A COMPARISON OF IEEE DOCUMENTS PERTAINING TO BATTERY CHARGERS IN SUBSTATION APPLICATIONS

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Abstract

IEEE 946 is a longstanding document that has been in circulation for many years, although it was recently revised with some significant changes. IEEE 1818 was published about five years ago, and IEEE 2405 is a newly released document based on a predecessor NEMA PE5 Standard. Each of these documents provides information and guidance for designing and specifying battery chargers for use in utility standby applications. While there are many consistencies, there are also many differences between the documents which can cause confusion for the end user.

Introduction

This paper presents an overview of IEEE 946, IEEE 1818, and IEEE 2405 as they pertain to battery chargers in utility standby applications. It highlights some of the similarities and differences, and provides suggestions and examples to demonstrate when one document should be utilized in favor of another.

IEEE 1818 covers the essential elements for substation design. IEEE 946 is broader and includes critical factors such as protection, coordination, instrumentation, and alarms. IEEE 2405 focuses specifically on the design and testing requirements for battery chargers, primarily from a manufacturer's perspective. There are additional guides and standards which are not addressed herein.

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Purpose of the Battery Charger

Battery chargers, commonly called float chargers in substation applications, are used to charge the stationary batteries, as well as supply power to normal, continuous dc loads. Most commonly the charger is a rectifying device, consuming ac power from the station auxiliary system and converting it to dc. Normal loads can include items such as protective relays, metering devices, Supervisory Control and Data Acquisition (SCADA) systems, and inverters.

Due to the response time of the charger, intermittent dc loads having relatively high inrush current, such as solenoids, and breaker trip coils and charging motors, are generally expected to be powered by the battery. Emergency dc loads such as backup oil pumps and emergency lighting are also expected to be powered by the battery, since they typically operate when ac power is unavailable.

Following an emergency event during which the battery has been discharged, the charger must be able to recharge the battery in a reasonable time, while also continuing to supply power to the normal loads.

In general, substation chargers operate at a constant dc output voltage. This is commonly known as float mode. Most connected loads on the dc system can tolerate a wide range of voltage. However, a typical substation battery demands a precise float charge voltage to maximize battery life and reliability.

Overview of IEEE Documents Pertaining to Battery Chargers

General

IEEE documents are intended to promote knowledge and consistency, and drive standardization across a particular industry. A document may be classified as a Standard, a Recommended Practice, or a Guide[1]. Standards are documents with mandatory requirements, and may be enforceable if adopted by the Authority Having Jurisdiction (AHJ). Recommended Practices cover procedures or positions that are preferred by IEEE. Guides offer various alternative approaches, in accordance with good practice, which are merely suggestions rather than clear recommendations. Each type of document may include one or more annexes. A Normative Annex includes official content which is separated from the body of the document for clarity or convenience. An Informative Annex includes basic information not considered vital to the document, for example a bibliography.

Evolution of Charger Documents

Over the past 50 years, the following documents have been developed to promote best practices in the design, manufacture, application, operation, testing, and evaluation of battery chargers.

NEMA PE 5:
First issued in 1996, NEMA PE 5 introduced best practices for designing a dc current source to charge a float battery and supply constant loads. The document has been widely used for substation and power generation applications, covering baseline specifications for input and output characteristics, alarms and controls, environmental and mechanical durability, and requirements for testing and documentation. NEMA PE 5 was updated and enhanced several times, most recently in 2003.

In 2022 NEMA PE 5 was superseded by IEEE 2405.

IEEE 2405:
The Standard for the Design of Chargers Used in Stationary Battery Applications was issued in 2022, replacing its predecessor NEMA PE 5.

IEEE 946:
In 1985, the nuclear and fossil-fueled power generation industry introduced this Recommended Practice for the design of dc power systems, primarily for use in power plant stationary applications. It provided guidance for installing and configuring Lead type batteries, battery chargers, and distribution equipment, in addition to recommending equipment ratings, selection criteria, instrumentation, protection, and controls.
IEEE 946 underwent revisions in 1992 and 2020, and was expanded to include other applications such as substation and telecom. In 2022, A PAR was approved to integrate the provisions of IEEE 1375 (inactive), and to further expand the scope to include photovoltaic and energy storage applications.

IEEE 1375:
Guide for the Protection of Stationary Battery Systems was last updated in 1998, and was transitioned to Inactive-Reserved status in 2021.

IEEE 1818:
Work on IEEE 1818 began in 2010, to create a Guide for the design of auxiliary ac and dc systems for electrical substations. The guide was published in 2017, covering batteries and charger design and maintenance, load transfer methods, dc panels, and interconnections.

Note: There is presently a PAR under review to convert the Guide to become a Recommended Practice.

IEEE 650:
In 1979 this Standard was introduced to cover the qualification of Class 1E battery chargers and inverters for nuclear power generating stations. It includes procedures for type testing and analysis methods to ensure equipment meets design specifications, and requirements for long-term maintenance. The scope was expanded to include Uninterruptible Power Supply Systems, and the most recent revision was published in 2017. In 2023 the NRC opened a proposal to officially endorse IEEE 650-2017.

IEC 60146-1 is the primary international Standard applicable to battery chargers. It sets the minimum requirements for all types of electrical converters, not exclusive to battery chargers.

DIN 41773 is a Standard defining charging modes and processes. For example, IU mode comprises constant-current/constant-voltage stages with the final stage being float-mode.

Figure 1 displays a short comparison of different documents' contents.

Topic	**IEEE946-2020**	**IEEE1818-2017**	**IEEE2405-2022**
DC system design & configuration	**X**	**X**	
Charger selection & sizing	**X**	**X**	
Performance & operation	**X**		**X**
Mechanical design		**X**	**X**
Input & output characteristics			**X**
Protective devices	**X**	**X**	**X**
Controls and alarms	**X**		**X**
Testing			**X**
Maintenance & replacement criteria	**X**	**X**	**X**

Figure 1: Short Comparison of Document Contents

DC System Design and Configuration

Number of Battery Chargers

Both IEEE 946 and IEEE 1818 recommend a minimum of one battery charger for each battery. Both documents go on to point out the benefits of having more than one charger. Redundant chargers can improve reliability in case of equipment failure. A second charger also adds flexibility, allowing one charger to be temporarily disconnected for maintenance and testing.

Connections and System Configuration

IEEE 946 offers several options for system layout and charger connections, dependent upon specific site design criteria. It offers guidance for power generation but defers to IEEE 1818 for substation applications. IEEE 1818 provides supplemental insight into advantages and disadvantages of different configurations, and while the information is intended primarily for substations it can be applicable elsewhere. Each case may have its own advantages and disadvantages, and the designer must take all aspects into consideration.

It is desirable to minimize the points of failure between the charger, battery, and critical loads. However, this must be balanced with the need for flexibility to accommodate maintenance and testing.

Connection examples presented in the documents include:

- charger directly connected to battery terminals, see figure 2.
- charger connected to line side of battery disconnect switch, see figure 3.
- charger connected to dc panel branch circuit, see figure 4.
- alternate configurations for improved flexibility and reliability, see figure 5.

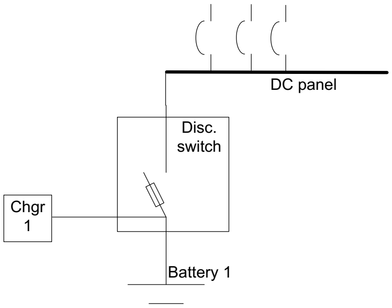

Figure 2. Charger connected to battery terminals.

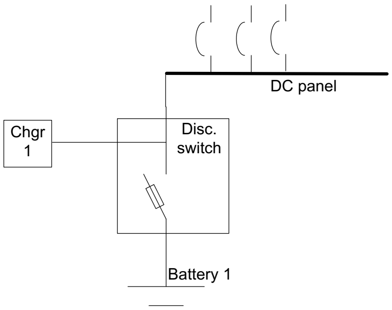

Figure 3. Charger connected to load side of battery disconnect.

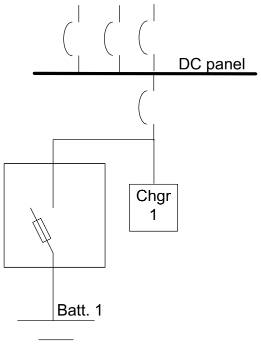

Figure 4. Charger connected to distribution panel branch circuit.

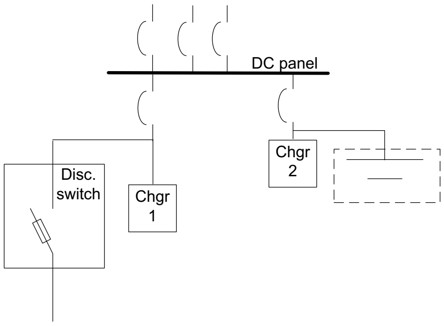

Figure 5. Alternate configuration for added flexibility.

Physical Location

IEEE 946 recommends the battery charger and battery should be as close as possible to electrical loads to reduce voltage drop through cables. A controlled environment is recommended to limit exposure to corrosive atmospheres, dust and dirt, sunlight, adverse ambient temperatures, and humidity. Equipment should be accessible for maintenance and allow adequate space for egress.

Charger selection and sizing

Battery Charger Selection

Two mainstream rectification topologies are commonly used in utility applications:

- Low frequency / line frequency models comprising SCR/thyristor, controlled ferro-resonant, and magnetic-amplifier (mag-amp) designs.
- High frequency (also known as switch-mode rectifier [SMR]) designs.

Neither IEEE 946 nor IEEE 1818 offers specific guidance on which topology should be applied, so it is left to the user to decide. Environmental factors may be significant for certain technologies, such as the switch-mode design with its higher energy density and forced cooling requirements.

Note: Forced cooling is not required for all SMR topologies. However, fans are required for SMR chargers with high energy density, and the fans may be the first point of failure. These designs are also more susceptible to dust and dirt. SMR chargers should include an N+1 configuration with redundant modules.

Sizing the Charger

IEEE 946 and IEEE 1818 are mostly consistent in the recommended methodology for sizing a battery charger. In simple terms, the battery charger should have rated output current suitable to supply the connected (normal) load while also recharging a discharged battery within a predetermined length of time. The user must assess and determine variables such as time to recharge the battery, charging efficiency, design margin, altitude factors, etc.

There is one minor difference in the methodologies. For power generation it is assumed that to recharge the battery the charger must restore the energy removed from the battery based on the estimated duty cycle. For substation applications it is recommended to assume a percentage of the nominal capacity rating (Ah) of the battery must be restored.

Battery Charger Input and Output Characteristics

IEEE 946 and IEEE 1818 recommend that a battery charger should meet the requirements defined in NEMA PE 5, now superseded by IEEE 2405. Users must evaluate available power sources to determine the proper input voltage, frequency, and number of phases. Other considerations include desired float voltage, maximum charging current (often limited by the battery), maximum acceptable ripple, and whether temperature compensation is required.

Performance and Operation

For battery chargers in utility standby applications, IEEE 2405 sets the minimum performance requirements that the charger must meet to ensure equipment reliability and personnel safety. IEEE std 2405 describes various optional alarms and features that may be added, but are not required. Both IEEE 946 and IEEE 1818 refer to these requirements. The following items are the essential performance parameters defined in the standards.

Current Limit

Battery charger output current limiting is necessary to protect charger power components and limit the current supplied to the battery during recharge. This can be done either actively or passively depending on the specific rectification topology. Arguably the most reliable method is active control including a feedback loop.

IEEE 2405 specifies that the charger current limiting circuit should limit the output current to 100% of its nominal rating. It is important to note that when two or more chargers are operated in parallel, the total available current will be the sum of all connected chargers. Special care must be taken with certain battery technologies to ensure recharge current does not exceed the manufacturer allowable limit.

Float and Equalize Modes

Utility standby battery chargers typically operate at constant dc output voltage selected to maximize the life of the battery. This is commonly known as float mode. IEEE 2405 defines the standard ranges for float voltage to accommodate different battery technologies and configurations. IEEE 946 recommends the charging voltage range should be coordinated with the minimum and maximum rating of the loads.

Certain battery technologies, or conditions, may occasionally require the charge voltage to be elevated above the normal float voltage setpoint. This mode of operation is known as equalize mode, or boost mode. Again, IEEE 2405 defines the minimum requirements. For most battery chargers, equalize mode may be selected to start either manually or automatically. IEEE 946 and IEEE 2405 defer to battery manufacturers' recommendations regarding the use of Equalize mode.

Load Sharing

In cases where more than one charger is operated in parallel, IEEE 946 suggests that both chargers should be of similar topology and power level. In this case, each charger may supply a portion of the load current demand. IEEE 946 recommends that multiple charger installations should employ load sharing, either actively or passively.

IEEE 2405 defines load sharing types. In active load sharing, charger circuits are either connected via a control cable or load sharing is performed using output dc regulation logic with no common wire connection. In both cases, the chargers are forced to feed the load equally. This method can have the advantage of placing even wear on components of both chargers.

Passive load sharing allows the connected chargers to split load, without influence, based on system conditions such as voltage setting, dc circuit impedance, operating temperature, and internal design characteristics. It is likely that one charger might carry all the normal load for an extended period, although the alternate charger should pick up the load in the event of failure of the first charger. Passive load sharing is generally more flexible when switching one charger out of service.

IEEE 2405 defines the requirements for parallel operation, including instructions on when load sharing can be performed, how load sharing circuits must behave when temperature compensation is utilized, and precautions related to failure of one charger.

Static and Dynamic Response (Voltage Regulation)

Precise dc voltage regulation is important to extend battery life and to prevent undesirable operation or damage to load equipment.

Static regulation applies while a charger operates under constant load. For static conditions, IEEE 2405 requires output voltage to be maintained within 0.5% in float mode, and within 1.0% during equalize mode. Intermittent loads, such as circuit breaker operation, can cause transients on the dc system. These dynamic system conditions can cause charger output voltage to oscillate, under a damped response, as the voltage controller attempts to regulate the output. IEEE 2405 requires dynamic regulation to not exceed 6% of rated output, and static regulation to be restored within 300ms. IEEE 2405 assumes that a battery is connected, and that the load step is within 10% to 90% of rated charger output. Higher levels of filtering in the charger may worsen voltage regulation and extend response time due to the passive filter dynamic response effect. Because they operate at a much higher frequency, switch-mode chargers often have better dynamic regulation than line frequency designs.

Ripple

Ripple is a steady state ac waveform superimposed on the dc power system, often related to line frequency or the operating frequency of the battery charger. High ripple content, especially at lower frequencies (such as sub 1 kHz) can adversely affect battery life and may cause undesirable operation of sensitive loads. Ripple can be suppressed by filtering the output of the charger. IEEE 2405 discusses two levels of filtering. For 125Vdc applications, ripple must be less than 100mV, or less than 2% of rated output voltage, with no battery connected. However, none of the documents provides an indication of which filter level should be used. The end user must determine potential adverse effects of ac ripple on the battery and connected equipment.

Protection Elements

Circuit Protection

Circuit breakers and/or fuses are required to ensure personnel safety and minimize damage to electrical equipment due to overload or equipment failure. Battery chargers are required to have ac input circuit protection to minimize the effect on upstream circuits from a fault within the charger. DC output circuit protection is also required to minimize internal damage from a fault at the battery or load devices.
IEEE 2405 provides instructions for sizing ac and dc circuit protection. IEEE 946, IEEE 1818, and IEEE 2405 are consistent in requiring that protection devices must be capable of withstanding available fault current, and must be coordinated with the respective upstream and downstream elements. While the content of the inactive IEEE 1375 standard has yet to be integrated into IEEE 946, it is still available to buy (even as an inactive standard), and provides a lot of useful information on circuit protection devices for batteries.

Surges and Electrical Noise

IEEE 2405 requires battery chargers to be designed to withstand electrical surges in accordance with ANSI/IEEE C37.90.1.

IEEE 946 recommends that chargers should have protection against electrical noise (EMI and RFI) caused by lightning and switching surges and refers to some IEC standards.

Alarms and Communication

Both IEEE 946 and IEEE 2405 recommend battery chargers should have the capability to notify the user of abnormal events. Typical notifications include low dc volts, high dc volts, ac failure, ground leakage, high rectifier temperature, or fan failure. Problems can be locally annunciated with indicating lights and digital displays. Alarms also may comprise dry-contact relays which can be connected for remote indication via PLC, SCADA, or DCS.

Alarms and charger status information can also be transmitted through a communication bus using protocols such as DNP3 (see IEEE 1815) or IEC61850. When such communication features are required, IEEE 2405 provides guidance on how they can be implemented.

IEEE 2405 includes an annex listing various optional alarms and status information. Each user should determine the appropriate level of notification. For a permanently manned facility, a simple notification of charger trouble may be all that is required. Remote, unmanned sites might need a lot more information to determine the priority for dispatching resources for troubleshooting.

Testing and Qualification

Battery chargers should be tested to demonstrate compliance with applicable requirements. IEEE 946 provides guidance on which standards should be used. IEEE 2405 defines two types of testing: type testing and routine testing. Type testing follows a methodology to prove that a representative charger design can perform all functions in accordance with the design specifications. Routine testing is performed, sometimes in the field but most often at the manufacturer's facility, to confirm quality standards are being maintained during the manufacturing process.

Maintenance and Replacement Criteria

IEEE 946 recommends that maintenance and replacement of equipment should be considered during the design phase of the dc system. Replacement under live service, access to the charger cabinet, safety space when doors are open, access to the critical components of the charger for cleaning and replacement, shrouding of dangerous voltage connections, and spares availability are among the items to be considered.

IEEE 2405 requires that recommended maintenance tasks and intervals be provided by the manufacturer. Other standards, such as NETA-MTS and NFPA 70B also provide guidance on charger maintenance.

It is important to note that extreme site conditions, such as high ambient temperature, and heavy dust, dirt, or other contaminants may demand more frequent maintenance and replacement.

Spare parts

Ensuring availability of spare parts is highly recommended to ensure dc system service continuity. Required spares should be evaluated based on the design and operating requirements of the site.

IEEE 946 and IEEE 1818 recommend that spare components or equipment such as a spare charger, should be considered based on the criticality of the system, user experience, availability of components, failure rate, lifetime, etc. IEEE 2405 recommends that a spare parts list should be included in the manual.

Conclusion

The battery charger is a key component of any utility standby system. IEEE 2405 was developed to ensure that manufacturers design and produce quality equipment with the features necessary to ensure reliable operation, and that equipment is tested to ensure compliance. IEEE 946 and IEEE 1818 were developed as tools for the end user, to aid in the selection of the appropriate technology, define the correct input and output parameters, and to determine the optimum method of connecting the charger in the dc system. DC system designers are responsible for applying all available resources to ensure the sustainability of the charger and the dc system as a whole.

References

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7- IEEE 1815-2012: IEEE Standard for Electric Power Systems Communications-Distributed Network Protocol (DNP3)