Chapter

Design of High Power Regenerative Battery Discharger System for Nuclear Power Plant

Kudiyarasan Swamynathan, N. Sthalasayanam and M. Sridevi

Abstract

In a Nuclear Power reactor, safety loads are backed by standby battery system. The healthiness of the battery is very essential requirement and prominent attention is given to availability and reliability of battery supply in nuclear plants. Hence regular monitoring and testing the performance of the battery is a prime requirement. The capacity and load cycle discharge testing of the battery is done annually and the current system employed is to discharge the battery current through resistor banks, which results in unusable power consumption and is uneconomical. The growing trend in power electronics field has given the new technology of regenerating the dissipated power to grid. This paper proposes a high power electronic regenerative technology with high efficiency, low harmonics to pump the dc power to the grid. Though, it is available at lower rating in industry, the paper proposes a high power regenerative discharge system. The topology selected is interleaved boost converter interfaced to a three phase grid connected inverter. The challenges involved are high power operation, steep current discharges with a minimal interference to the normal plant operation power supplies during the regeneration. This paper also presents the system design and simulation results.

Keywords: Regenerative battery discharger, Interleaved Boost Converter, Grid connected Inverter, harmonics reduction, nuclear safety load

1. Introduction

In nuclear power plants, the batteries and DC power system plays a prominent role in the reactor safety and shutdown. Hence the preventive maintenance and testing the capability of battery to cater the safety loads during power failure are done regularly as per nuclear standards. There is requirement of performing C10 and HRD discharging the batteries. The growing trend of large capacity NPP's being installed worldwide has increased the battery ratings substantially, resulting the discharge testing requirements to high current and voltage levels [1]. In conventional plants, resistor banks employed for discharging battery has resulted in power loss, hence there is a need to use the regenerate power electronics system in the battery application. Even though Low power discharge systems are available in the current scenario, the discharging of high power battery systems for higher currents and shorter duty cycles is the motivation behind this paper [2, 3]. The system employs two phase interleaved boost converter to step up the connected battery

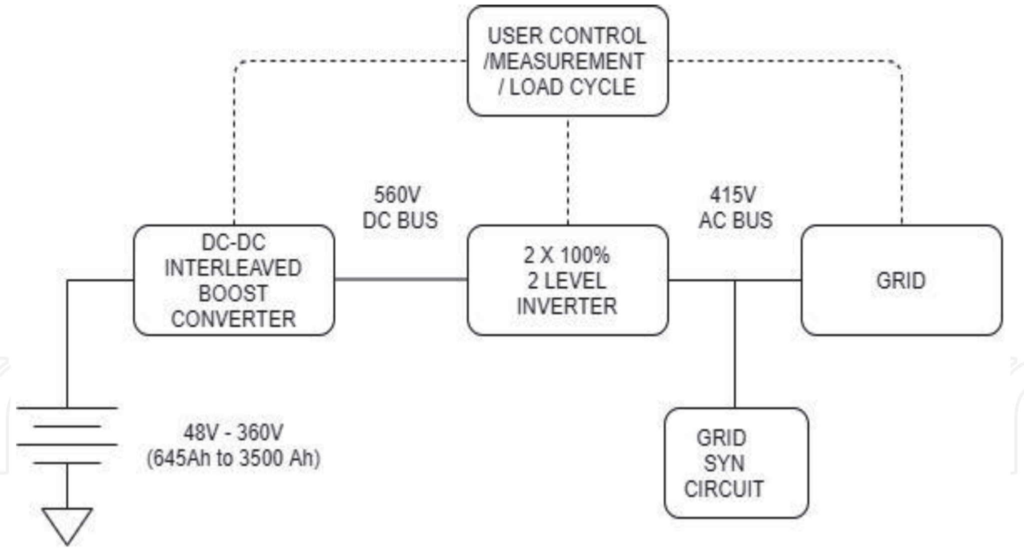

Figure 1.
Block diagram of grid connected regenerative discharger system.

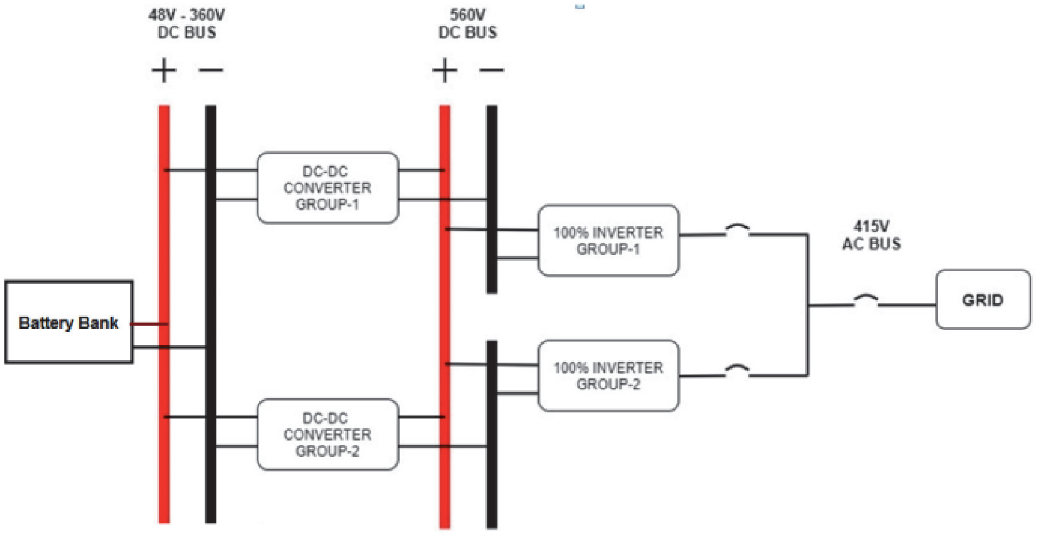

Figure 2.
Schematic of regenerative battery discharge system.

voltage level from (48–360)V DC to 560 V DC as shown in **Figure 1**. The boost converter topology is selected to ensure minimum DC ripples in the inverter dc bus.

The boost converter is modularized into two independent 50% power units and they are independently connected to 2 X 50% two level 415 V Inverter.

Accordingly the boost converter is designed in the modular approach, with two sets of 3 X 100A boost converter to provide required current rating as shown in **Figure 2**. The Grid connected inverter discharges the power to Grid by converting DC to AC. The output isolation transformers in the inverter reduce the third harmonic component and also provide isolation between grid and the plant system.

2. Regenerative power electronics topology

2.1 High power load cycles of batteries

The plant consist of the following battery banks for the reactor safety loads in the range of 48 V DC, 220 V DC, 360 V DC. Following are the various battery bank capacities with various DC voltage ranges as shown in **Table 1**.

In the nuclear power plant the load cycle is more complex when compared with other conventional plants [4]. A typical example of load cycle is given in **Table 2**.

2.2 DC-DC converter topology

The topology selected for our application is dual phase Interleaved Boost Converter (IBC). Interleaving is a method of multi-phasing in which two converters are connected in parallel. In interleaved boost converters, the number of phases has a significant impact on the current ripple [5, 6]. Though ripple content reduces with increase in the number of phases, the power circuit, on the other hand, the complexity of the circuit and triggering signals will be increase [7].

In this paper, a two-phase interleaved boost converter is selected as DC-DC Converter topology [8]. In a two-phase converter, there are two Output stages that are driven 180 degrees out of phase as shown in **Figure 3**. By splitting the current into two parallel paths, conduction losses can be reduced, leading to improved efficiency compared to a single-phase converter. The ripple generated from switch S1 and complimentary switch S2 cancels each other [9, 10]. Employing coupled inductors in this topology adds to the advantage of the input current-ripple cancelation from magnetic coupling between the phases. The frequency of the current ripple is twice for two phase IBC than the conventional boost converter [11]. The

Voltage (V)	Ampere hour (Ah)	No. of sets
48 V	800 Ah	4
48 V	1600 Ah	4
220 V	650 Ah	4
220 V	2400 Ah	2
220 V	3500 Ah	2
360 V	1900 Ah	4

Table 1.
Various batteries with different voltage rating and capacity available in the plant.

<table>
<tr><th rowspan="3">Discharge current duration (minutes)</th><th colspan="6">Battery bank voltage (volts) and capacity (Ah)</th></tr>
<tr><th>48 V
800 Ah</th><th>48 V
1600 Ah</th><th>220 V
650 Ah</th><th>220 V
2400 Ah</th><th>220 V
3500 Ah</th><th>360 V
1900 Ah</th></tr>
<tr><th colspan="6">Current (Amps)</th></tr>
<tr><td>0–1</td><td>200</td><td>500</td><td>350</td><td>600</td><td rowspan="9">600A for 240 min</td><td rowspan="9">522A for 60 min</td></tr>
<tr><td>1–10</td><td>200</td><td>500</td><td>100</td><td>290</td></tr>
<tr><td>10–15</td><td>200</td><td>500</td><td>150</td><td>290</td></tr>
<tr><td>15–16</td><td>200</td><td>500</td><td>150</td><td>590</td></tr>
<tr><td>16–30</td><td>200</td><td>500</td><td>150</td><td>590</td></tr>
<tr><td>30–60</td><td>50</td><td>100</td><td>50</td><td>590</td></tr>
<tr><td>60–240</td><td>50</td><td>100</td><td>50</td><td>20</td></tr>
<tr><td>240–840</td><td>25</td><td>50</td><td>10</td><td>20</td></tr>
<tr><td>840–841</td><td>—</td><td>—</td><td>20</td><td>50</td></tr>
</table>

Table 2.
The load demanded with required time duration of all battery banks available in the plant.

converter must be able to operate over a wide input-voltage range (40-400 V) to accommodate batteries of different voltages (48 V, 220 V, 360 V). Because of the wide input range, the converter also must be able to operate with a wide input-voltage to output-voltage ratio [12].

The controller sets the pre-set duty cycle as input for converter switching as the input voltage to converter is selected by the operator. The output voltage of the boost converter is fixed to 560 VDC for providing required DC bus voltage for the inverter module. The main design consideration of this converter is done with respect to the battery's end bank voltage [13]. During discharging of batteries, as the battery reaches the end bank voltage, the voltage boosting has to be done by the converter for the reduced input voltage to maintain a steady DC bus at inverter input and has to supply the rated current at the output. This design consideration is implemented through dynamic duty cycle variation based on the input DC voltage feedback to the converter [14, 15]. Switching frequency of the converter is selected nominally at 10 kHz and the duty cycle for the switching is selected as per the input-voltage equations of a traditional boost converter. The inductors selected for the converter is uncoupled type.

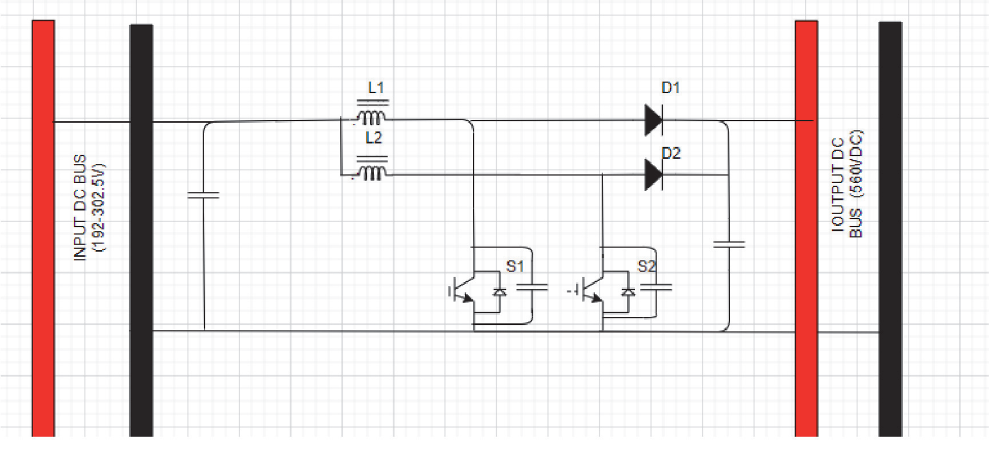

Figure 3.
Schematic of boost converter.

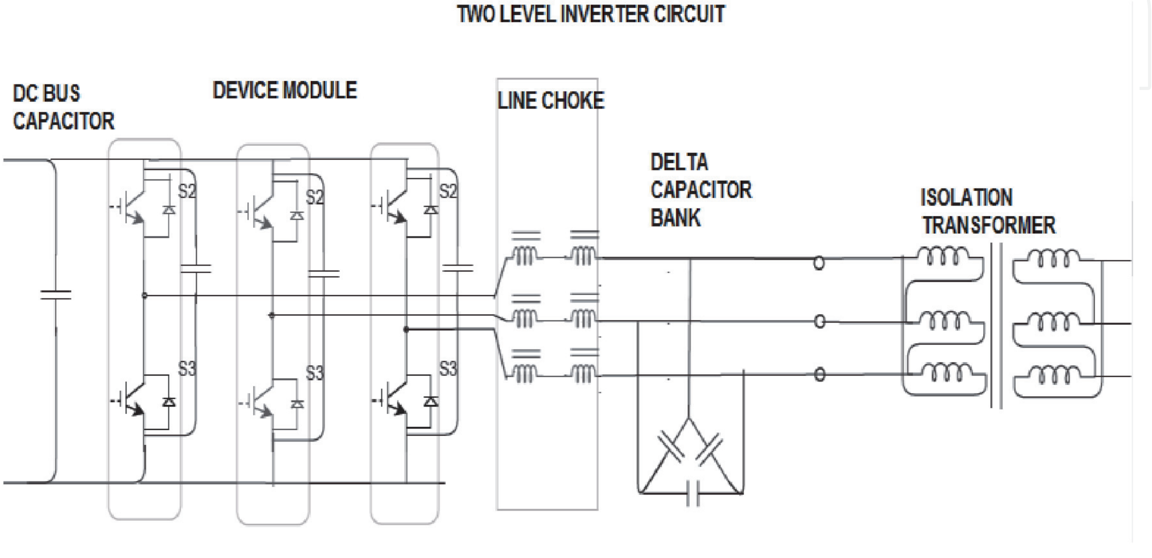

Figure 4.
Schematic of two level inverter systems.

2.3 Grid connected inverter topology

2 X 100kVA IGBT (Insulated Gate Bipolar Transistor) based inverter at the DC boost converter output operates in synchronism with Grid supply.

Two power stacks for each phase is designed for effective load sharing and thereby reduced heat dissipation [16]. The switching frequency of inverter is selected at 1 kHz. Sinusoidal PWM algorithm is implemented for generating inverter switching pulses. There are two inverters each rated 50% capacity (100KVA) connected parallel sharing the load. Inverter-1 is fed from Group-1 DC Boost converter and Inverter-2 is fed from Group-2 Boost converter. In case of failure of one inverter, the 50% load can be taken up by the second inverter. The topology of two level inverter is selected to reduce the complexity in inverter design. The output harmonics primarily 5th and 7th harmonic components are reduced with the help of LC Filter as shown in **Figure 4**. The 415/415 V output isolation Δ-Δ transformer eliminates third harmonics in the output. The inverter is in synchronized to grid during operating conditions. The battery power is delivered to grid with the help of inverter synchronized to grid supply.

3. Circuit parameter design

The design of interleaved boost converter is very similar to traditional boost converter design.

3.1 Duty cycle (D)

Generally output voltage equation of any conventional boost converter is given in (1), Duty cycle for any input and output voltages can be represented as (2),

$$\mathrm{V_O} = \frac{Vd}{(1-D)} \tag{1}$$

$$\mathrm{D} = \frac{(\mathrm{Vo–Vd})}{\mathrm{Vo}} \tag{2}$$

Boost converter to work with three different input voltages 48 V, 220 V, and 360 VDC respectively as represented below,

$D_{48V} = D_{max}$ = (560–48) / 560 = 0.914.
D_{220V} = (560–220) / 560 = 0.607.
$D_{360V} = D_{min}$ = (560–360) / 560 = 0.357

3.2 Current ripple (ΔI_O)

Each Boost Converter is designed for 30KW Power rating.
Load current I_O = Output power /Output voltage
$I_O = 33 \times 10^3 / 560$ = 59A.
For D < 0.5

$$Iorms = \frac{\mathrm{Io}\sqrt{\mathrm{D}(1-\mathrm{D})}}{2(1-D)} \tag{3}$$

For D > 0.5

$$Iorms = \frac{\text{Io}\sqrt{\frac{1}{2}(2D-1)(2-2\text{D})}}{2(1-D)} \tag{4}$$

By using (3) and (4), Output rms current is arrived for all modes as below.
Iorms (48 V) = 91.52 A.
Iorms (220 V) = 21.72 A.
Iorms (360 V) = 21.98 A.
Considering ΔI_O load current ripple to be 8% of output current. For evaluation, maximum duty cycle, in this case for input 48 VDC Input mode, current ripple (ΔI_O) is arrived to be 7.2 A. For other duty cycles also, ΔI_O can be arrived in similar lines [17].

3.3 Inductor value

For device switching frequency set at 10 kHz. The inductance parameter can be calculated as below.
Switching Time Ts = 1/fs.
= 1/10 kHz = 100 μs.

$$\text{L} \geq \frac{(V_{in} D_{max} T_s)}{2\Delta I_o} \tag{5}$$

For Vin = 48 V & D max = 0.914.
Substituting the values of Vin & D max in (5),
L ≥ (48)(0.914)(10^{-4}) / 14.
L ≥ 313 μH.
The inductance parameter is selected to be greater than 313 μH, so the optimized design value is 368 μH considering design tolerances.

3.4 Capacitance value

The capacitor selection is decided based on voltage ripple at output. Considering ΔV_O output voltage ripple to be 1 V.
For D = 0.914.

$$\text{C} \geq \frac{(V_O \text{D})}{\text{R}\ \Delta V_O F_s} \tag{6}$$

Substituting the values of V_o & D_{max} in (6),
C = (560) (0.914) / (100*1*10^5).
C ≥ 102 μF.
For D = 0.357.
C ≥ 199 μF.
For D = 0.607.
C ≥ 45 μF.

The capacitance parameter is selected to be greater than 200 μF. considering 5% margin, capacitance value arrived at 210 μF.

4. Simulation studies

The Boost converter circuit and two level Inverter circuit were simulated with the PLECS & PSIM power electronics simulation tools. The simulation parameters were decided based on the design parameters and various input voltage selections as tabulated in **Table 3** [18].

The Schematic of converter circuit for all the input voltages are designed and typical 48 V DC Input simulation circuit is shown in **Figure 5** [19]. The switching patterns of two IGBTs (S1, S2) used in the two phase IBC is shown in **Figure 5** [20]. The phase shift between the two phase limbs is 180 degrees.

For all the three modes and the output of 560 V DC was achieved and corresponding output voltage, inductor currents and input current were obtained graphically [21]. The 48 V Input DC circuit is simulated for duty cycle of 0.9142 and the results are represented in **Figure 6** [22].

The output voltage obtained for 48 V DC input circuit in simulation has very low ripple voltage content within 1 Volt [23]. The inductor current ripple is 30% and the input current ripple is 15%, which are well within design limits. Similarly, the duty cycle 'D' is varied for input voltages 220 VDC and 360 V DC as per the **Table 3** and the corresponding graphical results are shown in **Figures 7** and **8** [24].

The simulation results show very less ripple in input current and voltage compared to any conventional boost converter [25]. The Inverter design parameters were arrived with conventional methods, output LC Filter is designed for reducing higher order harmonics at output current and smoothening the output current. The simulation parameters are tabulated in **Table 4**.

Parameter	Input voltages		
	48 V	220 V	360 V
L1/L2	368 μH	368 μH	368 μH
C	210 μF	210 μF	210 μF
Duty Cycle	0.9142	0.607	0.357
Switching Frequency	10KHz	10KHz	10KHz

Table 3.
Simulation parameters for interleaved boost converter.

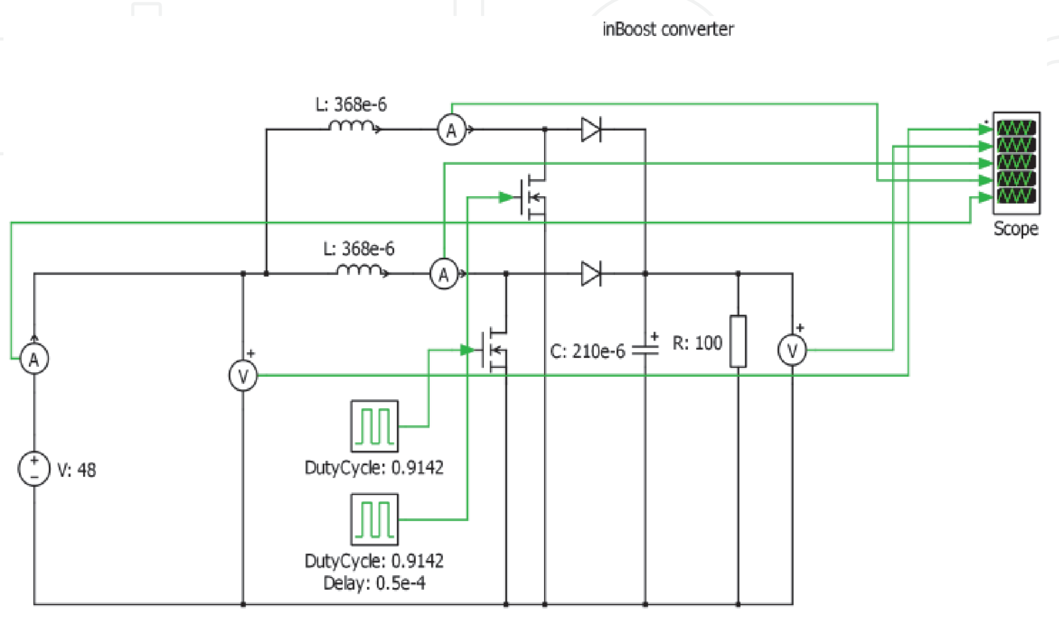

Figure 5.
Schematic of interleaved boost converter with 48 V input.

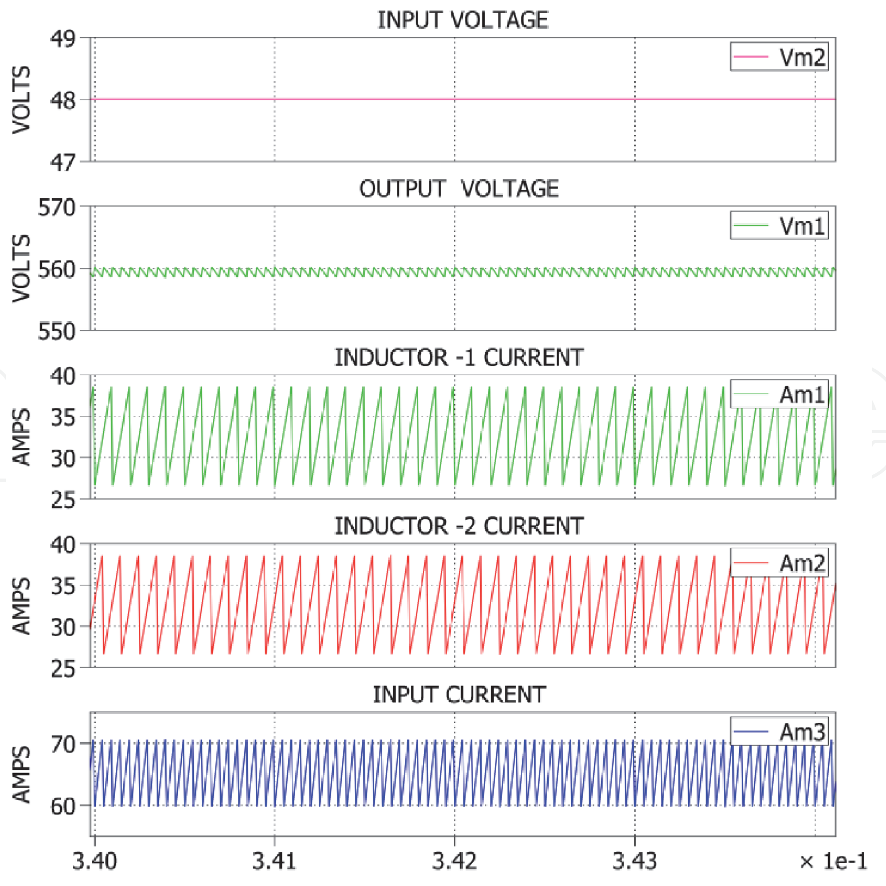

Figure 6.
Waveforms of interleaved boost converter with 48 V input.

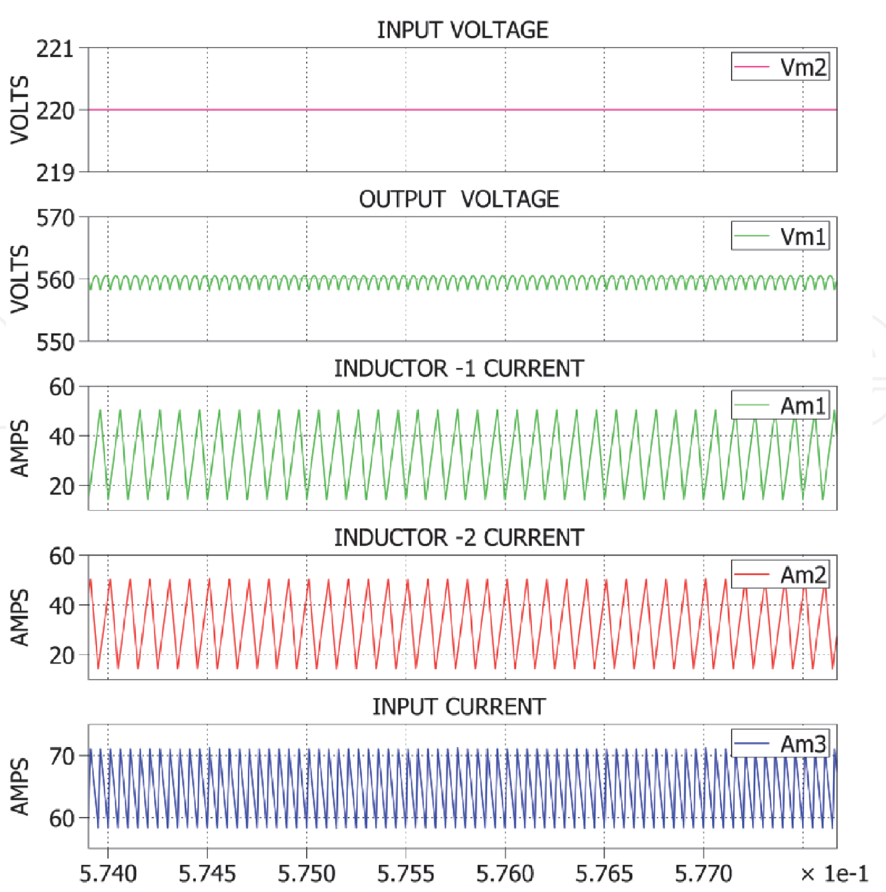

Figure 7.
Waveforms of interleaved boost converter with 220 V input.

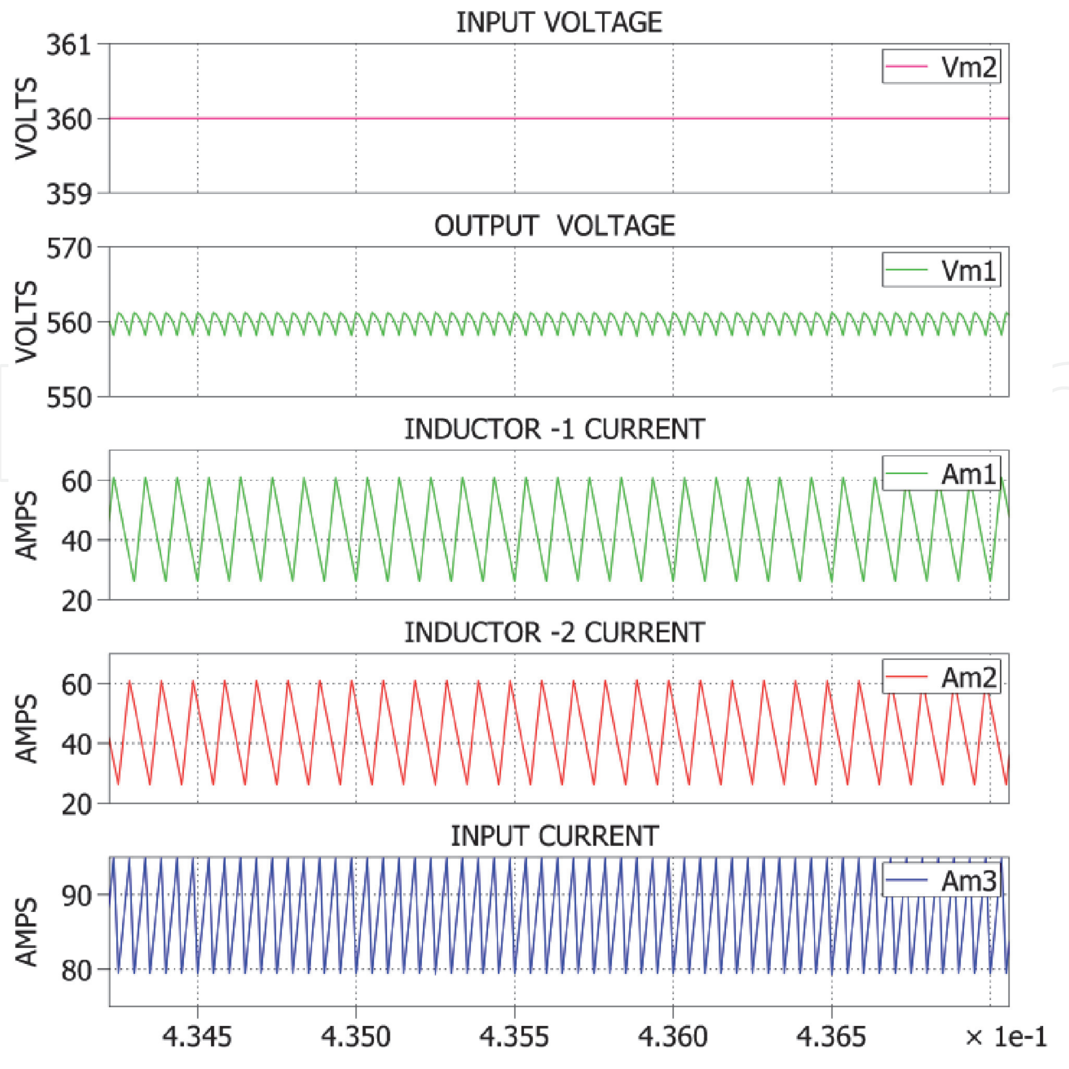

Figure 8.
Waveforms of interleaved boost converter with 360 V input.

Parameter	Values
Dc Bus Input	560 VDC
Output ‘C’	132 μF
Output ‘L’ Choke	380 μH
Δ-Δ Transformer	415/415 V
Switching Frequency	1KHz
Modulation Index ‘M’	0.8

Table 4.
Simulation parameters for inverter.

The Schematic of inverter simulation circuit with the PWM Generators is given in **Figure 9** and corresponding output voltage waveforms as obtained from simulation is shown in **Figure 10** [26, 27].

The FFT of output AC Voltage is shown in **Figure 11**. **Figure 11** also shows harmonic spectra in the waveform. The predominant harmonics in two level inverters are 5th and 7th harmonics, which is reduced by incorporating LC Filter at output [28]. The Δ-Δ Isolation Transformer at output gives circulating path for third harmonics zero sequence currents and thereby resulting very less third

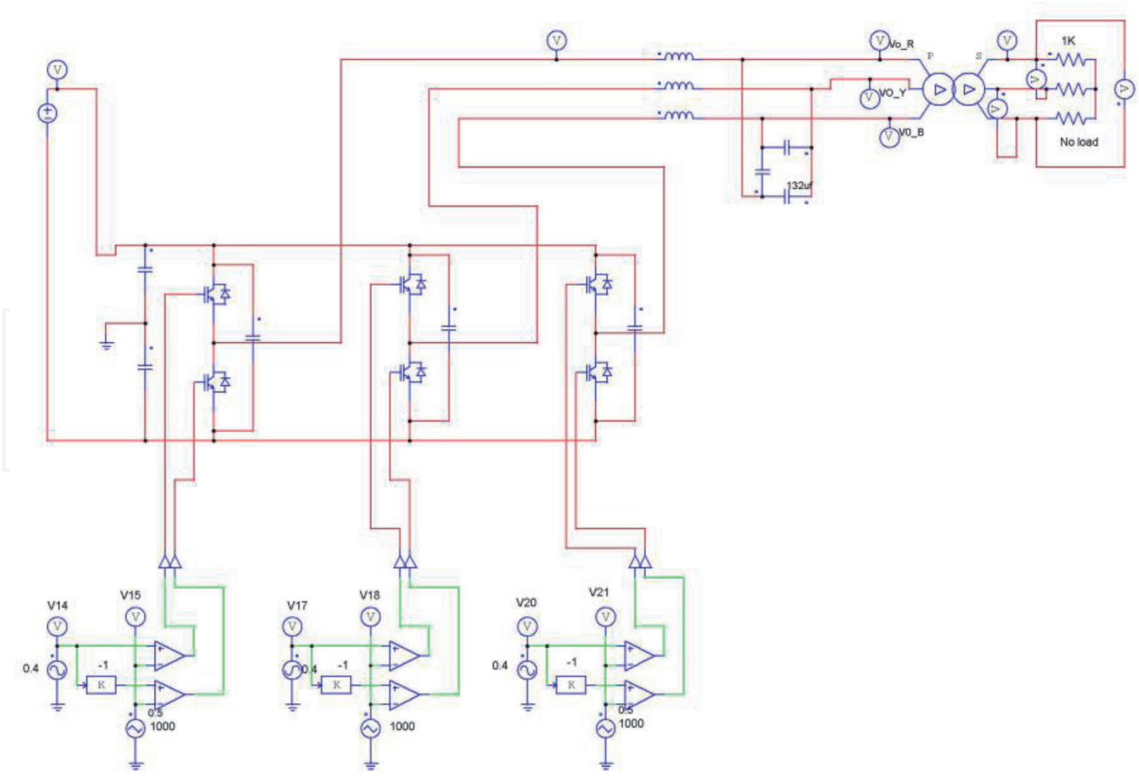

Figure 9.
Simulation of two level inverter systems

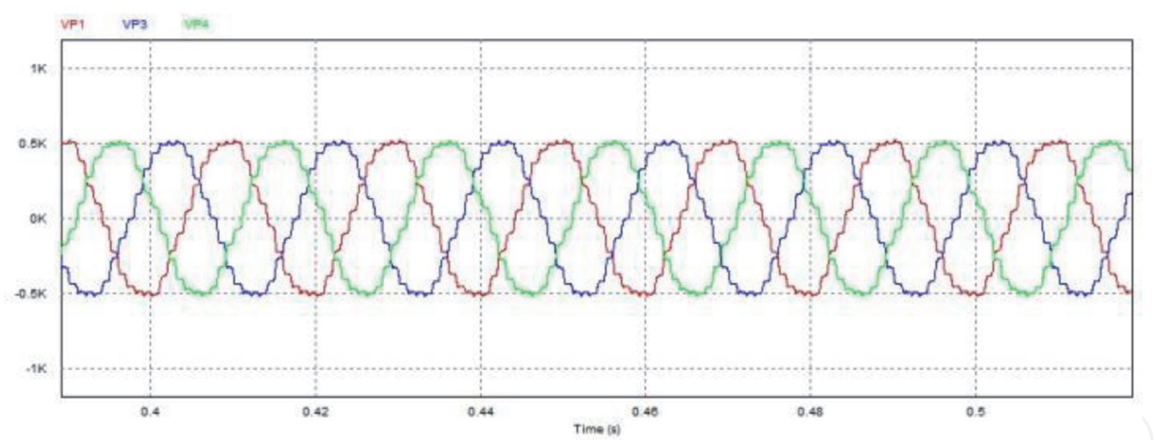

Figure 10.
Waveform of inverter O/P voltage.

harmonic output to load [29]. THD at output is calculated to be 7.2% as tabulated in **Table 5** [30].

5. Design parameter verification

All Design parameters were successfully verified in our simulation and the verification table is given in **Table 6**.

6. Challenges in simulation of high power converter

The very advantage of using interleaved converters for reducing the current and voltage ripple resulted in low design value of capacitances. However incorporating

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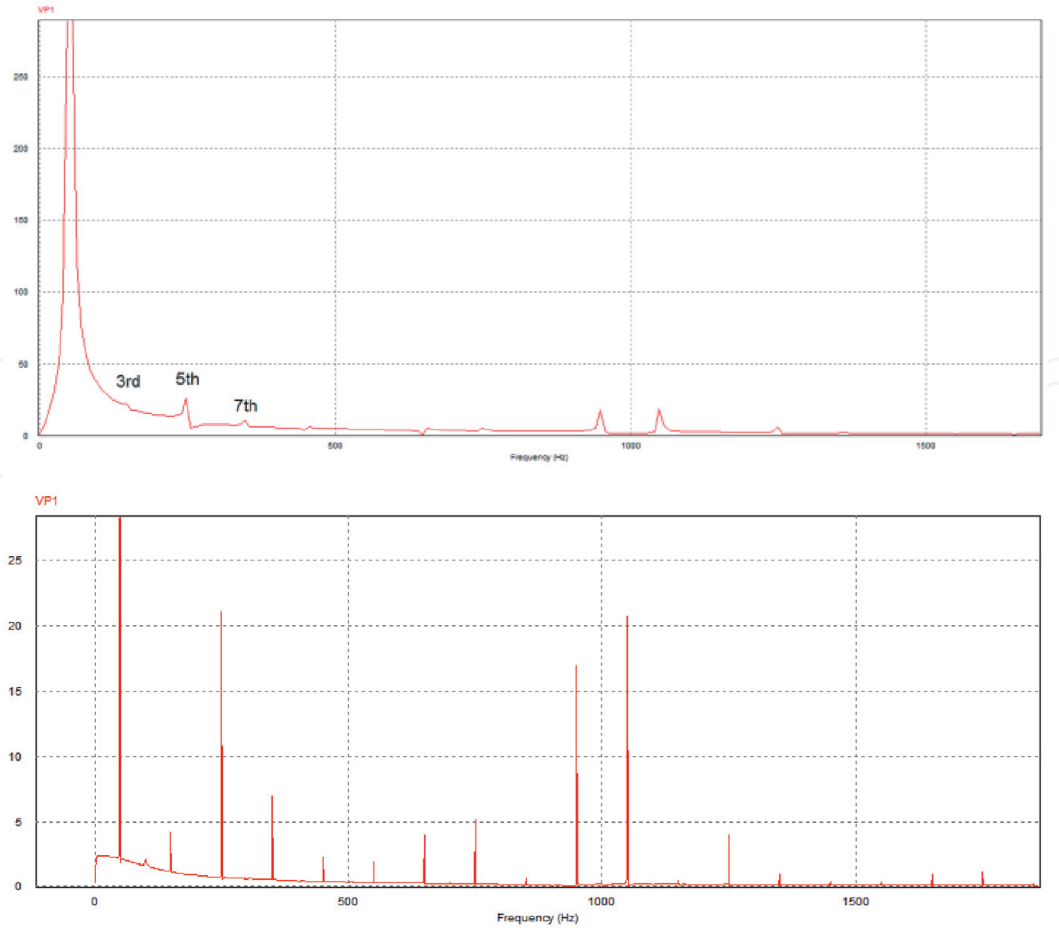

Figure 11.
FFT output of inverter output voltage.

Harmonic number	Percentage %
3rd	1 .2
5th	7.36
7th	5.47
9th	5.35
THD	7.2

Table 5.
Percentage harmonics in output voltage.

Parameter	Input voltages		
	48 V	**220 V**	**360 V**
BOOST CONVERTER			
Input Current Ripple	17%	20%	21%
Output voltage	560 V	560 V	560 V
Output voltage ripple	0.8 V	0.8 V	0.8 V
Duty Cycle	0.914	0.607	20.357
INVERTER			
Output voltage	415 V ± 5%		
Output current	150A		
THD	7.2%		

Table 6.
Design parameter verification of regenerative discharger.

two large inductances in both the switch stacks results in a real challenge in design as well as for simulation models. The simulation parametrization were calculated and designed for continuous conduction mode of inductor currents.The uncoupled inductor model is taken up for reducing the complexity in simulation.

7. Conclusion

The periodic testing and discharging the batteries to ensure the capacity and availability of battery systems is mandatory in nuclear power plants. The batteries of large power capacity are discharged with the regenerative technology to the grid by utilizing this technique. The design intents of lower current ripple and output voltage ripples is realized with the interleaved boost converter topology. The Harmonics in AC Output is well minimized with the help of optimum LC Filter design. This paper is conceptual base for designing high power battery regenerate discharge system without disturbance to normal plant operation with grid. A 100A Boost converter prototype model was assembled and was paralleled with 6 similar units for 600A Current capacity. Thus, the proposed design has a huge capacity to deliver energy savings, output voltage and current regulations with very minimum net harmonics for wide range of discharge currents and voltages.

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Conflict of interest

No conflict of interest.

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