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OFF-LINE INVERTER MAGNET POWER SUPPLY

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A high current, intermediate power, off-line inverter power supply has been developed for use with high inductance magnet loads. Two banks of paralleled switching transistors directly invert the rectified line at 5-10 KHz into the power transformer primary. Paralleled center-tapped secondaries are full-wave rectified directly into the inductive load. The primary switches are pulse-width modulated to provide the full range of output current. Regulation is $1:10^4$, with long-term stability about $2:10^4$. The control circuitry is highly noise immune. Protection for the semiconductors is provided by an over-current sensor which terminates the drive signal to the switches quickly enough to protect against all faults, including output short-circuits. The magnet is protected against over-voltage by the inherent free-wheeling operation of the secondary diodes. Electrical efficiency is greater than 80% over the entire current range, and the supply is extremely small and light weight. A triple unit, consisting of three water cooled 2.5 KVA supplies, measures 5 X 7 X 17 inches and weighs 30 lbs. Other units have been built with power to 4.5 KVA at 150 amperes.

Introduction

The efficient electrical design of an intermediate-power (requiring liquid cooling) beam transport magnet generally dictates the use of large cross-section conductors and low resistance coils. This, in turn, necessitates the use of large and expensive cabling to the power supply. Generally the magnet is located in a position where, due to the necessity for radiation shielding, space is expensive. In addition, the virgin beam transport line is a fertile environment in which parasitic equipment proliferates with extreme rapidity. Space is thus a premium and, with conventional power supplies which require large primary power transformers and bulky output filtering, the supplies must be located remote from the magnet. The cost of cabling and its installation thus becomes a significant factor in the over-all cost of the magnet system.

A major consideration in the development of the cost-optimized magnet system, therefore, is a small, light-weight power supply which can be mounted at, or in close proximity to, the magnet, eliminating the necessity for long cable runs. A further requirement, which has taken on more importance recently, is the maintenance of high electrical efficiency for the complete system over the broad range of operating currents necessary for various beams and beam conditions.

The high-frequency off-line inverter is an ideal solution in that the power transformer components can be extremely small and light weight. For the high inversion frequency, the high inductance magnet serves as the major component of the output filter.

In the past few years, with the vast television market as an incentive, there has been a rapid advance in the development of high voltage-high current switching transistors, capable of switching 10-20 amperes at up to 700 volts. Coincidentally, has been the development of fast, high current rectifiers which operate with extremely low stored junction charge.

The equipment described here is an application of these devices to the generation of high current dc power, as required for the operation of low resistance-high inductance electromagnets.

Power Circuit

The basic power circuit of the unit (Figure 3) is relatively straight forward. The three-phase line voltage is rectified directly and applied across a capacitor divider. One side of the power transformer primary is connected to the center tap of the divider, and the other alternately switched plus and minus by the power switching transistor banks. The power transformer secondaries (normally consisting of two or three separate center-tapped windings) are full-wave rectified directly into the inductive load.

In operation, the primary is driven only a portion of the total cycle, during which the corresponding secondary rectifier bank conducts. The primary switches are then turned off, and both banks of secondary rectifiers conduct as free-wheeling diodes for the inductive magnet load. During this portion of the cycle, the current decays according to the magnet time-constant and, since the free-wheeling current in the secondaries flows equally in opposite directions from the center-tap, the net core excitation is zero. The power primary is then switched in the opposite direction, for the second half cycle.

In this configuration, the capacitor divider serves to balance the system, as described below.

The magnet current level and its regulation is accomplished by adjustment and modulation of the conduction period of the switching transistors.

The drivers for the switching transistors are located on the control circuit board, and alternately excite opposite sides of the center-tapped driver transformer. The two separate secondaries of this transformer, (shunted with a base resistor) are applied directly to the emitter-base busses of the paralleled transistors. Excitation of one side of the center-tapped primary drives one switching bank, and the opposite side the other bank. This arrangement is ideal, in that the non-conducting switches are biased negative during the drive period. However, the driver circuitry must be carefully designed to eliminate transformer over-shoot on turn-off, thus driving both banks simultaneously.

The switching transistors used in these supplies are highly efficient. Although the β's are low, on the order of 1.5, the ratio of base power to switched power is high, up to 400. In this application the collector-emitter drop is of the order of 1% of the collector voltage. In switching this power the devices are, however, subject to the second-breakdown phenomena, and in design of the circuit extreme care must be exercised in the establishment of acceptable current-voltage conditions during the transition. There are a large number of these devices now available, whose switching characteristics are sufficiently different that they are not interchangeable.

The devices are driven well into saturation during the conduction period and the base must be cleared before the transition can commence. Subsequent to the base clearance, the junction must dissipate the energy stored in the power transformer leakage reactance during the turn off. In these power supplies, the transistor losses are dominated by this effect, and the low-leakage power transformer was a major design problem. The transformers used are ferrite torroids with close-spaced symmetrical windings, operated in the low μ region, so that the field is well contained.

Figure 4 shows the drive and collector currents for a supply operating at about 75% duty factor (5.5 kc switching frequency I_c = 12.5 amp and I_b = 8 amp for four paralleled Delco DTS-802 transistors). The 10 μsec clearance time subsequent to the termination of drive, is evident. After base clearance, the turn-off is accomplished in approximately 3 μsec. It should be noted that the summed currents for the paralleled transistors is displayed. The devices are self-balancing, both in clearance and turn-off, so that matching within a bank is not required. The figures shown are for off-the-shelf units.

Although the drive circuitry is arranged so that symmetry is inherent, the opposite banks of transistors are not identical, particularly with regard to base clearance time. Normally this effect would result in a net dc component in the transformer, which would result in eventual saturation of the core in one direction. In this circuit, the capacitor divider eliminates the dc component, and maintains the core in balance. Slight asymmetries in the secondary rectifiers can result is some core unbalance during the free-wheeling period, but this effect is small, and a reasonable matching of the rectifiers will suffice.

Figure 5 shows the transformer primary current in, and the voltage variation of, the capacitor divider center-tap. The mean center-tap voltage self-adjusts so that the peak currents through opposite banks are asymmetrical, to accommodate the asymmetrical conduction period; and the net charge is symmetrical.

Driver-Regulator

The control circuitry (Figure 3) consists of a master oscillator which generates the inversion frequency and also serves as a pulse-width limiter, to assure that drive signals to the opposite banks of switching transistors cannot over-lap. The power supply current shunt signal is compared to the reference signal from the control panel potentiometer in a differential amplifier. The output of the amplifier adjusts the bias on a pulse-width modulator, the output of which is applied alternately, through a flip-flop steered dual gate, to opposite sides of the center-tapped drive-transformer primary.

The gate is a dual quad-input, one of which is alternately enabled on opposite sides by the signal from the steering flip-flop. The other inputs (applied to both sides) are 1) the limited-width master oscillator pulse, 2) the modulated width pulse from the comparator, and 3) an enable signal indicating that the external interlock conditions are satisfied, and that the conditions of the protective circuitry, described below, are satisfied.

With this system, and with a magnet load with a time constant of 0.5 sec, regulation is to about $5:10^5$. The long term current stability is about 1:5000, determined primarily by un-compensated thermal junctions throughout the system. The regulation is stable against line variations of ± 10%, load variations of ± 10% and cooling water inlet temperature of ± 5°C. With reasonable care in the maintenance of thermal stability of the various junctions and components, it is estimated that the stability can be increased by about a factor of 5.

Protective Circuitry

In this inverter, the full line voltage appears across the two switching transistor banks in series. Inadvertent (noise induced) simultaneous conduction of the banks can result in the destruction of the switches and the line rectifier.

The junctions can withstand surge currents on the order of 10 times the operating current and, if the surge is restricted so that the junction does not heat inordinately, removal of the drive can terminate the current without second breakdown occuring. Protection against simultaneous conduction can, therefore, be provided if the over-current can be detected and drive terminated in a sufficiently short period.

For the supplies described here, a single sense transformer coupled to the junction of the two banks at the power transformer primary is used to measure the current in the same sense in both banks. The output of the transformer is fed to a Schmitt-trigger, the trip point of which is adjusted slightly above the normal operating level. With this device, over-currents are detected within 0.3 μsec. The Schmitt-trigger output flips a bistable flip-flop which removes the "protection" enable from the driver gates, clamps the pulse-width generator to zero width, and removes power from the driver transistors. The drive current is terminated within 0.7 μsec after the Schmitt-trigger trip level is exceeded.

This circuitry is fast enough to protect the supplies against any fault resulting in over-current. Under test, the output of supplies operating at full power have been short-circuited hundreds of times without adverse affect to the semiconductors. The supplies are extremely tolerant of abuse.

Subsequent to an over-current event, a manual reset is required before the supplies can be returned to operation.

The switches are also subject to thermal runaway due to second breakdown at elevated temperatures, and efficient cooling is mandatory. To protect against overheating due to interruption of the water flow (flow-switch failure) a thermistor temperature sensor is included. If the heat-sink temperature exceeds the safe value, the supplies are rendered inoperative in the same manner as for an over-current event.

The supplies are also provided with interlock circuitry which require the satisfaction of external conditions (magnet cooling water, etc.) before the power supply can be operated.

Electrical Efficiency

For these supplies, which are designed for relative low impedance loads, the power losses are dominated by the secondary rectifier junction drop (approximately 1 volt). Other losses include the line rectifier, the switching transistors and their drive system, the power transformer, and the current monitoring shunt resistor.

The power transformer windings are designed so that the losses are equally distributed between the primary and secondaries (core losses are negligible) and generally, for the 2.5 kVA units, do not exceed about 35 watts. The shunts are designed for 0.25 V (37.5 watts) at maximum current.

The switching transistor losses are dominated by the turn-off power and, therefore, are related to the inversion frequency. Depending on the transistor used and the operating conditions, the frequency is adjusted for optimum performance and the losses generally do not exceed 10 watts/device at maximum output (80 watts total for two banks of four devices), including the drive losses.

The line rectifier loss is dependent on the input voltage but is small, about 10 watts. The control circuitry and its power supplies dissipate about 15 watts.

Due to the dominance of the output rectifier losses the efficiency of the supplies is therefore dependent on maximum output current. For units operating at 150A-16V (2.5 kVA), the total losses are about 325 watts for an electrical efficiency in excess of 0.85. Since the dominant losses are approximately proportional to current, the efficiency is essentially constant over the entire operating range.

Mechanical Design

As noted above, the power supplies are intended for use in close proximity to a water-cooled electromagnet, and the design takes advantage of the availability of water cooling.

The power chassis consists of a 1/4" thick x 5" wide water-cooled copper heat-sink, to which all of the major dissipative components are thermally bonded. The length of the heat-sink is adjusted to accommodate the components, 8.5" for a dual supply and 13" for a triple.

The switching transistors are mounted on aluminum plates that are thermally bonded to, but electrically insulated from, the heat-sink. The aluminum plates serve as collector buses for the transistor banks, and as a mounting structure for the base and emitter busing and transistor pin-jacks, which are secured to it with thermally conducting epoxy. The bussing is carried from the transistor banks through holes in the heat sink to the power and drive transformers, which are mounted on its opposite side.

The secondary rectifiers are clamped directly to one edge of the heat-sink which, therefore, serves as a common bus for all of the power supplies. One end of the manganin current monitoring resistor is soldered directly to the heat sink, and a silicon-bronze stud, soldered to its electrically free end, extends through the rear cabinet wall and serves as one of the output terminals. A second stud, soldered directly to the center-tap of the power transformer serves as the other terminal.

The shunt resistor strip is thermally bonded to the heat sink and in normal operation does not vary more than about 3°C from the input water temperature.

Subsequent to the mounting of the transformers, shunt resistors and the wiring completed, the entire structure is vacuum potted with thermally conducting epoxy to form a single monolithic block firmly bonded to the heat sink. Leads from the power transformer secondaries extend from the epoxy block directly to the secondary rectifiers. Leads from the driver and current-sense transformers and the shunt resistors extend from the block to the control circuit board edge connector, which is mounted on a bracket extending from the edge of the heat sink.

The switching capacitors are mounted directly on NEMA-G10 board, upon which the necessary wiring is printed. One edge of this board extends into, and is secured by, the epoxy block.

For this design, all of the major wiring of the power chassis is sealed in, and firmly secured by, the epoxy. The transformers are completely encapsulated and their windings are mechanically stable. Except for the transistor mounting plates, and the capacitor leads on the printed board, all of the high voltage wiring is contained.

The completed package is extremely compact, but all of the active components of the unit are readily accessible for test and maintenance.

The cooling of all of the dissipative components is efficient, with no component exceeding a 25°C temperature rise.

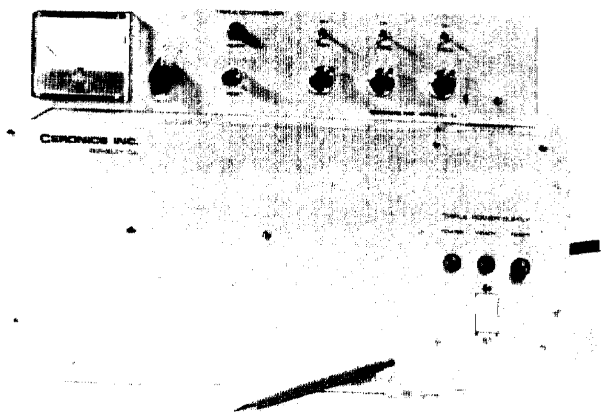
The cooling water requirements are modest (1/2 GPM will suffice) but the water circuit has been deliberately designed to be low impedance, so that it can be connected in series with the magnet load to allow the use of a single flow-switch for the entire system, and so that the thermal protection of the power supply (see above) will also protect the magnet.

Specifications

Power supplies of this general design have been constructed for operation at either 380 VAC 50 cycle or 220 VAC 60 cycle, 3-phase input. The application has been with doublet and triplet magnetic quadrupole lenses requiring currents in excess of 125 amperes, with a maximum power of 2.5 kVA. The units have, therefore, been mounted either two or three in a single package.

Other supplies have been built, with maximum current varying from 50 to 150 amperes. By adding core area and the number of paralleled switches, the power has been extended to a maximum of 4.5 kVA, with dual packaging. Generally, however, the standard units are to the following specifications:

Input		380 VAC or 220 VAC 3-Phase 50-60 Cycles
Power Factor		Essentially Resistive
Electrical Efficiency		≅ 0.85 over Full Range
Number Supplies/Package		Two or Three
Output - Each Supply		0-150A - 17 VDC 0-50A - 50 VDC
Long Term Stability (10% line-10% load-5°C water)		1:5000 of Full Rated Current
Ripple		1:1000 (Magnet Load)
Dimensions	Dual	19" x 5-1/4" Rack Panel x 5.5" Deep Weight 22 Pounds
	Triple	19" x 7" Rack Panel x 5.5" Deep Weight 30 Pounds
Control Panel		19" x 3" Rack Panel x 3" Deep Remote to 300 Feet
Cooling Requirements		1 GPM 25°C



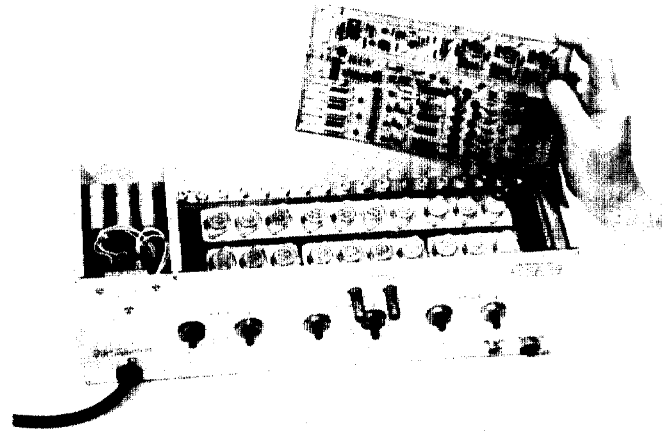


Fig. 1 & 2 Triple unit - three 2·5 kVA power supplies on a single 19" x 7" rack panel.

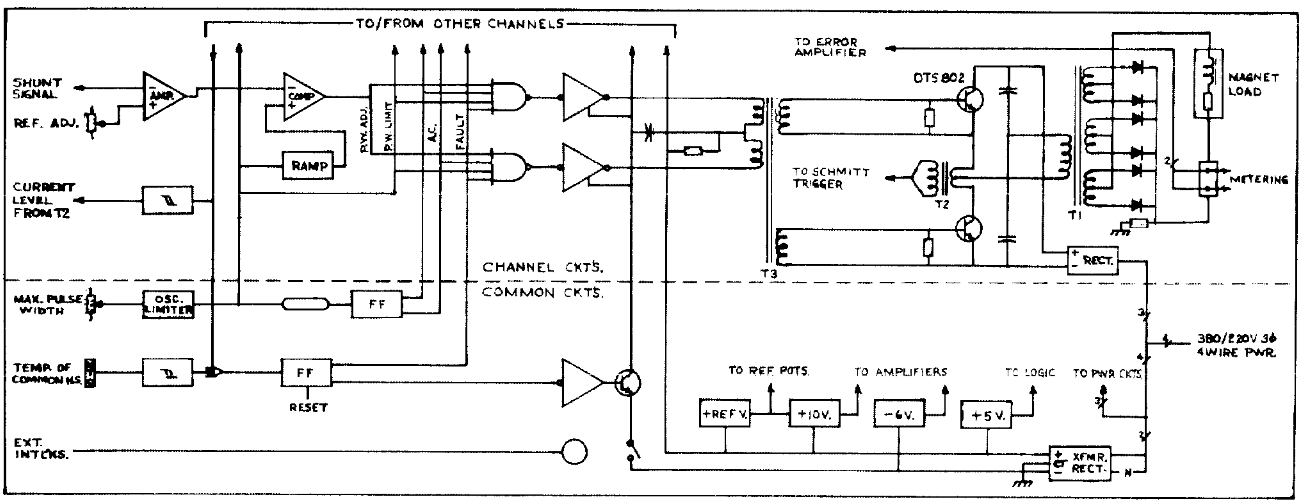


Fig. 3 Control logic & power circuits.

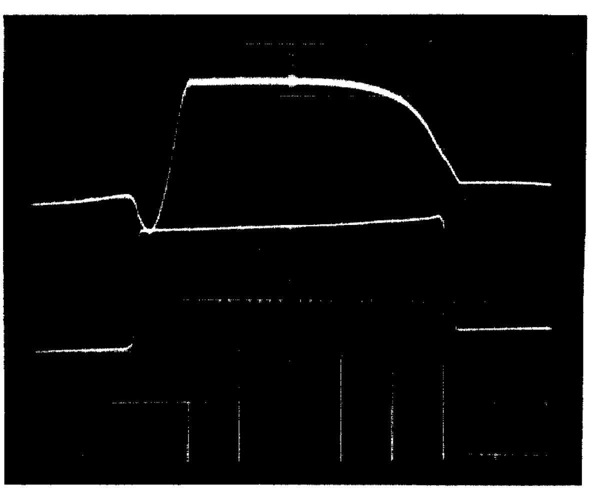


Fig. 4 Drive & switch currents (upper) drive 2A/div (lower) switch collector 5A/div.

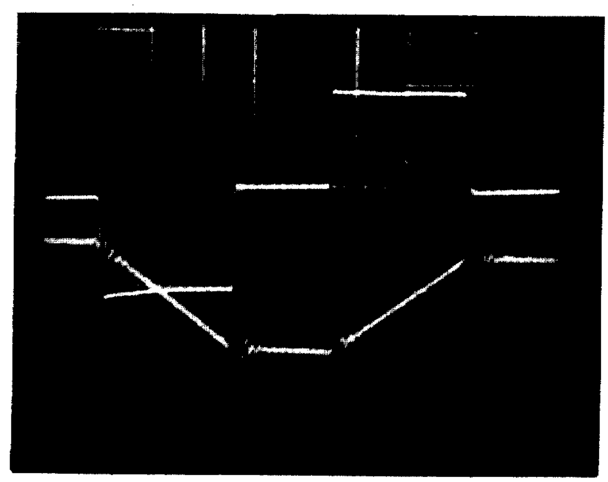


Fig. 5 Capacitor center-tap current & voltage (upper) current 5A/div (lower) voltage 20V/div.