Programmable Power Supply for MST'S Poloidal Field

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Abstract— **We are designing a new programmable poloidal field power supply for the MST reversed-field pinch. By providing flexible waveform control, the new supply will expand capabilities in oscillating field current drive, inductive current profile control, and other inductive techniques. The new power supply will allow use of the full flux swing of MST's poloidal transformer core without a separate core bias supply and its isolating inductor. It will also eliminate the risk of harmful surge currents due to core saturation on unplanned termination of the plasma discharge. Used together with the newly-installed toroidal field programmable power supply, the new poloidal supply will allow maximum use of MST's inductive capabilities.**

The existing toroidal field programmable supply is based on series-parallel high-power IGBT H-bridges and has an output of about 40 MVA. The poloidal supply will also use high-power IGBTs and will provide about 120 MVA capability. The supply will drive the existing poloidal primary windings, connected with a 10:1 turns ratio. H-bridges will be series-connected in groups of three to yield up to +/- 2700 V output; these groups will then be connected in parallel to allow output currents up to +/- 80 kA.

The power supply units are modular, enabling future expansion for more output capability, and are based on low-inductance laminated heavy copper buses. Waveform generation will be controlled using seven-level Pulse Width Modulation, to reduce IGBT heating and minimize output distortion and noise generation. Overall control of the new poloidal supply will be via General Atomics' Plasma Control System.

Keywords-MST; RFP; power supply; IGBT; PWM

I. INTRODUCTION AND MOTIVATION FOR BP PPS

The MST reversed-field pinch has been operated from its beginning with essentially the same poloidal field power supply. There are now strong motivations for increased plasma current, increased pulse length, and flexible waveform control. All three are possible on MST with programmable power supplies. A programmable supply to control the toroidal field (BT PPS) has recently been installed and has provided a new level of BT control and flexibility. A similar enhancement of control and flexibility in the poloidal field control is needed to achieve the above goals. This will be provided by the poloidal field programmable power supply (BP PPS).

One motivation for higher current on MST is illustrated by recent experiments with Pulsed Poloidal Current Drive (PPCD) at a toroidal current of about 0.5 MA, approaching the upper limit with the present poloidal supply. Electron temperature, ion temperature, and confinement times during PPCD have reached record RFP levels in these experiments, and are seen to improve as the current is increased. In addition to allowing higher currents, the new BP PPS will allow programming various waveforms to optimize PPCD, something that cannot be done with the present supply even at lower currents.

Oscillating Field Current Drive (OFCD) experiments on MST have demonstrated an increase in the plasma current, with the generated current still increasing at the time the plasma discharge begins to decay (Fig. 1). The new BP PPS will allow a longer discharge flat-top, allowing a better evaluation of the maximum current contributed by OFCD. Precise waveform control may also improve OFCD results.

With the existing poloidal field supply, operation at high current entails risk of damage to MST. With the present (ignitron-based) supply, if the plasma discharge terminates prematurely, there is no way to turn off the supply. Without the plasma load, the BP transformer saturates and the current through the transformer primary rises to dangerous levels. Fig. 2 shows an example of such an early termination. The BP PPS will operate in controlled-current mode, so that its output current will remain at a safe value even if the poloidal transformer core saturates.
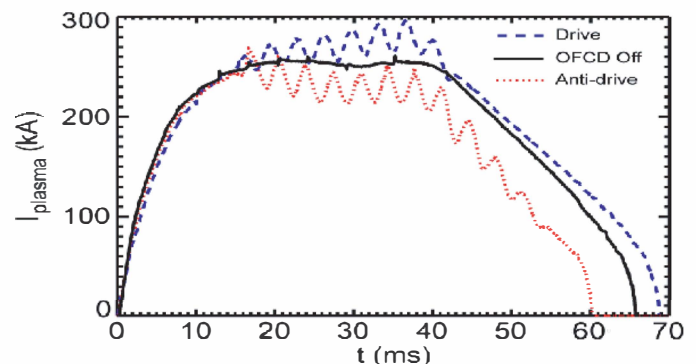

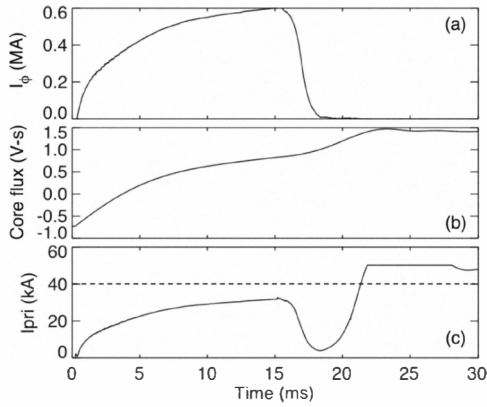Figure 1.   Plasma current waveform during Oscillating Field Current Drive on MST.

Figure 2. Effect of premature termination of MST discharge. Top: plasma current; center: BP core flux, showing core saturation; bottom: BP transformer primary current. For the bottom trace, the digitizer saturates at 50 kA; actual saturated core primary current is higher than value shown.

II.   MST's BT PPS

Experience gained in building and operating the recently commissioned BT PPS will be used in building the larger and more powerful BP PPS, which will be based on similar technology.

The BT PPS (Fig. 3) consists of 32 H-bridge modules using high-power Insulated gate Bipolar Transistors (IGBTs). Each module is powered by a bank of 450 V electrolytic capacitors connected in series to form a 0.13 F, 900 V bank; the capacitors are charged through relays which are open during an MST shot. Typical power supply pulse duration is 120 msec. Two H-bridge modules form a series pair to give +/- 1800 V output. Sixteen of these series pairs are connected in parallel to the BT transformer primary to yield a transformer primary current up to 25 kA (Fig. 4). Each series pair of H-bridges connects to the transformer through a flexible quad cable of about 15 m length. Capacitor shorting bars and relays, charging relays, and voltage monitors are shared between groups of modules, with diodes providing isolation.
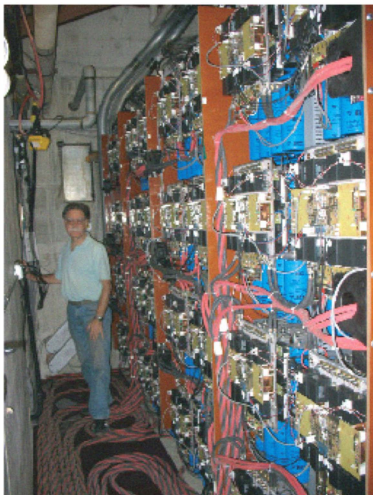

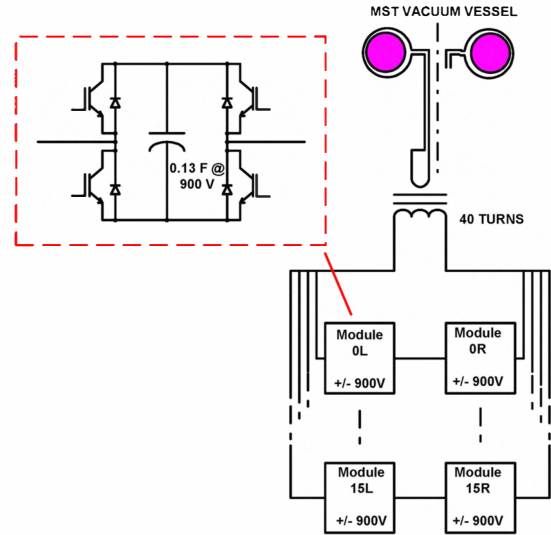Figure 3.   MST's BT Programmable Power Supply.

Figure 4.   Block diagram of MST's BT Programmable Power Supply.

The H-bridges are built on custom-made laminated heavy copper boards. The electrolytic capacitor banks have parallel-plate bus construction to minimize inductance; together with film capacitors mounted to the copper boards, this provides a low-inductance power supply connection to minimize voltage overshoot during turnoff of the IGBTs or plasma termination.

All H-bridges are switched together, giving three output voltage states (+1800 V, 0V, -1800V.) Three-level Pulse Width Modulation (PWM) with a carrier frequency of 5 kHz generates the desired analog toroidal field waveform.

The BT transformer windings can be connected at ratios of 20:1, 40:1, and 80:1. The windings are arranged so as to balance capacitance to ground; this minimizes noise from capacitive ground currents and minimizes voltage stress on the IGBT gate drivers.

III.   OVERVIEW OF BP PPS

The maximum current and voltage (single-turn values) demanded from the BT PPS are approximately 750 kA and 250 V. The poloidal field is generated using the existing 40-turn iron-core BP transformer, which has windings grouped in four sets of 10 turns.

Fig. 5 shows the topology of the new BP PPS. Triplets of H-bridge modules in series generate an output of +/- 2500 V; a total of 32 such triplets yields a total primary current of 75 kA. Note that this requires more current per module than the BT PPS. The higher output voltage also requires better isolation between the modules and ground.
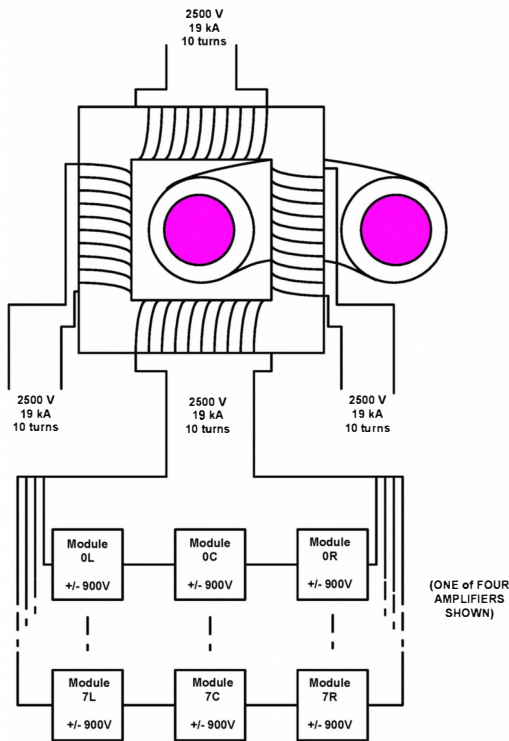
Figure 5.   Block diagram of MST's BP Programmable Power Supply

IV. ISOLATED MODULAR CONSTRUCTION

A goal in designing the BP PPS is to minimize the number and length of interconnect cables between modules, especially cables carrying high frequencies at high voltage. In addition the BP modules operate at higher voltage than the BT modules and thus need better isolation from ground.
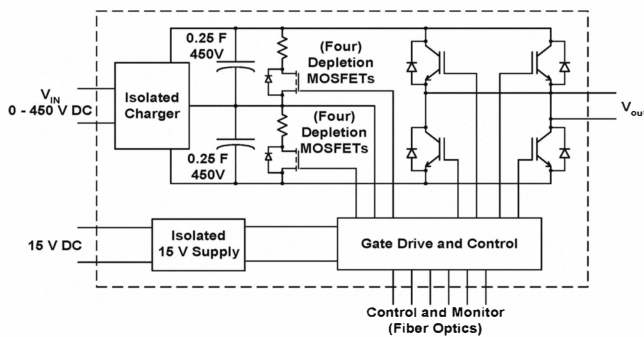

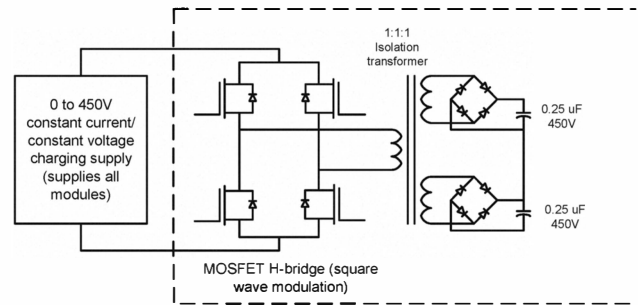Figure 6.   Isolated Module for BP PPS.

Figure 7.   Transformer-coupled charging system for BT PPS module.

The control and gate driver boards for the BP PPS modules are referenced to the center point of the module capacitor banks (Fig. 6). All control and monitor signals for the modules are carried via fiber optics. A simple ferrite core transformer-based power supply operating at about 20 kHz provides isolation; prototype transformers showed a capacitance from primary to secondary of only 7 pF.

A similar ferrite core transformer system can be used to charge each module's capacitor banks (Fig. 7). Operation at 100 kHz allows a compact charging transformer with a small number of turns to ease construction. A prototype of this charging system has a total transformer primary-to-secondary capacitance of 14 pF. Each module has its own low-capacitance transformer charging system; charging cables and power cables to the modules carry only dc. The low-capacitance coupling transformers eliminate the need for charging relays.

Each module has its own set of shorting resistors to safely discharge the module's capacitor bank. Depletion mode MOSFET switches of suitable ratings [1] are now available for use as "shorting bars". These can be controlled from the control and gate driver boards using gate drive transformers which thus need withstand a continuous voltage of no more than 450 V. A commercial MOSFET gate driver with Undervoltage Lockout controls the shorting MOSFETS; when power to the gate board is removed, the depletion-mode MOSFETs switch to the conducting state and discharge the capacitor banks through the module's shorting resistors.

V. SEVEN-LEVEL PWM

Each of the three modules of a series triplet can be controlled independently; if the module voltages are all the same, this gives a total of seven output voltage states. Any of various seven-level PWM schemes [2] can be used to control the output current. While seven-level PWM is slightly more complex than the three-level PWM used in the BT PPS, it has advantages that recommend it for use in the BP PPS.

Fig. 8 top shows waveforms from a low-voltage prototype system using three-level PWM. All three modules of a triplet switch together; if each module voltage is V and the PWM carrier frequency is f, the triplet output is a rectangular
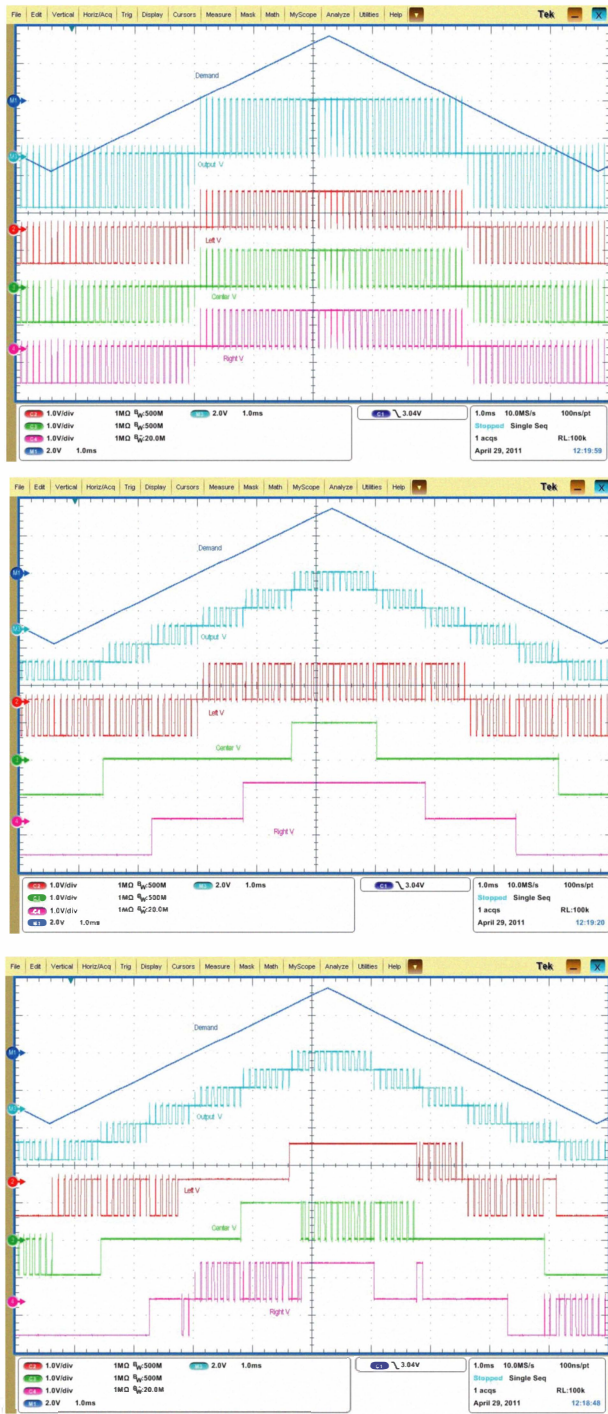
Figure 8. Low-voltage prototype waveforms for three-level PWM (top); seven-level PWM (center); and seven-level PWM with shared switching. For each plot, the traces are, top to bottom: (1) demand waveform; (2) system output voltage; (3) left H-bridge voltage; (4) center H-bridge voltage; and (5) right H-bridge voltage.

waveform of voltage 3*V with a fundamental frequency of 2f. Each IGBT switches at the carrier frequency f.

Fig. 8 center shows the same system using a seven-level PWM algorithm. If the demand waveform is slowly-varying, only one module in the triplet switches at the carrier frequency; the other modules switch only when the output must cross a major voltage threshold. Thus the output switching waveform transitions are of voltage V: the switching noise and output ripple are reduced to a third of those for the three-level PWM system. The two modules that switch infrequently have greatly reduced switching losses.

Fig. 8 bottom shows the system with a seven-level PWM algorithm in which the carrier frequency PWM switching is rotated among the three modules of a triplet. For slowly-varying demand waveforms, the average switching frequency for each IGBT is only slightly greater than one third that of the same system using three-level PWM, while the output voltage ripple and voltage noise are reduced to about a third of the system with three-level PWM.

In our application, IGBT lifetime is limited by temperature rise per pulse. Since switching losses contribute strongly to this temperature rise, a system using seven-level PWM has an advantage over a similar system using three-level PWM. The seven-level PWM system can put out significantly more current than the three-level system with the same IGBT heating and lifetime. Manufacturers' data sheets indicate that the modules can put out about 1.5 times more current using seven-level PWM than they can using three-level PWM, at the same time generating significantly lower switching noise and output ripple.

VI. CONCLUSIONS

The BP PPS will give MST significant new capabilities and will reduce the danger of damage to MST during high-current operation. Based on modules similar to those in the recently-installed BT PPS, the new supply will make use of new features such as isolated modular construction and seven-level PWM control to improve performance and reduce cost.

REFERENCES

[1] For example, IXYS IXTP6N100D2 MOSFETS are N-channel depletion mode MOSFETS with a breakdown voltage rating of 1000 V and a 6 A continuous current rating.

[2] D. Graham Holmes and Thomas A. Lipo, Pulse Width Modulation for Power Converters, Piscataway, NJ: IEEE Press, 2003.