

Switch Mode Battery Chargers for Utilities: Why? How? and Where?

Haissam Nasrat, Yves Lavoie, Steven Monk
Primax Technologies, Inc.
Montréal, Québec, Canada

Abstract

High frequency switch mode rectifiers (SMR) have been commercially available for over 30 years. Today they are the dominant technology in: Telecom, laboratories, medical and many consumer applications. Their success is mainly due to their compact size, modularity and cost effectiveness especially when N+1 or higher redundancy is required.

For over a decade, in Europe and Australia, SMR have been used in Utilities with a great level of success, while in North America, their acceptance has been minimal in Substation and Power Generation applications.

In this paper we want to help dc auxiliary power system engineers and designers in their technical assessment by examining the various differences between the SMR technology and low frequency chargers such as silicon controlled rectifier (SCR). We will also be comparing the Telecom installation model versus the typical Utility model because installation packaging is such an important part of the equation.

Introduction

The battery charger is an important component in a dc auxiliary system; it feeds the station loads and restores battery capacity after an outage. In the industrial and utility markets, there has been a push for a more compact design in control buildings, the need for easier repairs and shorter repair times and because of the pressures of budgetary constraints, users are looking for more options. Furthermore, when it's time to make a decision, one might think that a dc system is a dc system and be tempted to standardize all of its components for all sites, using the same technology for batteries, chargers and protection. In reality different installations require different technologies. For example, a dc system in a coal fired power plant must be resistant to more dust, heat, ground plane fluctuation, high intensity surges, etc.

In this paper we will be comparing two solid state topologies: high frequency switch mode rectifiers (SMR) and low frequency rectifiers such as Ferroresonant, Mag-amp and Silicone Controlled Rectifiers (SCR).

Basic decision criteria will be reviewed with relative advantages and disadvantages of each topology for the stationary substation application based on the site operating conditions and other requirements.

In addition, we will look at the various environmental and maintenance requirements that have resulted in successful SMR installations.

History

The technological evolution of battery chargers parallels very closely the deployment of rectifier devices. Before 1900, dc motor generator sets were the only electrical way to generate dc power, in the early 1900's, mercury arc rectifier vacuum tubes were introduced; ac current was rectified through an electrical arc created between electrodes in very low pressure mercury vapor glass bulb. The Thyatron was introduced in the 1920's; an electrical switch controlled rectifier vacuum tube using Argon for higher power applications. By the end of World War II, solid state germanium and silicon diodes emerged and so did the Mag-amp and Ferroresonant chargers.

In the 60's SCR chargers were introduced. In the late 70s Field Effect Transistors (MOSFET) and isolated gate bipolar transistors (IGBT) were developed; but it was only by the late 90s that more reliable higher power and frequency MOSFETs and IGBTs were commercially available thus allowing the emergence of SMR chargers.

System Review

In a typical dc system, one or more chargers are used. Multiple chargers may be required for redundancy, serviceability or for increased power needs. The charger is typically connected to one battery formed of one or more parallel strings and to dc station loads through a distribution panel. A typical layout is shown in Fig. 1. Chargers are designed to feed continuous loads (large instantaneous loads are usually fed by the battery), recharge the depleted batteries within a specific time frame and keep the battery in a fully charged condition.

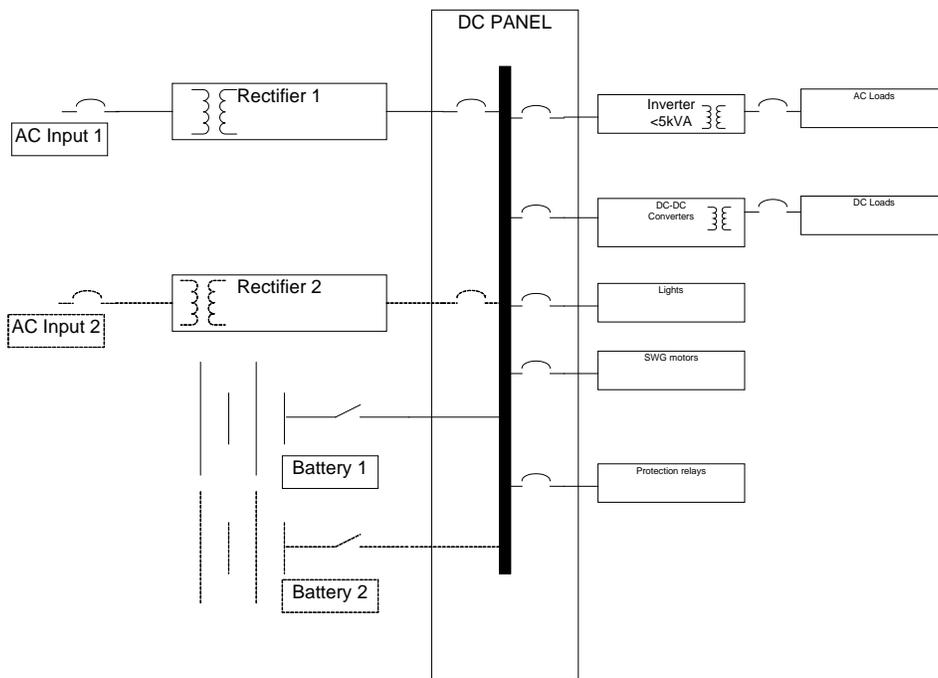


Figure 1. Typical DC Stationary System

Technology Review

In the following, the SCR based chargers representing the low frequency topologies and the MOSFET based chargers representing the SMR chargers, will be compared. Alarms, communication protocols and other options are not covered in this discussion.

SCR Type Battery Chargers

A typical SCR battery charger consists of “one single” conversion stage where the ac power is converted to dc power through an isolation transformer and an SCR bridge. A typical layout and waveforms are shown in Fig. 2. The charger output voltage regulation and current limiting are controlled by varying the SCR gate firing angle. The controller dynamic response time for a 10% to 90% step load (time-constant) is around 200 milliseconds. The dc output is filtered through a combination of inductors and capacitors to reduce the ac component to levels dictated by different standards. For example, NEMA PE5 requires 100mV rms ripple for 125Vdc filtered chargers.

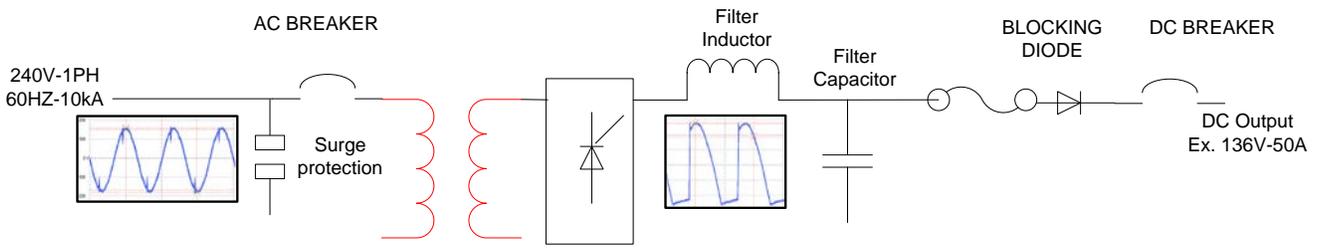


Figure 2. Typical SCR Battery Charger Layout

Since SCR chargers operate at low frequencies, transformers, capacitors and inductors are relatively large. Surge protection on the input and output are required to comply with the Electromagnetic interferences (EMI) and Surge Withstand Capability (SWC) standards. Passive or active filters can be added on the front-end to improve power factor and input current total harmonic distortion (THDi). These filters may increase the physical size of the charger or affect its efficiency.

When designing larger power chargers, larger power components are needed, e.g. larger isolating transformer, larger inductors, etc. However, the number of base components will usually remain the same.

Physically, SCR chargers are supplied in wall mount or freestanding enclosures. Front access to components is made through hinged doors.

SMR Type Battery Chargers

Single phase chargers are commonly available with Power Factor Correction (PFC) circuits providing a unity power factor correction and THDi lower than 5%.

Three phase chargers, depending on their input connection may or may not have PFC circuits. 3 phase-4wire units usually have PFC while 3 phase-3 wire input units have no PFC. Adding PFC to the 3ph-3wire designs implies more complex circuits and controllers. In all cases, international standards such as IEC require PFC for units drawing less than 16A/line. Usually, 3phase chargers are used in larger power applications, hence no real need for PFC.

Single phase PFC chargers are made of “four” conversion stages. Typical SMR layout and waveforms are shown in Fig. 3. The ac is rectified through a bridge rectifier; the resulting dc is then filtered and boosted to higher voltage (400Vdc for 240Vac mains) using a PFC circuit then chopped with a high frequency ac bridge using MOSFETs. The pulse width modulated output (PWM) is then transformed through a high frequency transformer, rectified and then filtered. Switching frequencies can be as high as a few hundred kHz.

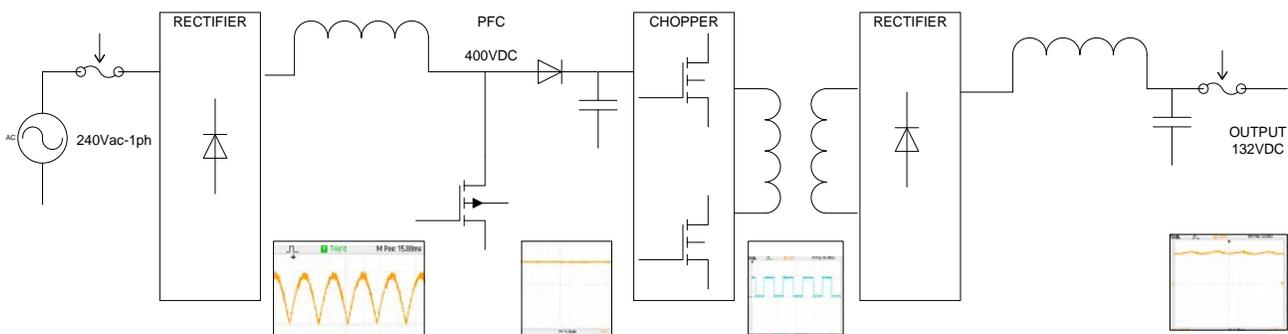


Figure 3. Typical SMR Layout and Waveforms

Output voltage regulation and output current limit are achieved by adjusting the high frequency PWM. The time constant is relatively fast, in the milliseconds range (e.g. 10ms). Operating at high frequencies, magnetics and filter capacitors are relatively small. Power density can be very high (e.g. 15W/in³).

Having smaller components, the integration of SMR chargers becomes possible on printed circuit boards providing compact designs. Forced air cooling fans are then needed in more compact designs to insure proper heat dissipation and preventing hot spots. Natural convection design, to be in line with IEEE1613, is also available but limited to lower power levels and may imply larger dimensions. Due to higher frequency operation and the absence of input isolation transformers, special attention must be paid in the design of surge protection on the input side to comply with the EMI and SWC standards.

Basic modules are designed with predefined power level e.g. 5.5 kW per unit. So when designing larger power chargers or when redundancy is required, more units are installed in parallel. Units are generally hot-swappable. One controller is needed to control multiple units. Fig.4 represents a typical SMR system.

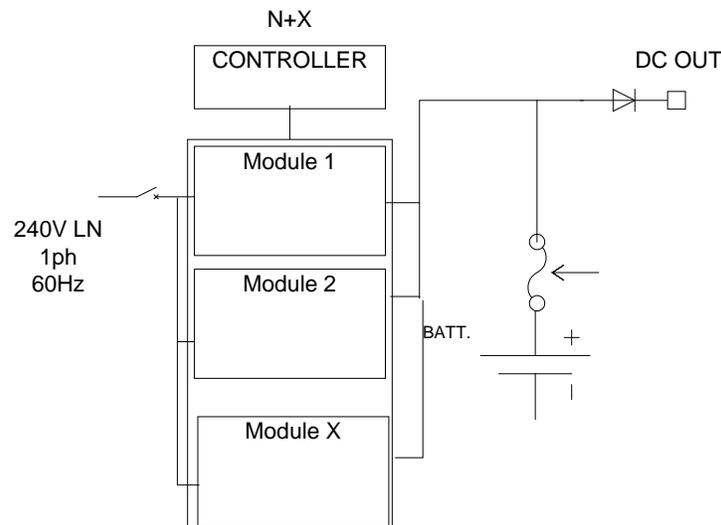


Figure 4. Typical N+x SMR System

Single phase fed PFC systems can usually operate over a wide range of input voltage with no de-rating (e.g. 175V-300V). At lower input voltages the unit output power is derated to account for the maximum input current the unit can handle without tripping its protection.

On the other hand, when sites have higher ac voltages than the individual units rating, an input step-down transformer will be needed. However, because of the PFC, over-sizing factors of this transformer will be very small.

Physical and Environmental Considerations

SCR chargers are available in wall mount and standalone enclosures where components are accessible through front hinged doors. Natural convection ventilation is standard in relatively large power units.

SMR units generally fit in 19" sub-racks and in more compact enclosures, saving space compared to SCR chargers. But if the requirement is for only one or two parallel units, the whole sub rack will be used, hence imposing a larger footprint than what is really needed; in this case, the size will be around the same as the SCR chargers but with the advantage of having space for future expansion.

Generally 100A_{dc} or less (fed by $\leq 240V_{ac}$ or 208V_{ac}) SMR systems will not require step-down transformers; this will make the whole charging system up to 50% lighter, when compared to SCR chargers, which will allow easier movement and wall mounting. If step-down transformers are needed on the input side then space requirements of SMRs and SCR would be very close.

Figure 5 shows different pictures of SCR versus SMR chargers and components.



Figure 5. 5KVA-60Hz vs. 100kHz transformer

125V-30A SCR in 19" wide cabinet vs. 125V-40A SMR unit

125V-200A SMR in 19" sub-rack

When designing enclosures for SMR, special attention must be paid to insure that forced cooled units won't fail because of excessive heat due to the accumulation of dust or stagnation of air. Thus, preventive maintenance programs must include vacuuming and fan replacement as per the manufacturer recommendations and the operational environment.

Service and Repair Considerations

Short and long term service and repair concerns are important factors when it comes to making a decision about charger topology. In case of a failure, the charger is one of the dc system components which can take the longest to repair, which becomes a costly event. This might include dispatching a crew of more than one technician for logistics and safety issues, shutting down of the dc system, connecting a temporary charger and battery, etc.

Using a "single" SCR charger in a dc system may lead to a single point of failure caused by any of the charger power or control components. The repair may require complex diagnostics and has to be done by skilled electrical technicians.

This failure can become an "urgent" concern that has to be treated promptly. On the other hand, urgency can be reduced if redundant charger configuration is used. In this case, the cost and usage of floor space will double.

SMR has different service requirements. Since a single charger is made of multiple power units, the failure of one unit will reduce the available dc power but does not shut down the system. As an example, a 150A charger composed of 5 x 30A units can provide 120A (4 x 30A) if one unit fails, which results in a "non-urgent" concern. Furthermore, if the charger has N+1 configuration, 100% of the rated dc power is still available after the loss of a single unit. Generally, the embedded diagnostic system will point out the faulty unit which can be replaced swiftly whether it's in a 19" rack or a typical utility style cabinet.

Repair of the SMR system can be done by a less specialized technician who would hot-swap a spare unit without shutting down the dc system. This can be considered as a great advantage of using SMR in stationary applications.

Cost Considerations

When looking at a new solution, direct and indirect costs should be considered. Direct cost can include material and installation. Indirect and long term cost can include maintenance, repair, spare parts, poor efficiency, poor power factor, etc.

Here we will focus on a the direct unit cost comparison of 125Vdc SMRs versus SCR filtered chargers not including options such as dc breakers and alarms which, if required, will be about the same for both. We will also consider that for under 100A requirements, 240V-1ph input will be used and for greater than 100A units, 480V-3 ph will be used.

Figure 8 presents the comparison for single non-redundant units. Figure 9 presents a comparison when redundancy is required so for the SCR topology a second charger is used and N+1 is used for SMR.

Observations

- Figure 8: A low power SCR charger is slightly more expensive than SMR. This is mainly due to the 60Hz isolation transformers, filter inductors and capacitors which are naturally larger than in SMRs. Larger components also affect the cabinet size incurring higher cost.
- Figure 8: Three phase SCR costs become less expensive than SMRs'. This is due to the fact that in 3 phase applications a step down transformer is needed since most available SMRs have 240V single phase input.
- Figure 9: when redundancy is required, N+1 SMR configurations have a noticeable cost advantage on redundant SCRs: Only one SMR power unit will be needed while a second complete SCR charger will be required.
- Figures 8 and 9: When comparing the price curves, one can clearly see that the SMR curve is quite linear due to the cost of adding identical SMR units to reach required capacity, while the SCR curve flattens out in larger applications due to the non-linear cost of different sized transformers, cabinets and other components

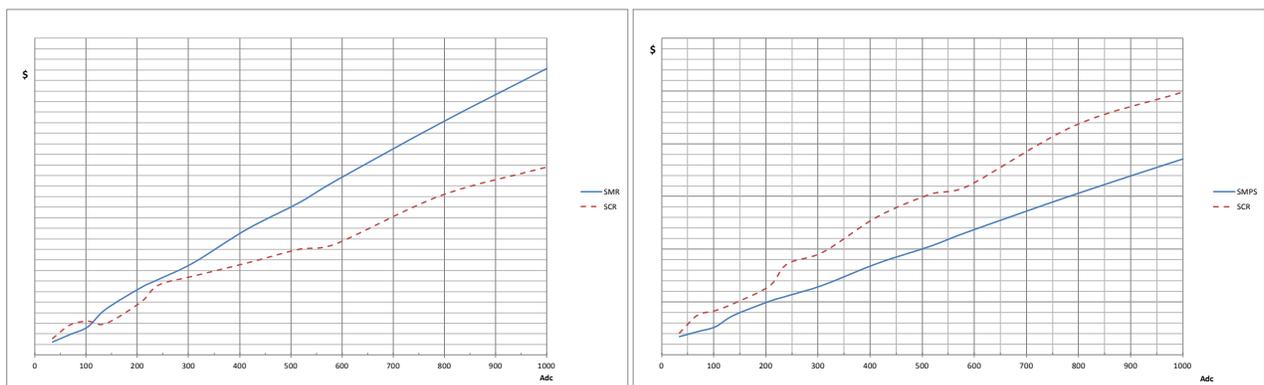


Fig. 8. Cost comparison: Single SCR vs. SMR

Fig. 9: Cost comparison: Redundant SCR vs. N+1 SMR

Specifics to Substation and Power Generation Applications Considerations

Chargers are usually positioned close to very low impedance power sources and to high power/high voltage busses. Figure 10 illustrates a typical high voltage ac bus section with inherent leakage capacitances connected to the ground.

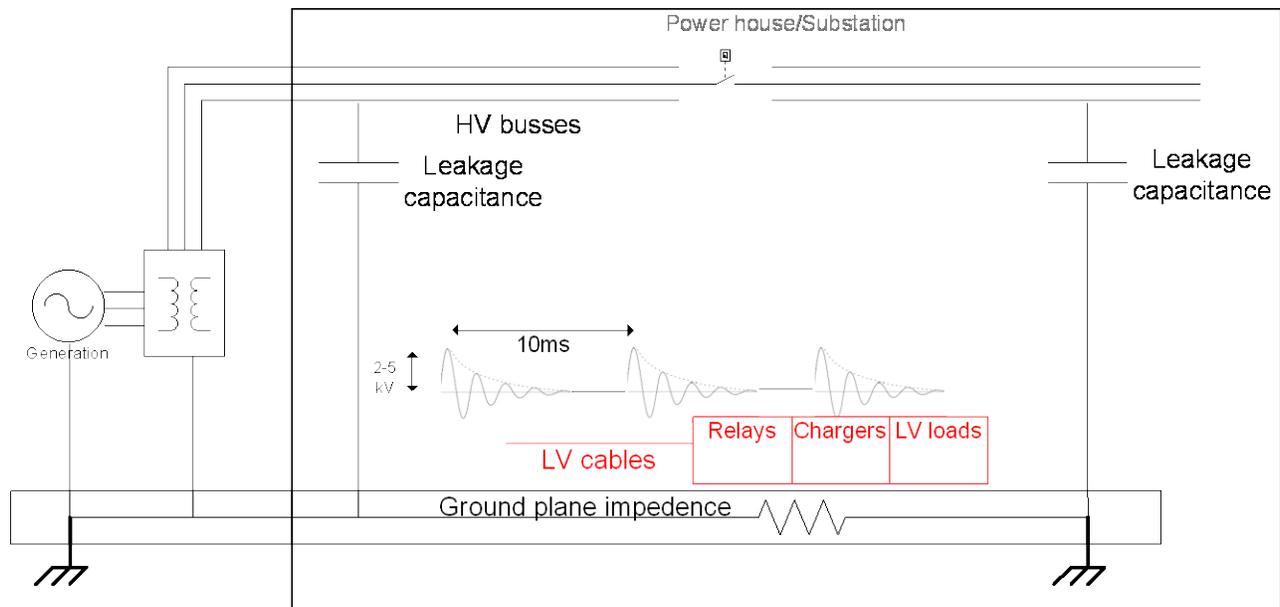


Figure 10

Many phenomena such as transients on the high voltage busses and ground potential rise may occur due to, among other things, lightning strokes on phase conductors, short circuits (phase to ground and phase to phase), switching activation to connect capacitor banks and inductive control circuits and for other substation operational requirements.

Resulting transients and their magnetic fields will affect all low voltage components in the station including battery chargers. Typical transients are damped oscillatory waveforms with crest voltage as high as 2-5kV reaching MHz frequency in both common and differential modes. Figure 11 shows typical oscillatory and fast transient SWC waveform as defined by ANSI/IEEE C37.90.1. These transients must be adequately addressed in the design of the chargers protection as well as in the design of the dc system.

On another level, poor PF and THDi in a substation are not as an important concern as in industrial applications where users are penalized by their electrical utility when not having the correct PF and THDi. Opting for SMR chargers rather than SCR chargers may help in resolving these issues.

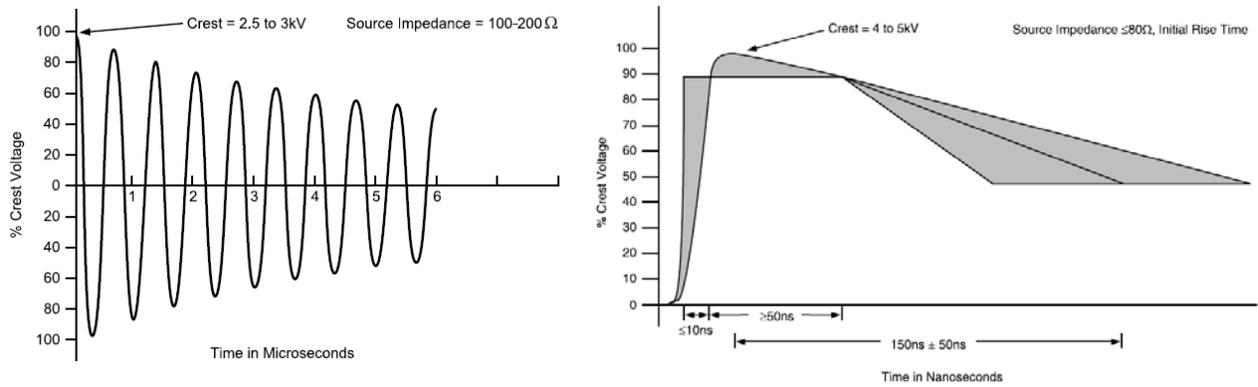


Figure 11: SWC Waveforms

SMR Experience Overview

SMR have been used in telecom for over 30 years and they represent the prevailing option for new installations as well as replacement systems. In Europe and Australia, electrical utilities and industrial users have installed SMRs for over 15 years. Some of these utilities exclusively specify SMRs.

Closer to us, in Canada some large utilities have changed their specifications and started using SMR in their substations and power generation stations. They started by introducing SMRs in their substations, later on, once confidence in the technology had been established they gradually introduced them in power plants to replace older chargers. Their maintenance procedures have been slightly adapted to take into account SMR specifics.

In one specific power generation and transmission utility, SMRs are used in over 35 generation sites including hydro, thermal and diesel and in over 50 high voltage (>66kV) stations. Interestingly enough, this utility decided to keep redundant configurations of SMR rather than using N+1 for reliability concerns. Success of their SMR installations is mainly due to the suitable environment conditions: relatively cool stations most of the year, almost dust free locations and a good maintenance program.

Furthermore, in the US and the Canadian industrial markets and mainly due to their compactness and serviceability, SMRs have been gradually introduced in:

- New gas turbine applications due to their adoption by gas turbine manufacturers and integrators.
- Prefab Electrical Houses for industrial applications such as mining, petrochemical and smelting.

What is right for me?

As usual, there is no simple answer. Different applications dictate different technologies. In the following comparison, we tried to list a high level overview of simple criteria the user has to evaluate and upon which he will base his decision.

Criterion	SCR	SMR	Comment
Scalable	No	Yes	SMR: additional units can be added as needed
Efficiency	Good	Better	SCR: 85% typical SMR: $\geq 92\%$ typical. E.g. for 10kW, 5% better efficiency saves 500W of heat.
Power management	No	Yes	In certain SMR designs, some units may go on sleep mode during float operation to increase efficiency.
Input power factor	Relatively poor	Very good	SCR: Typical 0.7-0.8 SMR: Typically 0.99 for PFC units. However active PFC adds 1 extra power conversion stage.
Low ripple	good	better	SCR : $< 1\text{kHz}$ ripple requires bulky inductors and capacitors to help extend battery life. SMR: Low frequency ripple is naturally non-existent.
DC Capacitors aging	Little effect	Some effect	SCR: Low frequency ripple increases which can shorten battery life. SMR: No low frequency ripple will appear. If PFC caps degrade, unit could shut down
Single point of failure	Yes	No	SCR: System shuts down. Your battery is discharging, your protection is jeopardized "N+1" SMR: No effect "N" SMR: Reduced power but no shutdown when more than 1 unit is used in parallel with safe-mode feature: With the balance of power available an "urgent" alarm can become "non-urgent"
Serviceability	easy	Very easy	SCR: Specialist skills required to repair SCR and PCBs SMR: Non specialized technician can hot swap units on-line.
System Reliability	Very good	Very good	SCR: proved over time to be tolerant and sturdy. SMR: N+1 configuration is reliable. In N application the loss of 1 unit reduces power of the system without total system failure.
Repair time	Good	Better	SCR: $\geq 1\text{h}$. Depends on your safety procedures: Protection Tagging, locking, zero energy, etc. SMR: $\leq 10\text{min}$. Very fast replacement of hot swap units without system shutdown
Phase unbalance & neutral currents	no effect	some effect	SCR: the 3 phases are balanced SMR: Using distributed single phase units in 3 phase-3wire systems might create unbalance.
Dynamic regulation	Good	Excellent	SCR: $\leq 300\text{ms}$ as per NEMA PE5 SMR: $\leq 10\text{ms}$
Transients	Tolerant	Sensitive	SCR: tolerant due the main transformer coupling attenuation SMR: 1ph having no ac isolation transformers: Very sensitive. Adding input filters or isolation transformers helps to improve tolerance.
Contribution into downstream Fault	Good	limited	SCR: does not typically limit energy during the first 10ms of a fault event due to their slower regulation time constant which helps to clear downstream protection. SMR: Very fast current limitation limits the available energy.
Weight	Heavy	light	SCR: 100s of pounds mainly because of transformers and filter inductors SMR: Few pounds per unit which can be installed and removed by one person.
Size	Large	Small	Except for 3phase SMR with step-down transformers where SMR systems are similar in size to SCR's
Heat tolerance	Good	Limited	SMR: extra care is needed
Dust tolerance	Good	Limited	SMR: Extra care is needed: units need to be dusted on regular basis and fans need to be replaced depending on the application.
Natural convection cooling	Yes	Limited	SMR: Fan-less units are limited in power
Spare parts	Individual parts	modules	Cost of recommended spares in a common SCR charger is typically more than 25% higher than 1 spare SMR module (not including installation cost).

Conclusion

Can we deploy the SMR on a larger scale for substations and power generation? Most probably yes. But not everywhere!

So far, low frequency chargers have been serving the stationary market very well but if improved flexibility, system reliability, serviceability and economics are considered, then SMR topology offers a good alternative. SMR chargers can help system engineers optimize their designs, service departments ease intervention procedures and can help planning/procurement teams to simplify documentation and deployment processes.

Bibliography

- IEEE946: IEEE Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Systems
- NEMA PE5: Utility-Type Battery Chargers
- IEEE519: IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems
- IEEE1613: IEEE Standard Environmental and Testing Requirements for Communications Networking Devices in Electric Power Substations
- ANSI/IEEE C37.90.1: IEEE Standard Surge Withstand Capability (SWC) Tests for Relays and Relay Systems Associated with Electric Power Apparatus
- IEC61000-3-2: Electromagnetic compatibility (EMC) Part 3-2: Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)
- Study of transient ground potential rise in gas insulated substations during fault conditions using electromagnetic field and circuit theory approaches: W. Ruan, F.P. Dawalibi and J. Ma, Safe Engineering services and Technologies Ltd, Montreal, Quebec.
(http://www.google.ca/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CCIQFjAA&url=http%3A%2F%2Fwww.sestech.com%2Fpdf%2FUser2000_A.pdf&ei=G8_wVIWrOMO1sATly4DQCg&usg=AFQjCNFJoeFS51E801nhBdLTs6zUag3LnQ)
- Substation Transients and Solid State Controls : W. C. Kotheimer, General Electric. NORTHWEST ELECTRIC LIGHT AND POWER ASSOCIATION 51st annual conference
(<http://apps.geindustrial.com/publibrary/checkout/GER-3204?TNR=White%20Papers|GER-3204|generic>)