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Author(s):

Josef B. Schillig, Heinrich J. Boenig,
James A. Ferner, Manfred K. Quissek,
Ferenc Bogdan, Gerhard O. Linhofer,
Markus Eichler, Gerhard Kasper, Richard
P. Marek, Jeffrey R. Martin

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Design and Testing of a 320 MW Pulsed Power Supply

Josef B. Schillig^a, Heinrich J. Boenig^a, James A. Ferner^b, Manfred K. Quissek^c, Ferenc Bogdan^d, Gerhard O. Linhofer^e, Markus Eichler^e, Gerhard Kasper^e, Richard P. Marek^f, Jeffrey R. Martin^g

^aLos Alamos National Laboratory, MS E536, Los Alamos, NM 87545, ^bNational High Magnetic Field Laboratory, Tallahassee, FL 32310, ^cQ Group Inc., Oconomowoc, WI 53066 (formerly with ^d)

^dABB Industrial Systems Inc., New Berlin, WI 53151, ^eABB Industrie AG, CH-5300 Turgi, Switzerland,

^fABB T&D, Dry Type Transformers, Bland, VA 24315, ^gBechtel Nevada Corp., Las Vegas, NV 89193

Abstract - For a 60 Tesla, 100 millisecond long pulse magnet five 64 MW (87.6 MVA) power converter modules have been installed. Each module provides a no-load voltage of 4.18 kV and a full load voltage of 3.20 kV at the rated current of 20 kA. The modules are connected to a 1430 MVA / 650 MJ inertial energy storage generator set, which is operated at 21 kV and frequencies between 60 and 42 Hz. They are designed to provide the rated power output for 2 seconds once every hour. Each module consists of two 21 kV / 3.1 kV cast coil transformers and two 6-pulse rectifiers connected in parallel without an interphase reactor, forming a 12-pulse converter module. As far as possible standard high power industrial converter components were used, operated closer to their allowable limits. The converters are controlled by three programmable high speed controllers. In this paper the design of the pulsed converters, including control and special considerations for protection schemes with the converters supplying a mutually coupled magnet system, is detailed. Test results of the converters driving an ohmic-inductive load for 2 seconds at 20 kA and 3.2 kV are presented.

I. INTRODUCTION

In early 1991 the newly formed Long Pulse Magnet Group of the National High Magnetic Field Laboratory at Los Alamos National Laboratory was chartered to design a high-field, long-pulse magnet which would provide the scientific users with a field of 60 T for up to 100 ms in a 48 mm bore. Los Alamos National Laboratory had just installed and commissioned a 1430 MVA / 650 MJ inertial energy storage generator set [1], which could easily provide the anticipated power and energy for this project. For many years the University of Amsterdam operated the worlds only high-field, long-pulse magnet operating at 40 T (100ms / 21 mm bore). Capacitor bank

driven magnets, about 150 mm in diameter and height, reach 50 T in 24 mm bores, 60 T in bores of 15 mm and up to 7 T in bores of 10 mm, but only for a few milliseconds. Early design work on the 60 T magnet, which is cooled to liquid nitrogen temperature (77 K) prior to each pulse to take advantage of the considerably increased conductivity and the improved resistivity to heat capacity ratio, showed that for mechanical reasons the magnet had to be built of multiple nested coils, each consisting of a high strength copper winding (GLIDCOP, 500 MPa to 600 MPa yield strength) and a high strength steel reinforcement shell (NITRONIC 40, 1.0 GPa yield strength). This nesting of mechanically independent coils not only drastically improved the cool-down time of the magnet, but also allowed the radial current density distribution in the magnet to be tailored to take full advantage of the mechanical properties of the materials used throughout the magnet and thus to minimize the overall size of the magnet, the key to reducing the peak power and energy required to reasonable levels. However, the power and energy levels needed to power a 60 T / 100 ms / 48 mm magnet were considerably higher than anticipated, based on scaling up from the Amsterdam magnet. Even though these levels were well within the capabilities of the generator set, the estimated cost for the power supplies was well beyond the budget available. As a consequence the bore size of the magnet was reduced to 32 mm. This smaller magnet design would still have an outer diameter of about 900 mm and would be about 100 mm high. The peak power needed to energize the magnet would reach about 250 MW peak and the energy stored in the magnetic field at 60 T would reach about 90 MJ, with about the same amount of energy being dissipated during a pulse by resistive losses in the conductor material.

Tailoring the current density implied, that the small, inner "high" current density coils could be energized for short periods of time only (about 200 ms), whereas the large, outer "low" current density coils could be energized for up to seconds. This, together with the goal to keep the maximum voltage in any part of the magnet below about 10 kV, led to a preliminary design in which the magnet was subdivided into coils, grouped into 3 galvanically independent but magnetically coupled coil groups. Each group consists of

several series connected coils energized by its designated power supply. The power supplies would be energized using the 1430 MVA / 650 MJ inertial energy storage generator set, which can deliver power at voltages up to 24 kV, currents up to 34.4 kA and frequencies from 60 to 42 Hz [2].

II. Power Supply Design

As the introduction suggests, designing a power supply system for a magnet of this size and complexity is quite involved. The magnet design, which is pushing existing technology to its limits, is the driving part in the design process for the overall system.

A. General Considerations

The power supplies have to accommodate the needs of the magnet design as closely and as cheaply as possible.

The main features expected of the power supply design were:

- Modular design
 - high flexibility for the magnet design
 - easy future expansion
 - minimal design effort
 - simple manufacturing
 - simple operation and maintenance
 - minimal spare parts inventory
- Series or parallel operation of modules should be possible
- State of the art designs and components
- Use of standard, proven technology
- Minimal component count
- Compact design
- Ease of operation
- Good controllability under variable frequency conditions
- Capability of operating over a wide input voltage range
- Minimal current ripple
- Flexible, high speed control and protection system

The preliminary magnet designs indicated that we would operate the different coil groups at voltages ranging from about 2.5 kV to about 10 kV, currents ranging from 15 kA to 20 kA and pulse durations (ramp-up, flat-top, ramp-down) for a nominal pulse ranging from about 250 ms for the small inner coil groups and up to 2 s for the large outer coil groups. To achieve minimal current ripple and good controllability, given the frequency range from 60 to 42 Hz determined by the normal pulse speed range of the 4-pole generator set (1800 to 1260 rpm), the modules had to be at least 12-pulse converters. Typical thyristors used in industry at the time had diameters of 75 to 100 mm, voltage ratings (V_{DRM}) of 5 to 6 kV and average current ratings (I_{TAV}) ranging from about 1.6 kA, for the smaller diameter and higher voltage devices, to about 3.3 kA for larger diameter and slightly lower voltage devices. Considering the typical voltage safety margin of about 2.5 required for this type of thyristor operation, a converter module with a 4 kV no-load voltage consisting of one or multiple parallel 12-pulse converter strings, made of two series connected 2 kV rectifier bridges, with a current rating of

20 kA for 2 seconds, seemed to be reasonable choice. The 20 kA / 2 s rating could be achieved by either multiple parallel fused thyristors in each rectifier branch of a single 12-pulse kV converter string, or multiple parallel 12-pulse 4 kV converter strings with only one thyristor in each rectifier branch, or combinations of these two versions. We estimate a need for either 2 to 3 parallel 100 mm devices or about 4 to 6 parallel 75 mm devices to meet this rating. The maximum I^2t anticipated for the big outer coil group would require about 1 to 1.3 s rating. With future, bigger magnets in mind we decided for a 2 second rating. Tailoring the allowable pulse duration of the modules to better match the shorter pulse durations of the smaller coil groups would not significantly reduce neither the component count nor the cost.

Basic design considerations, such as short-circuit currents at transformer size, and cost considerations required us to allow for about a 20 % voltage drop at rated current, i.e. a full load voltage of about 3.2 kV. These basic module ratings were confirmed in discussions with potential vendors.

With these basic determinations about the power supply system the magnet design could be finalized. The final magnet design now consists of 9 coils, grouped into three electrical circuits. Figure 1 shows a section of the magnet which at this time is being prepared for commissioning.

Fig. 1. Section of the 60 T / 100 ms magnet

Figures 2 through 5 show typical plots for the expected magnetic field as well as for the power supply voltage, current and power versus time during a nominal 60 T pulse. The 60 T / 100 ms magnet facility, and thus power supply system has to be capable of producing a wide variety of different field patterns (ramps, multiple steps etc.) within the limitations of the magnet, the power supplies and the generator set. Pulse patterns of up to 20 seconds duration have to be possible. Parallel with the initial magnet design the power supply design specifications were developed. Table 1 summarizes some of the main power supply requirements. We received bids from four potential vendors.

Fig. 2. Magnetic field versus time

Fig. 3. Coil group current versus time

Fig. 4. Coil group voltage versus time

Fig. 5. Active power versus time

Figure 6 shows the basic overall layout of the 60T / 100m magnet facility and the power supply modules. Each power converter module is supplied with 21 kV from the 1430 MV. / 650 MJ energy storage generator. At the synchronous speed (1800 rpm) of the 4-pole rotor 1260 MJ are stored in the shaft. The generator can release up to half of this energy during a load pulse, which would result in a final speed of about 1260 rpm. The generator, which is designed for 24 kV can maintain a 21 kV terminal voltage down to 1500 rpm. Below this speed the flux limitation (105 %) forces frequency proportional reduction of the generator terminal voltage and thus of the maximum converter output voltage.

TABLE I
BASIC POWER SUPPLY DATA

Number of modules	5
Converter pulse number	12
Rated module output current	≥ 20 kA
No-load module output voltage	≥ 4 kV

Powered by an infinite power grid:

Full-load module output voltage	≥ 3.2 kV
Inverter mode module output voltage	≤ -3.0 kV

Powered by the generator, all modules operating at rated power:

Full-load module output voltage	≥ 3.0 kV
Inverter mode module output voltage	≤ -2.8 kV

Pulse duration at full current	2 s
Pulse duration at full voltage	20 s
Frequency range	66 - 42 Hz
Voltage range	21 - 8.3 kV

(with appropriately reduced maximum allowable current)

Possible series connection of modules up to 4
(grounded at center point, i.e. ± 8 kV)

Fig. 6. Overall layout of the 60 T / 100 ms magnet facility and power supply one-line diagram

Designing the converters for a 21 kV instead of a 24 kV input voltage allowed us to obtain full power output down to 1500 rpm, meaning that we can extract 385 MJ of the 650 MJ of available pulse energy at full rating of the converters. The modules are designed to operate over the full, extended pulse speed range of the generator, i.e. from 66 Hz to 42 Hz. They can also be operated at voltages down to about 8.3 kV with accordingly reduced maximum output current. Each 12-pulse power supply consists of two, pulse rated 43.8 MVA, 21 kV to 3.1 kV step-down transformers, one in a delta-delta and the other in a delta-wye configuration. The transformers, each with an equivalent steady-state rating of 4.38 MVA, are of the cast coil type, ideal for indoor installation. The two 6-pulse rectifiers of the 12-pulse converters are connected in parallel without an interphase reactor. The "high" impedance of the transformers (30 % based on 43.8 MVA) allows for the direct parallel connection without excessive circulating currents as compared to the rated pulse current. Each module provides also an internal crowbar function, which in case of a crowbar request uses the thyristors of one of the phases of each 6-pulse rectifier as designated freewheel path. This is a protective function for the magnet, which allows for a natural L/R decay of the magnets magnetic field in case of power supply or magnet problems. In addition, a crowbar request also triggers the external, mechanical high speed crowbar switches

associated with each coil group, which close within about 1 to 15 ms, shorting the coil group terminals. The reversing switches allow the polarity of the magnetic field to be changed as needed.

B. TRANSFORMERS

The transformers are based on the manufacturers standard cast coil type product line. They are designed for an equivalent steady state rating of 2×4.38 MVA combined with a low nominal short circuit impedance of 3 % (based on the 4.3 MVA rating), which, compared to standard units ($x_T = 5$ to 1 %), considerably increases the short circuit loads. The unit would be regularly operated at the 2×4.38 MVA pulse-power level for up to 2 s at the time, i.e. at 30 % of the high short circuit current level.

The transformers were originally conceived as a three column two tier design, where the delta-delta and the delta-wye coil systems are mounted, one above the other, on a three column core to provide for a very compact layout. The prototype design did not pass the specified sudden short-circuit tests due to problems with the coil clamping and bracing. After analyzing the results and the design, the manufacturer opted to go with two separate transformers, one for the delta-delta and one for the delta-wye group which slightly reduced the

compactness of the original layout. Considerable effort was spent on analyzing the forces on the coils, which resulted in:

1) replacement of the original wire wound secondary winding with a foil wound winding, which considerably reduced the axial forces.

2) tighter manufacturing tolerances.

3) considerably stronger axial clamping and an improved radial bracing system for the coils.

This final design, with an of $x_T \approx 2.6\%$ to 2.7% (4.38 MVA base), passed the sudden short circuit tests (6 tests at 21 kV) without any signs of damage, deformation or displacement. Standard electrical tests performed before and after these tests indicated no change or deterioration due to the tests.

C. Rectifiers

In contrast to our initial layout ideas, an alternative design approach with two parallel 4.04 kV, 10 kA, 6-pulse bridges forming a 12-pulse rectifier with a no-load voltage of 4.18 kV and a full-load current of 20 kA was proposed. Each leg of the rectifier bridges consists of two series connected 94 mm thyristors ($V_{DRM} = 5.2$ kV, $I_{TAV} = 3.0$ kA for a 120° square wave at 70 °C). This approach eliminated the need for parallel thyristors and thus the need for fuses, an element which is quite difficult to dimension for the specified pulse operation. The parallel connection of the two 6-pulse rectifier bridges is done without an interphase reactor. The maximum expected circulating current will be about 4 to 5 kA_{pp} at $\alpha = 90^\circ$ and full voltage and 50 Hz (i.e. maximum flux), which results in an about ± 20 to 25% fluctuation of the 6-pulse bridge current at rated module current of 20 kA, which is still acceptable. The junction temperature rise during a 20 kA / 2 s pulse, under worst case conditions (12 kA / 8 kA current sharing), was calculated to be about 80 °C, resulting in a worst case junction temperature of about 110 °C, based on 30 °C case temperature. The actual temperature rise is more likely to be about 60 to 70 °C.

The rectifiers shown in Fig. 7 are built using the standard VERISTACK system design, a widely used high power, water-cooled rectifier system, designed for static VAR compensation applications [3]. The thyristors are triggered via a fiber optic system with the power for the trigger pulses derived from the forward blocking voltage of each semiconductor device. The converter design also includes the previously mentioned integrated crowbar feature. If a condition requiring a crowbar operation occurs, the controls fire the thyristors of the designated phase in each bridge continually (up to 120 ms) and block the firing of all other thyristors. The dc-current commutates into the designated crowbar path. This required the thyristors to be designed not only for the I^2t of a full pulse, but also for the additional I^2t of a crowbar operation. The crowbar operation envelope was defined as an exponentially decaying current with an initial amplitude of 25 kA and a time constant of 3 s. Calculations made, assuming proper converter function, showed that the junction temperature would reach a maximum of about 240 °C, which is about 60 °C below the maximum allowable junction temperature when no blocking is required. Because

the load breaker will at this time have disconnected the generator from the power supplies, there is no need for an blocking capability.

Fig. 7. View of power supply modules

Several fault scenarios were also analyzed. One scenario is failure to block (shoot through) occurring at the end of nominal 20 kA / 2 s pulse, the other is a thyristor fault i. one of the phases which is not part of the designated crowbar path, at the end of a nominal pulse. In the first case the peak current will reach about 47 kA at 60 Hz and about 55 kA at 50 Hz. This leaves the thyristors right at their blocking limit. In the second scenario the thyristor of the designated crowbar phase located on the same side of the bridge as the faulted thyristor will, together with the faulted thyristor form a short circuit which remains until the load breaker opens. In this case the I^2t of both thyristors increases rapidly and reaches values at which the thyristor casings break or even explode. Tests on several samples, specially prepared for these tests with edge faults, were performed. The initial peak current reached about 70 kA with a dc component time constant of about 45 ms. The test durations were up to 120 ms long, depositing I^2t 's of over $100 \cdot 10^6$ A²s, and showed that, while the casings cracked after about the first cycle, there was no explosion and the thyristors retained their mechanical integrity in the clamping direction.

These tests showed that most likely the thyristor column will remain intact in case of such a fault and thus could provide proper magnet protection. It was nevertheless decided to implement the following two measures. First we decided to modify the 5-cycle SF₆ load breaker to include an additional 3-cycle trip which would be initiated with any crowbar command. This would reduce the maximum interruption time from about 100 ms to about 70 ms and thus considerably reduce the potentially accumulated I^2t (from about $80 \cdot 10^6$ A² down to about $60 \cdot 10^6$ A²s). Further it was decided to include external, mechanical high-speed closing-switches across the terminals of each coil group, respectively across each power supply. The latter measure drastically reduces the thermal loading of the thyristors in the designated crowbar phases and increases the reliability of this protection function. It also allows us to consider the use of the crowbar function not only

as a protection means but also as an operation means to provide users with smooth, exponentially decaying magnetic fields without unduly stressing the thyristors.

III. Control and Protection

Each group of converters is controlled by a digital, programmable high speed controller (PHSC) combined with communication, I/O, signalization and thyristor firing control boards [4]. These three, highly flexible, RISC-processor based controller systems, which use a proprietary architecture, perform all supervisory control and protection tasks as well as the current feedback control for each coil group to have the coil currents follow the predetermined current patterns. The whole control process is organized in tasks with different interrupt priority. The highest priority tasks are generating the interpolated current setpoint and other values, reading and filtering of all analog inputs and the feedback control algorithms. All these are executed once every 500 μ s. The next lower priority tasks are fast protection routines (evaluated once during every 1 ms interval), followed by supervisory control and slow protection functions (every 5ms), and finally the lowest priority operations such as cooling pump control, push-buttons, panel indicators and pattern download related functions (every 10 ms).

A programmable logic controller "PLC" is used to perform higher level supervisory control functions for all the power supplies, and to provide all controls for reversing switches, crowbar switches, magnet related systems, safety and access control related functions and to interface with the three PLCs controlling the generator facility operations. The whole facility can either be operated manually, with the operator individually controlling each system, giving all the necessary commands to run a pulse, or automatically, where the operator only has to enter the desired pattern number, field polarity and waiting speed after the pulse. A sequence control logic, running on an additional, dedicated PLC, then issues all the commands necessary for the whole facility to produce the desired pulse pattern and to return to the waiting speed.

A magnet pulse is essentially defined by three current patterns. Pulse patterns are created using simulations and results from trial runs. These current setpoint and control parameter patterns are then entered in a PC based spreadsheet as a set of 200 targets, each target consisting of:

- Time stamp
- Current
- Upper voltage limit
- Lower voltage limit
- Estimated voltage needed
- Proportional gain
- Integrator time constant
- Control word to control:
 - Integrator reset and block
 - Operational crowbar close command
 - Pulse end flag

Prior to a pulse the pattern for each group is downloaded to the three controllers memory. During a pulse the processor then linearly interpolate between two subsequent target points, with a 1 ms discretization, to generate the actual current setpoint for the current controller, i.e. a pattern with up to 199 "linear" segments and a 1 ms resolution. The control parameters are needed to run the pattern with the necessary speed, accuracy and control. This setup allows for high flexibility in the operation and tuning of the control response and accuracy. Fig. 8 shows a possible structure of the control loop. The PHSCs are programmed using a proprietary function block style programming interface (FUPLA), a very flexible programming and debugging tool.

Fig. 8 Simplified current control block diagram

The processor based power supply protection consists of primary protection functions (ac-side overcurrent, dc-side overcurrent, differential current between ac-side and dc-side differential current between series connected modules etc.) and secondary protection functions (excessive deviation from the current setpoint pattern, adjustable overcurrent used for tailoring the protection level to the needs of the magnet, excessive I^2t , etc.). These protection functions are backed by a hard wired protection system consisting of ac-side overcurrent relays and hardware based dc-side overcurrent and overvoltage protection functions.

The power supplies are designed to survive the severe faults in the system and most importantly to provide maximum possible protection for the magnet. If a magnet section short across its terminals a crowbar command is issued, blocking the firing of all thyristors but the ones of the designated crowbar legs and triggering the crowbar switches. The thyristor crowbar guarantees fast crowbar action while the mechanical crowbar provides for reliable long term shorting of the magnet coil groups. The voltage drop across the switch is considerably smaller than the forward voltage drop across the free-wheeling thyristors and the drop along the cable connecting power supplies and magnet. Therefore the free wheeling dc-current readily transfers from the internal thyristor crowbar legs into the external crowbar switches. Should a crowbar switch fail, the thyristors of the free-wheeling path

can assume the full crowbar current of 25 kA with a decay time constant of 3 s at the end of a full 20 kA / 2s pulse without damage. Should a crowbar switch inadvertently close during a pulse, a very serious condition, a crowbar command is issued immediately terminating the pulse and shorting the other coil groups as well. A single coil group shorted by its crowbar, with the other coil groups still operating normally, would already at moderate currents destroy the magnet.

Low impedance faults on the 24 kV bus or on the converter transformer primary side are interrupted by a fast, current limiting, explosively triggered fuse system (I_S -Limiter) installed at the generator terminals [5]. This device limits the fault current in any fault to less than 100 kA and interrupts the current within one half to one cycle. Higher impedance primary side faults and secondary converter side short circuits, with the short circuit current limited by the transformer impedance, are interrupted by a 72 kV, 40 kA, 5 cycle, SF_6 puffer-type power circuit breaker. To prevent overvoltage conditions and possible breaker failure when opening the load breaker with non-zero dc-side currents (high dc-side inductances), any breaker opening command under non-zero voltage or current conditions is accompanied by a crowbar command to the converters. This is why crowbar and trip commands are designed to trigger the crowbar functions of all three coil groups simultaneously.

IV. Power Supply Testing

A total of seven power supply modules are installed and tested at Los Alamos. The first five modules are fully installed and are ready to power the 60 T / 100ms magnet. The additional two modules are partially installed and are, together with the above mentioned five modules, intended to power the four coil sets of the roughly 50 T outsert magnet of the 100 T short pulse magnet with a total maximum available power of 448 MW (613 MVA). The 100 T magnet is currently being designed and uses an about 50 T capacitor bank driven insert magnet to reach 100 T for several milliseconds.

Once installed, each converter module was subject to extensive testing. Starting with general protection and wiring system tests we then first checked the transformer phasing and the thyristor firing using a temporary 480 V feed and a 500 W "lamp" load. Then, the first three modules were tested using a temporary 13.4 kV power feed connected directly to the incoming generator facility switchyard feed, using a "dummy" load. The "dummy" load is shown in Fig. 9 and consists of a 192 MJ resistor bank which can be adjusted for resistance values ranging from 8.3 m Ω to 4.8 Ω and a series connected set of coils forming a 2.2 mH inductor. At first the resistor bank was set at high resistance values to limit the maximum possible current. Gradually the resistance values were lowered to about 1 Ω . This allowed for tests with currents up to 1300 A and provided a good tool to check the basic functionality of the modules and its controls without having to operate the generator. As part of these tests the circulating current between the two parallel, 30°-shifted bridges of a module was measured (see Fig.10). The circulating current agreed well with the results of a simulation using the Electro

Fig. 9. View of the "dummy" load with the resistor bank on the left and the inductor on the right side

Magnetic Transient Program (EMTP). The 13.4 kV tests of the remaining four modules were done using the generator operating at an initial speed of 1400 rpm. After the 13.4 kV tests all modules were individually tested with the generator operating at 21 kV and initial speeds ranging from 1600 to 1800 rpm (initial frequencies of 53.3 to 60.0 Hz). The resistance of the dummy load was gradually lowered to 1 Ω to allow for almost full power pulses at rated current. The pulse pattern usually used for these tests was 100 ms ramp-up, 1800 ms flat-top, and 100 ms ramp-down waveform shown in Fig. 11 and Fig. 12. To verify that the specific output voltage could be obtained at rated current the "dummy" load was adjusted to 140 m Ω cold, which resulted in an about 165 m Ω resistance at the end of a two second pulse. At 2 kA a maximum voltage of about 3.25 kV could be reached corresponding to 65 MW at the load.

Fig. 10. Bridge voltage and bridge, rectifier and circulating currents during a 13.4 kV test

Fig. 11. DC-current during a full power pulse with a single module

Fig. 12. Current setpoint and ac-current during a full power pulse with a single module

All modules were subject to several consecutive nominal pulses with the specified cool-down time of one hour between pulses. All modules passed these tests without any signs of overloading or deterioration. No temperature ratcheting effects could be observed. As a final test the two modules for coil group 2 were connected in series. So were those for coil group 3, forming 8.36 / 6.40 kV, 20 kA rectifiers. For the tests on group 3 the dummy load was set at 300 m Ω making for an about 120 MW peak load. This pulse was limited to 1 second (see Fig. 13). The rectifier group performed to our full satisfaction. During the one second pulse the speed of the about 240 ton generator shaft train dropped by about 100 rpm. For group 2 the load was left at 133 m Ω , limiting the power to about 53.2 MW and the pulse duration was thus set at 2

seconds. The lower resistance was a more demanding test for the control system and more representative of the actual control situation found when feeding a magnet. The control system in general works fine and provides the high flexibility we expected. The dc-current measurement which uses a flux nulling principle seems, in case of one of the transducer type used, susceptible to stray fields and, in case of the other type somewhat slow. These issues are being worked on. We also ran a variety of simple and more complex pulse patterns to test the performance of the controls and the overall pattern definition and download logic.

Fig. 13. Current setpoint and dc-current during a full power pulse with two series connected modules

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