High-Power Hybrid Shunt Compensator with Superconducting Magnetic Energy Storage

Andreas Steimel, *Senior Member, IEEE*, Leon David Voss

Ruhr-University Bochum
D-44780 Bochum
Tel: ++49 234 32 23890 Fax ++49 234 32 14597
e-mail: steimel@eele.rub.de

Siemens AG, A&D LD ID 1
D-90441 Nürnberg
Tel.: ++49 911 4336365 Fax ++49 911 4337363
e-mail: leon.voss@siemens.com

***Abstract* – A SMES presents an economic energy storage for short-term protection of sensitive high power loads from voltage sags and outages. It can be coupled to the protected load advantageously via a thyristor converter with controlled clamp valves, forming a shunt-connected UPS system. The principles of operation of the line-commutated interface converter and the requirements for UPS operation without the grid supplying the commutation non-active power are discussed. The concept has been verified by measurements on a 30-kW lab prototype, in which the SMES was modelled by a thyistor converter with appropriate control.**

***Index Terms* – Compensation, power quality, superconducting magnet energy storage, thyristor converters, uninterruptible power supplies**

I. INTRODUCTION

Quality and reliability of the voltage supplied to the customers by electric utilities – the so-called "power quality" – is an issue of increasing importance for all industrialised countries, watching e.g. the increase of large-scale disturbances. The number of voltage sags and outages due to protective clearing measures grows with increasing interconnection. While in former times power quality was guaranteed by the oligopolic, vertically-structured groups by keeping more or less ample reserves, nowadays with competition the suppliers are driven to reduce their assets and cut down redundancy. In a deregulated energy market the responsibilities for generation, transport and distribution are allotted to separated companies, so that the last link in the chain, the distributor, has no longer control of the generators anymore to compensate deficiencies.

The number of "critical loads" on the other hand is increasing with the complexity and automation of industrial processes. Customers are willing to pay for mitigation equipment. While in former times mainly data processing equipment in air fields, hospitals and government were protected by Uninterruptible Power Supplies (UPS) from the implications of power interruptions, there are more and more industrial processes of rather high power demand (in the Megawatt range) allowing no interruption of power delivery, as e.g. semiconductor plants or Internet provider facilities. For these applications the state-of-the-art battery-buffered UPS will prove to be insufficient. New approaches both in the energy storage system and in the grid interface system have to be examined.

II. SHUNT UPS TOPOLOGY

The higher the power demand, the less economical the so-called "on-line" UPS configuration will be, as the whole supported power has to be supplied by the converter system, with the consequence of high capital cost and high stand-by losses.

In these cases a so-called "off-line" or "shunt" UPS technology, as shown in Fig. 1, offers a significant improvement in efficiency.

Fig. 1. „Shunt" UPS topology

It consists of a static breaker for disconnecting the faulted network from the load and a parallel-connected converter (mainly voltage-sourced) with an energy storage system connected to the dc link. Under normal conditions the load is supplied via the electronic switch, stand-by inverter losses are avoided. To prevent overrating of the inverter the switch must have a very short disconnect time, to avoid "back-feeding" a fault of the short-circuit type, as the coupling inductance of the inverter should not be oversized either.

III. FAST ELECTRONIC AC SWITCH

In state-of-the-art "off-line" UPS systems the fast electronic switch is an antiparallel connection of thyristors, released in steady-state by a contactor. This means that the clearing time of the switch will in the order of several ten milliseconds. If as in our case a hybrid solution with a fairly low VSI rating is chosen, the demand on the detection and clearing speed is much higher; the total clearing time should not exceed two or three milliseconds. That is only possible with self-commutating semiconductor devices as Integrated Gate-Commutated Thyristors (IGCTs, [2]) or Insulated Gate Bipolar Transistors (IGBTs), mainly of the Injection-Enhanced type (IEGT, [3]). See Fig. 2.

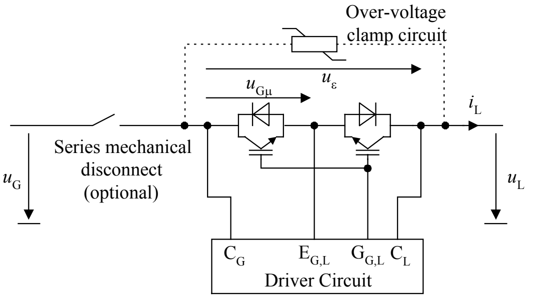

Fig. 2. Electronic switch for ac application with IGBTs

The fault detection scheme must be able to discriminate grid interruptions, grid shorts and transient disturbations produced e.g. by dynamic load changes or filter or transformer switching in the supported network. Such a system evaluating the admittance of the grid, with additional time-dependent blanking, has been developed and is described in detail in [4], [5].

IV. ENERGY STORAGE SYSTEMS

In general, the protection of sensitive loads from disturbances in the feeding ac network necessitates a source of stored energy. The classical UPS is typically supplied by a bank of lead-acid accumulators, which are still today the most cost-effective solution. Disadvantages for the application in voltage sag and outage compensation are the relatively low power density, as shown in the so-called Ragone Diagram (Fig. 3) displaying energy density vs. power density of different energy storage media. For typical fault durations of seconds the rated discharge time of several hours of the lead-acid accumulator is significantly oversized. In addition life-cycle costs are high due to high maintenance demand. Capacitors on the other hand have too low energy density, characterised by a discharge time of fractions of seconds. In the approached region of several seconds to minutes – necessary to start diesel-generator emergency units – flywheel and double-layer capacitor storages are nowadays already used in products of the railway industry to compensate the non-uniform power demand of traction vehicles, e.g. taking up recuperated brake energy in the substations. Both are restricted to powers in the sub-megawatt range. Superconducting Magnetic Energy Storage (SMES) systems offer very high power capability and in future high efficiency when high-temperature superconducting materials become available. SMES has already been discussed for utility application in the mid-70es [6].

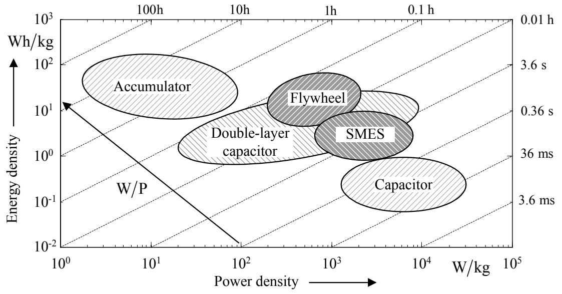

Fig. 3. Ragone diagram for energy storage media

The material exhibits zero resistance at low temperatures: For the initially available low-temperature (LTS) materials as Nb_3Ge the critical temperature is 23 K, necessitating cooling by liquid Helium (T= 4 K). In 1986 the so-called high-temperature (HTS) superconductors such as $HgBa_2Ca_2Cu_3O_x$ were discovered, having a critical temperature of about 132 K, for which liquid nitrogen cooling with significantly higher cooling system efficiency is sufficient. But fabricating compound conductors from which coils can be wound allowing energy storage is much more difficult for HTS materials, so that most SMES devices – in the range of up to 10 MVA/T_r ~ 1 s – are still of the LTS type [7], [8].

V. GRID INTERFACE CONVERTERS FOR SMES

In this section the issue of connecting the SMES – which is a storage of the constant-current type, in contrast to the other storage media exhibiting constant-voltage characteristics – shall be discussed.

All modern SMES-grid interface converters presented in the literature (e.g. [7], [8], except [4], [5]) use self-commutated voltage-source inverter (SC-VSC) technology, based on mass-produced IGBT inverters: First the SMES has to be coupled to the dc-link via a two-quadrant dc chopper; from the dc link the power is fed to the grid via a three-phase inverter (Fig. 4). The double power conversion produces considerable losses and is rather expensive.

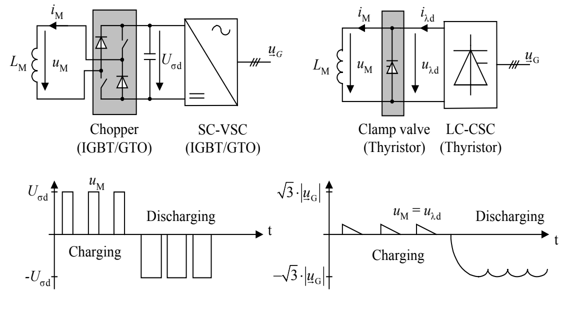

Fig. 4. Two possible SMES-grid interfaces

Line-commutated thyristor converters are inherently of the current-source type (LC-CSC) needing no extra dc chopper; they can be easily built up to powers of several hundred MW, as for HVDC applications. Thyristor converters are inexpensive and show considerably lower losses (e.g. for HVDCs the efficiency of an IGBT solution is about 97.5%, while that of a thyristor converter is up to 99.5 %). Another big advantage will be discussed later.

Two disadvantages of the line-commutated thyristor converter have to be taken into account: In case of the proposed application of an off-line UPS the commutating grid disappears in the fault case; so commutating nonactive power must be provided in form of capacitive filters and/or self-commutating IGBT inverters (of lower power). This will be discussed later in detail.

The second drawback is that in stand-by where the voltage across the SMES is zero a thyristor converter would normally be operated with a firing angle α of about 90^0, producing maximum nonactive power. This problem can be effectively solved by the feature of an additional clamp valve providing a free-wheeling path for the SMES current [9], a circuit well-known since the times of mercury-arc rectifiers, in German dubbed “Nullanode”.

When energy in the fault case is to be taken out of the SMES the converter operates in the inverter mode, and the clamp valve has to be a controlled one, a thyristor. As it is well known the range of action of the free-wheeling path will be the broader the smaller the pulse number p of the converter is. Let α_S be the control angle of the symmetrically-controlled line converter, the conduction range of the clamp valve will be

$$\alpha_{S\min} = \frac{\pi}{2} - \frac{\pi}{p} \leq \alpha_S \leq \alpha_{S\max} = \frac{\pi}{2} + \frac{\pi}{p} \qquad (1)$$

that is $30° \leq \alpha_S \leq 150°$ for $p = 3$ (three-phase midpoint rectifier M3CN) and only $60° \leq \alpha \leq 120°$ for $p = 6$ (three-phase bridge rectifier B6CN).

The pertaining reactive power vs. the active power of these two circuits, compared with the standard semicircular characteristic for symmetrical firing (M3C/B6C) is given in Fig. 5, under ideal conditions (relative short-circuit voltage $u_K = 0$ and thyristor hold-off time $t_q = 0$).

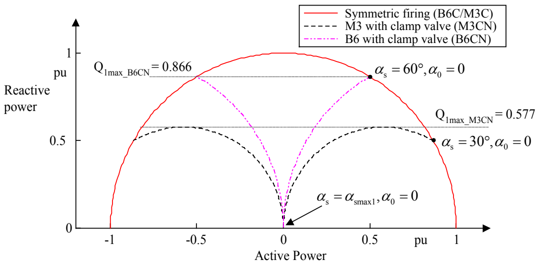

Fig. 5: Reactive power vs. active power for ideal thyristor converters with/ without clamp valves

The maximum reactive power is considerably smaller with the M3CN circuit. The minimal reactive power is reached if the thyristors are controlled subsequently in the following manner:

I. $0 < \alpha_S < 30^0$, α_0 no influence (≡ B6C!)
II. $30^0 \leq \alpha_S < 150^0$, $\alpha_0 = 0$
III. $\alpha_S = 150^0$, $0 \leq \alpha_0 \leq \alpha_{0\max} = 120^0$
IV. $150^0 \leq \alpha_S \leq 180^0$, firing of clamp thyristor blocked (≡ B6C!) (2a-d)

So two M3CN circuits have to be connected in series to obtain the common benefits of the bridge circuit, with the clamp valves connected to the transformer star point, instead of a B6CN circuit [10], to form a 2M3CN connection. The circuit diagram is given in Fig. 6.

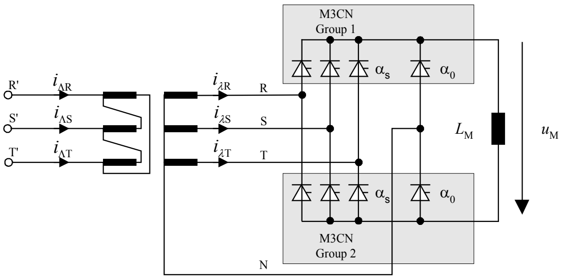

Fig. 6: Series connection of two M3CN converters

Fig. 7 shows the supply and the dc voltage as well as the thyristor and clamp valve currents in one M3CN group, for $\alpha_s = 90°$, the delay of the firing of the clamp valve $\alpha_0 = 15°$ and $u_K = 8\%$.

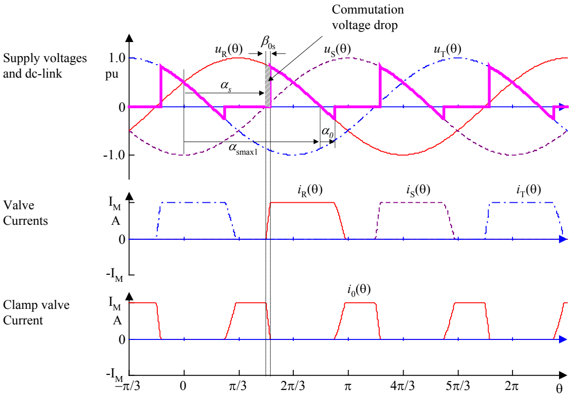

Fig. 7: Voltage and current waveforms of a M3CN thyristor converter with clamp valve.
$\alpha_s = 90°, \alpha_0 = 15°; u_K = 8\%$.

The average dc-link voltage of the 2M3CN converter is

$$\bar{u}_d = \frac{\sqrt{6}}{\pi} U_G \cdot \left[\cos\left(\alpha_S + \frac{\pi}{6}\right) + \cos\alpha_0 \right] - \frac{3}{2\pi} I_M X_K \quad (3)$$

with U_G the rms value of the grid line-to-line voltage, I_M the value of the dc-link (= SMES) current and X_K the commutation reactance.

The mentioned additional advantage over a VSI solution is that the SMES insulation requirements due to the lower dv/dt values of the converter voltage in the stand-by mode are strongly reduced, compared with a PWM dc chopper as can be seen in Fig. 4. This avoids high-frequency resonance oscillations stressing the insulation of the SMES.

The rms value of the fundamental of the line current (influence of commutation neglected) is:

$$I_1 = \frac{I_M}{\sqrt{2}\cdot\pi}\cdot\sqrt{2+\sqrt{3}\cdot\cos(\alpha_S-\alpha_0)-\sin(\alpha_S-\alpha_0)}\,. \tag{4}$$

Taking into account the influence of the commutation, the maximum allowable angle for the symmetrically controlled thyristors α_{Smax1} enters into the control laws (2a-d) instead of the value of 150^0 in II. And III:

$$\alpha_{\mathrm{S\,max\,1}} = \arccos\left[\frac{\sqrt{3}}{\sqrt{2}}\cdot\frac{X_K I_M}{U_G}-1\right]-\frac{\pi}{6} \tag{5}$$

while the maximum allowable angle for the clamp valve will be (instead of 120^0):

$$\alpha_{0\,\max} = \arccos\left[\frac{\sqrt{3}}{2}\cos\alpha_{\mathrm{S\,max\,1}}+\frac{1}{2}\sin\alpha_{\mathrm{S\,max\,1}}\right] \tag{6}$$

The active-reactive power characteristics for u_K = 8% and α_{Smax} = 128^0 are given in Fig. 8 for the analytical case and for a time-domain simulation, showing acceptable accuracy for inverter operation. Other control laws can be implemented as well, e.g. to produce a more constant reactive power in case of filters at the PCC with fixed capacitors, to avoid overcompensation.

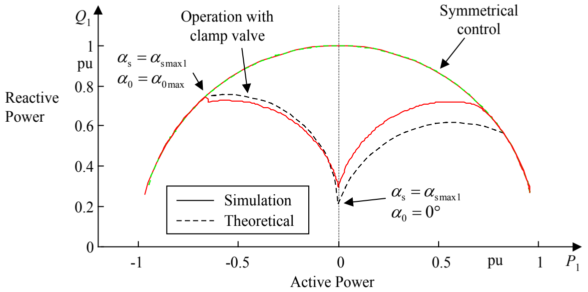

Fig. 8: Reactive vs. active power for a thyristor converter without and with clamp valve (u_K = 8%)

VI. LAB PROTOTYPE SYSTEM

To validate the theoretical considerations a laboratory prototype setup was developed, which is depicted in Fig. 9. The SMES is modelled by a thyristor converter with a rated current of 55 A and a smoothing inductor of 60 mH; by appropriate control an inductivity of 10 H, 50 H or 100 H can be emulated. With the rated grid line-to-line voltage of 400 V the rated power of the SMES interface inverter in the 2M3CN topology is 30 kVA.

The delta-wye coupling transformer is rated for 30 kVA, too, with u_K = 8%. Several simulations had shown that a reactive supply of 0.58 p.u. is required for proper commutation. This is divided into 0.23 p.u. of the fixed capacitors tuned to roughly the 3rd harmonic, to avoid parallel resonances with the grid, and the additional commutation capacitor C_λ at the input of the SMES converter with a rating of 0.35 p.u.

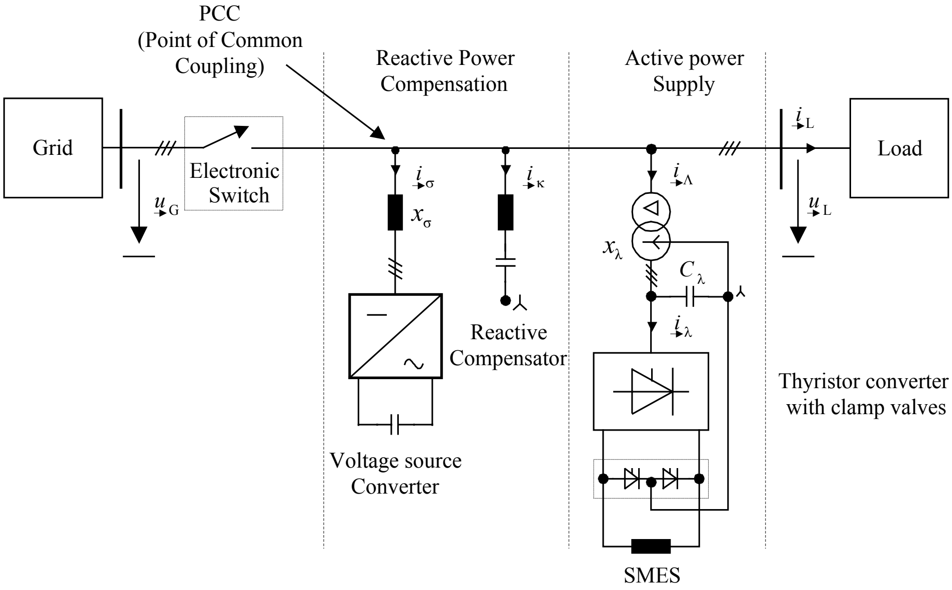

Fig. 9: Off-Line SMES-based UPS topology

TABLE I: Summary of component functionalities

Component	**Task under normal network conditions**	**Task under outage conditions**
Self-commutated voltage-sourced converter	• Current injection = 0 or inductive power compensation • Withstand line voltage	• Provide reactive current for line-commutated converter and load • Generate load voltage
Reactive compensation	• Provide capacitive non-active voltage support • Reduction of harmonic distortion (if necessary)	• Supply capacitive non-active power • Reduction of harmonic distortion (if necessary)
Electronic Switch	• Conducts load current and compensator no-load current	• Fast interruption of load current upon fault detection
SMES	• Absorb and store energy for compensation	• Supply load active power and compensator losses
SMES converter	• Current injection ≤ 5 %, covering SMES and own losses	• Provide full active load current

The IGBT-VSC covering only the variation from the mean reactive power was taken as available with 11.8 kVA and coupled via an inductance X_σ of 0.08 p.u. (in fact it is a LCL filter!). The electronic switch is made from two 100-A loss-optimised 1200-V IGBTs from Siemens/EuPEC, exhibiting 4 V voltage drop at rated current (diodes included!), corresponding to 2.54% losses based on the rated load. The fast fault detection clears clears in 1.8 ms. The load is a thyristor converter with inductive smoothing.

Table I gives an overview of the component functionalities of the realized compensator topology

VII. MEASUREMENTS

To verify the operation of the 2M3CN converter two measurements were performed without and with the additional commutation capacitor C_λ at the input of the converter with a capacitive rating of 0.35 p.u. (Fig.10). The SMES current is 55 A, the active power of the load was ca. 50% of rated load.

Without the commutation capacitor the maximum attainable control angle α_{Smax} was only 123.2^0 ($a_0 = 91.4^0$); the current at the primary of the interface transformer shows a staircase waveform, the notches in the secondary voltage u_λ are going down to zero, the notches in the primary voltage are clearly visible. The fundamental reactive power is 0.82 p.u. (= sin 123.2^0).

With commutation capacitors the maximum attainable control angle α_{Smax} was increased to 136.7^0 ($a_0 = 87.9^0$); the current at the primary of the interface transformer is nearly sinusoidal. There are practically no notches visible in the secondary or the primary voltage, the commutation mode is almost ideal. The reactive power is reduced to 0.35 p.u.,that is sin 136.7^0 minus the 0.35 p.u. delivered by the commutation capacitor. The use of C_λ can practically eliminate the need for further filters tuned to higher frequencies at the PCC. The control angles are guided to produce more reactive power, as mentioned above.

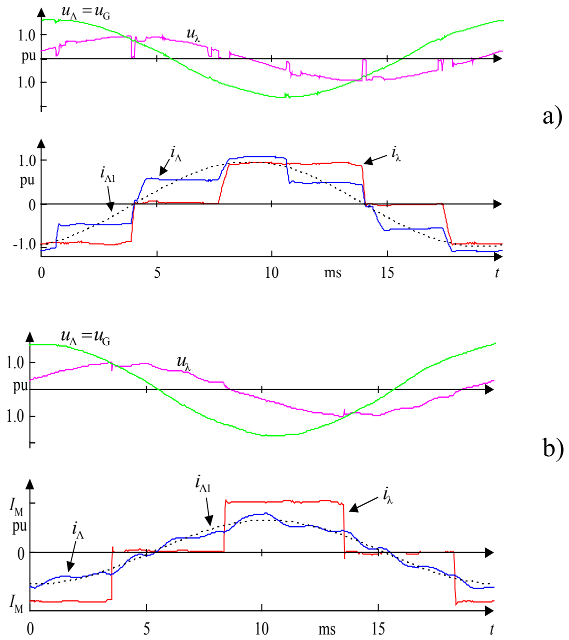

Fig: 10: Measured voltage and current waveforms of a 2M3CN thyristor converter with clamp valves

a) without comm. capacitors $\alpha_s = \alpha_{smax} = 123.2°$
$\alpha_0 = 91.4°$ $P_{\Lambda 1} = -0.51$ p.u. $Q_{\Lambda 1} = 0.82$ p.u.

b) with comm. capacitors $\alpha_s = \alpha_{smax} = 136.7°$
$\alpha_0 = 87.9°$ $P_{\Lambda 1} = -0.51$ p.u. $Q_{\Lambda 1} = 0.35$ p.u

Fig. 11 finally shows the performance of the compensator for the case that an outage was simulated by opening an upstream circuit breaker on the grid side of the electronic switch at $t = 150$ ms.

The active load was ca. 20 kW = 0.66 p.u. Upon successful detection of the fault after ca. 1.8 ms the IGBT switch opens instantaneously and the SMES is commanded to generate the pre-fault power of 20 kW.

Line (B) presents the load voltage maintained by the UPS system upon disconnection, line (D) the load current, while line (F) shows the VSC current and line (E) the SMES interface current

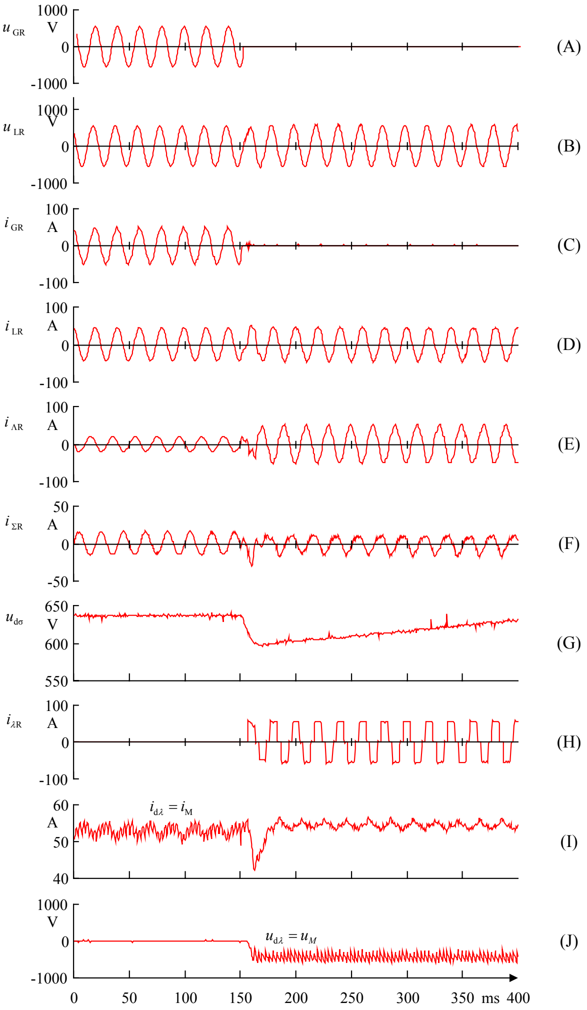

Fig. 11. Measurements of outage compensation with the 25-kW shunt UPS lab prototype

Line (G) gives the dc-link voltage of the VSC, it shows that the initial voltage dip is some 10%, and is recovered by dc-link control within 250 ms. This can easily be reduced by increasing the controller gain.

Line (H) represents the 2M3CN input current, starting within ~ 2 ms after outage occurrence and showing nearly ideal square-wave behavior.

Line (I) finally depicts the emulated SMES current, and line (J) the SMES voltage, which jumps from a totally smooth zero value in stand-by mode to some −540 V in regenerating mode.

VIII. CONCLUSIONS

After discussing the advantages of off-line or shunt UPS systems for protection of sensitive high-power loads from voltage sags and outages and selection of a SMES as energy storage the necessary interface components are described: The very fast IGBT switch separates the load from the faulting grid; to prevent back-feeding a grid short an extremely fast fault detection had to be developed. The energy from the SMES is fed into the load via a line-commutated thyristor converter with controlled clamp valves, reducing the reactive power in stand-by mode drastically. The commutation reactive power is supplied mainly by commutation capacitors of 0.35 p.u. at the input of the thyristor converter, a resonant filter at the PCC of 0.23 p.u and for regulation of reactive power an IGBT VSC rated at about 0.35 p.u.. Lab measurements with a 30-kW prototype (with a model of the SMES) demonstrate the proper functioning and the excellent dynamics of the proposed concept.

ACKNOWLEDGEMENTS

The authors kindly acknowledge the support of Prof. D. Povh and Dr. M. Weinhold, Siemens AG, Power Transmission and Distribution Systems.

REFERENCES

[1] Gyugyi, L.; Strycula, E.C.: Active AC Power Filters “, IAS Journal, Vol. 19-C, 1976, pp. 529–535

[2] Stillman, H. M.: IGCTs – Megawatt-Halbleiter-schalter für den Mittelspannungsbereich, *ABB Technik*, 1997, pp.12–17

[3] Murakami, K.; Matsumura, H.; Yamano, N.; Tchouangue, G.: Development in 4.5-kV press-pack IEGT for high power electronics applications, *PCIM*, Nuremberg, 2001

[4] Voss, L.D.; Steimel, A.; Lürick, R.: Transient performance and design issues for a parallel-connected voltage sag and outage compensator. *8. EPE Conf.*, Lausanne 1999

[5] Voss, L. D.: High-efficiency parallel-connected power electronic compensators for protection of sensitive loads from voltage sags and outages. Dissertation Ruhr-University Bochum, 2002; Fortschritt-Berichte VDI Rh. 21, Nr. 330, Düsseldorf 2002.

[6] Boom, R.W.; Peterson, H. A.: Superconductive Energy Storage for Power Systems. *IEEE Trans. On Magnetics*, Vol.8, 1972, pp.701–703

[7] Jüngst, K.-P.; Salbert, H.; Simon, O.: SMES compensator for fluctuating loads. *15th Intern. Conf. On Magnet Technology*, Beijing 1997

[8] Doht, H.-C.; Hilscher, M.; Prescher, K.; Unterlass, F.-J.: Design and behaviour of a superconducting energy management system (SEMS) for industrial power quality applications. *8. EPE Conf.*, Lausanne 1999

[9] Möltgen, G.: Converter Engineering – An intro-duction to operation and theory. J. Wiley and Sons, 1984.

[10] Zimmermann, P.: Über- und untersynchrone Stromrichterkaskade als schneller Regelantrieb. Dissertation TH Darmstadt, 1979