Smarter Solar Systems: Optimizing Power Flow and Backup with Advanced Inverters

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1. Introduction

1.1 Background to the research

In grid-tied residential systems, a solar panel – which provides DC power – can be directly connected to the grid through a DC-AC power converter and provide energy to residential AC loads and reduce the monthly electricity bill. When the grid-goes offline, however, it is required that the entire system goes offline. Solar energy also isn't always available in times such as long winters with little to no sunlight. It therefore is essential to store the energy when it's available and not needed – to be used later when the grid is offline or during winter periods of little sunlight – this is where storage devices are needed. Grid-tied systems then have a storage solution where the solar panel is connected to a storage device and the grid. Batteries are among the storage devices used to store this renewable energy. Since batteries also provide DC power, like PV panels, a power conditioning system (PCS) inverter is used to convert the DC power into AC power. These batteries can be recharged by the grid, through the inverter during night times. Therefore, the inverter requires bidirectional capability to charge the battery bank. Most efficient bidirectional inverters used today are based on two-stage architecture, which involves using a bulky DC-link capacitor. The control strategies used in these inverters are incapable of fully compensating for battery and grid complex disturbance and variations.

1.2 Objectives of this research

1.2.1 Purpose of the research

The purpose of this research is to analyse and design an efficient $220V$ grid tied, bidirectional inverter and its control strategy for a low voltage, $60V$ battery powered, $1kW$ residential PV system with storage.

1.2.2 Problems to be investigated

The problems to investigated include: several battery charging and discharge characteristics to select the most appropriate battery; several PCS architectures to select the most appropriate architecture and front-end converter; the bi-directional PCS's abilities to step up low voltage and reverse power; the dynamics of the bidirectional PCS, to develop a control strategy that allows DC-AC and then AC-DC power flow transition under complex battery or grid disturbance and variations.

1.3 Scope and Limitations

This research is focussed on the design and experimental verification of a newly proposed bidirectional inverter topology for battery storage systems. The developed system is limited to a single-phase system and may require further modifications before it can be implemented in a three-phase system.

1.4 Plan of development

Chapter 1 is the introduction. Chapter 2 reviews the literature in battery connected systems. Chapter 3 presents a thorough analysis of the inverter being designed, by presenting topology and analysing the modes of operation and power transfer; the effects of switching dead time and parasitic effects; the performance assessment; the efficiency and finally, the dynamics of the inverter. Chapter 4 then presents the design of the inverter by starting with the battery selection, sizing of the components, switch selection and design of the lead compensators. Chapter 5 details the simulated results of both the DC-AC and AC-DC power flows of the bi-directional inverter. Chapter 6 shows and discusses the experimental results. Further discussion is provided in chapter 7 by summarizing the key findings across the simulated and experimental results in relation the theory. Chapter 8 draws conclusions based on the discussions and chapter 9 makes recommendations based on the conclusions that were drawn.

2. Literature Review

This section details the literature review for the proposed topology design. It starts off with a broad overview of residential LV grid-tied systems and their power requirements. It then reviews the various storage options for residential applications. It then reviews the various power conditioning systems (PCS) and compares them for the best architecture. Lastly, control techniques for the PCS were reviewed. All the figures and tables were redrawn from their original sources for coherence.

2.1 Residential low voltage grid-tied systems

Most grid-tied residential systems make use of solar and or wind energy to reduce the monthly spending bill by using solar panels to supplement the energy provided by the grid. The cost reduction can be as much as 60 − 80% depending on the size of the residence and type of solar system installed [1]. During times when solar energy is mostly available, the residential loads are supplied by the solar panel and during the night, the grid is used to provide the energy. These systems either have storage or no storage options.

2.1.1 Grid-tied systems with no storage option

These systems are directly connected to the grid. The DC power provided by the solar panels is connected directly to a power conditioning system (PCS) which is then connected to the grid. This set up as shown in Figure 2-1.

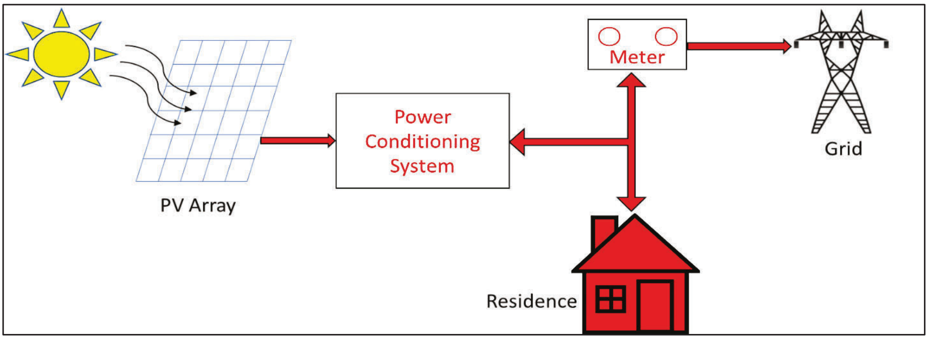


Figure 2-1 Grid-tied residential system with no storage option

The solar panel is directly converted into AC power from a PCS. The PCS steps up and converts the DC output voltage into AC voltage to match the grid and residential load standards [2]. When the solar energy is unavailable at night or during winter periods, of little to no sunlight, the grid provides the required energy. This configuration has the advantage of being cheap since no storage option is used. The major issue with this system is that it doesn't reduce the monthly bill by a large factor since, during peak times at night, there is no solar and the grid provides power; and when the grid goes offline, it is a requirement that the entire solar system also be taken offline because if it isn't taken offline, the power generated by the panels can cause shock to any personnel that may be repairing any damage along the grid. During this time, the residence will be without power.

2.1.2 Grid-tied systems with storage

To solve the issues of the directly connected grid-tied PV systems discussed in the previous section, storage options are included within the system as shown in Figure 2-2. The PV is connected to the storage device first and then the storage device is connected to the PCS.

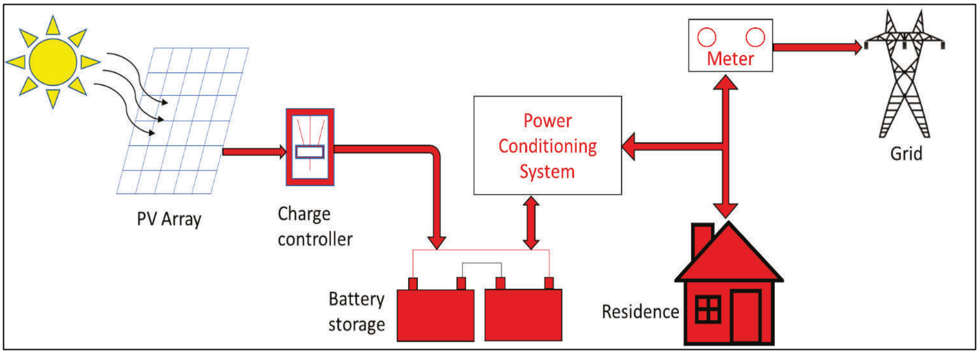


Figure 2-2 Grid-tied system with storage option

The solar panels are connected directly to a charge controller. The charge controller can either be MPPT or PWM. These are used to ensure that the storage device is charged efficiently such that, when the PV panels do not generate enough power for the load requirements, the storage device can provide the extra power needed [2]. The battery storage system is connected to a critical loads panels and not the main panel because the power provided by the storage backup is lower than the power provided by the grid. When the grid goes offline, the energy stored in the storage element can be sued to power the critical loads within the resident.

2.1.3 Low voltage residential load power and grid quality requirements

The power and its quality required by residential loads in a grid tied system was reviewed.

i. Power requirements

PV systems with battery backup are only used to power the critical loads within a residence. The critical loads within a residence are typically lights, TV's, cell phone or laptop chargers and fans. These loads need to be powered only for limited time through the battery backup system. Powering 5 incandescent light bulbs, a TV and charging 1 phone will consume about 800W for 3 hours – during load shedding instances, which typically last for approximately 2 and a half hours. A 1kW PV system with battery backup would be enough for this – but larger residences may require about 5kW during these times. A 1kW system with battery backup costs between R70,000 and R90,000 depending on the installation company and solar cells used. A 5kW system costs between R400,000 and R450,000. Not many residents can afford 5kW systems or above, especially since typical residences have basic critical loads – hence, a 1kW system is a popular choice for average residents and will be the focus of the book. For a PV system with a 1kW max power, 60V storage backup system, the number of PV cells connected in series needed to ensure that the battery pack is fully charged is 216 – which is six 12V PV panels connected in series and will have an open circuit voltage of 108V [3]. When this PV array is connected to a load the open circuit voltage will drop to about 72V – this will be enough to charge a 60V storage backup system. Typical 1kW inverters are rated between 12V to 60V and are usually priced R2,000 and R7,000 making them affordable for most residents interested in renewable cost saving alternatives. Table 2-1 shows the typical power require-ments for an EN 501060 [4] Standard grid-tied PV system with a storage option.

Table 2-1 Typical 1kW PV grid-tied system power requirements

Identification	**PV Panel** [3]	**Battery** [5]	**Inverter** [6]	**Grid** [4]
No. of Units	Six 12V Panels	1	1	
Rating	1200W	1000W	1000W	
Voltage	72V $nominal$	60V	60V	220V
Frequency			50Hz	50Hz
Power Factor			0.8	0.8
Manufacturer	ABC	XYZ	DEF	

The inverter is the PCS and the battery is the storage element. Specifications for standalone inverters are based on grid-standards because residential appliances were made to fitted to the grid.

ii. ***Power quality requirements***

The power quality expected from the inverter to be designed was also reviewed.

Table 2-2 Grid standard steady state voltage characteristics [4]

Parameter	Supply Voltage Characteristic according to EN 501060
Line frequency	LV, MV: mean value of fundamental measured over 10s $\pm 1\%$ $(49.5 - 50.5\ Hz)$ for 99,5% of the week -6% $(47 - 52\ Hz)$ for 100% of the week
Voltage regulation	LV, MV: $\pm 10\%$ for 95% of the week, mean 10 minutes RMS values
Total Harmonic Distortion	<8%

Table 2-2 shows the quality of the voltage at the output as per the EN 501060. The inverter to be designed will use these power quality requirements as a standard.

The harmonic standard for residential loads is far more complex and is defined for different classes of loads in the EN 61000-3-2 standard [7] namely, class A, B, C and D.

Table 2-3 Harmonic standard for Class A residential loads [7]

Harmonic order n	Maximum permissible harmonic current A
Odd harmonics	
3	2.3
5	1.4
7	0.77
9	0.40
11	0.33
13	0.21
$15 \le n \le 39$	0.15·8/n
Even harmonics	
2	1.08
4	0.43
6	0.30
$8 \le n \le 40$	0.23·8/n

The quality standard for class A equipment as shown in Table 2-3 defines loads such as, audio equipment and light dimmers. For class B equipment, which includes portable tool and arc welding equipment, the class A standard is multiplied by a 1.5 factor [7].

Table 2-4 Harmonic standard for Class C residential loads [7]

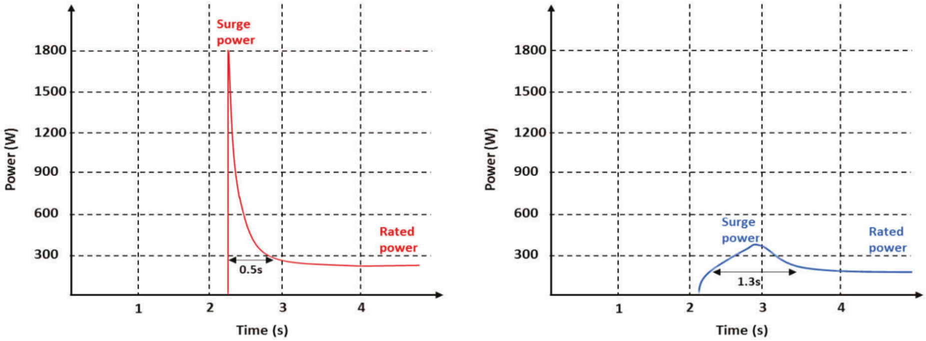
Harmonic order n	Maximum permissible harmonic current expressed as a percentage of the input current at the fundamental frequency %
2	2
3	$30 \cdot \lambda$ *
5	10
7	7
9	5
$11 \le n \le 39$ (odd harmonics only)	3
* λ is the circuit power factor	

Table 2-4 defines the standard for class C loads which include lighting equipment. For class C loads with a real power rating of greater than 25W, Table 2-4 is used. But for class C loads with power ratings of less than 25W, the 3rd harmonic current must be less than 86%; 5th less than 61% of the fundamental current [7].

Table 2-5 Harmonic standard for Class D residential loads [7]

Harmonic order n	Maximum permissible harmonic current per watt mA/W	Maximum permissible harmonic current A
3	3.4	2.30
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
$13 \le n \le 39$ (odd harmonics only)	3.85/n	See table 1

Table 2-5 defines the standard for class D loads which include, personal computers, radios and monitors with input power of less than 600W [7]. Considering a class D residential load such as a drill Figure 2-3 shows the surge power of the load when it is connected to the grid and inverter.



(a) (b)

Figure 2-3 Surge power of residential class D load (a) grid-connected (b) inverter connected

Figure 2-3 (a) shows that the load connected to the grid has a large surge power that is eight times larger than the power rating of the load. When connected to the inverter, Figure 2-3 (b) shows that the surge power is only 1.42 larger than the rated power of the load. Although this surge power is lower, its settling time is almost 3 times slower than the grid connected load. Therefore, it is advantageous to run household loads on an inverter rather than the grid [8].

2.2 Energy storage

Having reviewed that the best kind of system is a grid-tied system with storage option, energy storage options were reviewed. There are several types of renewable storage devices such as super capacitors – which are made of an electric double layer (EDL) [9]. These are only useful for short bursts of power and are therefore, used mostly in start/stop applications that require a lot of charge/discharge cycles during engine operation [9]. Flywheels are another source – they store energy in the form of kinetic energy as they rotate. Like super capacitors, can provide short bursts of power. Batteries are most used storage devices because they can provide a steady stream of power required for residential applications. As such, super capacitors and flywheels are only used to supplement batteries at times when a short burst of power is required [9]. Batteries were then reviewed in terms of their structure, charge and discharge characteristics.

2.2.1 *Chemical introduction to batteries*

A battery is a stack of electrochemical cells connected in series and/or parallel. A cell is an electrochemical device that transforms chemical energy into electrical energy and then electrical energy back into chemical energy [10]. Cells can be classified as either primary or secondary cells. Primary cells are non-rechargeable while secondary cells are rechargeable. This study was based on secondary cells as they are used in this design. The electrochemical cell as shown in Figure 2-4, consists of a negative electrode, a positive electrode, an electrolyte solution containing dissolved salts and a semi-permeable membrane.

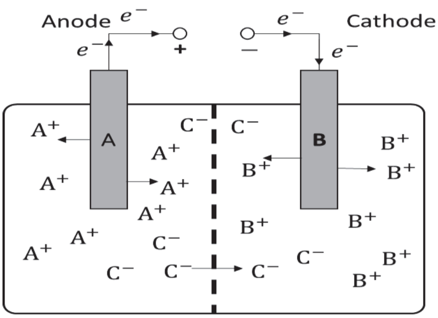


Figure 2-4 Secondary cell in charging mode

The negatively charged C ions are the salt solution and the bold dotted line is the separator. Only the salt solution ions can pass through the semi-permeable membrane. At the anode, Metal A gets oxidised and transfers its valence electrons to the other metal. Once it transfers its electrons, its ions get discharged into the solution. At the cathode the opposite happens, the metal B gets reduced and gains the electrons lost by A. This results in an electrical current flowing.

2.2.2 *Electrical introduction to batteries*

A battery provides DC electrical power to a circuit. It is only capably of direct current which is current in one direction. Figure 2-5 shows one of many electrical models of a battery.

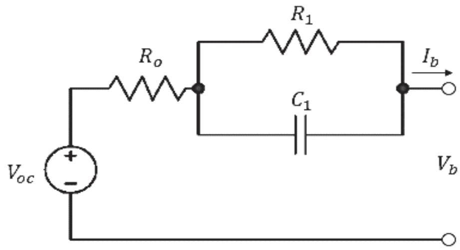


Figure 2-5 First order battery electrical equivalent circuit

V_{OC} represents the open circuit voltage of a battery, R_0 is the ohmic resistance of the battery associated with the electrolyte resistance and battery connection resistance. R_1 represents the polarization resistance and C_1 represents the polarization capacitance [11]. V_b in this case would be the terminal voltage of a battery. One ampere is exactly 1 coulomb of electrons per second [12]. All batteries are rated in amp-hours (Ah). A battery that is rated 1 amp-hour will, ideally be able to provide 1 ampere to a complete circuit for one hour before completely discharging but in real batteries the relationship between the amperes and discharge time is not linear. A battery C rating of amp-hour capacity is provided. A battery also has watt-hour ratings which is the total constant DC power provided by a battery before it discharges completely. A battery rated at 1 watt-hour can provide 1 watt of constant power for 1 hour before it discharges completely [12]. Some cells suffer from what is called the Memory effect. This is a phenomenon whereby if a cell isn't discharged fully between charge cycles, it starts adapting to the previous shortened cycles and thus reduces the capacity of the cell per charge cycle [13].

2.2.3 Charging a battery

Charging a battery is a significant part of any power supply design. The charging system depends on the battery being charged. There are two ways of charging a battery – slow and fast charge [14]. Slow charging a battery refers to applying a current to a battery for a long period of time without damaging the battery. This charging rate depends on the type of battery used. If a battery is charged continually even after it's fully charged, gas begins to form in the battery. For slow charging, the gas can recombine internally but if charging rate is above slow charging rate, the gas is unable to recombine, and pressure builds up inside and damages the battery in turn reducing the battery life cycle. The big advantage of slow charging is that it cannot damage the battery regardless of how long the battery is charged. The other advantage is that no end-of-charge detection circuitry is required meaning it's cheap and simple to build [14].

Fast charging refers to a charging time of between 1- and 2-hours max. Fast charging usually occurs when the cell's temperature is between 10 and 40 degrees Celsius. For temperatures below 20 degrees, the gas builds up raises the pressure more quickly and can damage the battery, it is therefore advisable to operate at 25 degrees Celsius. The typical charging curve of a battery is shown in Figure 2-6. This one refers to a typical lithium-ion battery charging curve. Several batteries have different charging curves due to their chemical composition and structure [14].

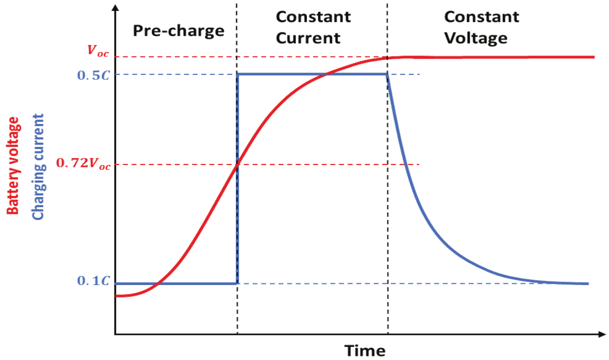


Figure 2-6 Lithium-ion cell charging curve

The charge curve in Figure 2-6 consists of 3 charging stages: pre-charge; constant current (CC) and constant voltage (CV) stages [15]. If the cell voltage is below 10% of the full open circuit voltage, the charge current used is termed the pre-charge current to prevent damage to the cell. This pre-charge is applied to the cell until the cell voltage reaches a threshold voltage of approximately 70% of the open circuit voltage. After that stage, constant current is applied. Cells are usually charged at 0.5C or less i.e. a charging current half of the cell's rated current. Once the voltage of the cell reaches the max voltage of 4.1V, the current reduces. There are several types of battery charging methods. A few were reviewed.

i. ***Constant voltage***

A DC power supply with a step-down transformer and a rectifier to provide constant DC voltage. To protect against battery damage, regulatory circuitry is included in the charger [16].

ii. ***Constant Current***

The charger is based on an unregulated voltage source. As shown in Figure 2-6 the current decreases as the battery voltage builds up. Often, protection circuitry is included to prevent overcharging. This type of charge is not suitable for all batteries [16].

iii. ***Trickle charge***

Designed to account for the battery self-discharge. In this type of charging, the charge rate differs depending on the frequency of discharge. It is not suitable for batteries that are vulnerable to overcharging like Li-Ion Batteries [16].

iv. ***Float charge***

This type of charge involves the battery and load being connected in parallel across the charger. They are held at a voltage level below the battery voltage charging limit. This type of charging is used mainly in back-up power systems. Lead-Acid batteries use this type of charging [16].

2.2.4 Discharging a battery

The discharge voltage appearing at the terminals of the battery depends on the type of current that the load draws; the internal resistance of the battery which varies with temperature, state of charge of the battery and age of the cell [17]. Figure 2-7 shows typical discharge curves of several cells.

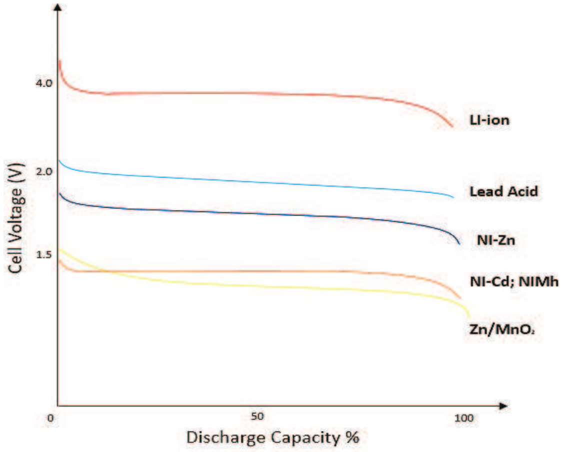


Figure 2-7 battery discharge curves of two batteries at a rate of 0.2C

Of all the types of batteries, lithium-ion battery has the highest open circuit voltage and its discharge curve is flat. The lead acid battery has the next highest open circuit voltage.

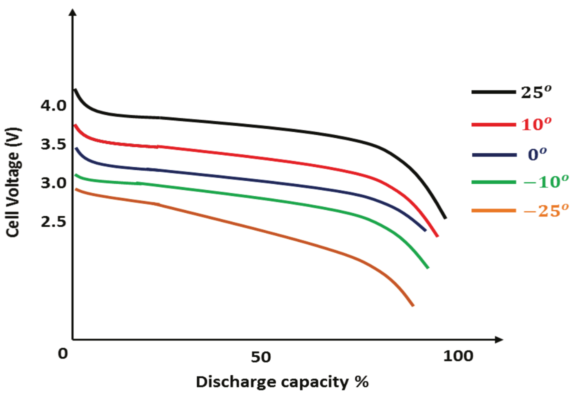


Figure 2-8 Lithium ion battery discharge curves at varying temperature vs discharge time

Figure 2-8 shows that the lithium-ion battery performs better at temperatures above 20 degrees. At low temperatures the electrolyte may freeze and suffer from lithium plating at the porous carbon electrode. At higher temperatures the battery may get damaged. Self-discharge is another factor of a battery discharge where it discharges on its own without being used. Lithium-ion batteries have lowest self-discharge rate of all batteries at 2% per month and nickel metal hydride batteries have the highest at 30%

per month. Lead acid batteries self-discharge at 4% per month. At temperatures below 20 degrees the self-discharge rate is at its lowest and gets higher as the temperature increases. Internal resistance is another factor to consider when discharging a battery. It decreases the terminal voltage of the battery and increases the voltage needed to charge the battery. Figure 2-9 shows the discharge curves of a lithium-ion batteries at different C rates [17].

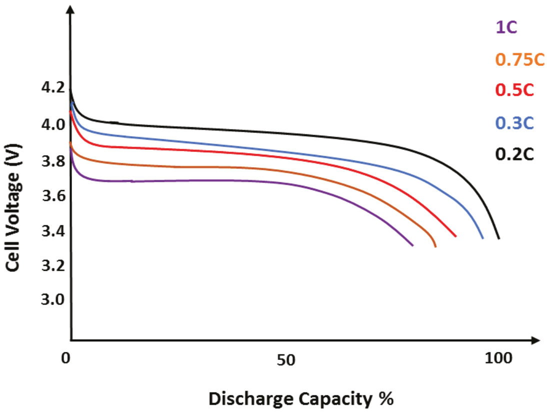


Figure 2-9 Lithium ion battery discharge curves at different C rates

The higher the discharge rate, the higher the voltage drop. A battery can be discharged at different C rates depending on the load. At 1C, the battery discharge curve is flat and has a high open circuit voltage. The higher the discharge rate, the lower the discharge voltage.

2.2.5 Types of secondary batteries

The various types of secondary cells are listed and discussed.

i. Nickel-Cadmium

This type of battery uses nickel oxide hydroxide and metallic cadmium as electrodes. The cells use potassium hydroxide as an electrolyte [18]. They have low internal resistance meaning they can supply high current without overheating. To deliver the high current, the anode and cathode are rolled into a spiral. The nominal voltage of the cell is 1.2V. the energy density of the cell is 50-150 W-h/L. It can be recharged 2000 times in its life-span. Its specific power is approximately 150W/kg at a discharge efficiency of 70-