



Charge regimes for valve-regulated lead-acid batteries: Performance overview inclusive of temperature compensation

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ABSTRACT

The main battery type employed in standby applications is the valve-regulated lead-acid (VRLA) battery. Float charging is normally used to maintain the battery in its fully charged state, however, float charging has limitations that can damage the battery and shorten its life. New charge regimes have evolved in recent years to tackle the intrinsic problems of float charging. The intermittent charge (IC) regime and the interrupted charge control (ICC) regime have been developed to prolong the service life of the battery in standby applications. The battery is normally maintained in the standby mode for a long period of time and there are infrequent discharge tests to verify the efficacy of the battery. Hence, the service life of the battery is highly correlated to its charge regime. This paper reviews the charge regimes for VRLA batteries, and assesses their charging performance and their impact on the service life of the battery. Recognising that temperature plays a significant role in battery operation, temperature compensation schemes are described for different charge regimes.

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1. Introduction

VRLA batteries have been used for more than 20 years in standby applications. There are several VRLA battery technologies available and the applications are increasingly varied. Batteries in standby applications typically spend over 90% of their service life in standby mode and generally experience only shallow discharges with a depth of discharge (DOD) between 5% and 50%. These batteries are designed to mitigate the impact of continuous overcharging on the conductive components of the cell and to deliver a high discharge rate in a short duration. Discharge only occurs when there is a partial or complete outage in the utility network or during emergency conditions [1–3].

The battery is recharged following the recovery of utility power. The battery is normally close to the fully charged state. Battery power, energy capacity and service life are the main factors in the design of a standby system with a VRLA battery as the energy source. The VRLA battery is typically designed to deliver a service life of 10 years at 25 °C, however, most VRLA batteries do not meet

this expectation. Adversely, premature failure of the VRLA battery has been observed at an early stage of its service with float charge regimes. Premature failure may be caused by improper material balance during the manufacturing process. Failure may also be caused by unfavorable working conditions. High overcharging current and high operating temperature cause premature failure because of increased water loss in the battery [4].

A proper charge regime with the appropriate temperature compensation scheme is critical to prolonging the service life of the VRLA battery. The charge regime should minimize the degree of overcharging to reduce the rate of positive grid corrosion and water loss. The charge regime should maintain the battery at or close to 100% state of charge (SOC) to prevent sulfation.

Float charging is the most common charging method for VRLA batteries. We shall see later that float charging may be implemented by a number of different regimes. Float charging maintains the battery in an overcharged state. The overcharging current induces water loss at the negative electrode of the battery and grid corrosion at the positive electrode. Moreover, a small gradual discharge at the negative electrode may occur even though the battery is overcharged. These effects reduce the service life of the battery [5–9].

Recently, new charge regimes have been proposed to overcome the intrinsic problems associated with float charging so as to prolong the service life of the VRLA battery. The primary charge and discharge reactions in a battery determine the charge performance of a charge regime, while hydrogen

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evolution, grid corrosion and sulfation determine the aging effects.

This paper reviews the charge regimes for VRLA batteries and assesses their charging performance and their impact on aging and service life. The typical operating temperature of a battery in standby or emergency applications may vary from 5 to 40 °C. The rationale for temperature compensation is discussed and the compensation schemes for different charge regimes are proposed. Experimental results are presented to compare different charge regimes and their effect on the life of the battery.

2. Charge regime review

Charge regimes recharge the batteries to a high SOC, but they also reduce the SOH of the battery. Charge regimes are purposely designed to charge the VRLA battery with a tradeoff between charge efficiency, difficulty of implementation and the effect on SOH and battery lifetime.

2.1. Essential modes of a charge regime

A charge regime consists of four fundamental modes, namely a bulk charge mode, an absorption mode, an equalization mode and a standby mode in that order as shown in Fig. 1.

In the bulk charge mode, a large charging current is provided by the charger at maximum power or at maximum current. The battery remains in this mode until the charge voltage reaches the regulation charge voltage ($V^{(1)}$), which is the recommended float charge voltage from the battery manufacturer. This mode aims to charge the battery at a high rate. In the absorption mode, the battery is charged at $V^{(1)}$ with a tapered charging current to minimize grid corrosion and hydrogen evolution. In the equalization mode, the battery is overcharged with a higher regulation voltage ($V^{(2)}$) for a short duration. $V^{(2)}$ is smaller than the recommended quick charge voltage from the battery manufacturer. The capacities of battery cells in a string of batteries typically show a small variance which means that they are not fully charged simultaneously. In the equalization mode, the fully charged cells are slightly overcharged to charge the undercharged cells to the fully charged state. In the standby mode, the bat-

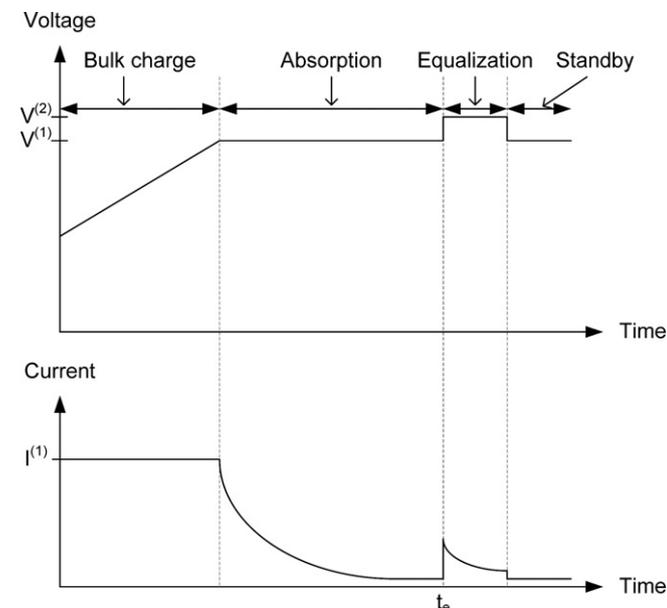


Fig. 1. Ideal operating modes in a charge regime.

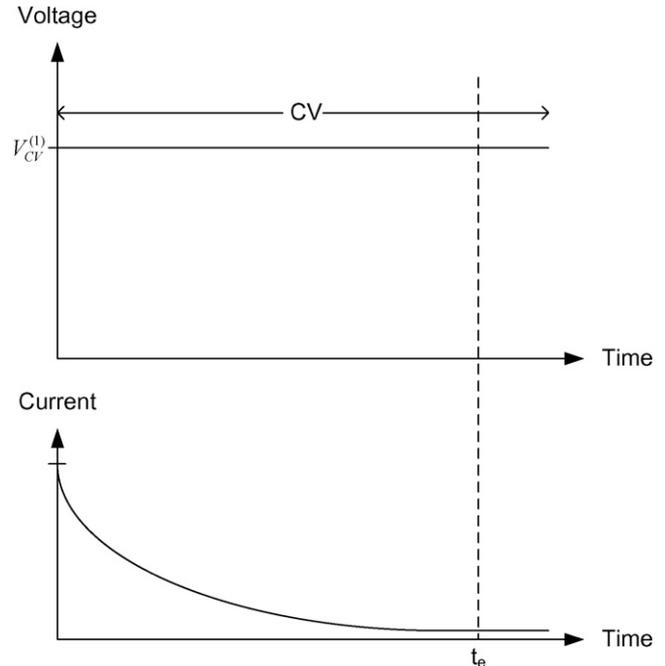


Fig. 2. A typical CV charge cycle.

tery is maintained at a high SOC by continuous overcharging [10,11].

Charge regimes for the VRLA battery may be classified as follows:

- constant voltage (CV) charge regime;
- constant current (CI) charge regime;
- constant current constant voltage (CICV) charge regime;
- constant current constant voltage constant voltage (CICVCV) charge regime;
- intermittent charge (IC) regime;
- interrupted charge control (ICC) regime.

The CV, CICV charge regimes are the traditional approaches to charging while the CICVCV is a modified version of the CICV regime [12,13]. The IC regime is an alternative voltage driven charge regime while the ICC regime incorporates current pulse width control. These regimes will be described in detail in the following sections. The operations, end of charge detections, inherent advantages and disadvantages are highlighted in each case.

2.2. Constant voltage charge regime

The constant voltage (CV) charge regime is illustrated in Fig. 2. The battery is charged at a regulation voltage ($V_{CV}^{(1)}$). The charging current is regulated by the internal resistance of the battery and it is not regulated by the charger. The battery is charged with a tapered current starting with a very high peak value of more than 10 C and maintained in the standby mode with a small overcharging current of about 0.002 C. $V_{CV}^{(1)}$ is the recommended float charge voltage from the battery manufacturer typically in the range of 2.23–2.3 V per cell [12,13].

The battery is continuously charged in the standby mode. The end of charge occurs at time (t_e) when the charging current reaches a steady value.

The CV charge regime is easy to implement and no extra sensing unit is needed to switch among the operating modes.

The large inrush current at the start of the charge process decreases the efficiency of the internal oxygen cycle and induces a high temperature in the battery. Consequently, the induced water loss from this regime is significantly increased.

The inrush charging current for a 16Ah battery can be higher than 160A. Thus, the current and power requirements of the charger are very demanding. The simplest way to overcome the large inrush current is to introduce current control in the bulk charge mode. Charging with constant regulated current mitigates these difficulties.

2.3. Constant current charge regime

In the constant current (CI) charge regime, the battery is charged with a regulation bulk charge current ($I_{CI}^{(1)}$) to the fully charged state and is maintained in overcharge at a small regulation overcharging current ($I_{CI}^{(2)}$) as shown in Fig. 3. There are two constant current operating modes. There is no charge voltage regulation, which means that the charge voltage can be as high as 3 V per cell [12].

The bulk charging current is selected to avoid any excessive battery temperature rise, $I_{CI}^{(1)}$ is limited to 0.4 C in order to mitigate grid corrosion and water loss.

When the battery is fully charged at time (t_e), the charging current is switched to $I_{CI}^{(2)}$ to maintain the battery in the overcharge state. $I_{CI}^{(2)}$ is limited to about 0.002 C to minimize grid corrosion and hydrogen evolution.

End of charge detection is very important in the CI charge regime to avoid damage to the battery. End of charge may be determined by using a timer or by sensing the charge voltage change. The timer determines the time duration required to recharge 105–110% of the previously discharged ampere-hours, which can be difficult to measure in practice [12].

Zero delta voltage detection is a better approach to detect end of charge. In the first CI mode, the battery voltage increases and reaches a peak value and then begins to decrease to a steady state value as shown in Fig. 3. The battery is fully charged when the voltage reaches its maximum value at t_e . The charging cur-

rent must change from $I_{CI}^{(1)}$ to $I_{CI}^{(2)}$ at t_e when zero delta voltage is detected.

In the CI regime, the battery is charged at a high charging current so that the charge time is shortened. There is a certain variance in the capacities of the cells in a string of batteries. Thus, the battery cells cannot be charged to 100% SOC simultaneously. The batteries are overcharged slightly at the end of charging by the high charge current, the undercharged battery cells are then charged to 100% SOC.

In the CI charge regime, there is no charge voltage regulation. The battery is charged by a high charge voltage up to 2.6–2.8 V per cell, which is determined by the charging current. The positive grid corrosion rate and the hydrogen evolution rate at the negative electrode of the battery are accelerated by such a high charge voltage. If the charging current is not switched to a small float current, adverse overcharging may occur with consequent damage to the battery.

The issue with end of charge detection may be addressed by introducing a constant voltage mode after the CI mode.

2.4. Constant current constant voltage charge regime

The constant current constant voltage (CICV) charge regime is the most popular charge regime for VRLA batteries. There are two modes in this regime, namely the CI mode followed by the CV mode. The battery is charged at a constant current in the CI mode with a bulk charge current ($I_{CICV}^{(1)}$) until the charge voltage reaches the regulated charge voltage ($V_{CICV}^{(1)}$). The battery is then switched to the CV mode where the battery is charged by a tapered current at $V_{CICV}^{(1)}$ as shown in Fig. 4 [12,13].

The bulk charge current, $I_{CICV}^{(1)}$, in the CI Mode is set up to 0.4 C to avoid excessive battery temperature rise. $V_{CICV}^{(1)}$ is set at the recommended float charge voltage given by the battery manufacturer normally in the range of 2.23–2.30 V per cell.

The battery is overcharged by the same charge voltage, $V_{CICV}^{(1)}$, when it is fully charged at time, t_e . End of charge is identified

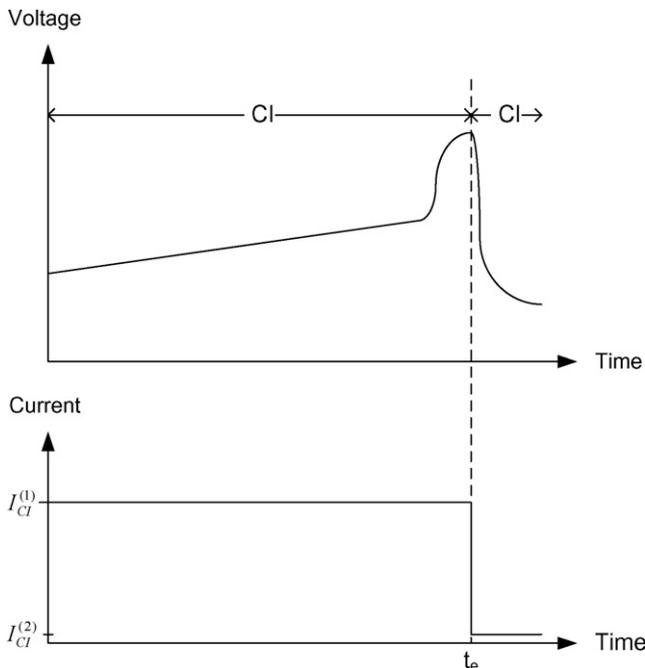


Fig. 3. A typical CI charge cycle.

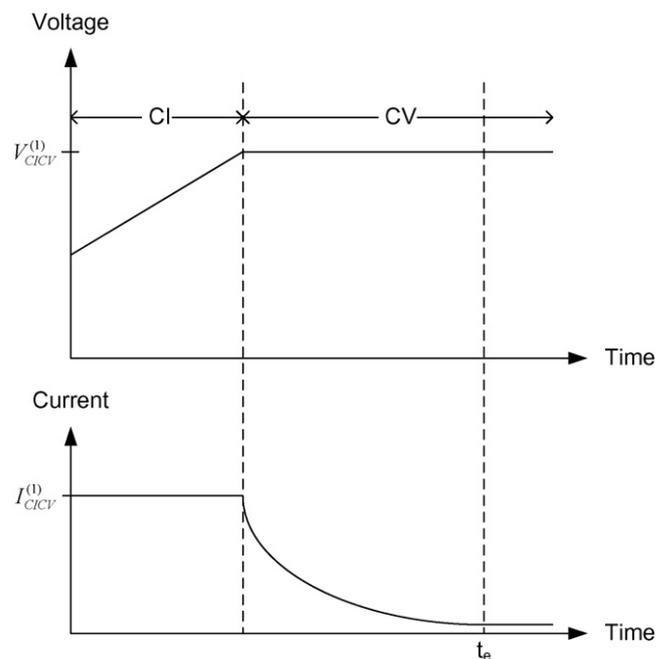


Fig. 4. A typical CICV charge cycle.

when the charging current reaches a small steady value, typically 0.0015 C.

The CICV charge regime balances the advantages and disadvantages of the individual CI and the CV charge regimes. The battery is charged at a high rate in the CI mode at the start of the charge cycle. The degree of overcharging is limited to a low value by a low regulation charge voltage in the CV mode.

The battery is overcharged slightly but continuously. The accumulated grid corrosion effects and water loss by hydrogen evolution severely damage the battery. As a consequence of aging effects at the negative electrode, the rate of hydrogen evolution increases with the service cycle. Gradual discharge of the negative electrodes occurs when the rate of hydrogen evolution is higher than the overcharge current. This gradual discharge occurs even though the battery is properly charged at the recommended float voltage.

This charge regime is straightforward to implement and it is commercially available at low cost.

2.5. Constant current constant voltage constant voltage charge regime

The constant current constant voltage constant voltage (CICVVCV) charge regime introduces an additional mode to improve the CICV charge regime, resulting in a CI mode, a high CV mode and a low CV mode as shown in Fig. 5. The charge cycle starts with the CI mode, in which, the battery is charged with a bulk charge current ($I_{CICVVCV}^{(1)}$) until the charge voltage reaches the high regulation voltage ($V_{CICVVCV}^{(1)}$). $V_{CICVVCV}^{(1)}$ is the recommended quick charge voltage given by the battery manufacturer normally in the range of 2.3–2.5 V per cell. $I_{CICVVCV}^{(1)}$ is selected up to the 0.4 C [12].

The charge mode switches from the high CV mode to the low CV mode when the charging current reaches a low regulation value ($I_{CICVVCV}^{(2)}$) which is 25% of the upper $I_{CICVVCV}^{(1)}$ or when the time duration in the high CV mode reaches the manufacturer’s recommended period of 8 h, whichever occurs first. In the low CV mode, the battery is charged at a low regulation voltage ($V_{CICVVCV}^{(2)}$) to 100% SOC. $V_{CICVVCV}^{(2)}$ is selected at the recommended float charge voltage given

by the manufacturer, normally in the range of 2.23–2.30 V per cell.

The battery is overcharged continuously at the end of the charge cycle and the end of charge is detected when the charge current reaches a small steady value. The high charge voltage in the high CV mode increases the grid corrosion rate and hydrogen evolution rate. This charge regime has a greater effect in shortening the life of the battery than the CICV charge regime.

A microcontroller, a timer and a current sensing module are needed to control and trigger the mode changes.

2.6. Intermittent charge regime

The intermittent charge regime was developed to avoid the continuous overcharging from the CV, CI, CICV and CICVVCV charge regimes. In an IC regime, the battery is charged to a high SOC initially and its SOC is maintained at a range of between 100% and a regulation SOC, typically 95–97%, which is determined by a regulation voltage as shown in Fig. 6 [14,15].

There are two modes in the IC regime, namely the CI mode and the IC mode. The battery is initially charged at a bulk charge current ($I_{IC}^{(1)}$) in the CI mode to a high SOC. When the charge voltage reaches the upper regulation voltage ($V_{IC}^{(1)}$), the charge mode is switched to the IC mode. In the IC mode, the battery is charged for a short period of time and then kept in open circuit until the battery voltages drops and triggers the lower regulation voltage ($V_{IC}^{(2)}$). At that point, it is recharged over a short period of time with a constant current ($I_{IC}^{(2)}$). The recharge process repeats intermittently as shown in Fig. 6. The range of SOC oscillation and the duty cycle (D) of $I_{IC}^{(2)}$ are determined by both $V_{IC}^{(1)}$ and $V_{IC}^{(2)}$. In the CI mode, $I_{IC}^{(1)}$ is set at the range of 0.1–0.4 C. In the IC mode, $I_{IC}^{(2)}$ is set at a value close to 0.05 C. $V_{IC}^{(1)}$ is set below the recommended quick charge voltage in the range at 2.40–2.45 V per cell. $V_{IC}^{(2)}$ is set above the recommended float charge voltage in the range of 2.12V–2.14 V per cell to restart the recharge process so as to maintain the SOC oscillation between 95% and 100%.

In the IC mode, there is no mode change when the battery is fully charged. End of charge is identified when the duty cycle of

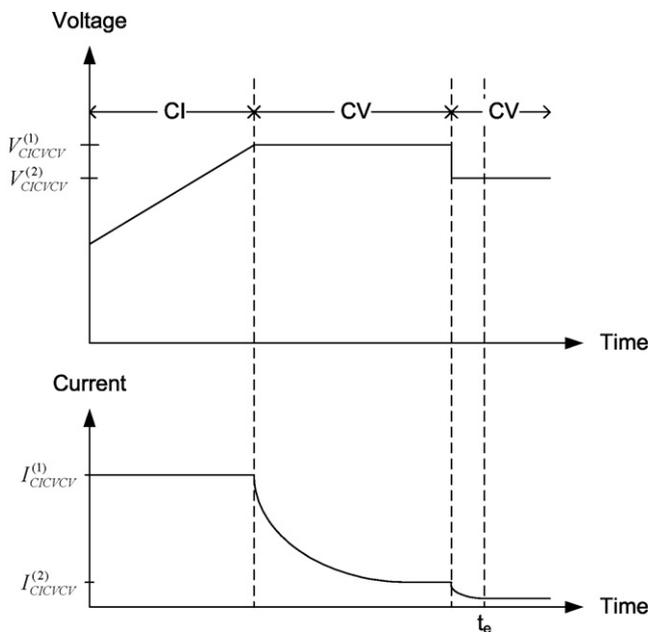


Fig. 5. A typical CICVVCV charge cycle.

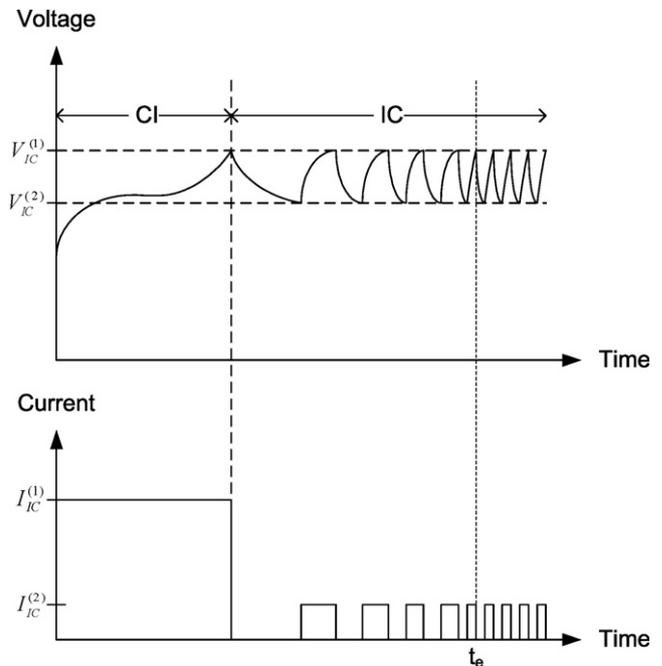


Fig. 6. A typical IC cycle.

the IC current reaches steady state value. The IC regime reduces the degree of overcharging of the battery and leads to longer battery life.

The charge performance of the IC regime depends heavily at the regulation voltages, $V_{IC}^{(1)}$ and $V_{IC}^{(2)}$. $V_{IC}^{(1)}$ is selected to fully charge the battery with the minimum degree of overcharge. $V_{IC}^{(2)}$ is selected to give sufficient voltage headroom for the recharging process in the IC mode. An excessively high $V_{IC}^{(1)}$ may induce additional positive grid corrosion while an excessively low $V_{IC}^{(2)}$ may keep the battery at an undercharged state for a long period of time, which increases the rate of sulfation. The IC regime has a tendency to undercharge the battery.

A microcontroller is needed to regulate the pulse current charge in the IC mode.

2.7. Interrupted charge control regime

The interrupted charge control regime is an improvement on the IC regime in terms of equalizing the cell voltages in a string of batteries; in reducing the degree of overcharging from the CICV charge regimes and in avoiding the potential problem of undercharging from the IC regime [16].

The ICC regime consists of four modes, namely the CI mode, the Rest mode, the ICC mode and the open circuit (OC) mode as shown in Fig. 7. In the CI mode, the battery is charged with a bulk charge current ($I_{ICC}^{(1)}$) at 0.1 C. The CI mode aims to charge the battery to a SOC above 97%.

When the battery voltage triggers the upper threshold voltage ($V_{ICC}^{(1)}$), the operating mode switches to the Rest mode in which the battery is kept in open circuit to reduce the battery internal resistances built up in the previous mode and to provide more voltage headroom for the ICC mode.

When the battery voltage drops below a lower threshold voltage ($V_{ICC}^{(2)}$) in the Rest mode, the operating mode switches to the ICC mode, in which, the battery is charged with regulated current pulses ($I_{ICC}^{(2)}$). These current pulses have a period of 30 s and a duty

cycle (D) of 33.3% at 25 °C. In the ICC mode, the battery is charged to 100% SOC with 2–3% overcharging to equalize the cell voltages.

When the battery voltage reaches $V_{ICC}^{(2)}$ again, the battery is fully charged and the operating mode proceeds to the OC mode. There are self-discharge reactions in the battery, hence, the battery voltage drops in the OC mode. When the battery voltage drops below a restart charge voltage threshold ($V_{ICC}^{(3)}$) the charge cycle is restarted with the CI mode [16].

The upper voltage limit, $V_{ICC}^{(1)}$ is set at the recommended quick charge voltage of approximately 2.45 V per cell to charge the battery to a high SOC in the CI mode. $V_{ICC}^{(2)}$ is set at the range 2.14–2.16 V per cell to trigger the ICC mode and $I_{ICC}^{(2)}$ is set at 0.05 C to avoid thermal runaway. $V_{ICC}^{(3)}$ is set at a value indicating an SOC of 97% to minimize the rate of sulfation. Generally, $V_{ICC}^{(3)}$ is selected at the range of 2.12–2.14 V per cell, which is dependent on the active materials in the battery.

The ICC regime is designed to fully charge the battery at the end of the ICC mode so that no sense unit is needed for end of charge detection.

The ICC regime overcharges the battery by 2–3% to equalize the SOC of the battery cells. In the OC mode, the battery is monitored to avoid excessive and continuous overcharging. The accumulated grid corrosion effect and water loss from hydrogen evolution is reduced.

In the ICC regime, the battery is charged to 100% SOC with a small amount of overcharging to equalize the cell voltages. The ICC regime monitors the battery voltage drop in the OC mode and recharges the discharged ampere-hours from self-discharge when the SOC is lower than 97%. By this mechanism, the hidden gradual discharge at the negative electrode of the battery is avoided.

The ICC regime is a complicated charge regime with five regulation parameters. A standalone control unit is required. This charge regime maintains the battery in the slightly undercharged state, thus, it processes a small potential danger of sulfation. Implementation with a microcontroller is usually straightforward.

3. Temperature compensation algorithms

Temperature compensation of all the charge regimes is very important to the proper operation of the VRLA battery. The battery can be installed in an environment with a large temperature range, typically from 5 to 45 °C for the emergency systems in offshore wind farms. The rates of water loss and grid corrosion are accelerated by high temperatures. The excessive water loss cannot be compensated by adding water into the battery. Hence, temperature compensation must be applied for reliable operation.

Temperature compensation schemes are required to maintain the battery at the desired SOC and to maintain the rates of water loss and grid corrosion at the minimum values to ensure long service life of the battery [17,18].

Manufacturers of VRLA batteries usually provide temperature compensation schemes for float charging. These temperature compensation schemes are based on testing and they are provided to alleviate the increased corrosion rate at the positive grid, the increased water loss rate and the extra heat generated by the internal oxygen cycle when the temperature is elevated [12,13].

A typical temperature compensation scheme for float charging can alleviate the drop of the overcharging current and the increase in charging time when the temperature is low. This temperature compensation scheme also reduces the excessive overcharging current when the temperature is high. In general these schemes may be successfully applied to the IC regime but the ICC regime requires a new approach.

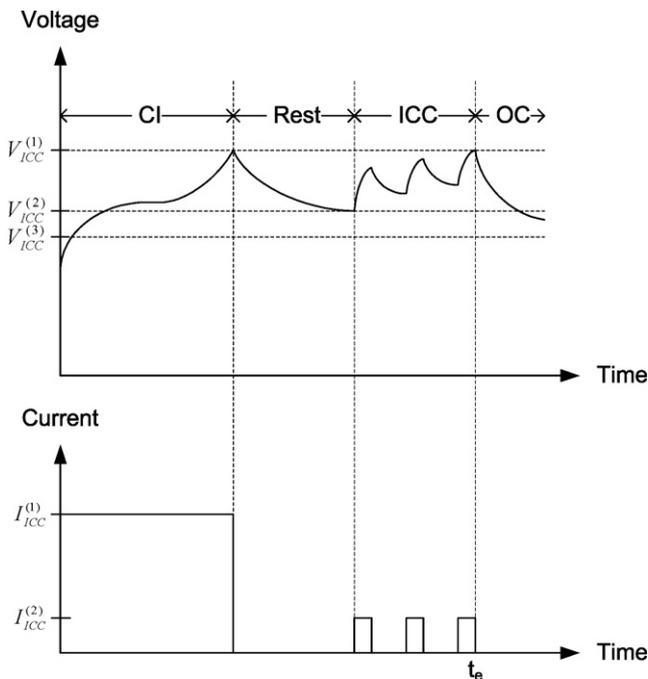


Fig. 7. A typical ICC cycle.

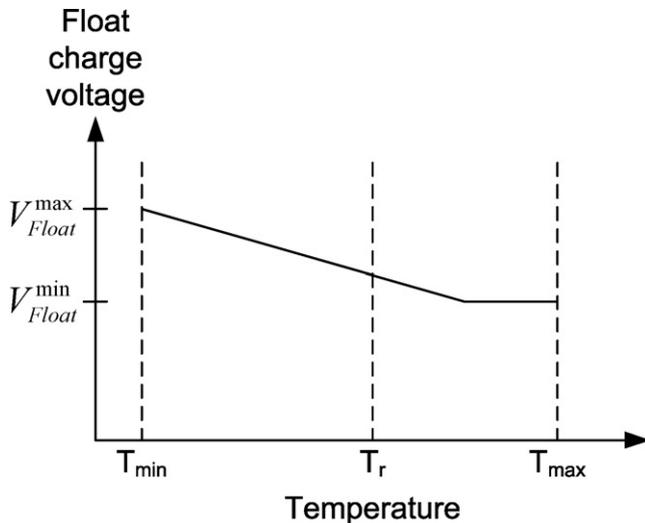


Fig. 8. A typical temperature compensation scheme for float charge regimes.

3.1. Temperature compensation scheme for float charging

Temperature compensation for float charging involves the adjustment of the float voltage to prevent thermal runaway when the temperature is high and to prevent cell gradual self-discharge when the temperature is low as shown in Fig. 8. The charge voltage in float charging is regulated according to the sensed ambient temperature or battery temperature. The charge voltage is increased at a rate of 3.33–5 mV per cell for a temperature drop of 1 °C from the rated temperature (T_r), typically 20 or 25 °C. The charge voltage is decreased at a similar rate for a temperature rise of 1 °C from the rated temperature. The charge voltage is bound by V_{Float}^{max} and V_{Float}^{min} . V_{Float}^{max} is dictated by the minimum operating temperature (T_{min}). V_{Float}^{min} is determined by both the maximum operating temperature (T_{max}) and the battery materials. Typically the minimum float charge voltage for the VRLA battery is 2.2–2.3 V per cell. The recommended temperature compensation scheme can be applied equally to the float charging regimes and the IC regime.

3.2. Temperature compensation scheme for the ICC regime

The temperature compensation scheme for the ICC regime adjusts both the charge voltage and the duty cycle (D) of the current pulses in the ICC mode. This temperature compensation scheme meets two essential requirements. Firstly, the battery has to be maintained at a high SOC in the open circuit mode. Secondly, the rates of water loss and grid corrosion are minimized in the CI mode and the ICC mode [19].

The temperature compensation algorithm in the ICC regime is shown in Fig. 9. Elevated battery ambient temperature lowers the charging voltage for a given charge current. Hence, the high regulation voltage, $V_{ICC}^{(1)}$, is decreased to prevent the battery from overcharging when the temperature is high. Simultaneously, the duty cycle of the current pulse is regulated at its rated value (D_{ICC}^{rated}) to shorten the charging time and protect the battery from thermal runaway. $V_{ICC}^{(1)}$ is decreased at a rate of 4 mV per cell with the minimum of 2.2 V per cell (V_{Float}^{min}). At low temperature, the charge voltage increases more for a given charge current in the ICC mode. This low temperature effect is compensated by decreasing D to alleviate the extra voltage rise. $V_{ICC}^{(1)}$ is maintained at the rated value of 2.45 V per cell (V_{ICC}^{rated}) and D is decreased at a rate of 0.83% with the mini-

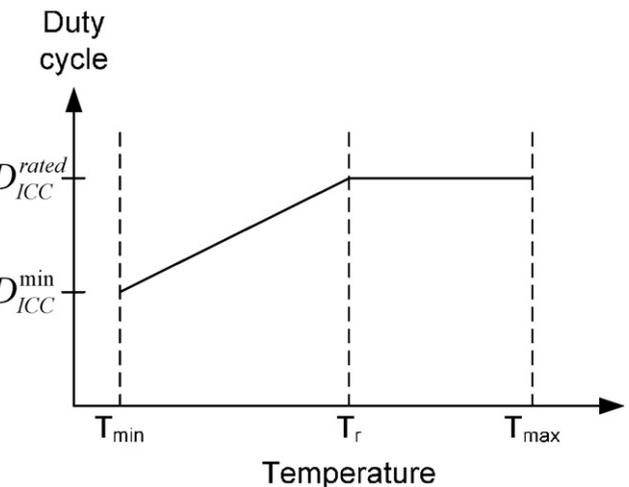
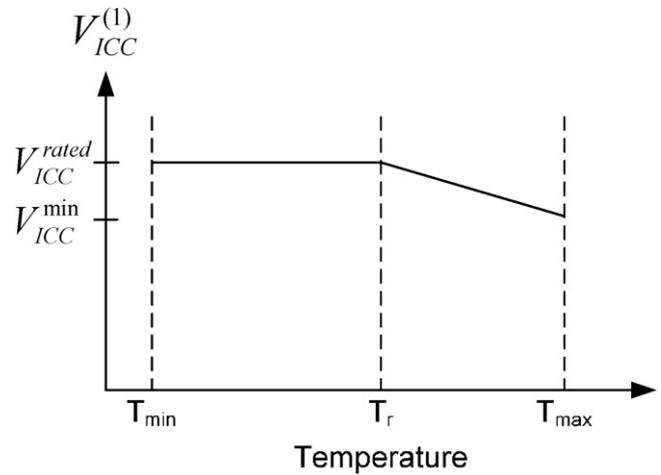


Fig. 9. A typical temperature compensation scheme for the ICC regime.

imum of 16.7% (D_{ICC}^{min}) for a temperature drop of 1 °C from the rated temperature.

4. Assessment of the charge regimes

Among the charge regimes described in Section 2, the CV, CICV and CICVCV regimes are collectively called float charge regimes. These charge regimes overcharge the battery at the recommended float charge voltage. The IC and ICC regimes are collectively called the alternative charge regimes. These charge regimes maintain the SOC of the battery in a range between 97% and 100% to avoid excessive overcharge. The design principles of the charge regimes are different, thus, their charge performances must be assessed by experimental measurements. The main assessment criteria are charge rate, temperature rise and the influence to the aging factors.

4.1. Aging factors of a VRLA battery

Several chemical and electrochemical reactions occur at battery electrodes. For clarity, the chemical and electrochemical reactions that take place in the battery are summarized in Table 1 and are referenced in numbers in the text to follow. During discharge, a VRLA battery produces 1 Ah by converting 4.5 g of lead dioxide (PbO_2), 3.9 g of lead (Pb) and 3.7 g of sulfuric acid (H_2SO_4) into lead sulfate ($PbSO_4$) and water (H_2O). The capacity of the battery depends on the active materials in the battery. The net effects of the chemical and electrochemical reactions on the battery are quantified by

Table 1
Electrochemical reactions in a VRLA battery cell

Positive electrode	
Charging reaction:	$\text{PbSO}_4 + 2\text{H}_2\text{O} \rightarrow \text{PbO}_2 + \text{H}_2\text{SO}_4 + 2\text{H}^+ + 2\text{e}^-$ (1)
Discharging reaction	$\text{PbO}_2 + \text{H}_2\text{SO}_4 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{PbSO}_4 + 2\text{H}_2\text{O}$ (2)
Oxygen evolution	$2\text{H}_2\text{O} \rightarrow \text{O}_2 + 4\text{H}^+ + 4\text{e}^-$ (3)
Grid corrosion	$\text{Pb} + 2\text{H}_2\text{O} \rightarrow \text{PbO}_2 + 4\text{H}^+ + 4\text{e}^-$ (4)
Negative electrode	
Charging reaction	$\text{PbSO}_4 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{Pb} + \text{H}_2\text{SO}_4$ (5)
Discharging reaction	$\text{Pb} + \text{H}_2\text{SO}_4 \rightarrow \text{PbSO}_4 + 2\text{H}^+ + 2\text{e}^-$ (6)
Oxygen reduction	$\text{O}_2 + 4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2\text{O}$ (7)
Hydrogen evolution	$2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$ (8)
Net reactions	
Net discharge reaction	$\text{PbO}_2 + 2\text{H}_2\text{SO}_4 + \text{Pb} \rightarrow 2\text{PbSO}_4 + 2\text{H}_2\text{O}$ (9)
Net charge reaction	$2\text{PbSO}_4 + 2\text{H}_2\text{O} \rightarrow \text{PbO}_2 + 2\text{H}_2\text{SO}_4 + \text{Pb}$ (10)

SOC and state of health (SOH). SOC is the ratio of the dischargeable ampere-hour to the current ampere-hour capacity (C) of the battery [20]. SOC is determined by the charge and discharge reactions in (9) and (10) in Table 1. SOH is the ratio of the current C to the rated C under the same load condition. SOH encompasses the overall effects from the major aging factors, namely positive grid corrosion, sulfation, active mass degradation by deep cycle cycling and dry-out by loss of water. These aging factors will now be described in more detail.

4.1.1. Positive grid corrosion

Positive grid corrosion in (4) is a natural process in a VRLA battery. However, the corrosion rate is increased by the overcharging current and by the acidity of the electrolyte. A longer life expectancy can be expected by maintaining the battery at the fully charged state with a minimum level of overcharging.

4.1.2. Sulfation

Sulfation results from the recrystallization of lead sulfate into a form that is no longer electroactive in the charge and discharge processes (its original fine crystals become larger [21]). The danger of sulfation always exists when the battery remains in a partly discharged condition for a prolonged period of time. When the battery is not being fully charged, the lead sulfate converts from an electroactive state to the highly crystalline state. This sulfation process is irreversible and results in a loss of capacity. Sulfation can be prevented by maintaining the battery at a high SOC.

4.1.3. Active mass degradation

A dominant aging factor in a battery in deep DOD applications is the loss of contact between the positive active mass and the grid. Transformation of PbSO_2 into PbSO_4 occurs in a dissolution–precipitation mechanism during discharging. PbSO_4 has a different morphology and crystallographic structure and it occupies more volume than PbO_2 . During recharging, the PbO_2 may be re-deposited in a slightly different morphology to the one that existed before. The mechanical and electrical contact between the grid and the active material deteriorates in prolonged cycling. Positive plate growth may cause a short circuit to occur in a single battery cell. These short circuits induce bridging of the concerned cell and create high overcharge voltages in the rest of the cells in the same string.

4.1.4. Loss of water

During charging, oxygen evolves at the positive electrode in (3) and hydrogen evolution (8) and oxygen reduction (7) occur at the negative electrode. The gelled form or the absorbent glass mat (AGM) separator in the battery facilitates the oxygen gas diffusion from the positive electrode to the negative electrode which allows

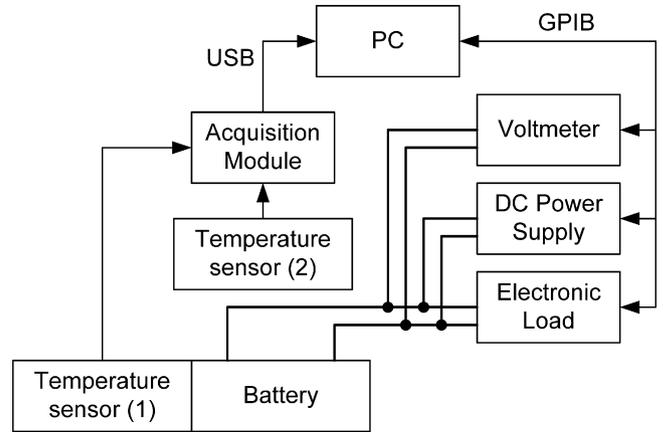


Fig. 10. Block diagram of the battery test system.

oxygen reduction to take place. An internal oxygen cycle is developed. This internal oxygen cycle is not 100% efficient, because some oxygen escapes through the valves of the battery. There is no hydrogen reduction in the battery. Thus, all evolved hydrogen escapes through the valves. The escape of oxygen and hydrogen from the battery causes increased water loss.

4.1.5. Experimental setup

A battery test system was set up to study the charging performance of four selected charge regimes, namely the CICV charge regime, the CICVCV charge regime, the IC regime and the ICC regime. Fig. 10 shows the block diagram of the battery test system. It consists of a PC with GPIB interface, electronic loads, a DC power supply, a voltmeter, a data acquisition module, temperature sensors and a temperature-controlled chamber. The PC controls the DC power supply, electronic load and the voltmeter through a GPIB bus. Ambient and battery surface temperatures were measured by temperature sensors. LabVIEW 8.0 of National Instruments was used to control all the connected instruments to emulate a battery charger employing different regimes and for data acquisition.

The battery under test was the Genesis 12 V, 16 Ah VRLA battery, model number G12V16EP. The battery was tested by a discharge/charge cycle, initially discharged to 73.5% SOC and then recharged by the test charging regime.

4.1.6. Charging performance

The main considerations in the selection of a charge regime for the VRLA battery in standby applications are the prolongation of service life and the recovery of the maximum capacity after a discharge event. The recharge times from 73.2% SOC to 97% SOC, which is the minimum SOC in the IC and ICC regimes, for each charge regime have been studied. Secondly, the temperature changes in a charge cycle have been investigated.

The battery was tested at an ambient temperature of 25 °C in a temperature-controlled chamber. Table 2 shows the charge control parameters. Fig. 11 shows the SOC changes during the

Table 2
Test charge regime parameters

Charge regime	Control parameters
CICV	$I_{\text{CICV}}^{(1)} = 0.1\text{C}$, $V_{\text{CICV}}^{(1)} = 2.22\text{ V/cell}$
CICVCV	$I_{\text{CICVCV}}^{(1)} = 0.4\text{C}$, $V_{\text{CICVCV}}^{(1)} = 2.45\text{ V/cell}$, $V_{\text{CICVCV}}^{(2)} = 2.27\text{ V/cell}$
IC	$I_{\text{IC}}^{(1)} = 0.1\text{C}$, $I_{\text{IC}}^{(2)} = 0.05\text{C}$, $V_{\text{IC}}^{(1)} = 2.4\text{ V/cell}$, $V_{\text{IC}}^{(2)} = 2.13\text{ V/cell}$
ICC	$I_{\text{ICC}}^{(1)} = 0.1\text{C}$, $I_{\text{ICC}}^{(2)} = 0.05\text{C}$, $V_{\text{ICC}}^{(1)} = 2.45\text{ V/cell}$, $V_{\text{ICC}}^{(2)} = 2.17\text{ V/cell}$, $V_{\text{ICC}}^{(3)} = 2.13\text{ V/cell}$, $D = 0.33$

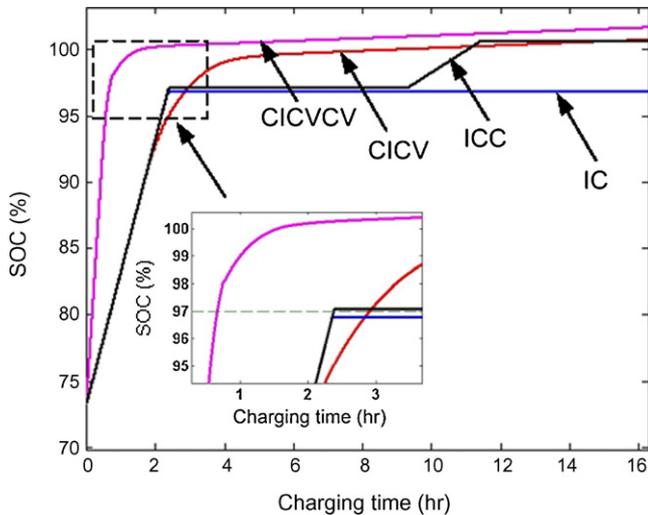


Fig. 11. SOC changes for different charge regimes.

charging process and Fig. 12 shows the corresponding temperature changes.

The CICVCV charge regime employed a large charging current in the CI mode, such that it charged the battery to 97% SOC in 0.66 h. However, the battery temperature rose to 29 °C, this high temperature could lead to thermal runaway when the ambient temperature is high.

The CICV, IC and ICC employed a charging current of 0.1 C in the CI modes so that the battery temperature was maintained below 26.4 °C in all cases. This reduced the rate of water loss and grid corrosion. Regarding the charge time performance, the ICC regime charged the battery to 97% SOC in 2.38 h, which is faster than the CICV and IC regimes; the CICV charge regime required 2.91 h while the IC regime required more than 24 h. In the IC charge regime, the first period for a stop and charge cycle in the IC mode was relatively long and therefore a longer charge time was needed.

The charge regime is selected by the tradeoffs between the charge time requirement to recover the maximum capacity and the temperature rise. If charge time is the sole consideration, the CICVCV regime is the right charge regime. If both charge time and temperature rise are considered, the ICC regime is the best choice.

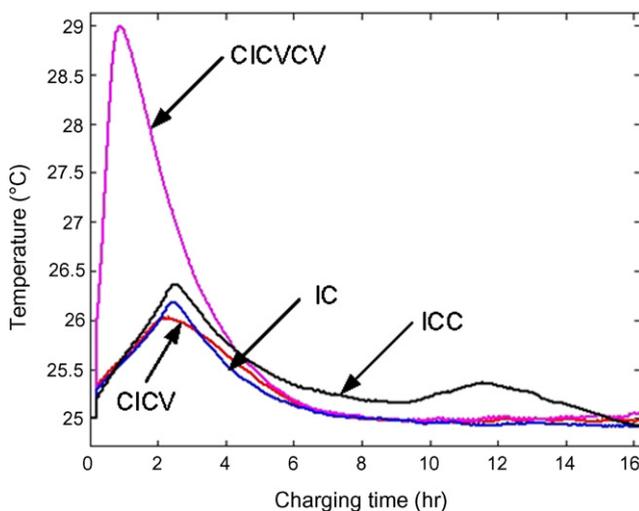


Fig. 12. Temperature changes for different charge regimes.

Table 3
Negative influences to the aging factors

Charge regime	Loss of water	Grid corrosion	Sulfation
CV	Significant	Small	Marginal
CI	Moderate	Significant	Marginal
CICV	Small	Small	Marginal
CICVCV	Moderate	Moderate	Marginal
IC	Marginal	Small	Moderate
ICC	Marginal	Small	Marginal

4.2. Influence of aging factors

The influences of the different charge regimes on the aging factors of the battery are summarized in Table 3. The CV, CICV and CICVCV regimes overcharge the battery at 13.6V with an overcharging current of approximately 0.00125 C. This mechanism successfully prevents the battery from undercharging. However, it cannot remove the danger of sulfation because of the hidden gradual discharge at the negative electrode. Hence, a marginal influence of sulfation may be found in these charge regimes.

The influence of grid corrosion on the battery from the CI and CICVCV regimes is significant and moderate respectively. The influence on grid corrosion from the CV regime is small.

Water loss occurs at a higher rate when the battery is charged at a high charge voltage or at a high charging current. The influence of water loss from the CV, CI and CICVCV charge regimes is significant, moderate and small, respectively.

The IC and ICC regimes are purposely designed to overcome the unavoidable overcharging that occurs in the float charge regimes with sophisticated control systems. Hence, these two charge regimes reduce the influences of water loss and grid corrosion to a marginal level and a small level, respectively as listed in Table 3. However, the IC regime may undercharge the battery such that there is a moderate effect on sulfation. The ICC regime overcharges the battery slightly at the end of charging by leaving the battery on open circuit to dilute the overcharging effects and reduce the effect of sulfation.

5. Implementation of the charge regimes

The deployment of a specified charge regime is determined by both the load characteristics and the circuit employed for implementation. Charge regimes for standby applications are mostly implemented in float chargers or trickle chargers. Trickle chargers can be further divided into the configurations for UPS systems and the configurations for emergency applications. Float chargers have the advantage of simple implementation while the trickle chargers are more generic to include all the charge regimes and are more adaptable in operating environments with wide temperature ranges. In general it may be stated that the float charger is suitable for the CV, the CICV and the CICVCV regimes while the trickle charger is suitable for all the charge regimes discussed in Section 2. The architectures of these chargers will be discussed in the following sections.

5.1. Float charger

The float charger is widely used in standby systems to charge the VRLA battery and it is recommended by battery manufacturers. Fig. 13 shows the block diagram of a typical float charger. In uninterruptible power supply (UPS) systems, the battery is usually float charged with a constant voltage. The battery is floated in parallel with the rectifier output and the load and it is maintained in overcharging at 100–170 mV per cell above the open circuit voltage of the battery. The output voltage of the rectifier and the float charge

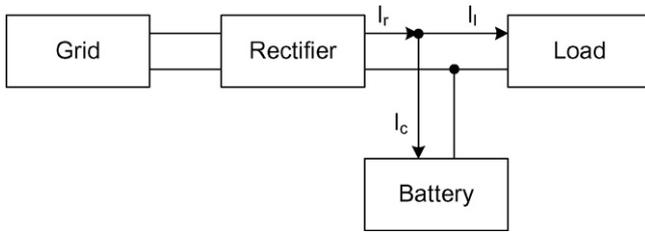


Fig. 13. Block diagram of a typical float charger.

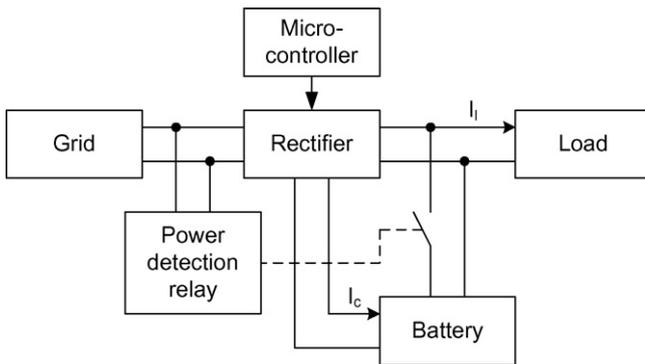


Fig. 14. Block diagram of a typical trickle charger for UPS systems.

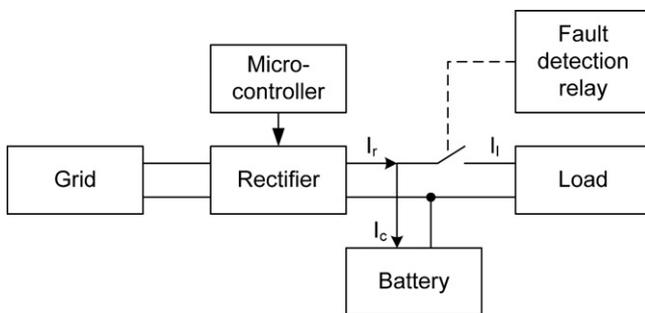


Fig. 15. Block diagram of a typical trickle charger for emergency applications.

voltage are determined by the operating voltage of the load. The output current of the rectifier (I_r) is determined by both the load current (I_l) and the charge current (I_c).

5.2. Trickle charger

The block diagram of a typical trickle charger that is used to charge the VRLA battery in UPS systems is shown in Fig. 14. In this trickle charge system, the battery is disconnected from the load and maintained at or close to 100% SOC. A power detection relay is used to detect power failure. In the event of power failure, the battery is automatically connected to the load and the battery supplies the critical emergency power. The rectifier supplies power to the load and the battery at two voltages and at two current ratings. The load voltage and the charge voltage are not coupled together, so that it is more flexible for use in different charge regimes. A microcontroller is used to regulate the outputs of the rectifier and control operating modes.

The trickle charger for emergency applications is different from that for the UPS systems. Fig. 15 shows the block diagram of a trickle

charger for emergency applications. The rectifier supplies power to charge the battery only. The battery supplies the critical emergency power when there is a fault. The rectifier is connected in parallel with the load and the battery but there is a fault detection relay on the load side. This fault detection relay is used to trigger the switch of the battery to power the emergency system. The rectifier can charge the battery at different voltages, depending on the charge regime. The charge power and the discharge power of the battery are different. The battery can be charged at 0.1 C and discharged at 4 C, which is determined by the power demand on the emergency system.

6. Conclusions

In this paper, the principal charge regimes commonly used for VRLA batteries in standby applications have been reviewed. The aging factors of VRLA batteries have been identified and described. Charge performances and their influences on the SOH of the battery have been assessed. Experimental work described in the paper has identified the ICC charge regime as the most suitable charge regime for batteries in standby applications, it is the most efficient at equalizing the cell voltages and at prolonging the service life of the battery. Implementation configurations and temperature compensation algorithms have been described to enable the battery to operate in a wide range of temperatures.

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