IX. REFERENCES

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