Design Considerations for Battery Maintenance Cost Reduction in Small Modular Reactor In-Plant Electrical Systems

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1. Introduction

Power demand is growing rapidly, driven largely by large-scale data center expansion. In response, small modular reactors (SMRs) have attracted significant attention as a next-generation power generation technology. SMRs offer high site flexibility and enhanced safety characteristics, making them promising candidates for installation near load centers. Notably, SMR designs by Korea Hydro & Nuclear Power (KHNP), NuScale and the others incorporate passive safety systems that do not necessarily require electrical energy for safety function actuation [1]. Nevertheless, maintaining continuous power supply availability remains critical from the perspectives of economics, plant availability factor, and overall operability for the plant operating organization.

Therefore, uninterruptible power supply (UPS) systems equipped with battery banks are expected to be extensively deployed throughout SMR in-plant electrical systems [2]. In nuclear power plant electrical systems, UPS configurations commonly employ batteries directly connected to the DC bus — a topology referred to as an online UPS. However, this arrangement continuously exposes the batteries to AC ripple currents generated by the battery charger or DC-AC inverter stages. Such ripple currents can accelerate battery degradation, shorten service life, and increase maintenance costs. Among the various sources of ripple current, this paper focuses on the DC-AC inverter stage, and reviews mitigation methods proposed in both industry standards and academic literature.

2. Battery Ripple Current and Its Effects on Battery Life in Single-Phase Online UPS Systems

Fig. 1 illustrates the configuration of a single-phase online UPS system in which the battery is directly connected to the DC bus. An AC-DC rectifier connected to the AC power system charges the battery and, once the battery reaches its designated voltage level, maintains the DC bus voltage while supplying power to the load. When AC loads are present, a DC-AC inverter is additionally connected to the DC bus, drawing from the battery as its input source.

As shown in the simplified input/output current waveforms of the inverter in Fig. 2, when the output AC frequency is denoted as ω, the inverter input current contains a ripple component at twice that frequency (2ω) [3]. Since the nominal AC frequency is typically 50–60 Hz, this corresponds to a low-frequency ripple in the range of 100–120 Hz, which has been widely reported to accelerate the degradation of both vented lead-acid and valve-regulated lead-acid (VRLA) batteries [4-5].

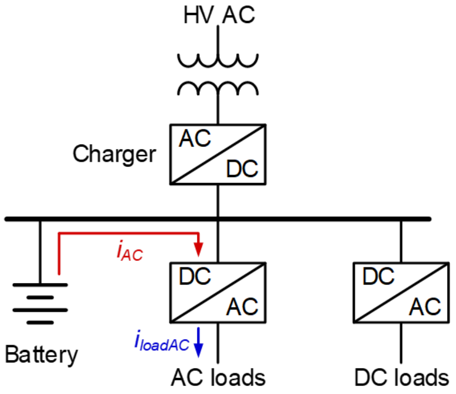

Fig. 1. Configuration of an online UPS system

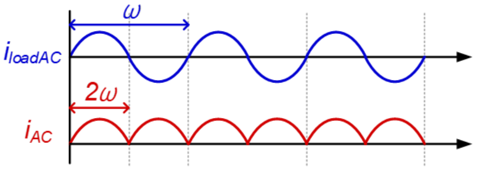

Fig. 2. Simplified waveforms of inverter input/output currents

It is worth noting that this ripple current flows even under steady-state conditions where battery charging or discharging is not required. In other words, whenever the inverter supplies power to AC loads, the 2ω ripple current is continuously imposed on the battery. Furthermore, since ripple current induces internal heat generation within the battery, thermal degradation caused by ripple cannot be effectively prevented by an ambient cooling system alone. Therefore, the magnitude of the AC ripple current must be limited to a level that does not critically compromise battery service life.

For this reason, IEEE standards also address AC ripple current limits for VRLA batteries. IEEE Std 1184 specifies that AC ripple current should be limited to 5% of the rated 8-hour capacity to mitigate battery degradation [6]. For instance, a 100 Ah VRLA battery has a ripple current limit of 5 A. While specifications may vary by manufacturer, experimental data consistently support this guideline. An analysis based on technical data from C&D Technologies indicates that battery life degradation is negligible when the ripple current remains within the limit specified in IEEE Std 1184 [4]. Furthermore, a study in [5] reports that a ripple current of approximately 15% of the rated 8-hour capacity results in a 3% reduction in expected battery life, with more pronounced degradation occurring at higher ripple levels.

3. Techniques for Battery Ripple Current Mitigation

Methods for reducing battery ripple current can be broadly classified into three categories: passive filtering, active power decoupling, and direct DC supply.

3.1 Passive filters

Passive filtering is the most widely adopted approach, employing inductors (L) and capacitors (C) placed on the DC bus to attenuate ripple current transfer to the battery. Since no additional power semiconductor switches are required, this method offers straightforward equipment qualification and inherently high reliability — both critical attributes for safety-related applications in nuclear power plants. However, effective attenuation of the low-frequency 2ω ripple (100–120 Hz) demands proportionally large L and C component values, resulting in significant increases in equipment volume and weight.

3.2 Active power filters

Active power filters (APFs) employ additional power electronic circuits — typically a bidirectional DC-DC converter with a buffer capacitor — to dynamically absorb the oscillating 2ω power, thereby preventing its propagation to the battery. Compared to passive filters, APFs offer a substantial reduction in passive component volume, as the energy buffer function is transferred to a film capacitor, which exhibits superior ripple handling capability relative to large electrolytic capacitors [3].

Nevertheless, the introduction of additional power semiconductor switches and associated control circuits entails increased system complexity. For nuclear power plant applications, each new active component introduces additional failure modes that must be rigorously evaluated under the equipment qualification framework.

3.3 Direct DC supply

The third approach eliminates the DC-AC inverter stage entirely by supplying loads directly with DC power via DC-DC converters. Since the 2ω ripple originates from the single-phase DC-AC inversion process, this topology removes the fundamental source of ripple generation. A significant portion of conventional AC loads receive AC power input only to internally convert it to DC for final load supply. Providing DC power directly through isolated DC-DC converters therefore eliminates an unnecessary conversion stage, offering potential improvements in overall system efficiency.

If DC interruption technologies — including DC circuit breakers and associated protection schemes — are validated for nuclear-grade applications in the future, the direct DC supply architecture could represent the most fundamental and permanent solution to the battery ripple problem in SMR in-plant electrical systems.

4. Conclusion

This paper analyzed the mechanism of low-frequency AC ripple current generation in online UPS systems and its degradation effects on VRLA batteries in SMR in-plant electrical systems. Three mitigation approaches — passive filters, active power filters, and direct DC supply — were reviewed with respect to their nuclear applicability. Each method presents distinct trade-offs between component simplicity, qualification burden, and ripple reduction effectiveness.

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