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THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 56, No. 7, September 1977
Printed in U.S.A.

No. 4 ESS:

System Power

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(Manuscript received July 26, 1976)

The No. 4 ESS system is powered from a 140-volt battery plant. Modular dc-to-dc converters located in system frames are used to change the 140 volts to the many well regulated voltages needed by the ESS circuitry. The 24- and 48-volt power required by the system is provided by bulk dc-to-dc converters with 140 volts as an input.

The modular converters require no field adjustments, are pluggable, and contain many alarm and shutdown features, some of which are routinely tested by the system. The 24- and 48-volt bulk converters are available in 2.5- and 5-kilowatt sizes and, similar to the modular converters, contain many alarm and shutdown features for the protection of their 24- and 48-volt buses.

All converters are designed for low EMI (electromagnetic interference) emission and to operate in a room ambient of 0 to 50°C with in-frame ambients as high as 75°C. As a function of the output voltage, efficiencies range from 65 to 85 percent. Most converters regulate remotely with typical end-of-life regulation performance of better than ±2.5 percent.

I. INTRODUCTION

1.1 Basic powering arrangement

Although No. 4 ESS requires less power per trunk than its predecessor No. 4A crossbar, because of its larger trunk capacity, total power required for a typical No. 4 ESS office (over 500 kW) is larger than that for a typical 4A office. The most significant difference in the power required by the two systems is that most of the power used in the 4A equipment is taken directly from a 48-volt battery plant, whereas most of the power for No. 4 ESS has to be processed to provide the many very tightly regulated voltages needed by its electronics.

Since most of the power for No. 4 ESS has to be processed, 140 volts dc was chosen as the basic power arrangement for the system. This was done to take advantage of lower battery plant cost and reduction in size and complexity of power distribution cabling that a high-voltage battery system affords for large electronic complexes.

In the powering arrangement for No. 4 ESS, 140 volts is distributed to in-frame modular dc-to-dc converters which provide the many well regulated voltages needed by the system circuits. The 24- and 48-volt power requirements of the system are provided by centralized dc-to-dc converter plants which replace the normal battery plants at these voltage levels. The cost of the 24- and 48-volt converter plants is the only economic penalty that has to be paid for the use of the 140-volt powering arrangement. However, this penalty is more than offset by the savings realized in the cost of the battery plant and distribution cabling.

In the design of the required power processing equipment for the No. 4 ESS system, most of the problems encountered were with the power for the switching machine, including the 1A Processor. As a result, the remaining part of this paper deals only with the power for the switching machine. Power for the remaining systems in the ESS office, all of which is obtained from the common 140-volt battery plant, is processed using identical or similar converters.

1.2 Converters for the Switching Machine

A total of fifteen in-frame modular dc-to-dc converter designs, ranging in output voltage level from −28 to +28 volts, and three bulk converter designs are used to supply all the voltages needed by the ESS circuits. To simplify the maintenance and minimize the cost of these converters, their designs were based on the following four standard basic power circuits: single-ended switching transistor circuit for output power levels of less than 30 watts, a ferroresonant circuit or a two-transistor pulse-width controlled circuit for output power levels between 30 and 350 watts, and a Silicon Controlled Rectifier (SCR) circuit for power levels above 1 kW.

1.3 Use of In-Frame Converters

To provide required voltages for the ESS circuits, in-frame modular converters are used instead of centralized voltage power plants because of system-required redundancy, required protection of the backplane wiring, and very tight voltage tolerances at the loads.

With in-frame converters, a loss of any one converter will result only in the loss of that frame or part of that frame. Since all critical frames in the system are duplicated, the use of an in-frame converter powering arrangement ensures that a loss of any one converter will not seriously affect the service capability of the system.

All signal-carrying conductor paths in the backplane are limited to under 6 amperes of continuous current. To protect them from overcurrent damage in case of an accidental cross to a voltage bus, all converters supplying power to the backplane are either rated below 5 amperes or the minimum steady-state load connected to them is within 5 amperes of their current ratings. All converters contain high-current shutdown circuits that are set to operate just above their rated output current levels. Any type of fault at the load that conducts over 5 amperes will result in the shutdown of the converter supplying that current without causing damage to the backplane.

The voltages used to power the integrated circuits of the system are regulated to very tight limits. At low voltages and high currents, the distribution voltage-drops quickly become an appreciable percentage of the output voltage levels. Therefore, converters supplying critical loads regulate remotely and are limited to low output power levels to minimize the distribution voltage drops between the converters and the loads they power. The loads for each converter are concentrated in a very small area to make remote regulation effective.

II. THREE-VOLT POWER FOR TTL LOGIC

To meet the required speed and accuracy of No. 4 ESS, the converters and the distribution system used to provide power to the 3-volt TTL (transistor-transistor logic) have been designed to meet 2.90 to 3.10 volt limits at the chips over a 20-year period for all line, load, temperature, and aging variations, including any voltage transients produced by a rapid change in the load current of up to ±10 percent. To meet these very tight limits, a precise common reference voltage is provided to all the 3-volt converters in a frame. With this arrangement, variation in the reference voltage does not have to be included in the 2.90 to 3.10 volt limits since its effect on the 3 volts is identical for all the TTL chips in the frame.

To meet the 2.90 to 3.10 volt requirements at the logic chips, converters supplying the 3-volt power use remote sensing and come in 4- and 8-ampere sizes to minimize distribution voltage drops. To keep voltage transients caused by load switching down to reasonable levels, low-inductance cables are used for the distribution of the 3-volt power to the backplane. In addition, for each 4 amperes of load, a 4000 μF cluster of capacitors is used to filter the ac load current variations induced by the logic. These capacitors are located on a printed wire board near the logic circuits. The board is connected to the backplane 3-volt bus by a connector. Finally, each plug-in card accommodating 3-volt logic circuits

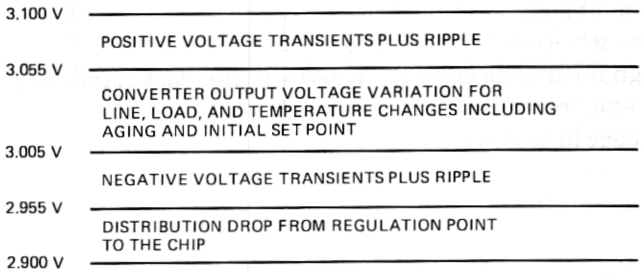

Fig. 1—Voltage allocation for the permitted 3-V voltage band.

contains 0.4 μF ceramic capacitors to provide high-frequency filtering of the load current.

Figure 1 shows the allocation of the 200 mV permissible deviation of the 3 volts among various voltage-variation contributors for which the converters and the 3-volt distribution system were designed to guarantee the 2.90 to 3.10 volt limits.

III. IN-FRAME CONVERTERS

3.1 Single-ended switching transistor converter

The single-ended switching transistor power circuit is used for all converter designs under 30 watts because of its cost effectiveness at low power levels. The basic block diagram of the circuit is shown in Fig. 2.

The power transistor is switched ON and OFF at a fixed 20-kHz rate by the control circuit through an isolation transformer. With the transistor ON, input voltage is applied across the primary winding of the transformer which reverse-biases the rectifying diode and results in an increasing ramp of current through the primary inductance of the transformer. When the transistor is turned OFF, the energy stored in the magnetizing inductance of the coil is discharged through the secondary

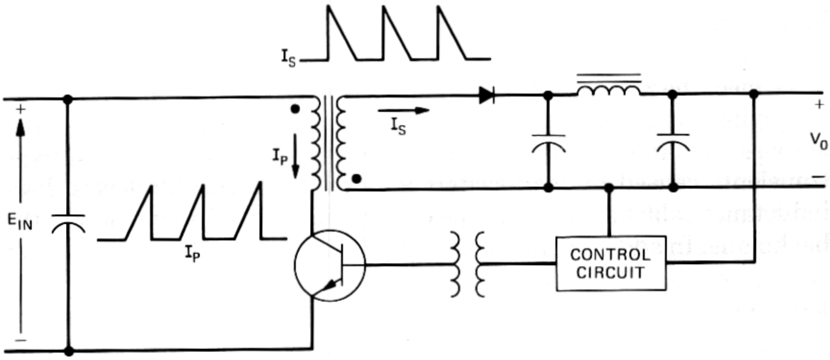

Fig. 2—Basic block diagram of a single-ended switching transistor converter.

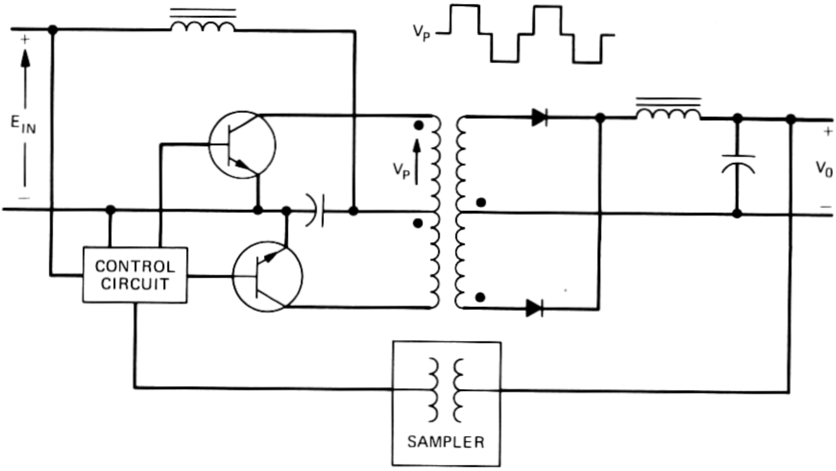

Fig. 3—Basic block diagram of a PWC converter.

winding into the output filter as a decreasing ramp of current. Output voltage regulation is achieved by varying the ON time of the transistor switch.

For ease of maintenance, for manufacturability, and to achieve long-term output-voltage stability, no adjustable components are provided in the converter. Required settings of the output voltage and alarm and shutdown trip levels are achieved by the use of very precise reference voltage sources and precisely trimmed thin-film resistor networks combined in a single hybrid integrated circuit.

To keep the radiated noise of the converter within the ESS EMI requirements, the following steps were taken in the design of the converters:

(*i*) RC networks are used across all fast-switching power devices.

(*ii*) Bypass capacitors are provided at the converter connector between all power leads and frame ground.

(*iii*) All ac loops are minimized by careful physical layout of the converter circuits.

(*iv*) Shielding is provided by the converter frame housing.

(Some or all of the above EMI suppression techniques are also used in the ferroresonant and PWC converter designs described in the next two subsections.)

3.2 Two-transistor pulse-width controlled converter (PWC)

A block diagram of the PWC converter circuit, which was designed for output power levels of 30 to about 350 watts, is shown in Fig. 3.

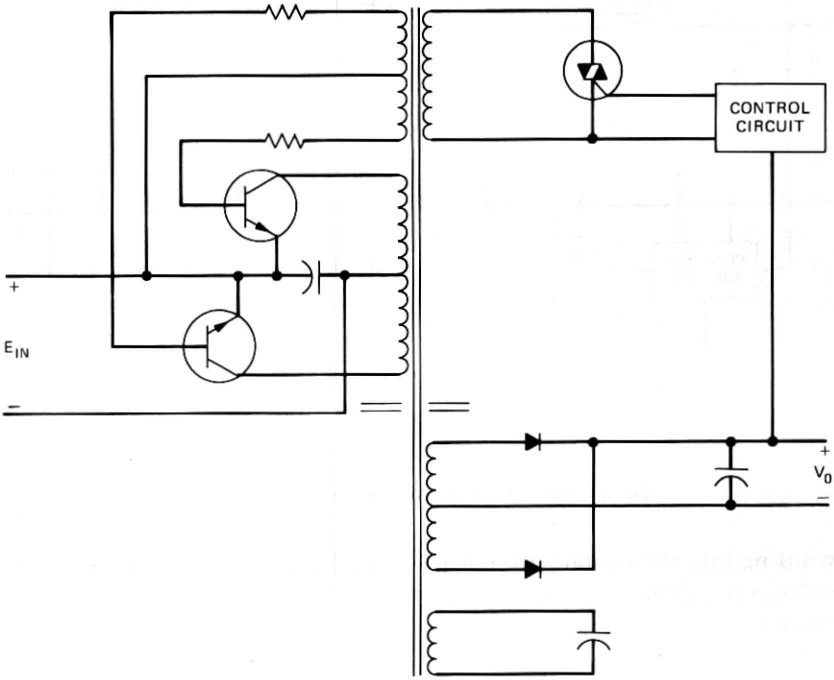

Fig. 4—Block diagram of a ferroresonant converter.

In the circuit, the power transistors are alternately switched ON and OFF at a fixed 20-kHz rate by the control circuit to produce a pulse-width controlled square wave voltage across the transformer primary. After this ac voltage is converted to an appropriate level by the transformer, it is rectified and filtered to produce the required dc output. Output voltage regulation is achieved by controlling the ON time of the power transistors.

Special features of the converter include high efficiency, fast response to load transients, and automatic symmetry correction of the power-transistor collector currents.

3.3 Ferroresonant converter

The ferroresonant converter was designed for output power levels of 50 to 200 watts. Its primary features are its simplicity and good EMI emission performance. A block diagram of a ferroresonant converter circuit is shown in Fig. 4.

The basic converter circuit is composed of a two-transistor self-oscillating power circuit and a transformer designed to have a high leakage inductance between the primary and secondary windings. An ac capacitor is connected across one of the secondary windings. Its capacitance is chosen to be at resonance with the transformer leakage inductance at the operating frequency of the converter, typically 150 Hz. This makes the secondary-winding voltages sensitive to the operating frequency of the power circuit—a feature which is used to regulate the output voltage of the converter. The operating frequency of the circuit is controlled by short-circuiting the control winding of the transformer, which is closely coupled to the base drive windings, at the desired termination time of each half cycle.

3.4 In-frame converter features

All in-frame converters have been designed with the following features for the protection of the circuits they power and for proper interface with the ESS: (*i*) high-voltage shutdown, (*ii*) high-current shutdown, (*iii*) high and low out-of-range output-voltage alarms, (*iv*) system-controlled test of alarm circuits, and (*v*) automatic input current inrush control. In addition, all low-voltage converters are provided with an output voltage clamp (a high-wattage zener diode) for the protection of the loads in case of an accidental cross between high- and low-voltage buses.

In the event of a high-voltage or high-current shutdown and during an out-of-range alarm condition, alarm signals are transmitted to the ESS and a visual alarm indicator is activated on the face of the converter. During the alarm test, which can be initiated automatically by the ESS or manually by the use of a frame switch, the entire out-of-range alarm circuitry of the converter is checked for proper operation and, if everything is functioning properly, an all-pass signal is sent to the system.

In addition to having the above features, all in-frame converters have been designed for low EMI emission, to regulate remotely, and to operate in an aisle ambient temperature of 0 to 50°C with in-frame ambients as high as 75°C. The converters require no adjustments in the field and are pluggable for easy maintenance.

3.5 In-frame converter performance characteristics

Typical performance characteristics of the three basic in-frame converter designs just described are shown in Table I. In this table, regulation pertains to static output-voltage regulation for all load, line, and temperature variations, transient voltage covers peak output voltage transient at the point of regulation for a 10 percent step change in the output load, efficiency is presented for various output-voltage levels, and EMI emission covers radiated noise levels of the converters referenced to 15 μV/m at a distance of $\lambda/2\pi$, where λ is the wavelength in meters at the frequency of measurement, over the frequency range of 50 kHz to approximately 100 mHz.

Table I — Typical in-frame converter performance characteristics

	Regulation	Transient Voltage	Efficiency	EMI Emission
Single Transistor Converter	0.2%	1.0%	70% −3 V 75% −5 V	−20 to −40 dB
PWC Converter	1.0%	1.0%	75% −5 V 80% −9 V	−20 to −40 dB
Ferroresonant Converter	1.5%	5.0%	65% −5 V	−30 to −50 dB

IV. THE SCR CONVERTER

Converter designs above the 1kW range generally employ SCR power circuits because of the high power-handling capability of the SCR switches. A block diagram of the SCR circuit used for the 24- and 48-volt bulk converters is shown in Fig. 5.

SCRs Q1 and Q2 are alternately triggered on by the control circuit. When Q1 is turned on, the input voltage plus the initial voltage across capacitor C1 is applied across the primary winding of the transformer. With transformer winding polarities as shown, the rectifying diode (CR1) is initially reverse-biased, resulting in a sinusoidal current flow through Q1 because of the resonant action of C1 and the inductance of the primary winding. Sinusoidal current flow through Q1 continues until the voltage across C1 reverses and becomes equal to $E_{\text{in}} + nV_0$, at which point the rectifying diode becomes forward-biased. With the diode forward-biased, the constant voltage across the output filter capacitor clamps the C1 voltage to $E_{\text{in}} + nV_0$, forcing the current through C1, and hence Q1, to go to zero. The energy stored in the primary inductance of the coil is then transferred through the diode into the output filter as a ramp of current. Similar circuit operation to that just described occurs during the next half cycle when Q2 is fired. Output voltage regulation is achieved by controlling the firing frequency of the SCRs.

In an actual application, the SCR converters are used to form power plants consisting of an array of converters operating in parallel together with the necessary plant alarm circuits and distribution fuses. To achieve the needed reliability of the plants, the number of converters connected in parallel is always one more than required to power the maximum load of the plant. With this arrangement, if any one converter malfunctions, it is automatically disconnected from the output bus without affecting the output voltage of the plant.

For the protection of the plant output voltage and the loads, the following features were designed into the converter: (*i*) high-output-current limit, (*ii*) high-voltage shutdown, (*iii*) high-current shutdown, (*iv*) reverse-current shutdown, (*v*) automatic output-disconnect switch, and

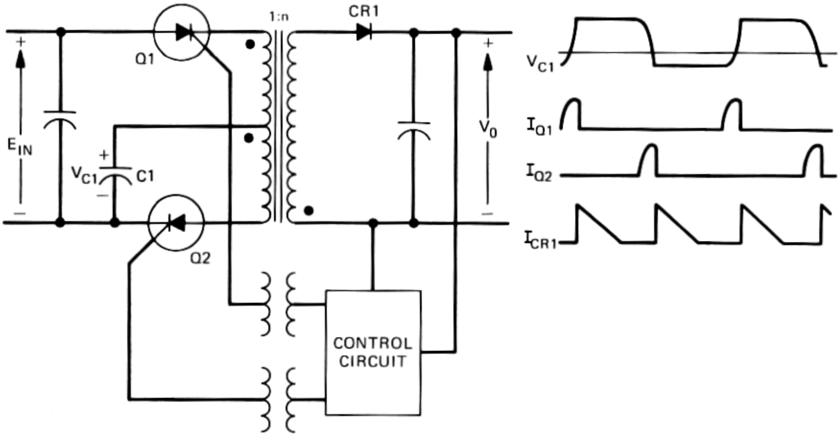

Fig. 5—Basic block diagram and waveforms of the SCR converter.

(*vi*) low-current alarm which is activated when the converter is grossly misadjusted or is incapable of delivering its rated output current. In addition, approximately 0.5 farads of capacitance are included in the output filter of the converter to help the plant in clearing faults at the load by operating distribution fuses without greatly affecting the output voltage of the plant.

Typical performance characteristics of the converter are as follows: (*i*) efficiency—83 percent for 24-volt output and 86 percent for 48-volt output, (*ii*) static output voltage regulation for load, line, and temperature variations—0.3 percent, (*iii*) peak output voltage transient for 10 percent step change in load—0.2 percent, and (*iv*) EMI radiated noise level—15 to 30 dB below 15 μV/m at $\lambda/2\pi$ over the frequency range of 50 kHz to approximately 100 MHz.

V. PHYSICAL DESIGN CONSIDERATIONS

5.1 In-frame converters

Two major factors determined the overall physical features of the modular power supplies and their application in the switching frames: (*i*) isolation of 140 volts for personnel protection and (*ii*) thermal management.

While 140 volts dc is not considered to be a particularly hazardous voltage, it should be treated with respect. Therefore, it was deemed prudent to isolate and identify those areas in the frames where 140 volts is present. The modular converters are mounted in special shelves at the bottom of the switching frames immediately above the in-frame distribution fuses. The input power is fed down the frame upright, through the fuses, and then directly to the converter input connections at the rear of the frame. All exposed 140-volt wiring is covered by an insulating panel mounted to brackets integral to the shelf, and appropriate warning labels are affixed.

The power shelves are themselves modular and can readily be adapted to accept various combinations of modular converters as needed by the individual frames. Two power shelves can be installed, one above the other in a frame, or one can be used if its capacity is sufficient. An air deflector is installed above the topmost shelf where necessary to divert hot air out the rear of the frame away from the switching circuits.

Because of the need to localize the converters, to provide EMI emission protection and 140-volt personnel protection, and because of the general packaging density of the converters themselves, there is little free air flow through the converters. All major heat sources are mounted on heat sinks which are affixed to the front of the converters with their heat-exchanging fins in the aisle. In this way, a predictable environment is assured and thermal performance was determined with considerable confidence. Figure 6 illustrates the shelves with a variety of power supplies installed.

An exception to this general physical arrangement is the 3-V, 2-A converter used to power bus drivers and bus receivers. Circuit considerations require that this converter be located close to the bus at the top of the bay, and be mounted in the same 80-type apparatus mountings as the bus. Since no 140-volt power is available at that location, this converter is powered from the 24-volt bulk converter output—the only low bulk voltage utilized in all bays.

5.2 Bulk converters

Early in the development of the bulk converters, it became apparent that heat removal would be the major physical design problem. In order to be acceptable from a floor space point of view, the bulk converter frames would be required to dissipate far more heat than any other frame in the No. 4 ESS. Reliability considerations prohibited the use of forced convection since the best available blowers or fans have failure rates many times greater than that required for the entire converter.

The design has evolved through several stages. The 24-volt converter plant provides 5000 watts of output power per 2-foot, 2-inch bay with internal dissipation of 1200 watts. The two converters are mounted one above the other with an air-deflecting baffle in between. Heat removal is via large internally mounted heat sinks.

The later 48-volt converter plant, shown in Fig. 7, provides 10,000 watts of output power per 2-foot, 2-inch bay with internal dissipation of 1800 watts. This increase in dissipation was made possible by mounting the converters side-by-side so as to allow both converters ac-

Fig. 6—No. 4 ESS frames with power shelves. One 3-V, 8-A converter is shown partially withdrawn at bottom.

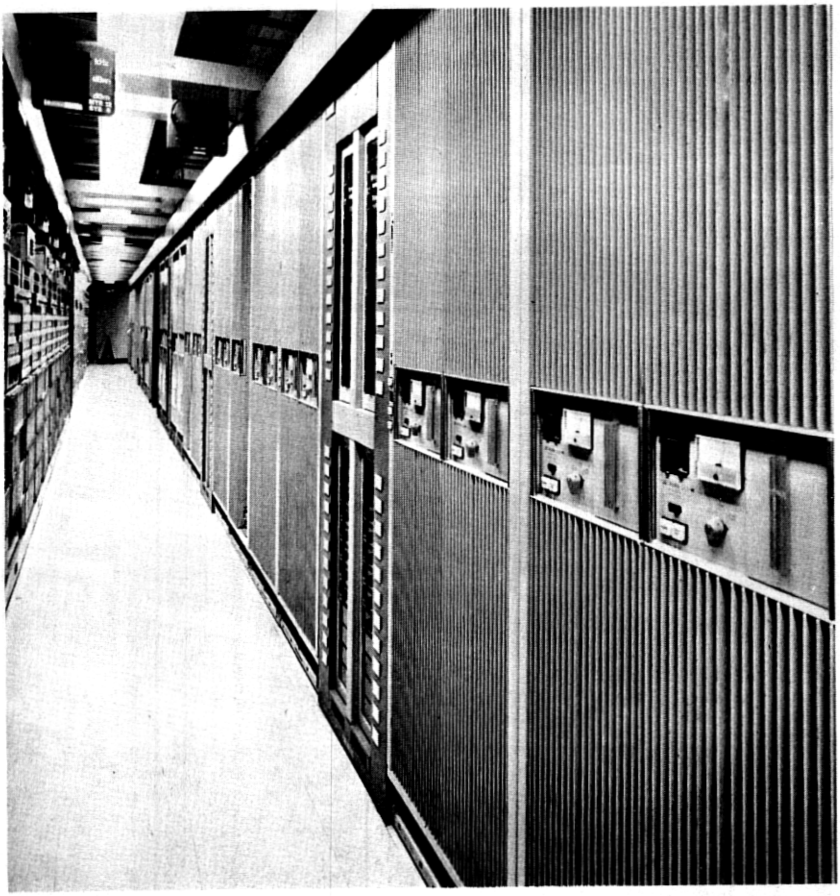

Fig. 7—625B converter plant lineup in Kansas City No. 4 ESS office.

cess to optimum cooling air, and by the provision of massive top-to-bottom heat sinks covering both front and rear surfaces. Air vents at top and bottom provide for additional cooling via two large internal heat sinks. All heat-producing elements are mounted directly to the heat sinks with electrical isolation provided by a heat-conductive epoxy lamination within the heat sink.

VI. SUMMARY

Modern-day electronic systems require a variety of tightly controlled voltages for proper operation. As a result, power equipment has become an important part of all new system designs. Typically, it occupies up to 25 percent of total equipment volume and represents 10 to 20 percent of total system cost. Major problems encountered in the design of the power arrangement for No. 4 ESS were the need for a large amount of power at very low voltages and high power density inside the frames. These requirements necessitated special converter and power distribution designs that could operate reliably at very high temperatures. To satisfy all of the voltage requirements of the switching machine, as well as those of the remaining systems in the No. 4 ESS office, a standard line of converters was developed to minimize the development effort and the cost of the equipment. In addition, since most of the power for the No. 4 ESS office had to be processed and could not be used directly from battery plants, 140 volts was chosen as the basic power arrangement for the office to reduce cost and simplify power-distribution cabling. Cost savings realized with the 140-volt versus a comparable 48-volt power arrangement for a typical No. 4 ESS office are approximately 15 percent of the total battery plant and distribution-cabling costs. This saving varies with the cost of copper.