Power Factor Corrected (PFC) low harmonics Rectifier Technology in Industrial UPS Systems

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Abstract - IGBT (Insulated Gate Bipolar Transistor) switching technology was introduced for inverters about 20 years ago. This paper elaborates the application of IGBT based rectifiers enabling active PFC (Power Factor Correction) and bi-directional power conversion with low harmonics feedback.

IGBT Boost Rectifier topology is explored and compared with traditional thyristor frontend. Associated advantages related to technical specifics and operation- / maintenance aspects including safety / availability are outlined. Finally cost of infrastructure and ownership are worked out from a neutral perspective.

Index Terms — PFC Rectifier, 6-Pulse, 12-Pulse, IGBT, Harmonics, UPS, Double Conversion, Bi-directional Converter

I. INTRODUCTION

UPS (Uninterruptible Power Supply) systems are a vital part of a processing plant safeguarding continuity, safety and reliability. AC power is converted (rectified) to the DC link backed-up by batteries (stored energy) and transformed (inverted) back to AC feeding the connected critical loads.

Double conversion, industrial grade UPS systems with isolation transformers traditionally use 6- or 12-Pulse Thyristor rectifier topologies which are robust but polluting the feeding mains with harmonics in conjunction with a variable power factor.

II. INDUSTRIAL UPS TOPOLOGIES

Industrial UPS systems are characterised by their true double power conversion topology operated in a full on-line mode. The critical loads are always feed by the inverter whose power demand is supplied by the rectifier which converts input AC-power to DC and keeps the battery-bank in a fully charged condition. A separate bypass line acts as a hot-standby source enabling make-before-break transfers from inverter mode in case of associated failures or short-circuit handling. Independent isolation transformers in every power conversion stage (including bypass) enables excellent de-coupling, floating DC-link with selectable working window for highest availability / safety and offers any voltage levels irrespective of given mains. Grounding schemes of output network can be selected based on the plant requirements including floating IT topology.

The following paragraphs elaborate two alternative technologies available for the rectifier sections while the inverter is assumed to be based on an IGBT bridge with PWM (Pulse Width Modulation) control scheme.

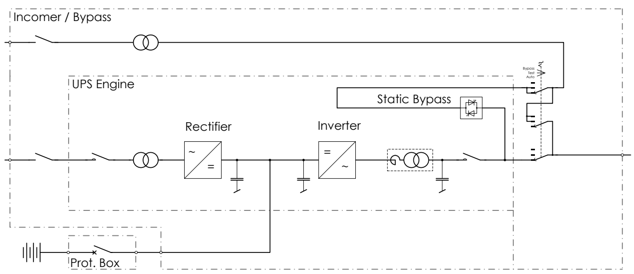

Fig. 1 Simplified Industrial UPS block diagram

III. THYRISTOR UPS-RECTIFIER

A. *6-Pulse Thyristor Rectifier*

Applying a 6- or 12-Pulse phase controlled thyristor power bridge is the traditional and well proven way converting 3-phase AC power to DC.

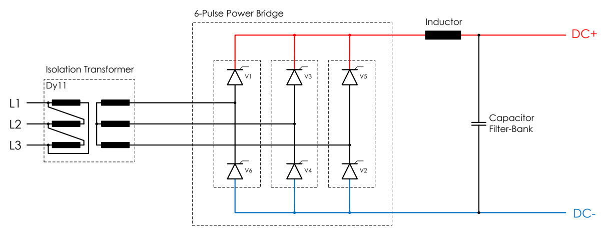

Fig. 2 Diagram of 6-Pulse Thyristor rectifier

Sinusoidal input voltage is adapted by a 3-phase isolation transformer based on the target maximum DC-level. Typical winding schemes are Dy11/ Dy1 giving 30° phase shift or Dd0 for in-phase output. Thyristors are fired pair-wise at calculated firing-angle depending on actual power request.

The pulsating output current is smoothened by means of the DC-inductor and capacitor filter. DC superimposed ripple voltage frequency is 6 x mains frequency (300Hz / 360Hz).

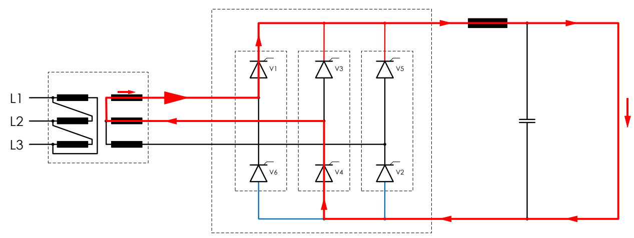

Fig. 3 Power Flow with fired Thyristors

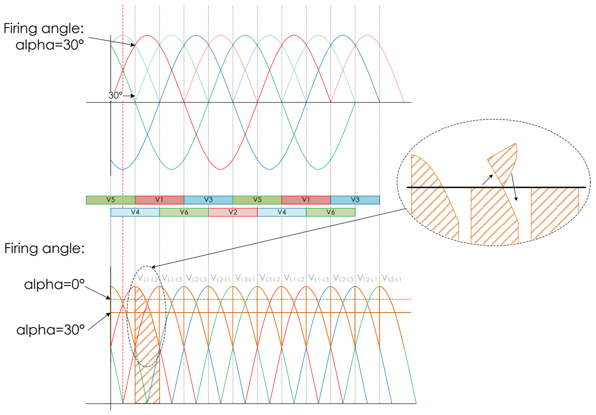

Fig. 4 6-Pulse phase controlled firing scheme

1) *Electrical Characteristics and key figures*: Input current wave shape is showing typical 6-Pulse pattern with harmonic contents around 28% of fundamental value. Input power factor (PF) depends on actual voltage levels at input and output but may not exceed 0.9 inductive in best case. Upstream power supply (especially dedicated diesel generators) must be oversized by a kVA-factor of 2.5 to 3.0 in order to cope with the injected harmonics and variable power factor.

2) *Input Current*: Fig. 5 illustrates the typical input current wave shape at robust supply capacity.

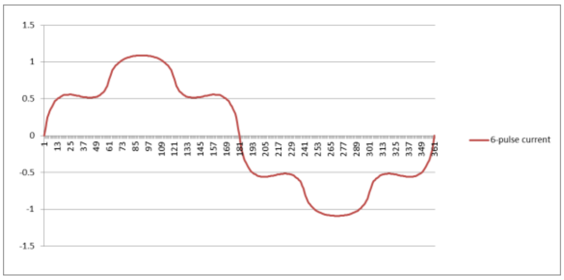

Fig. 5 6-Pulse input current snap-shot

B. *12-Pulse Thyristor Rectifier*

A 12-Pulse scheme comprising two 6-Pulse bridges is typically applied for higher current ratings or reduction of injected mains harmonics.

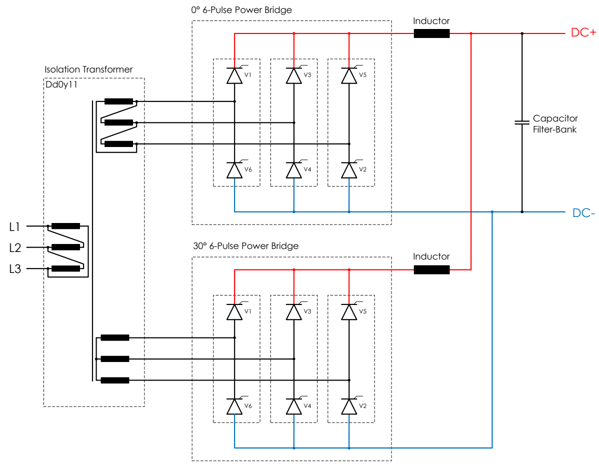

Fig. 6 Diagram of 12-Pulse Thyristor rectifier

Sinusoidal input voltage is adapted by a 3-phase isolation transformer based on the target maximum DC-level. Typical winding schemes are Dd0y11 / Dd0y1 giving two independent secondary circuits, one with 0°- and the other with 30° phase shift.

Each one of the two identical 6-Pulse thyristor bridges is connected to its dedicated transformer secondary windings whose output voltages are displaced by 30°. Thyristors are fired pair-wise at calculated firing-angle depending on actual power request. The pulsating output current of each bridge is smoothened by means of the DC-inductors and common capacitor filter. DC superimposed ripple voltage frequency is 12 x mains frequency (600Hz / 720Hz).

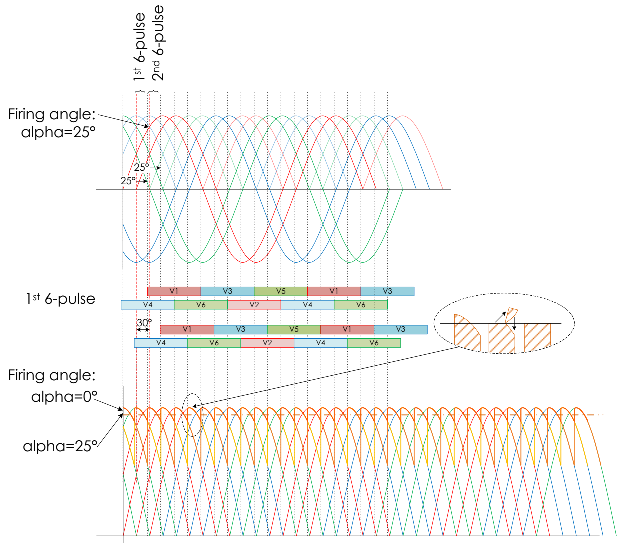

Fig. 7 12-Pulse phase controlled firing scheme

1) *Electrical Characteristics and key figures*: Input current wave shape is showing typical 12-Pulse pattern with harmonic contents around 12% of fundamental value. Input power factor (PF) depends on actual voltage levels at input and output but may not exceed 0.9 inductive in best case. Upstream power supply (especially dedicated diesel generators must be oversized by a kVA-factor of 1.5 to 2.0 in order to cope with the injected harmonics and variable power factor.

2) *Input Current*: Fig. 8 illustrates the typical input current wave shape at robust supply capacity.

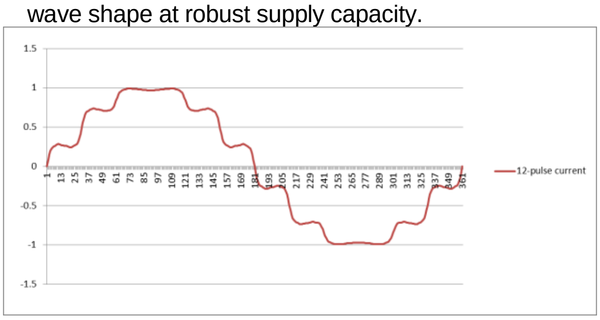

Fig. 8 12-Pulse input current snap-shot

IV. PFC IGBT RECTIFIER

A. Technology of PFC Boost Rectifier

Replacing thyristors with IGBT's enables the freedom to control the current flow irrespective of the mains frequency and associated phase zero-crossings. Switching frequencies in the kHz range are facilitated.

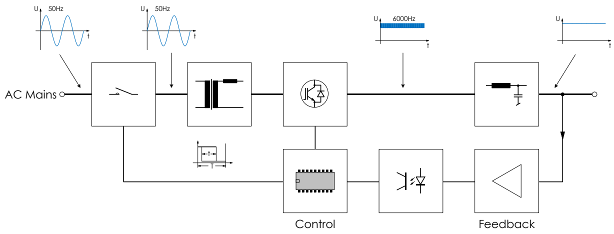

Fig. 9 Blockdiagram of PFC Boost Rectifier

Sinusoidal input voltage is adapted by a 3-phase isolation transformer based on the target minimum DC-level. Typical winding schemes are Yy0 or Dd0 giving in-phase output. IGBT's are switched at fixed frequency but variable pulse width (PWM modulation) as to keep the input current sinusoidal and in phase to the voltage (Power Factor Correction) while securing the target DC level at the output. The DC-Boost process is based on "charge-and-release" cycles of the transformer embedded inductor as illustrated in figure 10. The residual output ripple is smoothened by means of a capacitor filter. DC superimposed ripple voltage frequency is typically similar to the switching frequency (kHz).

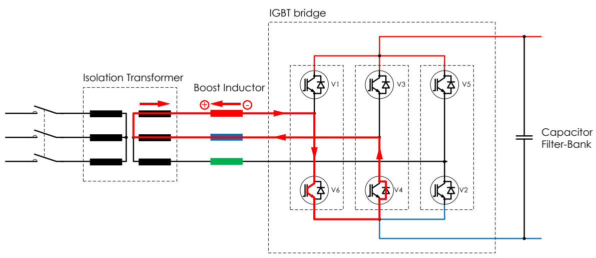

Fig. 10 PFC IGBT bridge illustration during charge process = Step 1.
Boost inductor is charged by closure of IGBT V6 and closed feedback through free-wheeling diode of V4.

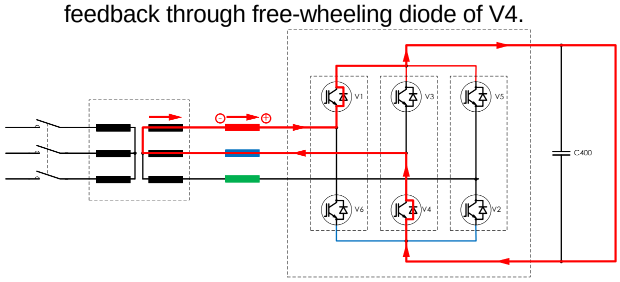

Fig. 11 PFC IGBT bridge illustration during discharge process = Step 2.
Boost inductor is discharged after opening of IGBT V6 through free-wheeling diodes of V1 and V4.

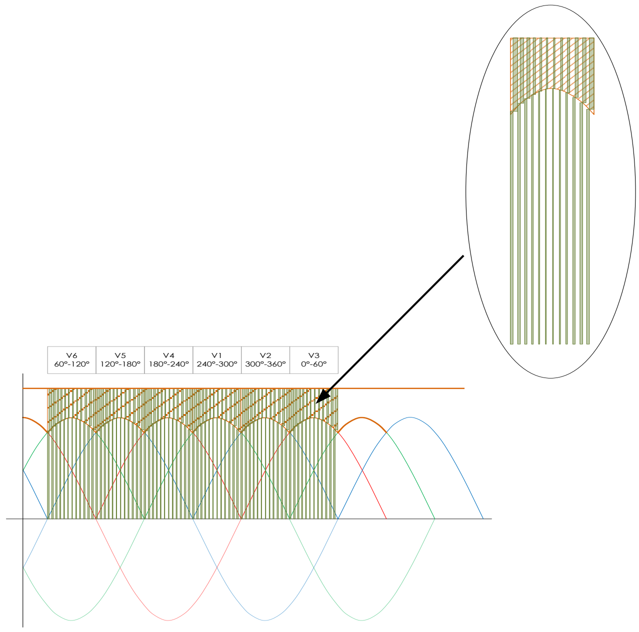

Fig. 12 Illustration of boost rectification process

B. Application in Industrial UPS Systems

The following section gives details on the typical application in Industrial UPS Systems:

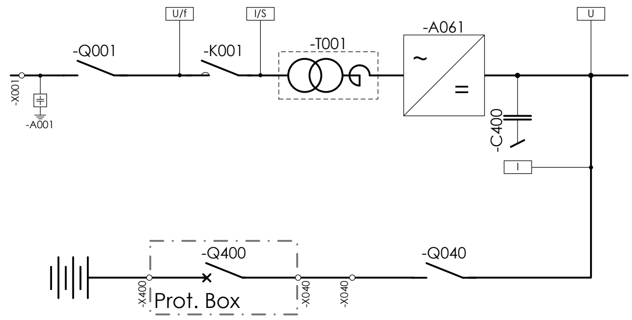

Fig. 13 Block diagram of UPS PFC rectifier

Input Power is routed via protection- / switching device Q001 to contactor K001. Internal DC pre-charger will gradually charge the DC link to nominal level automatically once the rectifier-on command is given. This enables K001 to close, input isolation transformer is energised and PFC rectifier bridge A061 will start delivering regulated DC power to the intermediate circuit including battery which can now be connected by closing Q400. Active battery current limitation assures a smooth recharge-process.

1) *Electrical Characteristics and key figures*: Input current wave shape is close to sinusoidal with harmonic contents less than 5% of fundamental value. Input power factor (PF) is actively corrected to >0.98 in a very wide load level range. Upstream power supply (especially dedicated diesel generators) must therefore not be oversized.

2) *Input Current*: Fig. 14 illustrates the typical input current wave shape at normal supply capacity.

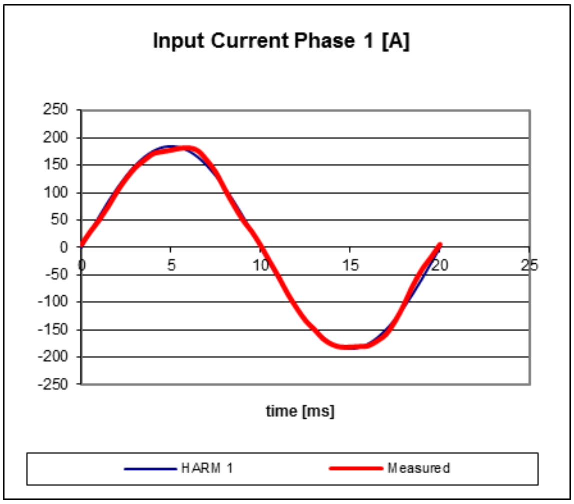

Fig. 14 PFC rectifier input current snap-shot

V. BI-DIRECTIONAL POWER CONVERTER

A IGBT PFC rectifier as outlined in chapter IV facilitates a bi-directional power flow enabling rectifier- and inverter function with the same hardware. Its key components are 1:1 in line with a true industrial 3-phase inverter:

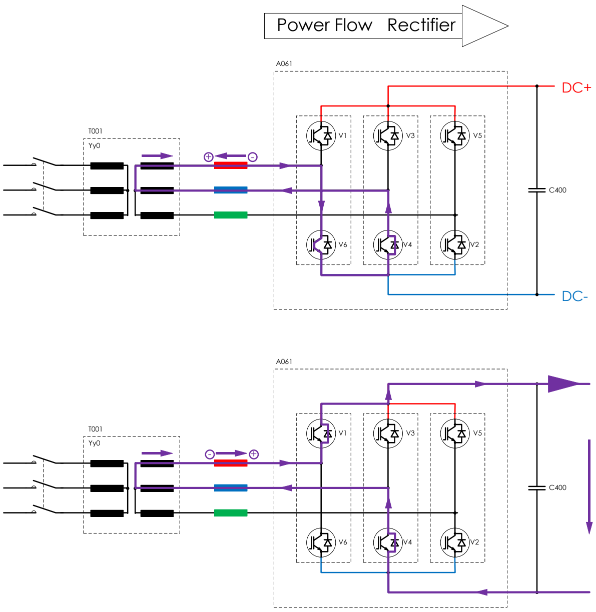

Fig. 15 Converter in Rectifier Mode

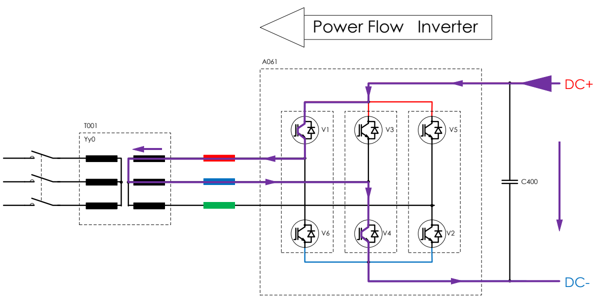

Fig. 16 Converter in Inverter Mode

This given bi-directional power converter topology can be controlled to feed-back sinusoidal power to the mains supply.

VI. UPS INTEGRATED BATTERY DISCHARGER

UPS batteries whose performance and availability is mission-critical require maintenance not only limited to visual inspection but also periodical discharge testing. Traditionally this requires connection of associated resistor load banks involving reasonable labour effort and wiring / switching activities. The captioned UPS system is typically not available for the critical loads during such testing.

Embedding a bi-directional power converter instead of thyristor rectifiers in industrial UPS systems gives the opportunity of a built-in active battery discharger based on constant current.

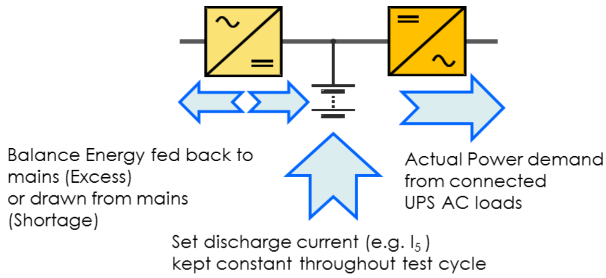

Fig. 17 Illustration of managed battery discharge-test

Battery testing process can be initiated / controlled typically over UPS HMI and / or connected computer with associated frontend allowing more elaborated testing parameters including download facility of test results incorporating discharge graphs for future reference. The actual UPS load is secured at any time hence does not need to be disconnected. Any irregularity (mains-failure, sudden loss of battery performance) will immediately interrupt a running test. Normal UPS mode is then re-instated immediately thanks to the excellent dynamic performance of the PFC rectifier.

VII. COMPARISON OF RECTIFIER TOPOLOGIES

The following table gives an overview on key technical disciplines which are of significance for an Industrial UPS environment:

Discipline:	Thyristor Rectifier:	IGBT PFC Rect.:
Control Scheme	Simple Analog or Digital	Complex Digital Processing
Input Current Harmonics THDI	6-Pulse: 27-30% 12-Pulse: 10-14%	< 5%
Input Power Factor	0.7-0.86 @ 100% 0.5-0.7 @ 50%	>0.98 10-100% load
Input Voltage Range	+/- 10% +/- 15% optional	+10/-15% +/- 15% optional
Inrush Current	6-10 x nominal	6- 10 x nominal with time delay
Soft Start	yes	yes, with auto-matic pre-charge
Galvanic Isolation	yes, with isolation-transformer	yes, with isolation-transformer

Efficiency	Typ. 92% @100% Typ. 77% @20%	Typ. 92% @100% Typ. 82% @20%
Nom. DC levels	110, 220, 400 V No centre tap	110, 220, 400V, 600 V No centre tap
DC Ripple	< 2% without battery connected	< 1% without battery connected
Dynamic Response	Poor, <500ms @100% load step	Good, <100ms @100% load step
Generator Oversizing	6-Pulse: 2.5–3.0 12-Pulse: 1.5–2.0	1.0-1.2

Table I Comparison of rectifier topologies

VIII. COST SAVING POTENTIAL

Introduction of IGBT PFC rectifier technology combined with a built-in constant current battery discharge feature by means of a bi-directional power converter (instead of a simple thyristor frontend) offers significant cost saving potential throughout the service life of the equipment.

Significant disciplines are evaluated in view of cost but also on human- and process safety.

A. Initial Equipment Investment

Thanks to the fact that power IGBT's are widely used in many modern power conversion equipment their cost is gradually decreasing with growing availability among reputed manufacturers. This in combination with state of the art powerful controllers does result in a similar equipment cost level compared to a traditional 12-Pulse thyristor rectifier frontend being compliant to an equivalent specification level.

B. Cost of UPS related Upstream Installation and Power Generation

Significant savings in the upstream supply scheme are accessible considering the following areas:

1) *Power Generation Equipment Size*: Upstream power capacity can be aligned to UPS nominal real input power (kW) due to power factor correction (PF>0.97). This typically translates in 20% lower input current compared to similar UPS size with thyristor rectifier. Generator oversizing (especially for dedicated Emergency Diesel Generators EDG) due to high harmonic currents and variable power factor is not applicable.

2) *Reduced conductor cross-sections for power wiring and associated switching- / protection devices:* Lower nominal current rating allows further cost savings on installation-, protection-, and power distribution gear.

3) *Harmonic voltage levels are kept very low:* Harmonic current feedback inducing voltage distortion in supply network is negligible. No additional upstream filtering is required due to connected UPS equipment.

C. Operation- and Maintenance Costs

With a predicted design-lifetime of 20 years it is obvious that the associated operation- and maintenance costs play an important factor in the overall consideration.

1) *Online battery performance assessment*: Automated periodical battery performance assessment by short duration predefined constant current discharge gives peace of mind in battery availability without any human intervention.

2) *No need to rent and connect dedicated load banks for battery testing during commissioning and scheduled maintenance:* Integrated battery discharge feature by means of bi-directional power converter facilitates constant current testing while UPS is still backing-up the critical loads. Simplicity of operation does not require high-level engineers nor any other special tools or equipment. Discharge Power is recycled rather than dissipated (=wasted) in hot air which may create limitations on air-conditioning due to excess heat in switch rooms. Overall turnaround time can be reduced significantly.

Furthermore it is important to state that highest personnel safety levels are assured by an integrated control scheme and the fact that no power wiring disconnection / reconnection is required for a complete UPS maintenance programme including full battery discharge testing.

IX. CONCLUSION

As of today PFC IGBT rectifier technology has a proven track record for power conversion equipment operated in harsh environments. The technical benefits compared to legacy thyristor topologies are obvious while still honouring stringent specifications for an Industrial UPS System with traditional DC levels and full galvanic isolation.

Additional features raise the value for invested capital while efforts for supply infrastructure are mitigated. Cost of ownership is reduced by facilitated operation and maintenance concept at outstanding safety and equipment availability levels.

X. VITAE

Matthias Dreier started his career in Industrial UPS / Power Electronics business in 1995 as Electrical Service Engineer for GUTOR Electronic LLC where he has progressed as Senior Field Engineer / Training Instructor, After Sales Service Manager, Engineering Competence and Expertise Manager and finally Technology Manager. 2010 he decided to join the Statron Group as Technology Director where he heads R&D, Tooling and Application Engineering.