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Design and Simulation of a Dual Conversion Transformerless Online and Line-Interactive UPS

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Abstract

In this paper, a dual-conversion online static UPS and Line-Interactive UPS system was modeled and simulated using PSIM software. The components of the proposed design were specified based on pre-defined constrains, and the dynamic behavior of the system was modeled through state-space equations. With the system components characterized, a suitable controller was developed for closed-loop control of the buck and boost circuits. A battery charge management controller was also developed to ensure the robustness of the design. Overall system performance was analyzed under varying load and line conditions. Conversion bypass switching was simulated and the overall system performance was analyzed while observing the state of charge – SOC behavior of the battery.

Keywords: Online UPS, Line-Interactive UPS, PID controller, Converter Design, Energy Storage.

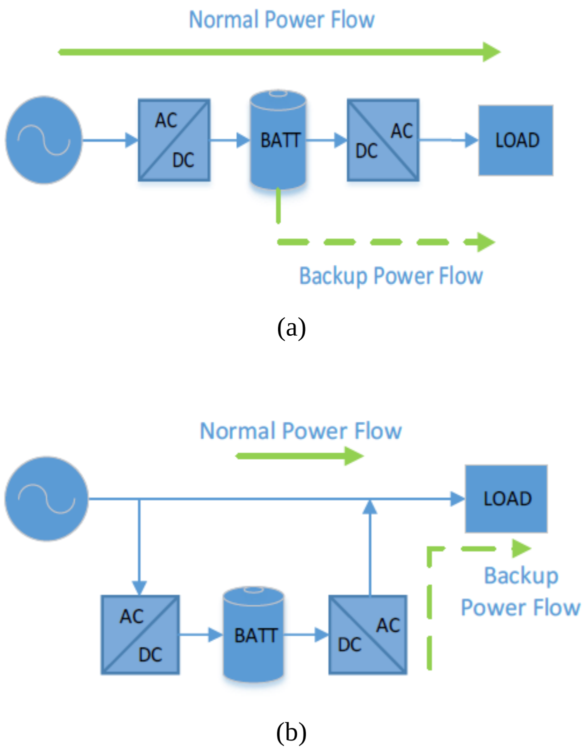
I. Introduction

Modern life has created a society dependent on electrical powered devices. For the largest parcel of those equipment applications, such as electronic gadgets, home entertainment systems, electric tools and others, eventual failures in their operation are, at most, inconvenient. On the other hand, for some critical applications, uninterrupted continuous operation is a necessity. The objective behind Uninterruptible Power Supply (UPS) is to guarantee uninterrupted and reliable power delivery to vital loads, meeting minimum power quality standards.[1] Those vital loads, such as medical facilities, life support equipment, data centers and others, are sensitive not only to power outages, but also to several common conditions commonly observed in power grids like undervoltage, overvoltage, harmonics and transients. UPS systems also protect critical systems from line frequency variation.[2,3] There are several industries which require continuous power delivery to function properly or effectively. Some of those industries, where power failure would carry grievous or expensive consequences, are datacenters, health care, telecommunication, weather forcasting etc.

There are several types of UPS technologies and models. They are mainly divided in (a) Static type UPS and (b) Rotating type UPS. Static type UPS are also divided in (a) Online type (b) Offline type and (c) Line interactive type.[5]

Static UPS systems are composed of power converters and an energy storage device (typically a battery). A UPS system is characterized as Online-Static when the load is connected to the grid through the UPS system power conversion circuits.[10]When the load is connected directly to the grid and the UPS is in standby, the UPS is characterized as Offline.[11]When the load and the UPS are both connected directly to the grid, and the UPS can determine any power outage or below standard power quality, theUPS is characterized as Line-Interactive.[12]Line-interactive UPS is a suitable choice for hybrid energy storage system.[14,15] The Online, Offline and Line interactive UPS are shown in figure 1.

There are different types of applications which are benifited from the use of UPS systems for the uninterruptable supply of power. Like, emerging technologies using UPS systems to store energy collected through solar power to be used during data center peak times take advantage of smaller sized UPS systems to distribute the storage of energy.[3,4,13]



(a)

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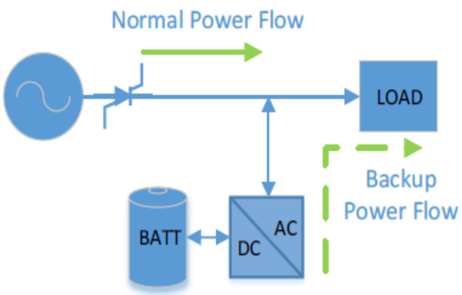


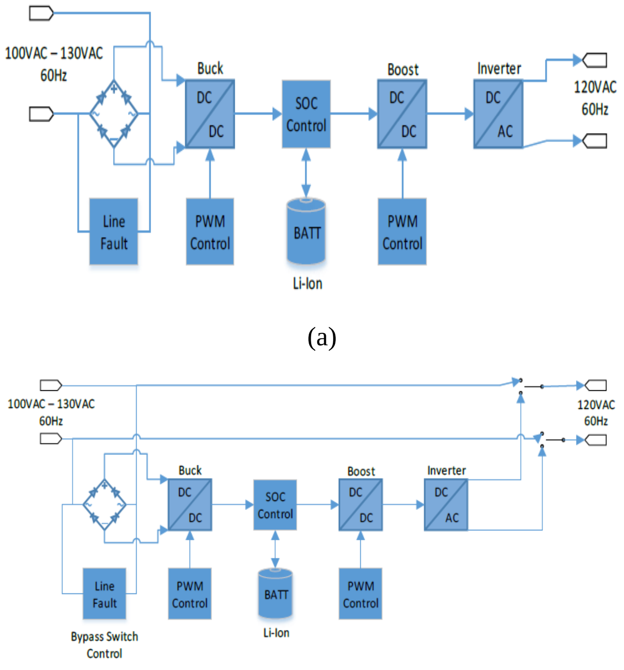
(c)

Fig. 1. UPS type : (a) Online, (b) Offline and (c) Line- interactive

In the following sections, the modeling and simulation of the system is illustrated.

II. Simulation and Modeling of the System

The design of a dual-conversion online static UPS system was modeled. A simplified diagram of the system is presented in figure 2 (a). This type of system is an Online UPS system. A better model would include the ability to bypass conversion and leave the system in a standby state when the line power is considered above a predefined quality standard. Having the system in a standby state would improve efficiency, but the quality of the power delivered to the load may not be as good as the Online system ensures. The simplified diagram of Line-Interactive type UPS is shown in figure 2(b).These two simplified diagrams of figure 2 are implemented in PSIM for analysis which is discussed on section IV.



(a)

(b)

Fig. 2. Simplified System Diagram of UPS
(a) Online UPS and
(b) Line interactive UPS

III. Convertet Modeling

The converters were controlled for the required output power, voltage and current by the PWM varying duty cycle. The block for controlling converter and feedback system for output regulation are shown in figure 3. Where, *H(s)* is the sensor gain, $G_{vd}(s)$ is the converter control-to-output transfer function. $G_{vg}(S)$ is the converter line-to-output transfer function and $G_c(s)$ is the controller gain.[9]

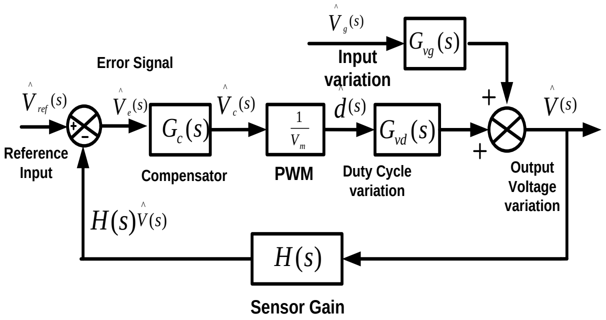


Fig. 3. Feedback control diagram for converter.

Buck Converter Modeling

The dynamics of the system components were modeled using the state-space method in order to design PWM controllers for the buck and boost converters. A summary of this analysis is presented here. Where Rm, Rc, R_L and Ron are parasitic components of the switch, capacitor and inductor. For the state-space characterization, small signal model has been considered.

The equations for analyzing the buck converter dynamics are found considering open and close operation of the switch, M. In following euqtions, V_L is the voltage across the inductor and $I_c$is capacitor current.

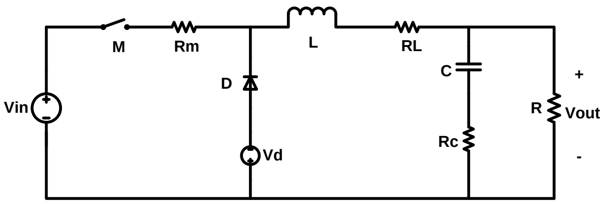


Fig. 4. Buck Converter Model

When switch M is closed:

$$V_L = V_{in} - R_{on}I_L - V_{out} = L\frac{di(t)}{dt}$$

$$I_C = I_L - \frac{V_{out}(t)}{R} = C\frac{dV_{out}(t)}{dt}$$

When M is open:

$$V_L = -V_d - V_{out}(t) = L\frac{di(t)}{dt}$$

$$I_C = I_L - \frac{V_{out}(t)}{R} = C\frac{dV_{out}(t)}{dt}$$

Then, the state space model of these equations has applied and transfer function of the system was calculated from the the state space model:

$$G(s) = C(sI - A)^{-1}Bu + Du$$

$$G_{vout\_D}(S) = \frac{V_{in} - R_m I + V_d}{LC[s^2 + s(\frac{DR_m}{L} + \frac{1}{RC}) + (\frac{DR_m}{RLC} + \frac{1}{LC})}$$

For the buck converter, the inductor and capacitor values were selected to suit the battery specifications. The selected battery is a 48V, 20Ah, Li-Ion battery with a charge current rating of 25% &5A. So, output of buck converter has to be 48V. Considering an allowable current ripple to be 10%, we getΔi=0.5A. Also, considering an allowable voltage ripple to be 2% results in ΔV=0.96V. Since the input line voltage range is 100Vac -130Vac and the output voltage of the buck converter is 48V, we can consider the nominal output voltage of the rectifier circuit to be 110Vdc and the nominal PWM value (D) to be 0.4363. Assuming a switching frequency of 100kHz, the inductor and capacitor values were chosen to be 500uH and 100uF respectively. Also, for the MOSFET, $R_m = 50\text{m}\Omega$, and the diode, $V_d = 0.7$ V. With the buck converter parameters defined, the system transfer functionis will be asbelow. The design specifications and parameters are shown in Table 1.

$$G_{vout\_D}(S) = \frac{120}{(5\times10^{-8})s^2 + (5.302\times10^{-5})s + 1}$$

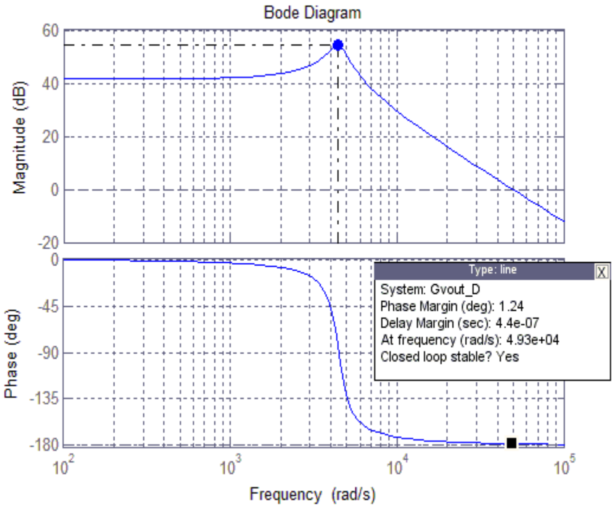


Fig. 5. Bode Plot of transfunction, Gv_{out_D}

Table 1. Design Specifications

Parameters	Buck Converter	Boost Converter
Input voltage, Vin	110Vdc (Nominal)	48Vdc
Output voltage,Vout	48Vdc	160Vdc
Current ripple, Δi	10%	10%
Voltage ripple, ΔV	2%	2%
Switching Frequency, fs	100KHz	100Khz
Capacitor,C	100uF	50uF
Inductor, L	500uH	200uH

Table 2. Design Specifications

Inverter	
Input voltage, Vin	160Vdc
Output voltage,Vout	110Vac
Frequency	60Hz
Switching Frequency, fs	100KHz
THD	16.5%
Conversuion Efficiency	>90%
Energy Storage	
Battery voltage (Li-ion)	48V @ 20Ah
Initial SOC	0.5
Charge Current	25% &5A

The bode plot of transfunction,G_{vout_D} is plotted in Figure 5. It is found that the phase margin isvery low, so it can be said the transfer function is marginally stable, hence there is a need for designing a PID controller. With the configured PID controller the combined transfer function is shown below. The corresponding bode plot of the system is shown in Figure 6. From Figure 6, it is seen that the phase margin is good enough to make the converter stable.

$$G(S) = \frac{1.47s^2 + (3.149\times10^4)s + 1.206\times10^8}{(5\times10^{-8})s^4 + 0.01168s^3 + 13.33s^2 + (2.325\times10^5)s}$$

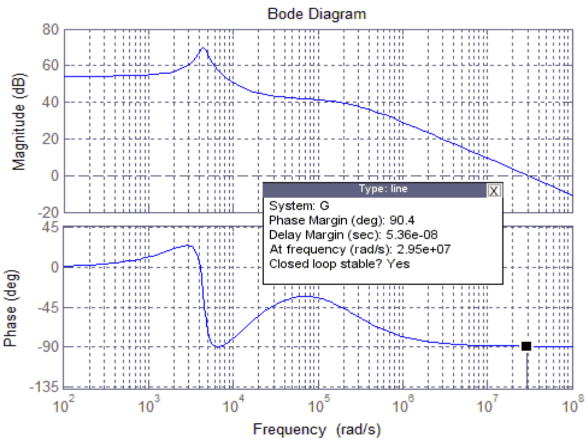


Fig. 6. Bode Plot for the system of the Buck Converter

Boost Converter Modeling

A Boost converter is modelled using same fashion. The corresponding equation of boost converter is found when switch, M is closed and open.

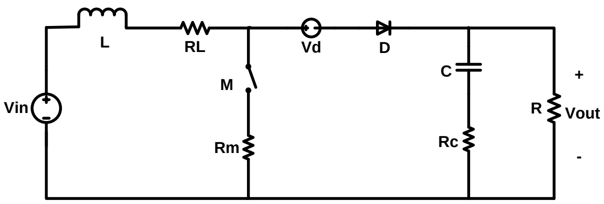


Fig. 7. Boost Converter Model

When switch, M is closed:

$$V_L = V_{in} - R_m I_L = L\frac{di_L(t)}{dt}$$

$$Ic = -\frac{V_{out}(t)}{R} = C\frac{dV_c(t)}{dt}$$

When switch, M is open:

$$V_L = V_{in} - V_d - V_{out}(t) = L\frac{di_L(t)}{dt}$$

$$Ic = I_L - \frac{V_{out}(t)}{R}$$

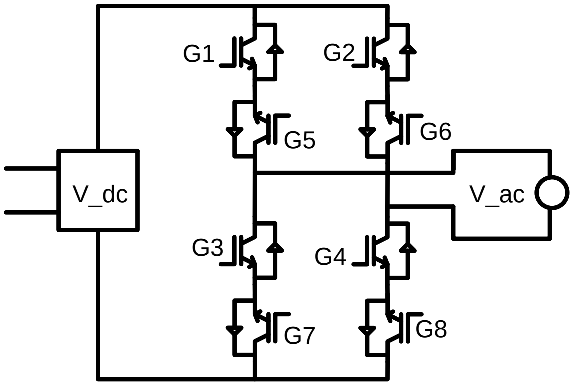
After applying state space model the corresponding transfer function,G_{vout_D} of Boost converter is-

$$G_{vout\_D}(S) = \frac{(s + \frac{R_m D}{L})(-\frac{1}{C}) + (\frac{-IR_m + V_d + V_{out}}{L})(\frac{D'}{C})}{s^2 + s(\frac{DR_m}{L} + \frac{1}{RC}) + (\frac{DR_m}{RLC} + \frac{D'}{LC})}$$

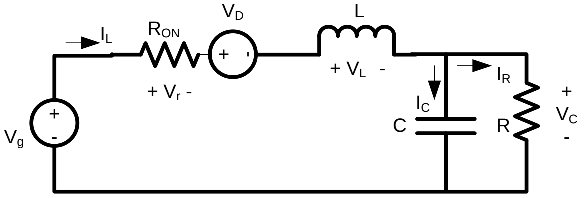
L=200uH and C=50uF were taken to minimize the ripple of the output voltage and for producing an acceptable transfer function. Similar to the buck converter analysis, R_m = 50 mohm, and V_d = 0.7V were taken for the boost converter also. The Boost converter is not stable and phase margin was not adequate initially.To stabilize the system, a PID controller was configured to compensate the system transfer function in the same fashion as with the buck converter. However, stability of the boost converter control proved to be inadequate during switching of Line-interactive UPS. For this reason, the boost converter was run in the open-loop mode for the Line-Interactive version of the system in this research.

DC to AC Inverter Modeling

An IGBT based PWM inverter is used to convert the DC voltage to the AC voltage (modified sign waves).



(a)



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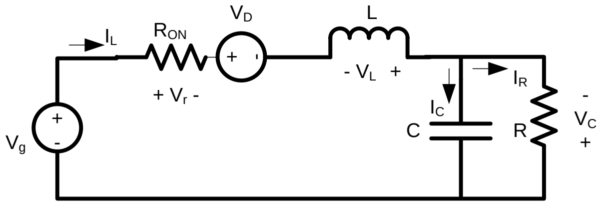


(c)

Fig. 8. Modified sine wave inverter:
(a) The bridge inverter
(b) Equivalent circuit of the inverter for mode 1
(c) Equivalent circuit of the inverter for mode 2

In the Inverter there were used eight IGBTs insted of four, so that the module can be used as rectifier if requires. During the mode-1, G1 & G4 switch is turned on and others are off and the antiparallel diodes of the G5 and G8 conducts. For mode-2, G2 & G3 switch is turned on and others are off and the antiparallel diodes of the G6 and G7 conducts. The output of the inverter is 110V, 60 Hz ac. Considering the Mode1 and Mode 2 as the above figures the transfer function is derived as following:

$$Gvd = \frac{\hat{v}_o}{\hat{d}} = \frac{\left(\frac{2D}{C} - \frac{1}{C}\right)\left(-\frac{2R_{on}I_L}{L} + \frac{2V_g}{L}\right) + \left(s + \frac{2R_{on}D}{L} - \frac{R_{on}}{L}\right)\left(\frac{2I_L}{C} - \frac{2V_c}{RC}\right)}{\left(s + \frac{2R_{on}D}{L} - \frac{R_{on}}{L}\right)\left(s + \frac{2D}{RC} - \frac{1}{RC}\right) - \left(\frac{1}{L}\right)\left(-\frac{2D}{C} + \frac{1}{C}\right)}$$

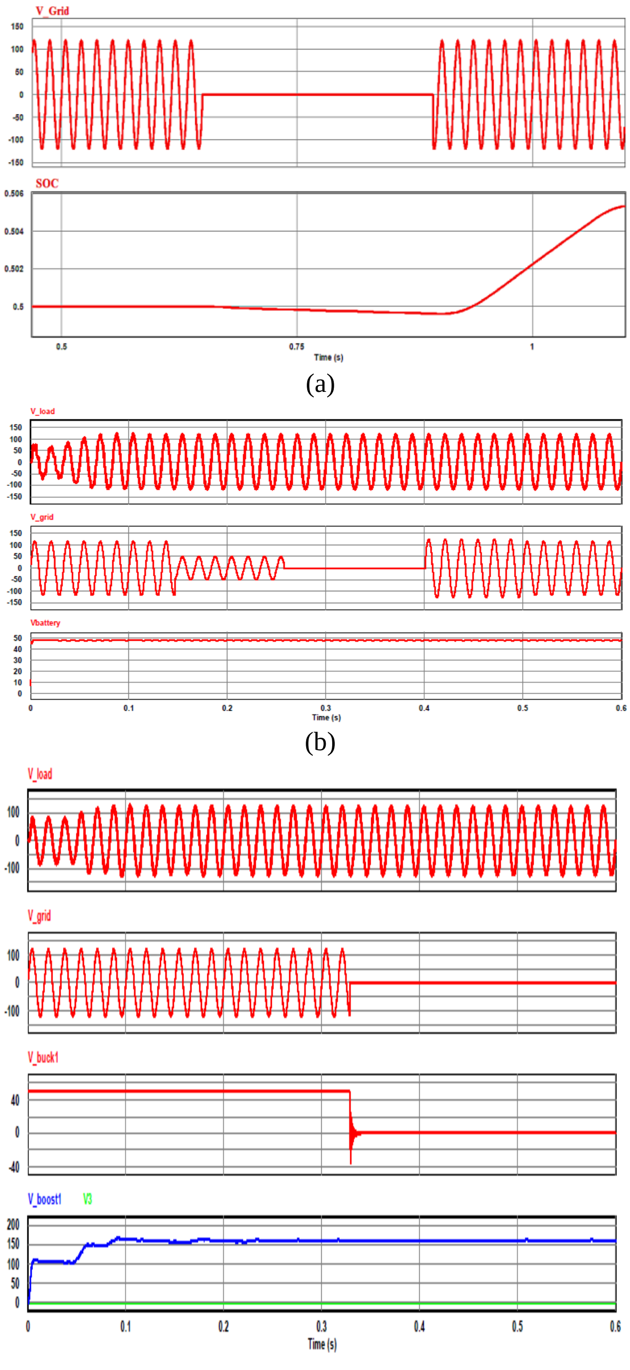
Considering the the diode voltage drop as negligible and the value of the inductor as L=100 uH, capacitor C=680uF, IGBT on resistance Ron=10 mΩ, we get around 16.5% THD for the inverter output voltage.

IV. Schematic and Simulation Results

Simulations were divided into two separate models: Online and Line-Interactive. Testing consisted of varying the line voltage level while simultaneously monitoring buck converter operation, battery SOC, and boost converter operation. Results for the online system are presented first.The simulations are done in PSIM. The simplified diagram of online and line-interactive UPS in figure 2(a) & 2(b) are implemented in PSIM.

Online UPS Simulation

The SOC vs the line voltage plot in figure 9(a) shows that the energy stored in the battery starts to decrease when the grid loses power, and subsequently increases when grid power is restored. The battery SOC was initially set at 0.5 for simulation purposes. Figure 9(b) shows that the load voltage remains unaffected with the change of the grid voltage.Figure 9(c) illustrates the response of the system to a loss of grid voltage. The buck converter operation stops, however the boost converter voltage remains fairly constant, and the load voltage remains regulated. PSIM simulations prove the integrity of the online UPS model. The load voltage is maintained regardless of the state of the grid, as long as the battery has adequate charge.



(a)

(b)

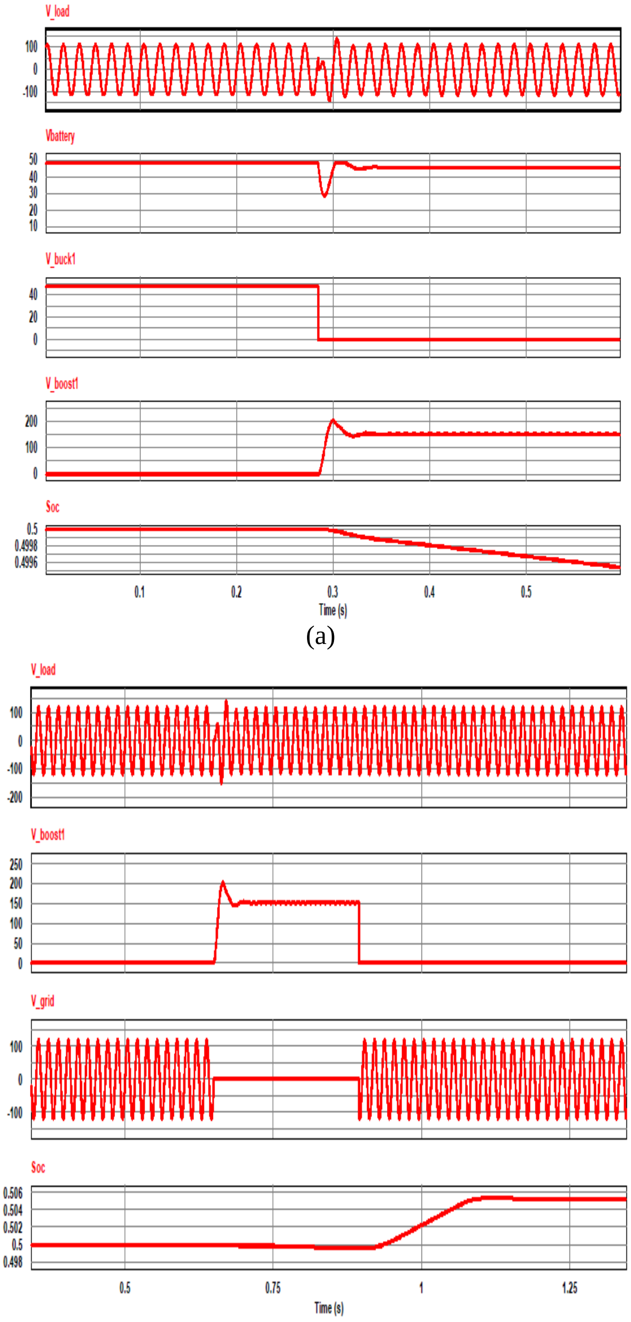
(c)

Fig. 9. Online UPS Simulation:
(a) Voltage and Battery SOC Plots
(b) Load Voltage, Grid Voltage and Battery Voltage Plots
(c) Load Voltage, Grid Voltage, Buck Converter Voltage and Boost Converter Voltage

Line-Interactive UPS Simulation

The Line-Interactive version of the model was also simulated. Stability of the boost converter control proved to be inadequate during switching of this case. For this reason, the boost converter was run in the open-loop mode for the Line-Interactive version of the system in this paper. Phase difference between the grid volage and inverter output was causing large currents during bypass switching events. In order to avoid this situation a PLL (Phase-Lock-Loop) circuit could be employed to ensure synchronization between the inverter output and the grid voltage.

To simulate the Line-Interactive version without losing stability of the boost converter, closed-loop control of the boost converter was removed. With the boost converter operating open-loop, the following results are obtained.



(a)

(b)

Fig. 10. Line-Interactive UPS Simulation:

(a) Load Voltage, Battery Voltage, Buck Converter Voltage, Boost Converter Voltage, and Battery SOC.
(b) Load Voltage, Boost Converter Voltage, Grid Voltage and Battery SOC

Figure 10(a) shows the response of the system when the grid voltage is lost. The buck converter stops to work and the boost converter starts supplying the load and the battery SOC begins to deplete.Figure 10(b) further illustrates system operation. When the grid voltage is lost, the battery SOC is decreasing. Later, when the grid voltage is restored, the battery SOC increases until it reaches a limit set by the battery SOC controller.

V. Conclusions and Future Work

Simulations of the Online UPS system and the Line-Interactive UPS system presented very promising results. The PID controllers configured for the PWM control of the boost and buck converters restore stability to the subsystems and regulate the load voltage and battery charge respectively. Both systems consistently supply power to the load regardless of the state of the grid, as long as the battery SOC is adequate. It is suspected that phase difference between the grid volage and inverter output of Line-Interactive UPS was causing large currents during bypass switching events. In order to avoid this situation, a PLL (Phase-Lock-Loop) circuit should be employed to ensure synchronization between the inverter output and the gridvoltage.The detailed analysis of isolated high frequency transformerless/ transformer-based UPS system for small energy storage can be done as future work of this project.

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