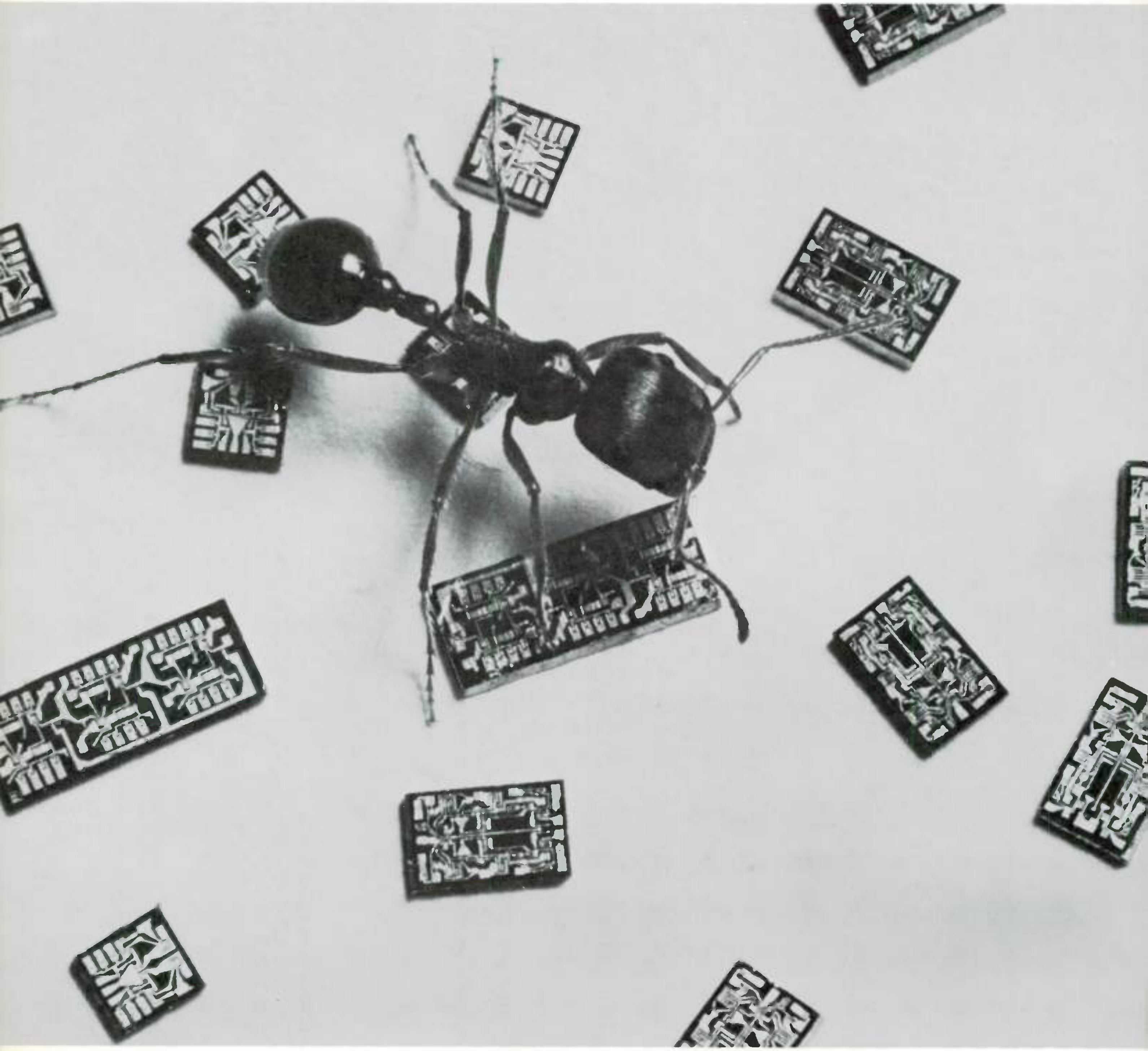
Westinghouse ENGINEER
July 1966

World Radio History



An enterprising Westinghouse staff photographer found yet one more way to demonstrate the tiny size of integrated circuits—and an ordinary ant (much enlarged) found them useful for a game of ant-agrams.

World Radio History

Westinghouse ENGINEER
July 1966, Volume 26, Number 4

Editor
Richard W. Dodge

Managing Editor
M. M. Matthews

Assistant Editor
Oliver A. Nelson

Design and Production
N. Robert Scott

Editorial Advisors
T. P. Jones
Dale McFeatters
T. J. Murrin
W. E. Shoupp
Robert L. Wells

Subscriptions: United States and possessions, $2.50 per year; all other countries, $3.00 per year. Single copies, 50¢ each.

Mailing address: Westinghouse ENGINEER,
P. O. Box 2278, 3 Gateway Center,
Pittsburgh, Pennsylvania 15230.

Copyright © 1966 by Westinghouse Electric Corporation.

Published bimonthly by the Westinghouse Electric Corporation, Pittsburgh, Pennsylvania. Printed in the United States by The Lakeside Press, Lancaster, Pennsylvania. Reproductions of the magazine by years are available on positive microfilm from University Microfilms, 313 North First Street, Ann Arbor, Michigan.

The following terms, which appear in this issue, are trademarks of the Westinghouse Electric Corporation and its subsidiaries:
Micarta; Rototrol.

Cover design: Static conversion of dc power to ac power is the subject of this month's cover. Artist Thomas Ruddy included a representation of a battery, one source of dc power, and a thyristor, the basic element in the inverters discussed in this issue.

World Radio History

Static Fixed-Frequency Inverters... Reliable Sources for Normal and Emergency AC Power

K. M. Watkins

Battery-and-inverter standby power systems supply continuous ac power in the event of transients or disruption of the primary source. Inverters are also used for supplying high-quality ac power, for frequency conversion, and dc-to-dc conversion.

The modern fixed-frequency static inverter provides power of higher quality for both normal and emergency uses than could be obtained only a few years ago. Voltage regulation and frequency stability are better, and transient response faster, than in alternative equipment. This performance, along with reliability and low maintenance requirements, have led to use of the inverters in a wide variety of sizes and applications.

The main use is in battery-supplied ac emergency standby power systems, especially for critical loads where instantaneous take-over is necessary if the primary power supply is disrupted. Other important uses are as high-quality power supplies for computers and other data-processing and control systems, as ac frequency converters, and, in conjunction with a rectifier, as dc-to-dc converters. Ratings have been rapidly extended over the past few years from kilowatts to megawatts as prices of semiconductor devices have fallen and as device ratings have increased.

A static inverter is a unit that changes dc power to ac power without mechanical movement; its active elements are power semiconductor devices. (The inverters built from thyratrons or similar devices for ultrahigh-voltage dc power transmission are not covered in this article.) M-g sets and relay-type chopper circuits can perform a similar function and may be lower in initial cost. However, when operating and installation costs are considered, the static inverter is less expensive for many applications. Moreover, decreasing semiconductor costs are rapidly reducing the prices of static equipment, making that equipment ever more competitive.

The advantages of static inverters over the alternative equipment are: more precise control of basic parameters (voltage, frequency, and response time); low maintenance requirement and hence less downtime; lighter weight and easier mounting arrangements (they can be freestanding); and cleanness (no lubrication nor brush dust).

Power output of single units ranges from less than 1 kva to more than 250 kva. Efficiencies run from 65 to 85 percent, depending on input voltage and application. Voltage regulation is ± 1 percent for three-phase systems of more than 20-kva rating. For low-power single-phase systems, ± 5 percent is standard.

Frequency can be held to any reasonable degree of stability required, because it is a function of the master pulse generator and is made independent of line or load changes. This is a big advantage over rotating machines. Standard units have better than ± 0.25 percent stability. Where greater accuracy is required, a stability of better than ± 0.05 percent is achieved by controlling oscillator temperature. To prevent long-term frequency drift, the pulse generator can be synchronized to a utility line; this arrangement is often used in computer and data-processing applications where real time is important.

Uses of Inverter Systems

Although the utility companies have achieved exceedingly high standards for continuity of supply, many industrial power systems need "life insurance." The static inverter and standby battery system is such an insurance policy because it provides continuous ac power from the battery if line power is disrupted. It thus provides time, depending on the battery size, until the line power returns, or to allow orderly shutdown of a critical industrial process, or until a diesel or gas-turbine generator can be started up for a long-term emergency power source.

Power supply for computers and data-processing equipment is an ideal inverter application because good regulation and frequency stability are prime requirements. The equipment usually is run continuously from the inverter to decouple it from power-line transients, which may result from lightning or industrial load switching. The battery acts as a filter of almost infinite capacity; this is extremely important in computer and data-processing systems because a miscount can have disastrous results. Due to the cleanness of an inverter and its relatively low noise level, it can be located closer to its load than rotating machinery and in a clean-air environment if required.

Inverters are often used as the power source for instrumentation and control circuits in such locations as steel mills, chemical processes, and power plants. Even if main drive power is lost, these plants require power continuity for instrumentation and the closing down of the process in an orderly manner. For some processes, sufficient backup power is supplied to run at reduced speed; examples are systems that must be cleared of the process material–molten glass for example. Where boilers are used, flame scanning and instrumentation must always be available or an expensive mishap can occur.

Another use is for frequency conversion. In an automatic train-control system used by the Chicago and North Western Railway Company, adjacent power lines were causing 60-cps excitation interference. The problem was solved by use of 100-cps inverters for excitation; the pick-up coils, tuned for 100 cps, do not respond to the 60-cps field. M-g sets were first considered for this application, but static inverters were chosen because of their low maintenance requirements. The units were built in outdoor cabinets and mounted on concrete-block foundations alongside the track to keep installation cost low. The inverters have given excellent service over a wide range of ambient conditions.

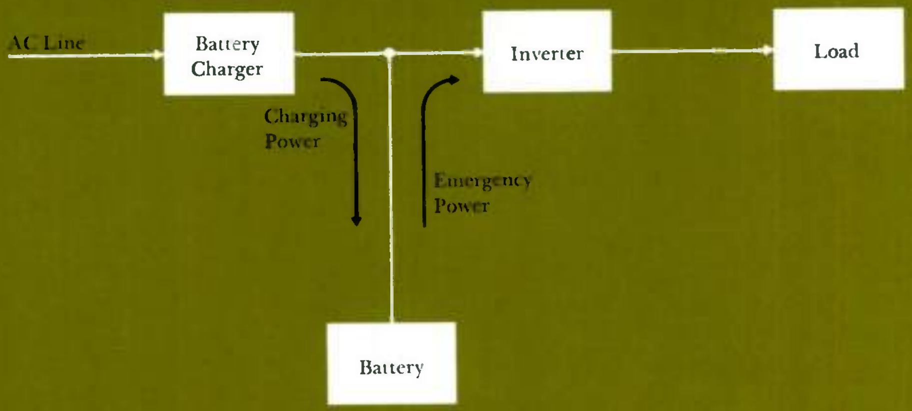
Static Inverters

The Westinghouse line of inverters is based mainly on two types. For high power (over 20 kva) and three-phase applications, the AccurCon wave-synthesis type is used; for lower power, the parallel type is used.

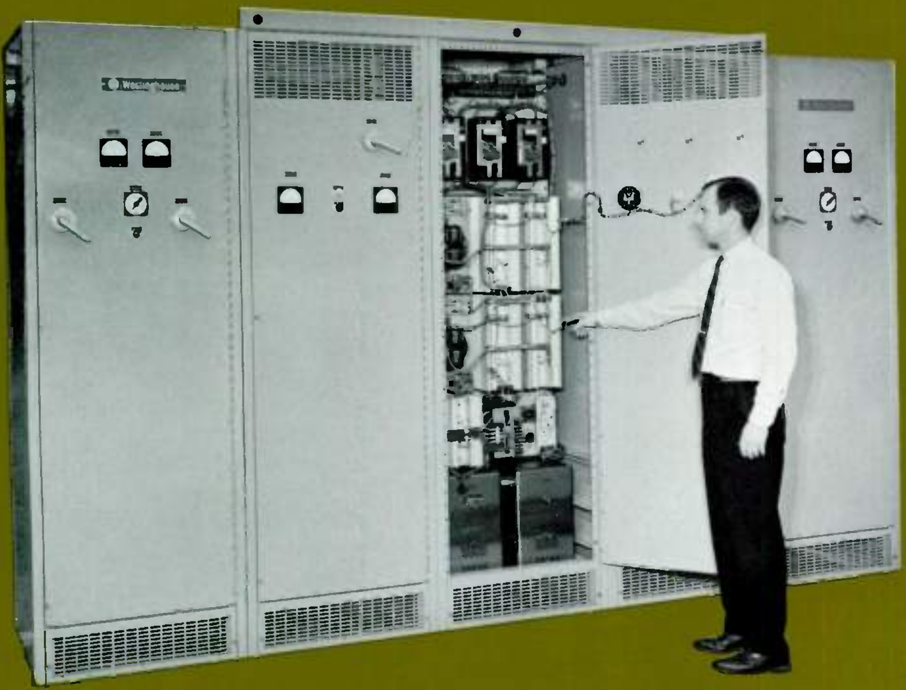
Wave-Synthesis Inverter–This type has multiple stages, each consisting of a thy-

---

K. M. Watkins is an engineer in the static apparatus development section, General Control Division, Westinghouse Electric Corporation, Buffalo, New York.



1—Typical inverter system consists essentially of charger (a regulated static rectifier), battery, and static inverter. The battery takes over the load instantly if line power fails; it also acts as a large filter to absorb line transients.



Two 10-kva inverters connected for use in parallel. Two separate battery chargers and batteries were applied in this system to give complete redundancy for supplying a critical load.

ristor bridge inverter, connected to form a stepped wave that approximates a sine wave. It is essentially the inverter described in the article beginning on page 104 of this issue, but with a fixed-frequency master pulse generator instead of an adjustable-frequency pulse generator. This type performs best at power levels from 20 kva up. There is no top limit to the power output, as the modular construction makes it easy to add stages. Adding stages also makes filtering easier, and response time to a transient step of load or input voltage is improved as the number of stages increases. A three-phase, six-stage, four-wire system under 50-percent load change returns to within two percent of normal output voltage in about 50 milliseconds and is within one percent in 150 milliseconds. Total harmonic distortion is less than five percent in standard units and can be kept below three percent if required. Forced-air cooling keeps physical size down, and alarm circuits can be fitted to respond to loss of air flow. The cooling fan is run from the inverter to ensure continuity of the cooling.

A four-wire three-phase system can be unbalanced, but the maximum phase rating must not be exceeded. Load unbalance of phases is reflected in slight line output voltage variations due to load regulation of the equipment. Overload capability typically is 120 percent for 30 seconds and 150 percent maximum. Current-limit fuses protect the components against larger overloads.

Parallel Inverter—This type is simpler than the wave-synthesis inverter. (See *Parallel Inverter Operation*, page 101.) Although voltage control is not as precise, it is a sound reliable power source that is lower in cost and completely self-protecting against overloads, including short circuits. Voltage control and filtering are performed by a ferroresonant transformer. Worst-case load and line regulation can be taken as ± five percent, and total harmonics are also around five percent for worst conditions. Single-phase inverters are manufactured as standard units in sizes up to 10 kw. Three-phase units of this type are not made because internal phase shifts in the ferroresonant transformers prevent achievement of a reasonable tolerance on the phase displacement.

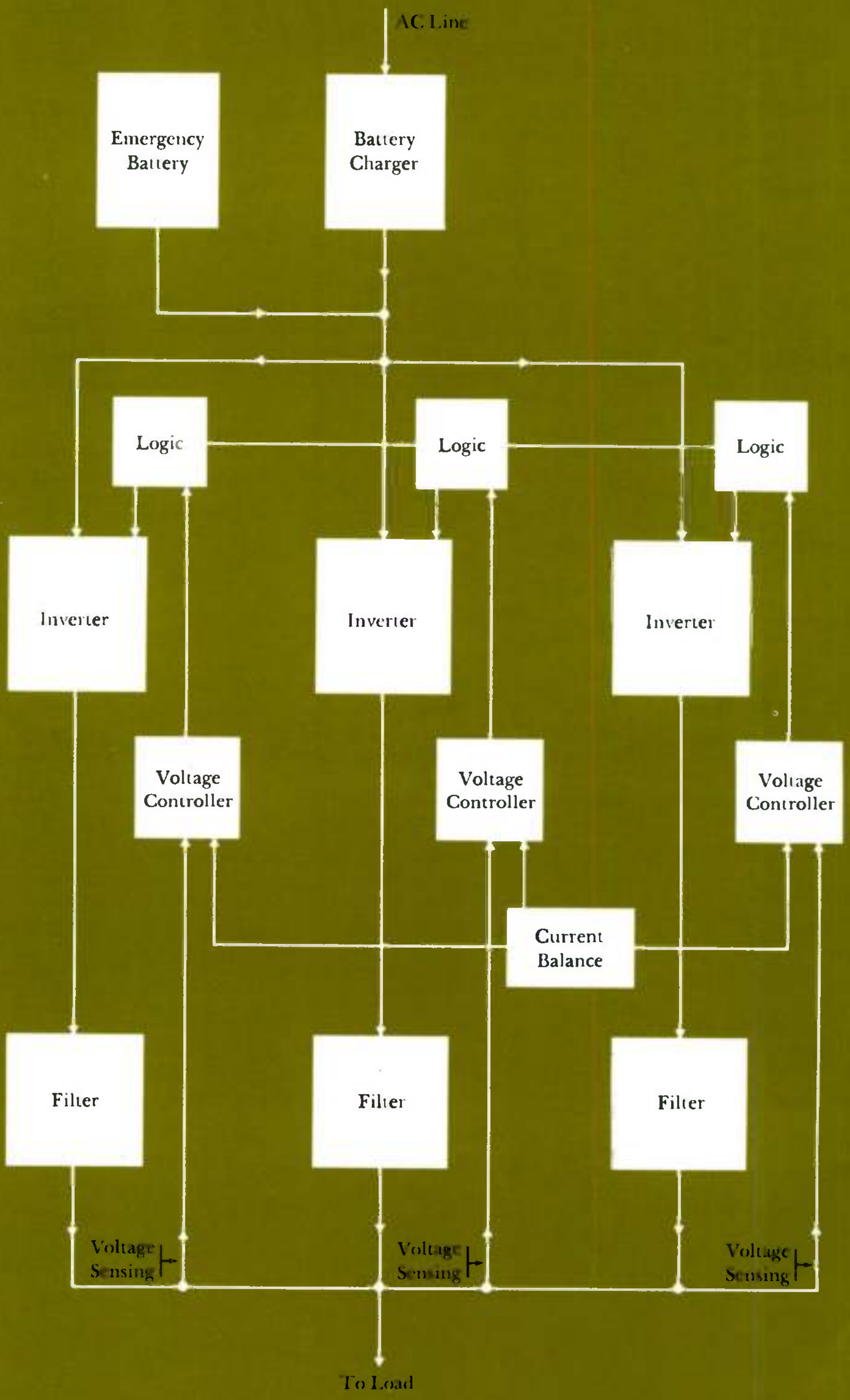
For the higher power ratings, ferroresonant transformers are connected with primaries and secondaries in parallel, or the primaries are paralleled and the secondaries used as individual two-wire supplies. In the latter case, an overload or short circuit on one secondary is not reflected in the output of the others. Only the faulty section of the load is then current limited; output voltage from the other sections is not affected. Load decoupling is thus obtained, and only a portion of the load is lost due to distribution failure. If the utmost assurance of continuous service is desired, redundant use of several inverters should be considered, either in a load-sharing system or as separate units.

Inverter Systems

A typical inverter system is illustrated in Fig. 1. For this example, the rating is assumed to be 25 kva, three phase, four wire, 208/120 volts rms, either 50 or 60 cps.

The choice of battery type for a particular application depends on such factors as volume, weight, maintenance, and costs; each type has advantages and disadvantages, and each application has its own considerations. The lead-acid type is lowest in first cost; lead-calcium is close to it in cost and does not require a boost charge; nickel-cadmium costs more but is lighter and more compact.

The battery must have sufficient power storage for the desired time. (In this example, a 260-volt lead-acid type is assumed.) In returning full energy to the battery after discharge, the energy taken out of the battery must first be returned. This energy is calculated on an ampere-hour basis and restores the battery to about 85 percent of its rated capability. The remaining charge is replaced as a function of the voltage applied to the cells. It is called the boost charge and is a product of voltage and time; a 260-volt battery is normally boost-charged at 280 volts. This charging is done periodically to ensure maximum power storage by the battery. The battery gradually loses maximum storage power if the boost charge is left beyond one month.



2—Large amounts of power can be provided by operating inverters in parallel. Since the inverters can operate individually, this arrangement is also a way of providing a redundant inverter for maximum system reliability. It also permits running on only one inverter when load demand is low.

World Radio History

The battery charger is sized to provide the full-load requirements of the inverter, with sufficient excess capability to recharge the battery from 210 to 260 volts in less than eight hours. Its current requirement is based on the input at full load at 210 volts, which is the discharged level for a 260-volt battery. This is 150 amperes. The charger is a static controlled-rectifier unit with a current-limit feature for complete protection over the working voltage range and a boost-charge level of 280 volts.

At the 25-kva power rating of the example, the inverter would be of the wave-synthesis type. Its multiple stages are displaced in time to give a stepped wave rich in the fundamental wave and low in harmonic content. Filtering the output smooths the steps, and total harmonic content of less than five percent is achieved.

The cost per unit of rating of inverters and battery chargers decreases as ratings increase. For batteries, however, a simple relationship of cost to rating cannot be derived because of the large number of variables present.

Applying Inverter Systems

For optimum reliability, the inverter should always be considered the prime power source. The philosophy behind this approach is that an inverter failure can occur, even though it is unlikely, and it is best to find out as soon as it occurs because the line power is then available for backup. If the inverter is held as the standby unit, any deterioration in a component may not be detected until the line fails and the inverter is required for service. This is precisely the worst time to learn that a component has failed.

Scheduled testing at regular intervals has not proved to be a satisfactory substitute for continuous use, because testing may lapse when no failures occur over a period of time. Running the inverter continuously but picking up load only when the normal supply fails requires a considerable addition of components if the load is to be picked up without noticeable power interruption. Reliability of the transfer system becomes a matter of major concern.

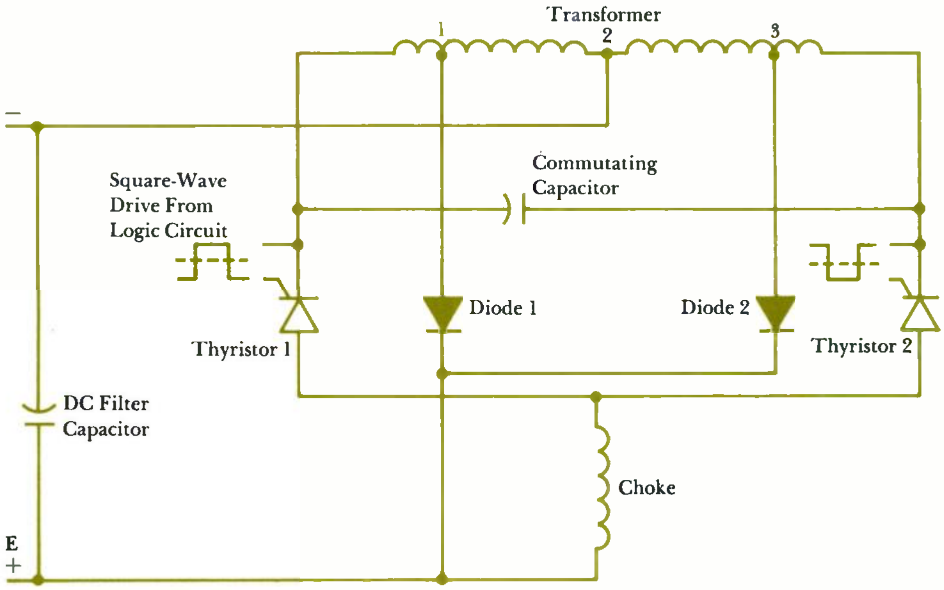
Parallel Inverter Operation

The parallel inverter, like other static inverters, is based on thyristors—semiconductor devices that can switch power. A thyristor can block voltage in both the forward and reverse directions until a positive signal is applied to its gate electrode; then the device conducts in the forward direction when it has positive voltage on its anode. A thyristor is turned off by reverse-biasing the anode to a negative potential for a short time.

The main components of a parallel inverter are illustrated schematically in the diagram. When positive gate drive is applied to thyristor 1, it conducts. Current flows from E+ through the choke to the anode of thyristor 1, through the thyristor to terminal 1 of the center-tapped transformer, and out of transformer terminal 2 to the negative line. Thus, a voltage of E+ is developed at transformer terminal 1 with respect to the common terminal 2. (Potential drops across thyristors, diodes, and elsewhere can be ignored.) At transformer terminal 3, by transformer action, a voltage of E− is developed. The combination voltage developed across terminals 1 and 3 is thus 2E, so 2E is also developed across the capacitor.

After thyristor 1 has been on for a half cycle, the positive gate drive is removed and applied to thyristor 2. This thyristor turns on, and transformer terminal 3 (and hence the capacitor) reverse-biases thyristor 1 for the length of time taken by the capacitor to discharge through the transformer and into the load. This turns off the thyristor. The capacitor then recharges to 2E, but with reverse polarity. At the end of this half cycle, thyristor 1 is gated on again, and thyristor 2 loses its drive and is turned off. The cycle repeats until the unit loses its supply of power.

When an active load such as a motor or a ferroresonant transformer is driven by the inverter, current flow sometimes is into and not out of the inverter. Consequently, diodes are included to form a low-impedance path from the load to the dc filter. Assume again that thyristor 1 is conducting. When the load regenerates, the cathode of thyristor 1 is made positive with respect to its anode, and this reversal of polarity makes it stop conducting. There is now no load for the regenerating power, and emf rises until the anode of diode 1 goes more positive than E+; the diode then conducts and "clamps" the regenerated voltage to E+. On the next half cycle, diode 2 performs the same function. Thus, the regenerated power is stored in the dc filter and not wasted.



The price of commercial power is so low that the costs of power losses in the inverter conversion are negligible in comparison with the cost of just one shutdown. This is a strong economic reason favoring continuous inverter use. Moreover, due to local conditions, the voltage control from an inverter may often be better than that of the line, and transients on the line do not get through an inverter system to the load. It would be a shame to throw away these advantages by use of the inverter in any mode other than as the prime power source.

As in most other types of electronic equipment, component failures are most likely to occur in the first 500 hours of operation. Consequently, an inverter should be connected and run as soon as possible after installation even though the load may not be available.

When a large amount of power is required, it can be provided in several ways. One is by the use of a large inverter rated for the maximum power requirement; it would be the wave-synthesis type with enough stages to handle the load. The inverter could run with loss of a stage, although voltage balance would be disturbed and harmonics would increase. The amount of disturbance in losing one stage is inversely proportional to the number of stages, and the equipment keeps on delivering usable power until a convenient time can be chosen for servicing it.

Another way to provide a large amount of power is to use several inverters of either type in parallel, such as three 100-kva units to supply 200 kva of power (Fig. 2). They would be designed to operate either in parallel or individually. Complete redundancy of one inverter is then provided, and only one need be used for 50-percent load.

Paralleling of an inverter with one already operating under load is achieved in three simple steps. First, the pulse generators are synchronized and the logic sequencing signals locked together. Power is then applied to the unit not under load and the output voltage set high (to within about ½ percent of the load voltage). The output lines of the two units are then coupled together. If the third inverter is required, it is put on in the same manner. When the inverters are running in parallel, the highest-voltage unit acts as the master voltage regulator. As paralleling occurs, a current balance circuit ensures that the input to the inverter is kept evenly matched. Two of the inverters thus act as slaves to the third, but they retain their individuality once the power link is broken.

If the inverter is under open-loop frequency control through a synchronizing circuit to the local utility company, the synchronizing controller must be restricted to a frequency range of about 59.5 to 60.5 cps. Sometimes when a line failure occurs, a frequency reduction may be generated by active loads on the bus to which the inverter is synchronized. If the synchronizing controller is nonselective, the inverter follows the frequency change until an excessive volt-second condition occurs and the inverter transformers saturate.

Transfer of load from inverter to utility line requires that the sources be synchronized and in close phase relationship with each other. If the phase relationship is incorrect when transfer is initiated, high circulating currents can be set up the same as in paralleling any two sources out of phase. The inverter either will trip out or, with excessive mismatch, blow its protective fuses.

Either manual or automatic phase adjustment control can be provided. *Manual* control is used mainly in low-power systems with ferroresonant-transformer output. When a make-before-break transfer is to be initiated, the two sources are adjusted to be in phase. The "make" contacts are then closed, and the inverter runs in parallel with the other source until it is disconnected. The length of time the inverter runs in parallel is not critical.

Automatic make-before-break transfers are carried out by use of a closed-loop phase-lock circuit (Fig. 3). Here, time for the paralleling must be only a matter of cycles. The reason is that, in a practical closed-loop system, an error has to be present for partial correction of the system. When the automatic phase-lock circuit is used, slight variations of two or three degrees will exist, depending on loading changes and voltage regulation of the two lines. However, when the inverter output is physically connected to the alternate source, there is no error between the inverter output sample and its reference. Over a period of many cycles, a drift can then take place, causing the phase relationship to change between the sources. This is not a problem as long as the transfer and break take less than about 10 cycles.

Adding to an Existing Battery

In many installations, electric generating stations for example, a battery may already be provided for emergency operation of contactors and other control functions. However, energizing contactor coils and starting motors can cause the battery output to dip for short durations below the lowest allowable inverter input voltage. This does not mean that the inverter must have a separate battery; instead, the system can be modified as shown in Fig. 4.

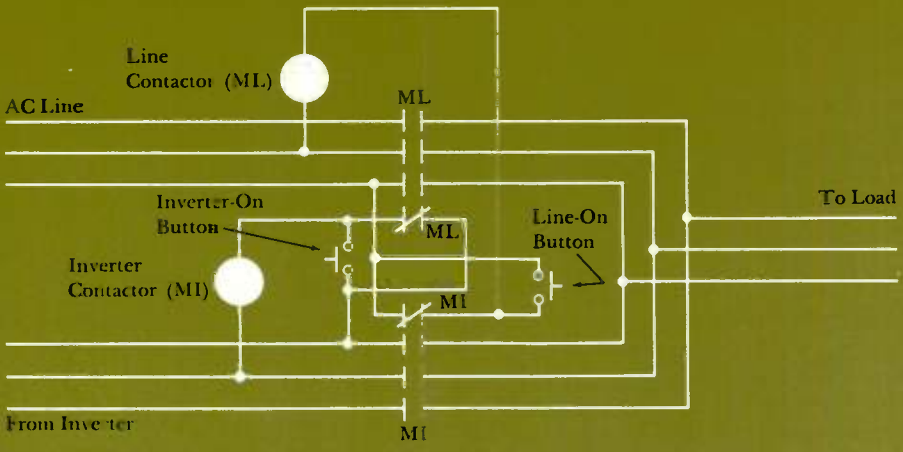
A capacitor bank acts as the extra power source for short-duration dips; the blocking diode prevents discharge back into the battery. If long-duration dips occur, a small battery can be used in place of the capacitor bank. This battery's rating can be quite low, and extra charging facilities are not required because the auxiliary battery follows the larger one on a long-term basis. A choke can be used to absorb overshoots that may occur when inductive loads are switched off on the main battery.

Conversion of DC to DC

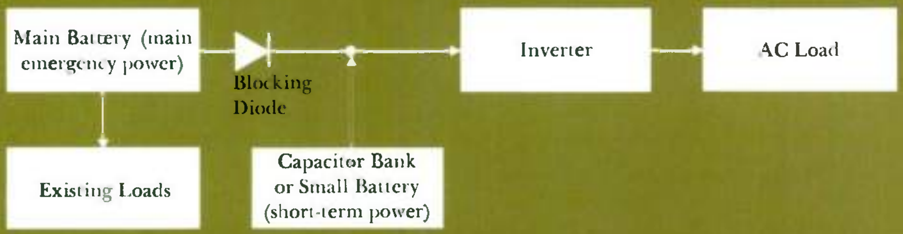
In many inverter applications—mainly computers, data-processing equipment, and increasing numbers of control circuits—ac emergency power from inverters is reconverted back into dc. The double filtering process that takes place going from dc to ac and then back to dc is reflected in the efficiency, cost, and size of the power equipment.

For low powers (up to two kva), an economical *direct* dc to dc system can be built with a half-wave inverter (chopper). For higher powers (two kva upwards), a full-wave inverter-transformer-rectifier combination running at high frequency proves

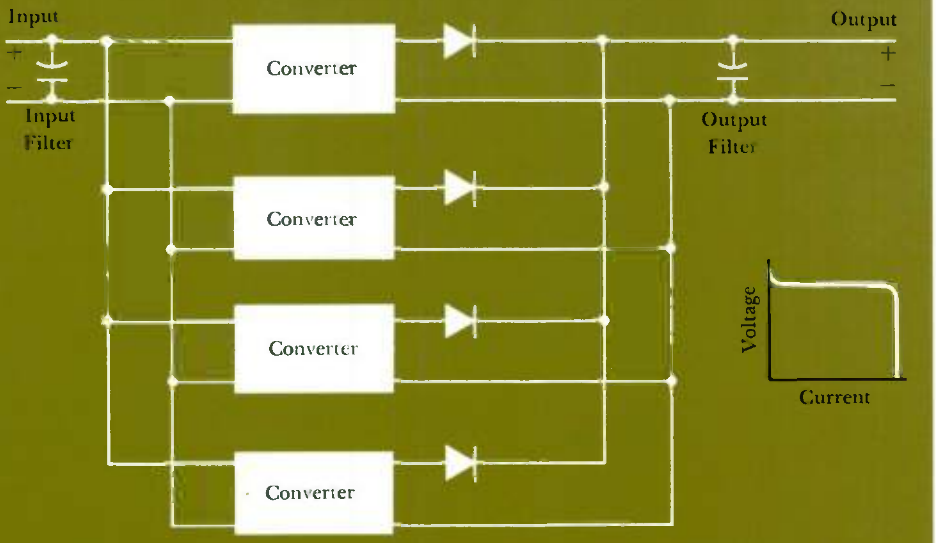
World Radio History



3—Load can be transferred between inverter and main power line by this automatic make-before-break phase-lock circuit. The transfer is initiated by pushbutton or by loss of either source. Transfer is accomplished in a few cycles.



4—When a standby battery is used for other loads besides an inverter, its voltage output can dip momentarily below acceptable inverter input level. Adding a capacitor bank or a smaller battery is an economical way to compensate for these dips. A blocking diode prevents discharge back into the main battery.



5—Several dc-to-dc converters can be connected for parallel operation. Each converter's output characteristic is similar to the idealized curve.

more economical. It generates a square wave which is then rectified; the dc output produced is a reproduction of the dc input, and the system acts as a dc-to-dc transformer. Voltage control can be introduced by means of thyristors in the rectifier portion of the equipment. Often, ripple that may be present on the battery can be reduced when voltage control is added.

The use of dc-to-dc converters in parallel has attractive features (Fig. 5). The converter output characteristic is constant voltage to its maximum load and then current limited. Only a blocking diode in series with each output is added to each converter. On full load, the converters run at the voltage of the lowest converter; at minimum load, they run at the highest voltage level. Close voltage-control adjustment keeps regulation of the overall system to about the same value as that of a single converter with the addition of the blocking-diode regulation.

A redundant unit can easily be added to the system. Should any unit fail, the individual output reduces and no fault load is seen by the remaining converters. This is because of the blocking diode, which prevents any power flow back into the faulty converter.

This plan thus provides both parallel operation and redundancy easily and with maximum safety. Control-circuit redundancy is often provided for system reliability; this plan is just a logical extension of the principle to the power source. It can be used to advantage where transistorized control or instrumentation circuits are the load.

Conclusion

Static inverter ratings have been rapidly extended in recent years as the cost of semiconductor devices has fallen and as device ratings have gone up. As a result, many applications that were pipedreams only a few years ago are now installed and operating. The precise performance that static equipment can deliver provides more closely regulated power, for both normal and emergency uses, than could previously be obtained.

World Radio History

Static Adjustable-Frequency Inverters and AC Motors...A Versatile Team for Industrial Drive Systems

C. G. Helmick

Adjustable-speed drives using inverters combine the advantages inherent in accurate and stepless motor speed control with the simplicity, low cost, and minimum maintenance requirements of ordinary ac motors.

Conversion of direct current to adjustable-frequency alternating current with static equipment sized for industrial drive applications has been a goal of engineers for years. The reason is simple: if such conversion could be made practical, then conventional ac motors would be given the same flexibility as dc motors because their speed could be adjusted steplessly, accurately, and through a wide range. In the past few years, such conversion *has* been made practical and, as it often turns out, a whole new set of capabilities has resulted. These capabilities are being exploited in many industrial applications, from man-made fiber production to metal-mill runout tables and various processing lines. However, successful and economical application of adjustable-frequency inverter drive systems depends on an understanding of their special capabilities and limitations.

Advantages

Some of the advantages of inverter drive systems are associated with the use of adjustable-frequency drives in general and could just as well be derived from the use of an alternator driven by a dc motor. Other advantages, however, are unique to the static inverter and cannot be obtained easily from other types of systems. Naturally, the most economical applications for inverters are those that take advantage of the unique features.

One *general* advantage, for example, is the freeing of the squirrel-cage induction motor from its limitation of a single speed or, at best, a few speeds. Adjustable frequency provides adjustable speed; the ac motor now can perform with much the same flexibility as the dc motor, but without the drawbacks and restrictions associated with brushes and commutators. Moreover, groups of ac motors can be run in close coordination without speed regulators or other types of feedback control. In fact, with synchronous motors the speed matching can be made perfect, since all motors run in synchronism with the inverter frequency. The cost advantage of the ac motor over the dc motor, as well as the important reduction in maintenance expense, can produce important savings in such group drive applications.

The *unique* advantages of the static inverter include precision speed control. Frequency, and therefore motor speed, is established by a low-power oscillator that can easily be controlled to ± 0.25 percent or better. With special care, an accuracy of ± 0.05 percent is obtained reliably over a wide range, without the use of regulators or digital techniques. In addition, the oscillator sets the inverter frequency regardless of load or input-voltage variations, thereby giving the inverter a transient performance equal to its steady-state performance.

Two more unique advantages, both stemming from the use of solid-state power conversion, are high efficiency and lack of periodic maintenance requirements. At full load, for example, the inverter operates with 85 percent efficiency, while m-g set efficiency is 75 percent. At partial loads, the advantage is even greater. This factor alone is of major importance in round-the-clock applications of the larger drives, where energy costs are substantial. The inverter requires no periodic maintenance, mainly because it has no rings, brushes, commutators, bearings, and so on. This characteristic can provide important savings in reduced downtime as well as in maintenance.

Another unique advantage of the inverter system is its ability to operate from a battery during loss of utility power. The inverter operates from a constant dc voltage input, regardless of output frequency, so it is quite capable of operating from a battery without interruption of service. It would be virtually impossible to duplicate this performance with an m-g set because an adjustable-voltage dc source would be required. In one plate-glass plant, for example, a standby battery is used to avoid production outage, even in the rare event of prolonged utility outages, because a power failure could damage equipment worth millions of dollars.

Basic Inverter System

Whether one inverter or several inverters are used in an installation, a common rectifier for conversion of plant power to dc power is supplied (Fig. 1). The rectifier has simple diode circuitry for best reliability. It provides the necessary power for all inverters at constant dc voltage. (Constant voltage is used because it provides for the most effective switching of the inverter thyristors without resorting to separate additional circuitry for this purpose.)

The inverter employs thyristors as the power switching devices to generate ac output power, under control of a master oscillator that governs the frequency of operation. Inverter output frequency is adjusted by adjusting the oscillator frequency with a control potentiometer. Logic circuitry coordinates the action of all thyristors and trims the output voltage to hold within design limits under all specified conditions. This voltage control function is tied in with the requirement of ac motors to operate at constant volts per cps. As the operator reduces the inverter frequency to obtain lower speed, the inverter voltage must be reduced accordingly (220 volts at 60 cps, 110 volts at 30 cps, etc.). In the Westinghouse Accur-Con inverter system, this reduction is accomplished automatically by a simple and unique method of pulse-width control (See *Principles of Inverter Operation,* page 107.) Other kinds of voltage control in common use require either complicated logic or slow-acting electromechanical equipment.

If a system requires standby power in the event of a utility outage, a battery or other energy-storage device can be connected as shown. Such elements may range from capacitors for 20-cycle outages up to large storage batteries for outages of 30 minutes or longer. In either event, the inverter operation and its load can be made entirely unaware of any disturbance both during the outage and during recovery.

C. G. Helmick is a product line administrator in the static power apparatus group, General Control Division, Westinghouse Electric Corporation, Buffalo, N.Y.

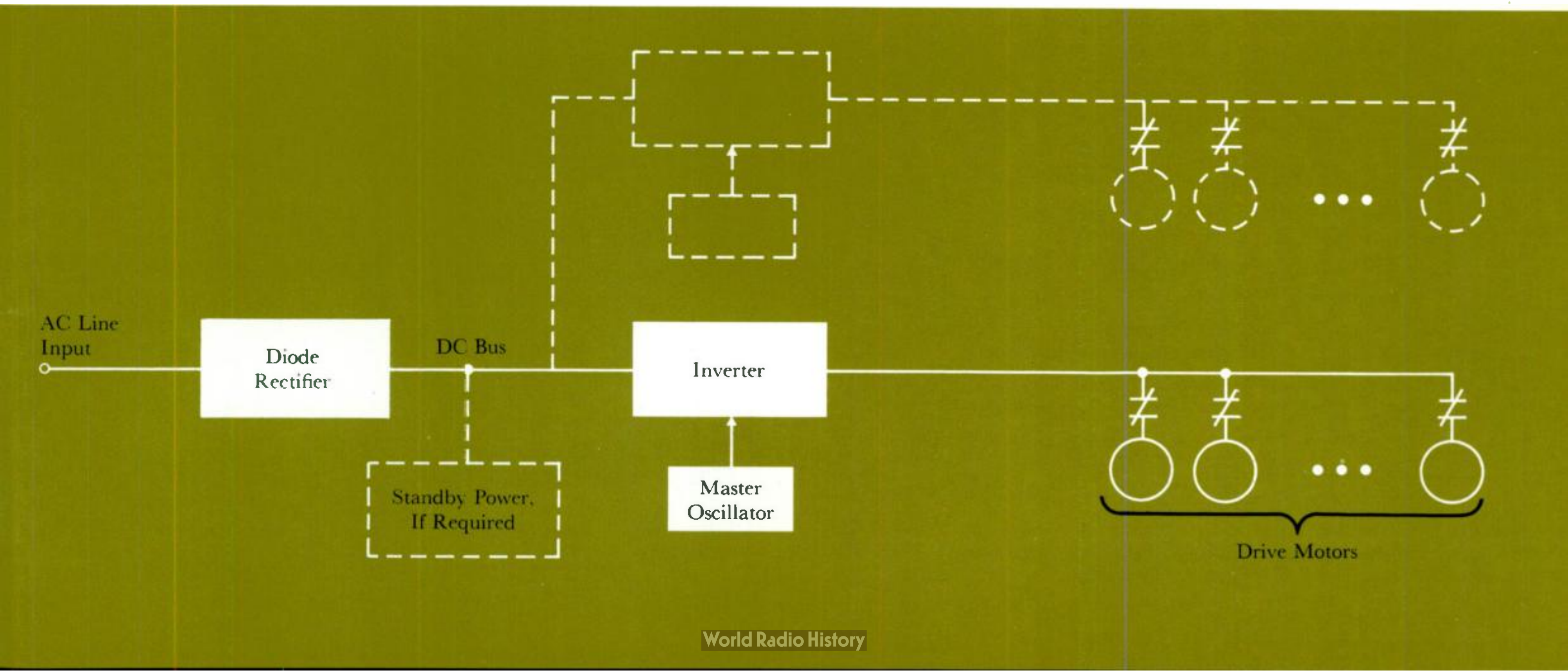
World Radio History

The motors used may be either induction or synchronous, depending on the accuracy of speed control required by the application. With induction motors, speed matching between units will be within ± 2 percent of top speed even with widely varying load conditions on each motor. Synchronous motors will have true speed matching at all frequencies of operation. Since the inverter supplies the same *synchronous* speed to all motors, any required differences in *shaft* speeds between motors must be achieved by different gear ratios, different pulley ratios, or, in some cases, by different pole combinations. Once the design ratios are established, however, all motors act as a coordinated group. Occasionally, mechanical speed adjusters are used on motors whose shaft speeds must be adjusted independently of each other.

Rating the Inverter

The selection of an inverter rating for a given application is little different from selecting an alternator drive for the same purpose. In either case, the basic information required is: Horsepower rating of each motor at maximum speed; type of motor (to determine its input requirements); number of motors to be run at one time; speed range required for continuous operation; and any *peak* loading requirement, such as acceleration, special motor starting conditions, or momentarily applied load.

With the motor output rating known, its input requirement in kva is found from efficiency and power-factor data obtained from the manufacturer. (Care must be taken not to underestimate the input requirements of synchronous motors, which have low power factor.) The total load on the inverter is found by adding the motor inputs, usually allowing a 10 percent safety factor for variations in motor data. The total is the continuous rating.



1—An AccurCon inverter drive system consists essentially of a rectifier, one or more inverters, and the drive motors. The adjustable output of a master oscillator governs the output frequency. A battery or capacitors can be included for emergency power supply.

To achieve the speed range specified, the engineer balances the gear ratio required (if any) with the motor frequency and pole combinations. A four-pole motor usually is chosen because it generally produces the optimum performance. A maximum frequency in the neighborhood of 120 cps is often aimed for because it reduces the size of both motor and inverter transformers. If a gear ratio is used, this frequency objective can usually be achieved. Without any gear ratio, however, the desired output speeds fix the frequency range. Minimum frequency should be no less than 10 cps because motor operation becomes marginal at such low speeds.

With kva and frequency range established, the voltage range must be specified next. As mentioned earlier, motors must operate at constant volts per cps to produce constant torque capability. The general practice is to use a standard 60-cps motor voltage, such as 220 volts or 440 volts, and to ratio the required voltages at other frequencies. Thus, a motor designed for 220 volts at 60 cps would be specified as 440/110 volts, 120/30 cps. Note that 440 volts at 60 cps would *not* be chosen because this would require 880 volts at 120 cps, which is above the standard 600-volt insulation class. In addition, when motor frequencies go below about 20 cps, the motor terminal volts per cps must be increased to avoid loss of torque. This "boost" in low-frequency volts per cps is much more easily provided by the inverter than by an alternator. The alternator requires more iron and excitation, often resulting in increased frame size. The inverter inherently has *more* than enough volts per cps at low frequencies.

Calculation of peak loading conditions is more important in applying inverters than in applying alternators. An alternator merely sags in voltage, possibly dropping motors out of synchronism but not usually blowing fuses. The inverter, on the other hand, tries to switch the excessive current until a "misfire" results in a short circuit across its dc input. The

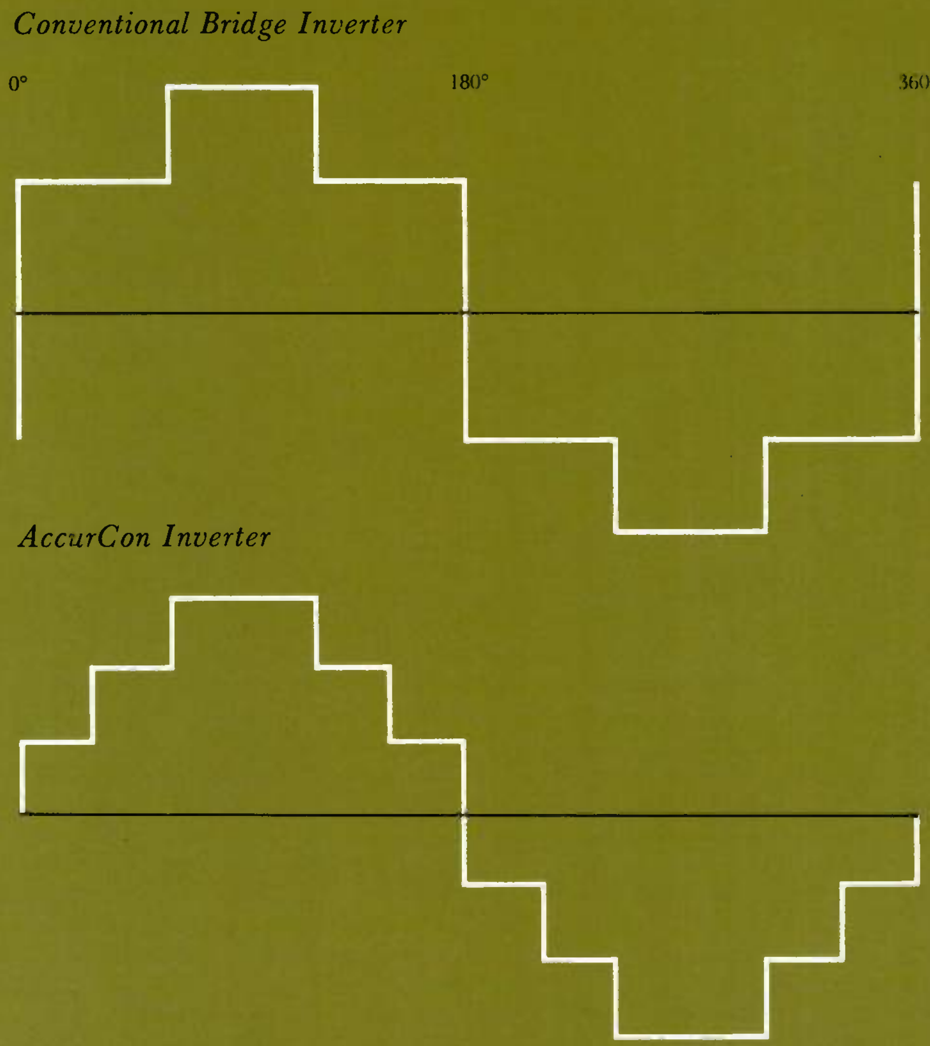
World Radio History

misfire is a failure of a thyristor to switch properly, and the ensuing short circuit across the dc bus blows the protective fuses and thus interrupts operation. For this reason, the inverter must be carefully selected to stay within its design limit, which is generally 150 percent of the continuous rating. For conditions of high peak loading, such as line-starting several motors at once, the inverter may have to be oversized.

A special factor in inverter application is that of power-supply disturbances, because the inverter has no kinetic energy of rotation to ride through power interruptions. All inverters do have a fair amount of capacitance that provides limited energy storage, but once the dc voltage drops below a certain level the inverter cannot switch properly. Thus, inherent carryover ability of inverters is limited to a matter of cycles, after which the unit must automatically shut down or else blow fuses. This means that in inverter use, as with most types of static equipment, the application must be examined to determine if added energy-storage devices are necessary. For noncritical loads, an orderly shutdown without fuse blowing is entirely satisfactory, and it permits restarting immediately after return of input power. For critical loads that cannot tolerate such interruptions, carryover can be extended by the use of capacitors or a standby storage battery.

Practical Effects of Wave Shape

Because an inverter produces its ac output wave by switching, the waveform has steps. The stepped wave is, at best, an approximation to the ideal sinusoidal shape. However, by using more thyristors to provide more steps, a closer approximation to the ideal is obtained. In the AccurCon inverter, the number of steps in the wave is double the number of stages used. Thus, the voltage output of a typical six-stage AccurCon inverter has 12 steps per cycle, while that of a conventional three-phase bridge inverter has six steps per cycle (Fig. 2). The measure of waveshape quality is in the *harmonic* distortion contained in the wave; the waveform of the bridge inverter illustrated in



2—The output voltage waveform from a conventional three-phase bridge inverter has fewer steps and therefore more harmonic distortion than that of a typical AccurCon inverter. Consequently, the latter is a better power source for motor operation or other critical loads.

World Radio History

Fig. 2 has some 30 percent distortion, while the AccurCon inverter has less than 15 percent.

The operation of induction motors is not generally affected adversely by normal harmonic distortion from a typical inverter output wave, say of 30 percent total harmonic distortion. First, the motor current wave is usually much smoother due to the filtering action of motor inductance effects, and it is motor current that directly establishes flux and torque. Second, since an induction motor operates on the principle of the rotor "slipping" with respect to the stator flux, there is substantial damping torque tending to oppose speed fluctuations. Thus, speed stability is rarely a problem with induction motors.

With synchronous motors, on the other hand, two factors make the situation different. First, a nonexcited motor such as a reluctance motor has nowhere near the same filtering action. The leakage reactance of such motors is substantially less, and the motor current wave can show severe peaks throughout each cycle. In a typical reluctance motor, for example, the six-step wave of Fig. 2 can produce an instantaneous peak of 175 percent of the fundamental wave. The 12-step wave produces a peak of only 125 percent under the same conditions. In either case, the inverter thyristors must be capable of switching this peak current; otherwise, a misfire and fuse blowing will result whenever the instantaneous peak occurs during a switching interval. It also follows that the 12-step inverter has a greater margin of safety because its peak current is less for the same basic conditions.

The second point of difference between synchronous and induction motors when operating from inverter power supplies concerns speed stability. A synchronous motor produces torque by operating with the rotor position lagging behind the stator field by a certain "load" angle. A common analogy is a "mass-spring" system, where increased deflection produces more torque (the spring) while angular changes require accelerating the rotor mass. In effect, the mass-spring system is an energy-storage element that can be set into oscillation, limited by whatever

Principles of Inverter Operation

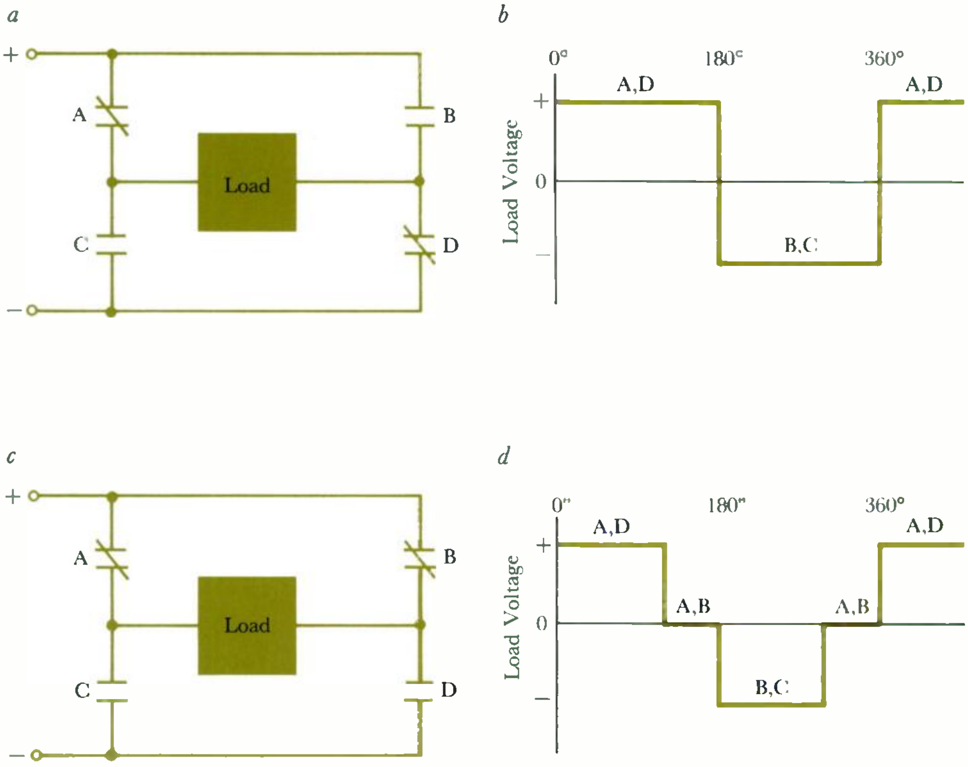
The basic principles of inverter operation can be illustrated by a switching analogy—a single-phase bridge arrangement of contacts connecting a load to a dc supply as shown. With contacts A *and* D *closed* (a), *current flows through the load. When these contacts are opened and contacts* B *and* C *closed, the current flow is reversed. The result is that the load is switched alternately from + to −, giving the load voltage shown in* (b). *The* RATE *of switching is the sole factor governing frequency of this wave; if the switching signals are derived from an accurate timing source, the output frequency will be just as accurate.*

The same switching analogy can illustrate voltage control as well. With A *and* D *closed* (a), *the positive half cycle begins. Next, only* A *and* B *are closed* (c), *which connects both terminals of the load together and results in a load voltage of zero. Then, only* B *and* C *are closed, giving the negative half cycle of voltage. Last, only* A *and* B *are closed, again producing zero voltage at the load. The cycle then repeats, giving the waveshape of* (d). *Although the frequency is still determined by the switching rate, the* WIDTH *of the positive and negative pulses is controlled by the length of time the* D *and* C *contacts are open. In this manner, the average voltage of the wave can be reduced as desired.*

*To achieve a three-phase output, a number of single-phase bridges are interconnected.**

---

*Helmick, C. G., and Lipman, K., "Adjustable-Frequency Power Inverter Systems for Industry," *Westinghouse ENGINEER*, November 1963, p. 167.



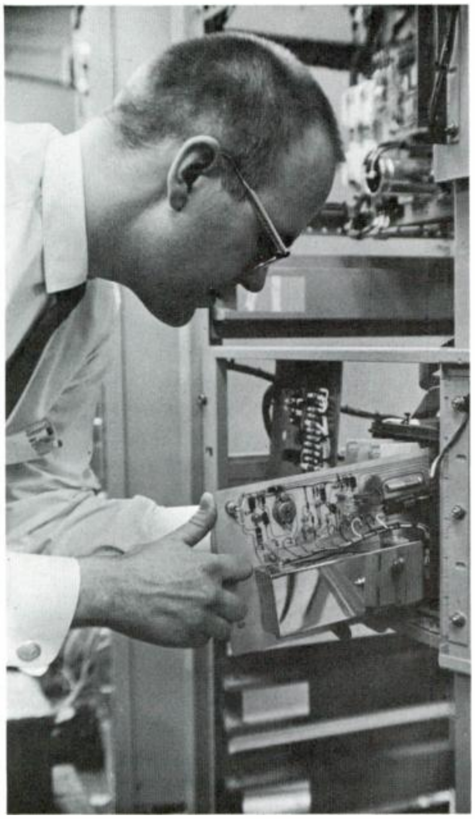
Inverter operation is illustrated by analogy with a bridge arrangement of switching contacts. Full voltage output is shown in *a* and *b;* reduced-voltage output through pulse-width control in *c* and *d*.

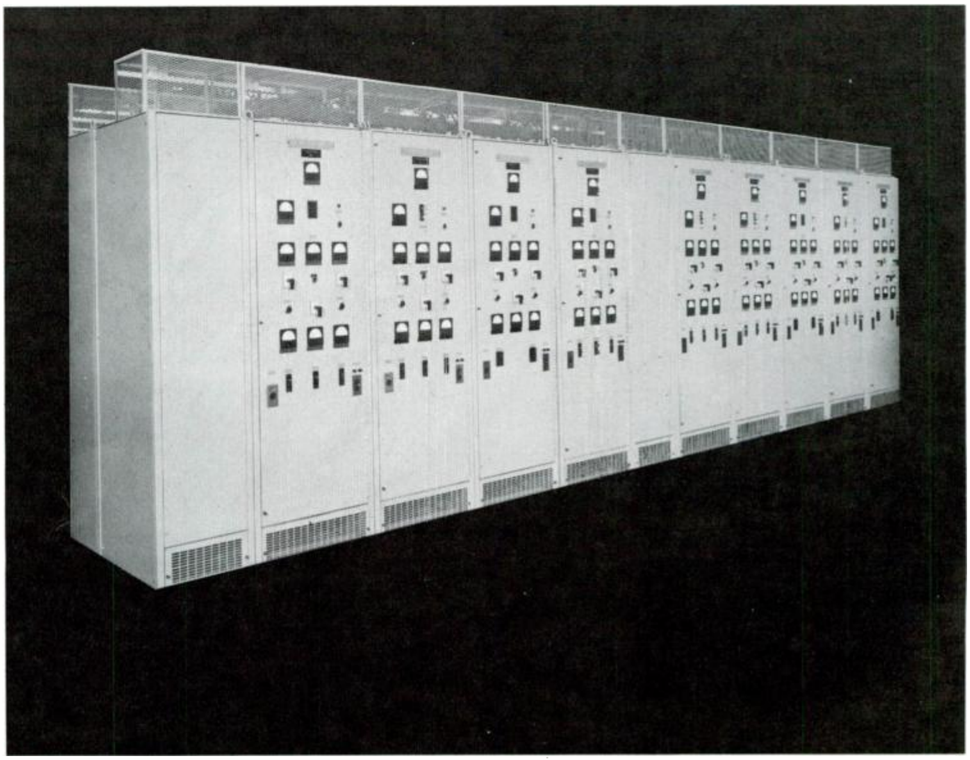
damping torques are available to make the oscillation die out. These damping torques are usually much less in synchronous motors than in induction motors, and at low frequencies there may not be enough damping to prevent sustained oscillation.

Synchronous motor stability depends on many factors, including the motor design parameters, system inertia, load damping, frequency of operation, inverter design parameters, and certainly the harmonic content of the inverter waveform. The six-stepped wave of Fig. 2, for example, has a heavy fifth harmonic, which can be thought of as a voltage rotating at five times speed in a direction opposing motor rotation. This can aggravate a speed oscillation by opposing normal damping torques. In contrast, the 12-stepped wave has as its lowest harmonic the eleventh, which is much smaller and also too high in speed for the motor to respond to actively. In summary, the inverter system designer must always consider motor stability in making his application, and untried motors must always be tested for stability.

The AccurCon Inverter System

Standardized subsystems provide basic flexibility in the AccurCon inverter system, making possible considerable custom designing for specific application requirements while using highly standardized parts for economical production and testing. For example, the lower half of the inverter in the photograph is completely standardized, having interchangeable





The logic drawer of an AccurCon inverter *(above, left)* has a front-opening door for easy access to the logic boards, which pull out for testing or replacement. The oscillator board shown has a temperature-control oven to assure frequency accuracy to ± 0.05 percent. Drawout construction and accessible component arrangement *(above, right)* facilitate field testing and service, as well as initial manufacture and adjustment. The lower half of this 60-kva unit contains standardized power and logic elements for the basic inverter. The upper half contains the rectifier and also the magnetic controls and transformers that fit the unit to the particular application. In a typical inverter lineup *(right)*, units are connected by buses on top.

World Radio History

power drawers and a logic drawer with printed circuit boards. These same parts can be used for ratings from 25 kva to 120 kva, regardless of the voltages and frequencies required in a given application. A second standard power module is used to increase the power rating; adding a third produces ratings as high as 750 kva in a single inverter. The custom variations required are achieved by the design of the output transformers, but all units have the same logic drawer and boards.

Component accessibility and drawout construction facilitate assembly, testing, and servicing. Troubleshooting the system also is simplified by provision of test points and by the interchangeability of parts (which permits troubleshooting by substitution). Parts interchangeability also minimizes the number of spare parts that have to be stocked, even for large installations.

Applying the Inverter

In each of the typical applications that follow, the inverter was selected because it outstrips all its competitors in overall performance, including economic performance. Whether chosen on the basis of accuracy, reliability, efficiency, continuity of service, reduced maintenance, or space saving, the choice was evaluated in dollars to achieve an end result.

The most attractive applications are those where the *unique* features of the inverter can be exploited. Nearly always, these are applications of groups of motors requiring coordinated operation.

An annealing-oven conveyor, for example, may require 50 to 75 one-horsepower gearmotors operating together and sharing load. A good selection is a squirrel-cage motor with five to eight percent slip, which will insure the necessary load sharing between motors. In this case, there is considerable saving in the first cost of the ac motors over dc motors. Additional savings accrue from lower installation and starter costs. Maintenance shutdowns for servicing need be scheduled much less frequently for the ac motors than for dc motors. It is important also that such a system have minimum downtime. Deriving the adjustable-frequency power from an inverter is consistent with industry trends toward static equipment and reflects the present emphasis on greater production availability from drive systems.

Perhaps the most common application for static inverters is in the man-made fiber industry. Production of these fibers places unique demands on a drive system because it requires precise speed accuracy for tight quality control, good transient performance to avoid shipping yarn with undetected lengths off specifications, and a high degree of service continuity to avoid extensive production losses and even equipment damage. (Power interruptions of only a few seconds can cause a complete machine shutdown and can upset critical chemical processes for many hours.) Small synchronous motors are almost invariably used to assure absolute speed matching of large numbers of motors fed from a single inverter.

Most such processes require several inverters for one machine, to supply different groups of motors performing different functions in the process. This requirement lends itself nicely to economizing through use of a complete lineup of inverters with a common rectifier and also common equipment to supply the necessary carryover during utility-system disturbances. Another saving is achieved by use of digital monitoring equipment that can scan many inverters to detect any off-speed operation. Such a sampling technique replaces the individual analog recorders that otherwise would be required. It is feasible because an inverter cannot drift suddenly off-speed unnoticed, which an m-g set can easily do as a result of system disturbances. The saving in instrumentation alone can amount to several thousand dollars in a typical installation.

A single-motor application can occasionally be justified economically, but it is more difficult because less expensive single-motor drives can often compete for a given set of requirements. The choice of an inverter in such a case must depend on one or more unique features that cannot be matched by other drives. An example is a critical metering-pump drive in a chemical plant, requiring precise operation in a highly explosive environment. The use of an inverter and an explosion-proof ac motor instead of its dc counterpart virtually eliminated the need for maintenance and periodic inspection of commutator and brushes. Substantial disassembly is required even for visual inspection of an explosion-proof dc motor, with the result that maintenance is expensive or even overlooked. The latter is intolerable in a critical process, since it may cause an unexpected breakdown.

While it is difficult to tabulate comparative drive-system costs for the static inverter and its competitors, some general guidelines have been established in the preceding paragraphs. As a single-motor drive, for example, the AccurCon inverter has higher first cost than a static dc drive, an eddy-current coupling, or a variable-pitch pulley drive. If its unique capabilities can be converted to dollars, however, the inverter can be justified.

For coordinated group drives, on the other hand, there is a distinct first-cost saving through use of ac motors instead of dc motors; the use of adjustable frequency is then justifiable. A given comparison depends on the number and size of motors used and whether special performance (precise speed, for example) is a requirement. With these conditions, the first cost alone of the inverter should be competitive with that of other adjustable-frequency drives. There are actual dollar savings in reduced floor space, maintenance, energy costs, and installation costs. The installation costs of an m-g set with its special foundation and alignment, or of an eddy-current drive with its water cooling system, can dwarf the cost of installing an inverter system.

Continuing developments in the technology of static power conversion promise additional economic benefits. While first cost probably will remain at present levels, new techniques undoubtedly will provide more rating from the same space, greater application flexibility, and further reliability improvement. The future, then, should see ever-increasing uses for static inverters, with increasing opportunities for profitable application throughout industry.

World Radio History

Steam Turbines for Nuclear Power Plants

Walter Sinton

In contrast to the present trend to superpressure steam turbines for large fossil-fired plants, the turbines for large nuclear plants of today are still restricted to relatively low inlet steam conditions. Despite this handicap, nuclear turbine ratings are approaching those of the largest superpressure turbines.

The comparatively low pressure and temperature of steam generated by today's nuclear plants provides a real challenge to the steam turbine designer. Pressurized-water reactor systems supply steam to the turbine at pressures ranging from 450 to 1000 psig, at essentially dry and saturated conditions (i.e., no superheat). Steam temperatures, depending on pressure, are in the neighborhood of 500 degrees F. And yet, despite these low inlet steam conditions, the turbines being built for today's large nuclear plants are comparable in rating with the large superpressure units used in fossil-fired plants, where inlet steam pressure is 3500 psig and inlet and reheat temperatures are 1000 degrees F.

To develop high turbine ratings with low inlet steam conditions, the turbine designer is restricted to a design approach with two basic limitations:

1) To offset the relatively low energy content per pound of steam, the turbine inlet and exhaust must pass large volumetric flows; and

2) Because of the lack of superheat in the inlet steam, moisture separation, reheat, or both must be used to prevent prohibitively high moisture content in the turbine exhaust stages which would cause excessive blade erosion and reduce thermal efficiency.

The success of turbine designers in overcoming these limitations is illustrated by the following comparison: the largest nuclear steam turbine now under construction at Westinghouse will have a rating of 1021 mw for inlet steam conditions of 730 psia and 0.25 percent moisture; in comparison, typical large superpressure turbines being built today have ratings ranging from 300 to 800 mw.

Basic Thermal Cycle

A straight regenerative cycle (steam extracted only to heat feedwater) with inlet conditions of 650 psig dry and saturated would result in exhaust moistures of 20 to 24 percent, which would be prohibitively high for large units. Therefore, the turbines for the first generation of nuclear plants, such as Shippingport and Yankee-Rowe, were designed with one stage of external moisture separation at approximately 10 percent of inlet pressure. This arrangement reduced exhaust moisture to approximately 13 percent, a satisfactory level from the standpoint of blade erosion, and produced a 2½ percent improvement in thermal efficiency compared to a straight regenerative cycle.

Additional cycle efficiency improvement has been obtained in all units designed by Westinghouse since Yankee-Rowe (Table I) by using live-steam reheat following external moisture separation at the exhaust of the high-pressure turbine.

A single-stage reheat cycle provides a thermodynamic gain ranging from about 1½ percent at 500 psig (dry and saturated) inlet conditions, to 2½ percent at 1000 psig. The optimum reheater pressure is 25 to 30 percent of turbine inlet pressure. The amount of steam required for reheating is approximately six percent of the steam generator flow.

A typical power cycle arrangement is shown in Fig. 1. This configuration specifically applies to the 616-mw unit manufactured by Westinghouse for the Connecticut Yankee Atomic Power Company at Haddam, Connecticut. The flows, pressures, temperatures, etc. shown in Fig. 1 represent a gross load of 600 mw at the generator terminals for an exhaust pressure of 1.5 inches Hg abs. The turbine is a three-casing 1800-rpm tandem-compound unit with a double-flow high-pressure element and a quadruple-flow exhaust with 44-inch last-row blades. A longitudinal section view of the turbine is shown in Fig. 2.

The moisture separator and steam reheater are combined in a single shell, as shown in Fig. 3. The number of separator-reheater elements required depends on volumetric flow and rating. Each separator-reheater element is sized to handle 125 to 200 megawatts of turbine capacity. The moisture separator operates on the demisting principle: steam is passed through stainless-steel wire mesh blankets and leaves the separator in a dry and saturated condition. The steam then passes over a bank of tubes where it is reheated to approximately 100 degrees F superheat. The separated water drains to the feed-water-heating system. The effectiveness of the moisture separator in removing water from the partially expanded steam is illustrated by the heat balance in Fig. 1. At a load of 600 mw, a total of 530,000 lb/hr of water is removed by four separator elements.

Economic studies indicate that six stages of feedwater heating are justifiable for large nuclear units. The highest-pressure extraction point is located in the high-pressure element of the turbine at a pressure that fixes final feedwater temperature at approximately 435 degrees for maximum load. The second extraction comes from the high-pressure turbine exhaust, which also supplies the separator-reheater elements. The remaining four extraction points are in the low-pressure turbine.

Steam Turbine Design

Moisture removal and erosion control are major considerations in the design of steam turbines for application with nuclear reactors generating dry and saturated steam. Moisture is removed at extractions to the feedwater heaters. The low-pressure extraction points are particularly beneficial. For example, approximately two percent of the total mass flow to the low-pressure turbine exhaust is removed in the form of free water by extraction steam flowing to the lowest-pressure heater.

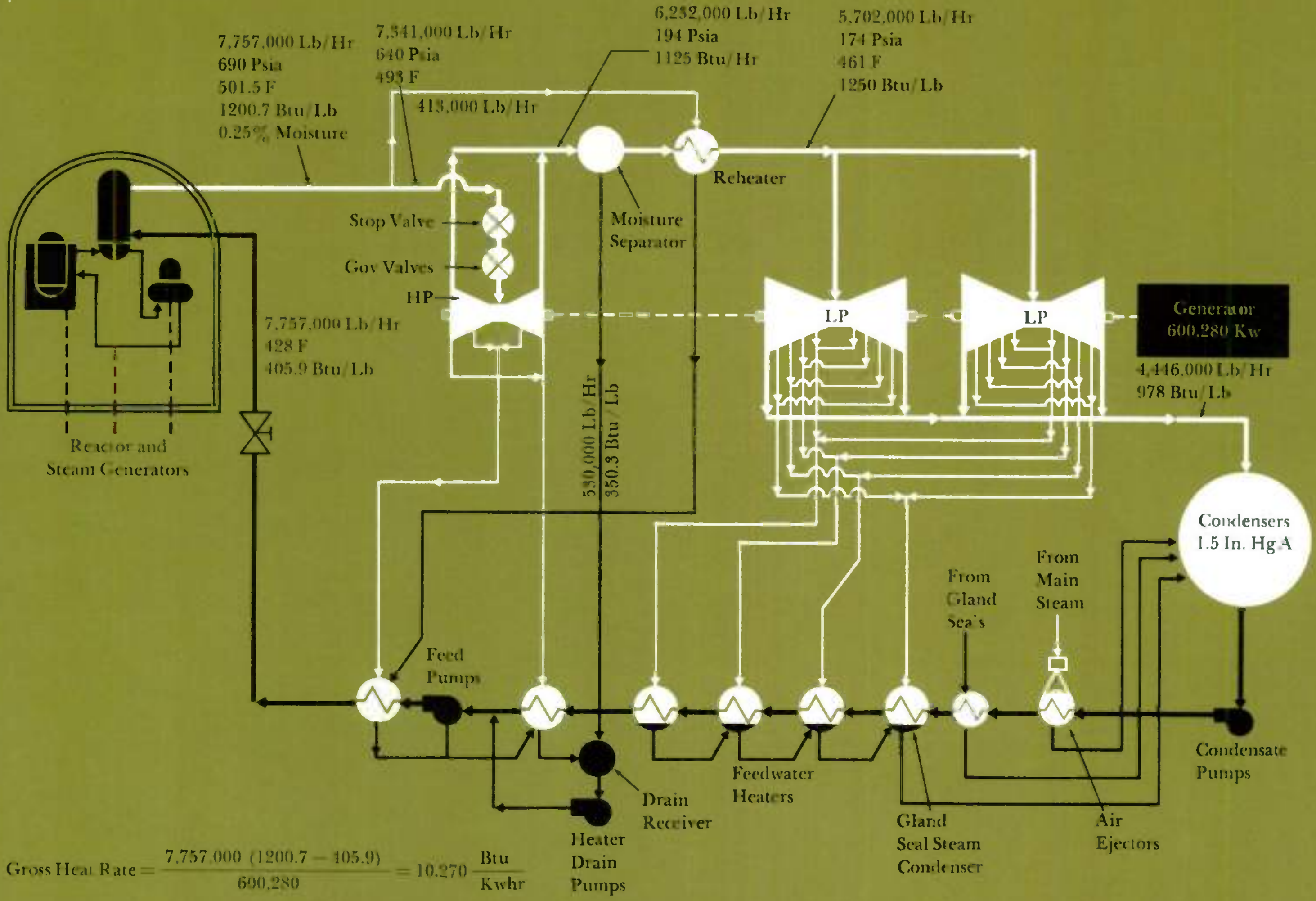
An additional moisture removal device at the inlet to the last rotating row in the low-pressure turbine has proved particularly effective in minimizing erosion of the critical blade-tip area. This device consists of a narrow circumferential slot just ahead of the inlet to the tip of the

---

Walter Sinton is Manager of the Apparatus Engineering Section, Large Turbine Department, Westinghouse Electric Corporation, Philadelphia, Pennsylvania.

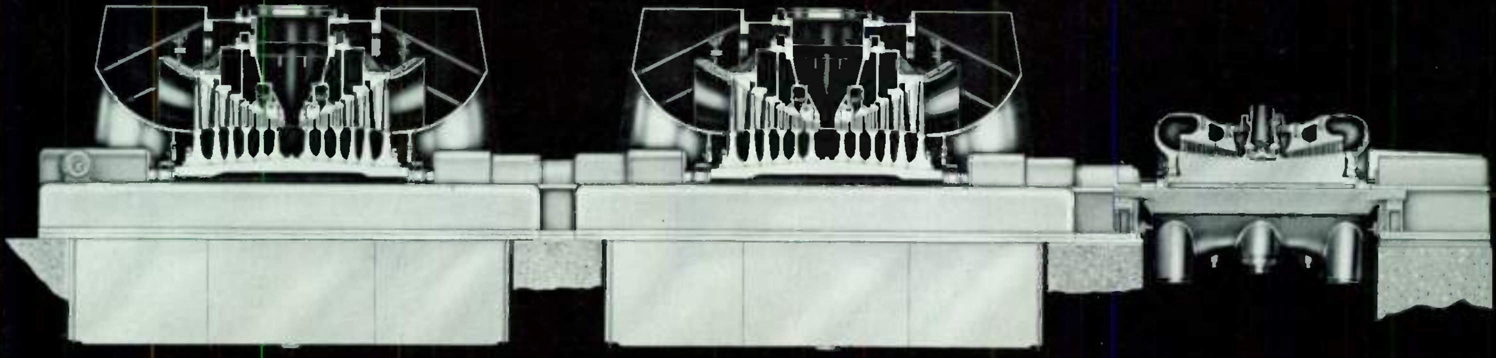
World Radio History

1–Typical Heat Balance Arrangement for Nuclear Unit



$$\text{Gross Heat Rate} = \frac{7{,}757{,}000\ (1200.7 - 405.9)}{600{,}280} = 10{,}270\ \frac{\text{Btu}}{\text{Kwhr}}$$

2–Three-Casing 1800-rpm Unit With Quadruple Exhaust



World Radio History

last rotating blade. A small quantity of blade-path steam flows through this slot directly to the exhaust, and by eductor action sucks a considerable amount of free water from the main steam flow at the tip area. This device has been tested and optimized on a half-scale laboratory model.

Adequate axial spacing between the stationary and rotating blades also is a key factor in minimizing low-pressure blade erosion. Further protection against erosion is provided by recessed stellite strips on the leading edges of the longer low-pressure blades at the critical tip zone.

For best efficiency, nuclear turbines should be designed for multivalve operation whenever control-stage blade stresses will permit partial-admission operation. Large 1800-rpm units up to 700 mw maximum can be designed for three valve points, with 50 percent minimum arc of admission, by using available high-damping material for control-stage blades.

The improvement in turbine part-load heat rate for multivalve operation is substantial. Typically, for a three-valve-point design the load carried at the primary valve point is approximately 75 percent of unit capability. At this load, the turbine heat rate is 2¾ percent better than would be obtained with a single-valve-point design of the same maximum capability.

Turbine Configurations

All Westinghouse nuclear plant applications in the United States have been single-shaft, 1800-rpm units (Table I.) The choice of 1800- rather than 3600-rpm elements is influenced by the following factors:

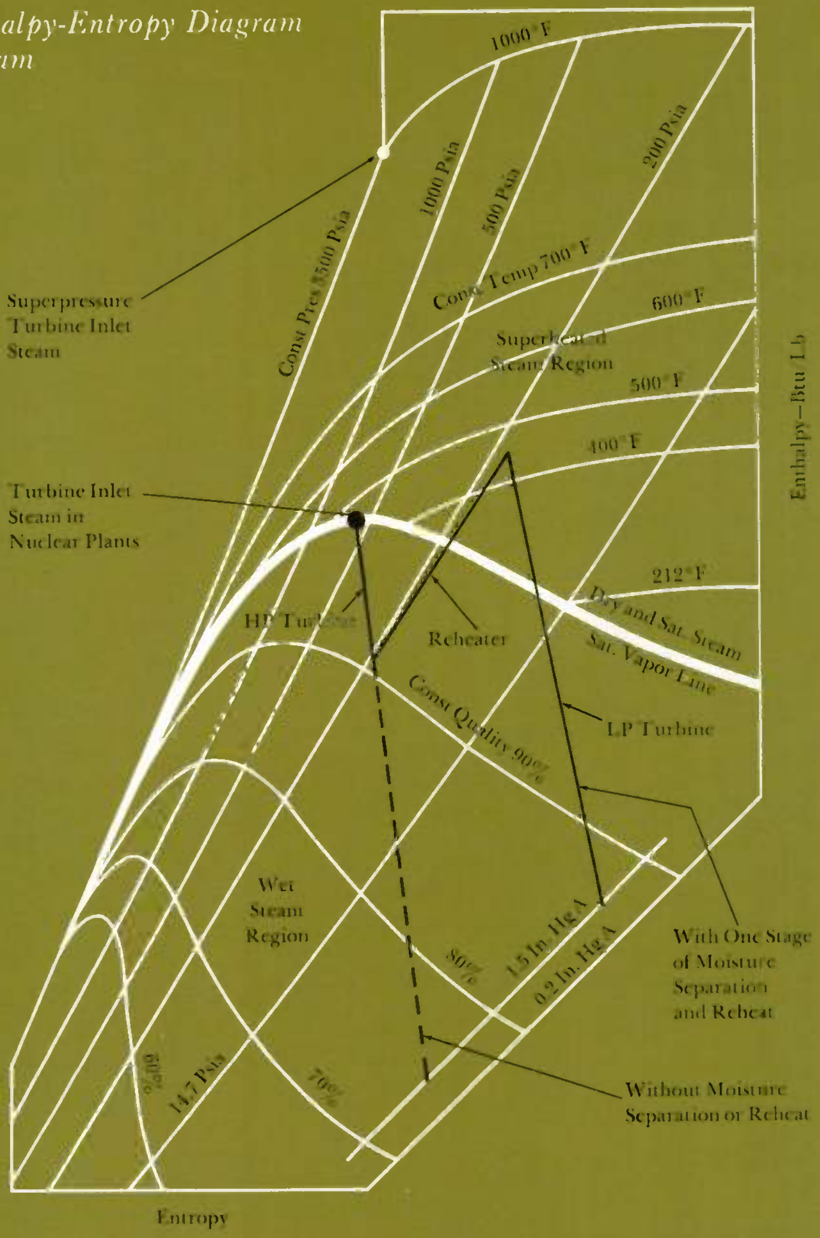
1) Fewer exhaust ends are required for a given rating;

2) Lower tip speed of 1800-rpm last-row blades reduces the possibility of erosion;

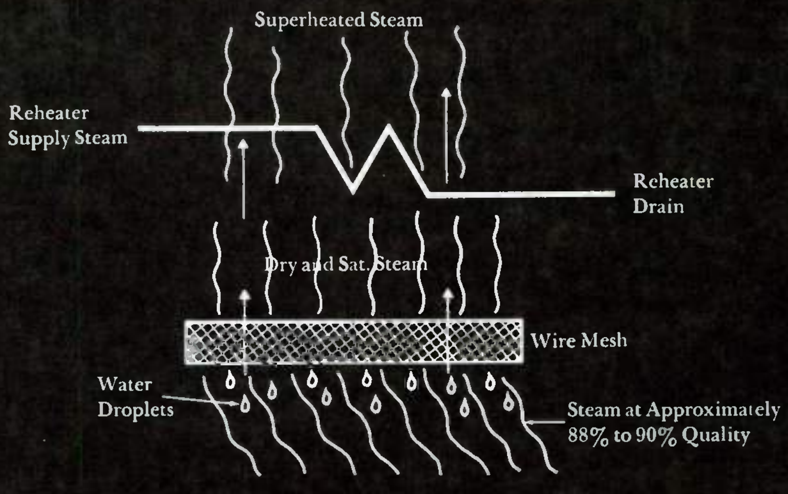
3) In certain cases, the plant can be simplified by eliminating the interceptor valves and relief valves from the piping system between the separator-reheater elements and the low-pressure turbines.

To clarify this last point, if intercept valves are omitted, the instantaneous re-

3–Enthalpy-Entropy Diagram for Steam



4–Combined Moisture Separator and Reheater



World Radio History

Table I–Westinghouse Nuclear Turbines 100 Mw and Above for Dry and Saturated Steam

Rating Mw	*Utility*	*Station*	*RPM*	*Configuration (single shaft)*	*No. and Length of Last Row Blade*	*Year Shipped*
100	Duquesne Light Company	Shippingport	1800	One Casing	1–40 in.	1956
185	Yankee Atomic Power Company	Rowe	1800	Two Casing	2–40 in.	1959
450	Southern California Edison Company	San Onofre	1800	Three Casing	4–40 in.	1965
616	Connecticut Yankee Atomic Power Company	Haddam	1800	Three Casing	4–44 in.	1966
160	Union Electrica Madrilena (Spain)	Zorita	3000	Two Casing	2–28 in.	1966
497	Rochester Gas & Electric Company	Brookwood #1	1800	Three Casing	4–40 in.	1968
1021	Consolidated Edison Company of New York	Indian Point #2	1800	Four Casing	6–44 in.	1968
728	Florida Power & Light Company	Turkey Point #3	1800	Three Casing	4–44 in.	1968
809	Consumers Power Company	Palisades #1	1800	Three Casing	4–44 in.	1968
739	Carolina Power & Light Company	H.B. Robinson #2	1800	Three Casing	4–44 in.	1968
450*	Wisconsin Electric Power Company		1800	Three Casing	4–40 in.*	1968
728	Florida Power & Light Company	Turkey Point #4	1800	Three Casing	4–44 in.	1969

**Subject to Change*

jection of full load results in the turbine overspeeding due to water flashing to steam in the moisture separator. When a large increment of load is suddenly rejected, the energy of this flashed steam plus that stored in the turbine and piping system after the inlet stop and governing valves are closed can cause turbine overspeeds in excess of the 120 percent designed for in conventional units. However, by using specific combinations of 1800-rpm elements, some nuclear plant turbines and generators have been designed with the same safety factor at these higher maximum speeds as conventional units have at 120-percent speed.

We would emphasize that as a result of the Northeast Blackout of November 15, 1965, most electric utilities have a different attitude toward separating large units from the line. New orders for nuclear turbines carry the stipulation that interceptor valves (backed up by stop valves and necessary relief valves) be provided to keep the units from speeding up and tripping.

A longitudinal section typical of the 1800-rpm three-casing Westinghouse design is shown in Fig. 2. Steam is admitted to separate nozzle chambers, in the center of the double-flow high-pressure element, from four individual governor valves through flexible pipe loops. These governor valves are mounted in pairs, two on each side of the high-pressure turbine. Each pair of governing valves receives steam from a single-stop valve attached in a "Y" configuration. The entire stop-valve and governing-valve assembly is sled-mounted and anchored to the turbine foundation above the floor line. Governing-valve sequence is such that the first two valves open together for 50 percent arc of admission; hence, three valve points are provided.

A separate blade-ring design and solid high-pressure rotor forging assure reliable, trouble-free operation. Seal strips in the high-pressure and low-pressure blade path are retained in double-depth grooves by Monel caulking strips to minimize erosion effects. Little maintenance is required with this arrangement.

In most installations, the separator-reheater elements are disposed symmetrically under the operating floor in a compact arrangement to shorten crossover piping as much as possible. These elements and associated piping can also be located above the operating floor; while such an arrangement may be aesthetically undesirable, it does offer design economies in some plants.

Table II–Typical Exhaust Arrangements for Tandem-Compound, 1800-rpm Turbines for Nuclear Plants

Number of Exhaust Ends	*Last-Row Blade Length*	*Nominal Maximum Rating*
2	40 inches	275 mw
4	40 inches	550 mw
6	40 inches	850 mw
4	44 inches	750 mw
6	44 inches	1100 mw
2	52 inches	520 mw
4	52 inches	1050 mw

Construction of the 1800-rpm low-pressure turbines is essentially the same as that of 1800-rpm elements in many non-nuclear plants. The rotors are built up of alloy discs shrunk and keyed onto an alloy shaft. The inner cylinder has separate carrier rings for inlet-end stages to minimize possible distortion effects on seal clearance. In addition, thermal shields are attached to the outside of the blade ring to reduce temperature gradients that cause distortion.

A list of various exhaust arrangements with their approximate capability, for cycles similar to that illustrated in Fig. 1, is shown in Table II.

Conclusion

The large 1800-rpm turbines operating in nuclear plants have been extremely reliable and have established excellent availability records. Design improvements in units currently being shipped should result in even higher availability and further reductions in maintenance cost.

Nuclear power plant costs will become competitive with fossil-fuel-fired plants in more and more geographical areas as plant sizes continue to increase. Proven concepts are available to permit the design of steam turbines for the largest nuclear plants now in the planning stage.

A New Lightning Arrester for Distribution Systems

Charles H. Carothers

Solder sealing, a better and smaller valve block, and a new gap element design have been applied to the Type LV distribution lightning arrester to improve performance and reliability.

The electric utility lineman will be the first beneficiary of the improvements in the Type LV distribution arrester—he will have a smaller and lighter device that is easier to install on the pole crossarm, and because of its improved reliability, under normal circumstances he should never have to climb the pole again to replace it.

The major improvements in the new LV lightning arrester include the use of solder sealing to make the device absolutely impervious to moisture, a new valve block that is only half the size of its predecessor, and a new gap assembly designed to take advantage of the smaller valve block. This single-pole arrester is manufactured in ratings from 3 to 21 kv for indoor and outdoor application, at altitudes up to 12,000 feet.

A cutaway sketch of the new LV arrester is shown in Fig. 1. The major operating components are the gap elements, valve blocks, and dropout assembly.

The gap elements withstand normal 60-cycle system voltage and determine the sparkover value for lightning surges or other system overvoltages. When this sparkover voltage limit is exceeded, the surge is shunted to ground through the arrester. The gap elements interrupt the power-follow current at the first current zero following the surge. The magnitude of the power-follow current is limited by the nonlinear resistance blocks to a value that the gap assembly can easily interrupt. These blocks have low resistance to lightning surge voltages and high resistance to normal 60-cycle system voltages.

The dropout device operates only if the arrester should fail; it disconnects the ground lead so that a failed arrester cannot become a permanent fault and cause a line lockout. In the early years of distribution arrester manufacture, this dropout feature was extremely important because arrester failures due to moisture entry were more numerous than they are today. Although the use of solder sealing has materially reduced the possibility of moisture in the new LV arrester, the ground-lead disconnector is still recommended due to other factors that can cause an arrester to fail.

Solder Sealing

Today's conventional distribution arresters can withstand nearly all of the conditions they are subjected to in field application, but arresters still fail. Most of these failures cannot be attributed to misapplication or high-current surges; studies reveal that about 90 percent of the failures are caused by moisture which has entered the arrester through damaged, deteriorated, or generally inadequate seals. Moisture reduces the radio influence voltage start level, changes the valve block characteristics, alters the gap sparkover voltages, and damages internal insulation. All of these effects contribute to the eventual failure of the arrester.

Solder sealing can eliminate this basic problem of seal failure, as demonstrated by 30 years of Westinghouse experience in sealing intermediate (IVS) arresters, capacitor bushings, and submersible transformer bushings. Although methods of gasket sealing have improved, experience has shown solder sealing to be the only reliable, permanent metal-to-porcelain seal.

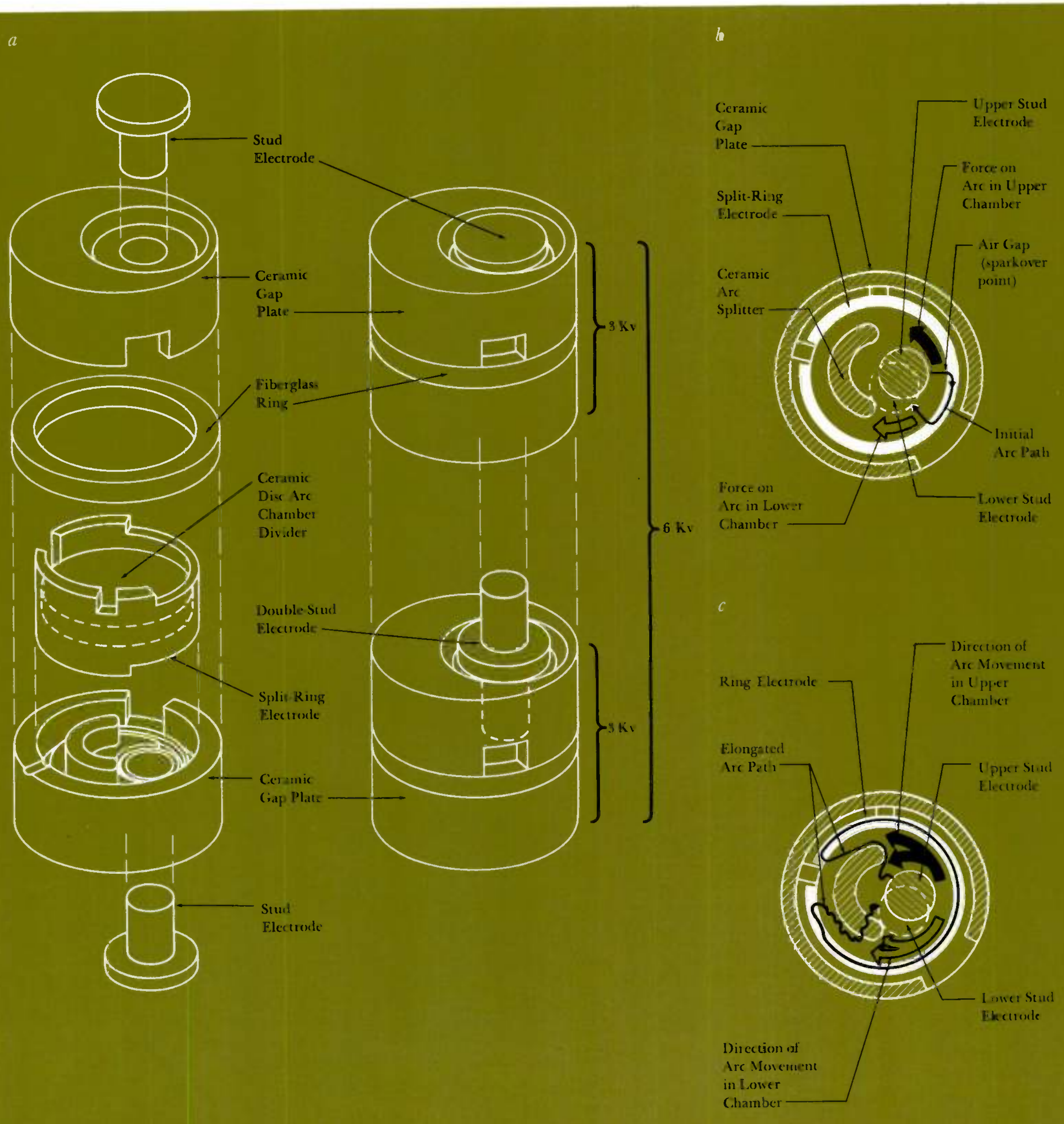
Solder sealing is best described as a fusion between solder, porcelain, and metal. The sealing process begins with the manufacture of the porcelain housing. A special platinum band is applied around the top and bottom of the glazed porcelain and fired. The platinum bands become part of the porcelain itself, and provide a suitable transition medium between porcelain and solder. The porcelain is placed in a jig to center a tinned cap around the porcelain, and the recess between the platinum band and the metal cap is filled with molten solder. This establishes metallic continuity between the porcelain housing and the metal cap, producing a seal that is inde-

1—Cutaway view of solder-sealed Type LV lifetime distribution lightning arrester (rated 9–10 kv) shows the various components as they are assembled in the arrester. An insulating cap is molded from a polyvinyl chloride material, which has excellent insulating and weathering properties.

2—*(a)* A gap assembly for the solder-sealed distribution arrester consists of 3-kv segments, connected in series to obtain the desired voltage rating. *(b)* The initial sparkover path is from the upper stud electrode, to the ring electrode, to the lower stud electrode. *(c)* The final elongated arc path makes it easier for the gap to interrupt the arc and prevents localized heating of electrodes.

C. H. Carothers is an engineer in the Lightning Arrester Section, Distribution Apparatus Engineering Division, Westinghouse Electric Corporation, Bloomington, Indiana.

World Radio History



World Radio History

pendent of climatic conditions, temperature fluctuations, installation treatment, or length of service.

Reduction of Valve Block Size

The greatest single contributing factor to the arrester's smaller size has been the development of a new valve block with better thermal absorption capability than that of previous blocks. The new distribution arrester valve block has been reduced to half the size of its predecessor, yet has twice the thermal absorption capability. This valve-block development was originally prompted by the advent of extra-high-voltage transmission systems, where the energy absorption requirements of lightning arresters had increased beyond conventional arrester techniques.

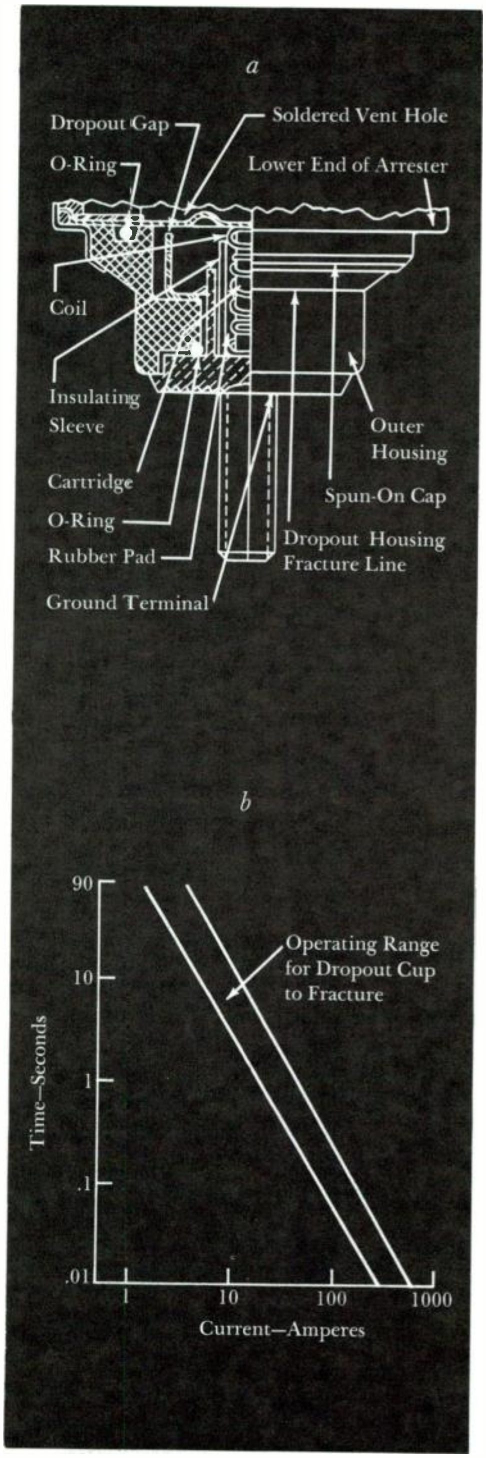
The increased thermal absorption capability of the block has been obtained primarily by the development of a new ceramic binder. A measured mixture of silicon carbide and ceramic binder is molded into small blocks in hydraulic presses under many tons of pressure and fired in kilns at temperatures in excess of 2000 degrees F. Precise control of each processing step assures constant and reliable electrical characteristics.

The number of valve blocks required in an arrester depends upon its voltage rating and varies from one block at 3 kv to seven blocks at 20 kv.

Gap Structure

The action of the gap structure in the solder-sealed arrester is self-driving in that the current in the arc acts on itself to move and elongate the arc to several times its original sparkover length. As the arc is stretched, it is cooled by contact with the cool ceramic arc-chamber walls. This stretching and cooling action eases the interruption of power-follow current and prevents burning or pitting of the gap electrodes to assure consistent sparkover characteristics for the life of the arrester.

The gap assembly consists of 3-kv segments (Fig. 2a), each consisting of two stud electrodes, a split-ring electrode, two mated ceramic gap plates, a ceramic disc arc chamber divider, and a fiber glass ring. When two or more 3-kv gap segments are used in series, a double-stud electrode between adjacent segments ties them together, both electrically and mechanically.



3—*(a)* Dropout assembly disconnects the ground lead if the arrester should fail. *(b)* Time-current characteristics of the solder-sealed Type LV arrester dropout device.

When an overvoltage surge appears at the arrester, the shortest sparkover distance provided by the gap structure is a double-gap path from the upper stud electrode, to the surrounding ring electrode, and then to the lower electrode, as shown in Fig. 2b. If several gap segments are connected in series, the surge current discharge travels through each gap segment in the assembly in the same fashion.

After the surge is discharged to ground, the power-follow current from the connected power source follows the same ionized path to ground for the remainder of the current half-cycle in which the surge occurred. While the power-follow current is flowing to ground, a current loop is formed by the arc across the air gap and the current flowing in the ring electrode. A differential of flux density is built up inside this loop producing a force on the arc that drives the arc out of the sparkover area. The magnetic field associated with the arc and current loop continues to act on the arc to force one foot of the arc toward the slit in the ring electrode while the other foot moves along and around the stud electrode away from the sparkover point (Fig. 2c). This same sequence of events occurs in each arc chamber in the gap assembly. The stud electrode is located off center from the center line of the gap to allow the arc to be stretched over a longer distance. This self-driving action of the gap combined with the current-limiting ability of the valve blocks ensures the interruption of power-follow current at the first current zero following the surge discharge.

Ground Lead Disconnector

Although the solder-sealing technique eliminates the major cause of arrester failures, a failure is still possible under unusually adverse conditions such as excessively high lightning surge currents, abnormal system voltages, misapplication, or a combination of these. Although such conditions are rare, a disconnecting

World Radio History

device can prevent any possibility of a line lockout (permanent fault on the line) due to a failed arrester.

The Westinghouse dropout device, illustrated in Fig. 3a, operates as follows: When the lightning surge passes through the arrester, it has the choice of two paths through the dropout assembly to ground—a coil or a gap, which are paralleled. Since the coil inductance appears as a high impedance to a steep-front lightning surge, the voltage drop ($E = L\, di/dt$) across the coil exceeds the breakdown voltage of the shunting gap, and the gap sparks over, discharging the surge to ground. Since the impedance of the coil is low to 60-cycle current, the power current that follows the surge transfers to the coil to flow to ground. The coil is made of wire large enough to handle normal values of power-follow current, which usually flows for less than one-half cycle before being valved off by the arrester. However, if the arrester is damaged, the dropout device is subjected to additional cycles of power-follow current, which quickly heats the coil and causes a cartridge, which is contained within the coil, to fire. This fractures the dropout housing and forces the ground lead away from the failed arrester. This prevents a line lockout and provides visual indication to aid in locating the damaged arrester for replacement. The range of actual parting time of the ground lead from the arrester is shown in Fig. 3b.

The dropout unit is free of radio-noise since the dropout gap is shunted by the coil to drain off any leakage current passed by the arrester. This coil arrangement protects the molded insulating cap from external tracking due to leakage current over the outside of a contaminated arrester, and also keeps the cartridge out of the leakage-current path.

During the development of the lifetime solder-sealed arrester, many tests were conducted to verify the dropout operation. In connection with these tests, a pressure venting method was also developed. A small hole is provided in the bottom plate and sealed with solder. Should the arrester dropout operate, low values of fault current will melt the solder from this vent hole. At higher fault cur-

Table I–Insulation Withstand Test Voltage

Voltage Rating of Arrester Kv (RMS)	*Impulse Test 1.5×40-Microsecond Full Wave, Kv Crest (BIL) (Minimum)*	*Alternating Current 60-Cycle Test Voltage–Kv (RMS)*	
		1 Minute Dry	*10 Second Wet (7000 Ohms/In³)*
3	45	15	13
6	60	21	20
9	75	27	24
12	85	31	27
15	95	35	30
18	125	42	36

Table II–Westinghouse Lifetime Solder-Sealed Type LV Distribution Arrester Performance Characteristics[1]

Arrester Rating							
Maximum Line to Ground Kv RMS Allowable	3	6	9–10	12	15	18	12
60-Cycle Sparkover							
Minimum Kv RMS	6	11	18	23.5	27	33	37.5
Impulse Sparkover[2]							
ASA Front of Wave Kv Crest							
Average	17	32	42	52	63	75	94
Maximum	19	35	50	60	75	90	100
Sparkover (1½×40)[3]							
Maximum Kv Crest	14	26	38	49	50	58	63
Discharge Voltage[4]							
Maximum Kv Crest With the Following Crest Current Values							
1,500 amp	10.0	19.0	30.0	38.0	45.0	54.0	63.0
5,000 amp	12.4	23.0	36.5	46.0	55.0	66.0	77.5
10,000 amp	13.8	26.0	41.0	52.0	62.0	74.0	87.0
20,000 amp	15.5	29.0	46.0	58.0	70.0	83.0	97.0
65,000 amp	19.0	35.0	56.0	71.0	85.0	103.0	120.0

[1] Values apply to both positive and negative polarity surges.

[2] Rate of rise is 100 kv per microsecond per 12 kv of arrester rating.

[3] Values given result in arrester operation for 100 percent of the surges.

[4] Discharge currents wave shape is 8×20 microsecond.

World Radio History

rents, the arc between the broken section of the dropout and the end cap of the arrester (as the ground lead falls away) develops sufficient heat to "burn through" the end cap, and releases any internal pressures. The venting hole is opened only when the arrester has failed. Normal operating temperatures will not melt the solder nor burn a hole through the bottom arrester end cap.

Tests

The solder-sealed distribution arrester has been manufactured and tested to meet all ASA and NEMA standards.

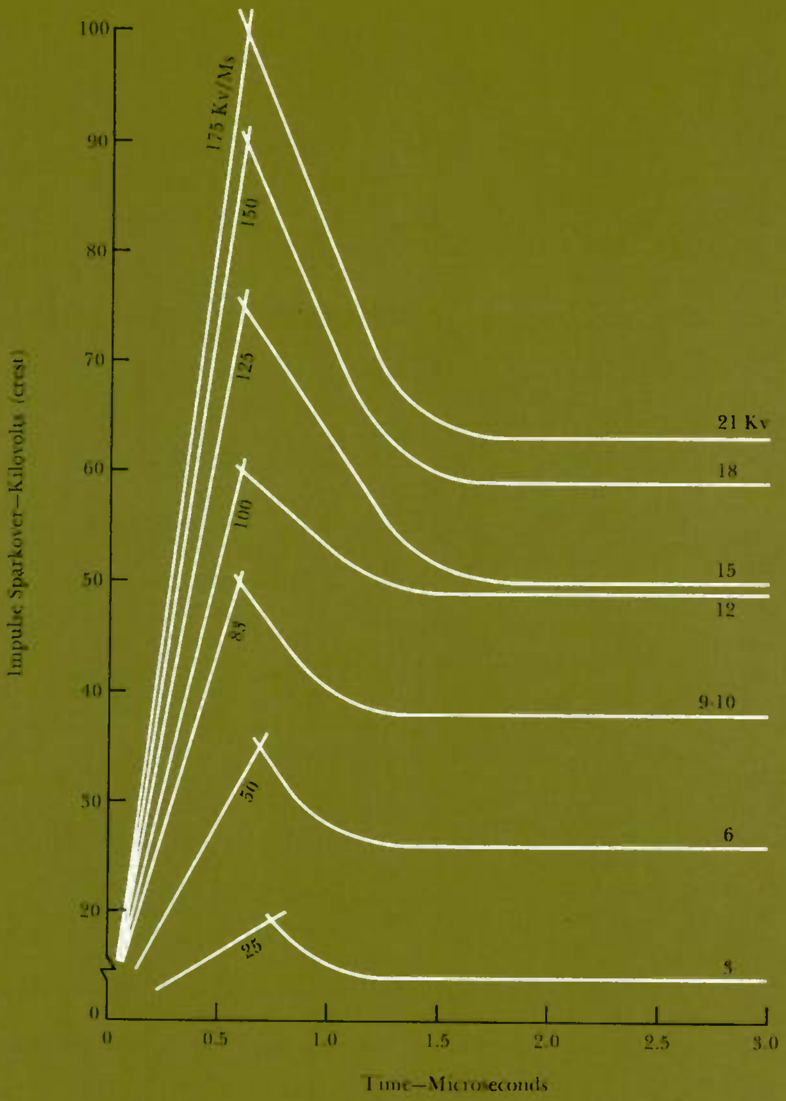
Both impulse and power-frequency withstand tests were run on the housing for each rating. The line connection was made to the top stud, and the ground connection was made to the bottom metal sealing cap. The arrester mounting clamp was at ground potential and the internal parts were removed. All of the ratings exceeded the NEMA withstand test voltages listed in Table I.

Many arresters of each rating were run on the power frequency sparkover tests. The 60-cycle sparkover of all arresters was well above the standard requirement of 1.5 times arrester rating. The minimum power frequency sparkover test results are listed in Table II.

Impulse sparkover tests were performed on all ratings of the new design according to standard requirements. The maximum impulse sparkover values are listed in Table II and the volt-time characteristics are plotted in Fig. 4. The discharge voltage characteristics of the arrester were obtained from tests of all ratings in accordance with standards. These test results are also listed in Table II.

Other tests performed include low-current, long-duration and high-current, short-duration withstand tests, duty-cycle tests, radio-influence tests, and dropout tests. In all cases, the solder-sealed arrester exceeded industry standards.

A number of production tests on each solder-sealed Type LV arrester and on samplings of parts are designed to insure that all manufactured arresters are of highest quality and will continue to meet all applicable arrester standards.



4—Maximum impulse sparkover volt-time characteristics in kv crest for the solder-sealed Type LV arrester.

Photo—A new valve block that is only half the size of its predecessor made possible this size reduction in the LV distribution lightning arrester.

World Radio History

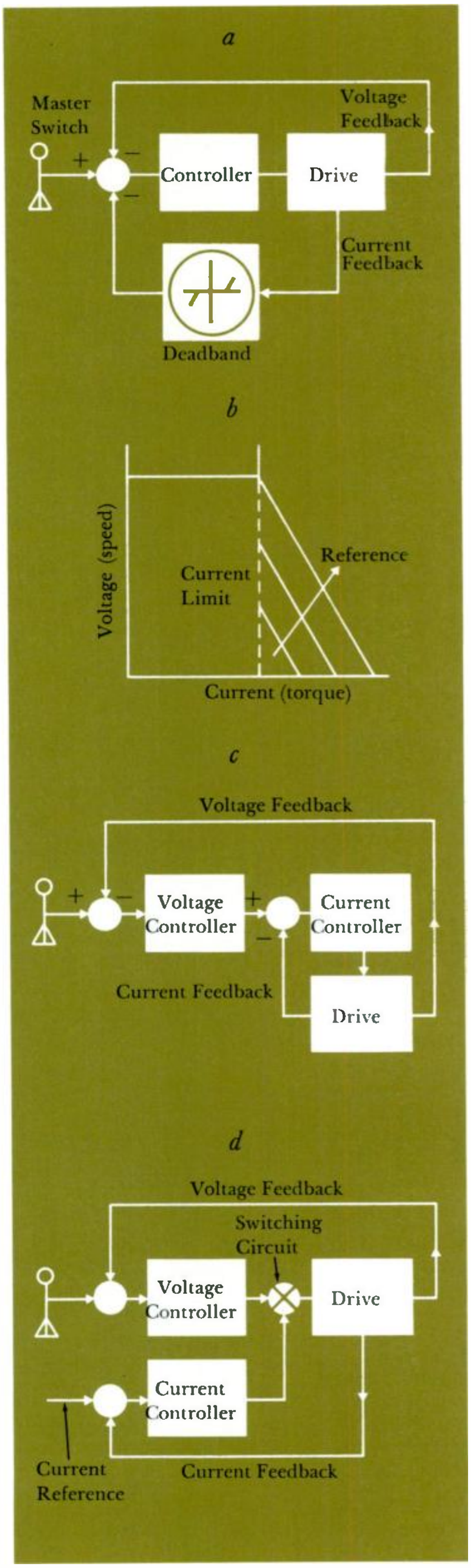
Parallel Control System Regulates Motor Speed and Torque

H. Eisele
A. M. Vance

Application of the parallel control principle gives new capability to dc drives for equipment that requires fast acceleration within current limits and without overshooting. The system has been applied successfully to excavating equipment.

The versatility of adjustable-voltage dc drive systems accounts in large measure for their continuing popularity. A large part of this versatility comes from the ease of controlling the dc motor's speed and torque: at constant field excitation, speed is proportional to armature voltage and torque is proportional to armature current.

The applied armature voltage and current can be regulated in a number of ways, and improvements in the way of doing it are constantly being sought to improve drive performance, reduce costs, and tailor the drive to specific types of service and to specific environments. A newly applied concept known as parallel control is one of the latest and most effective approaches to these goals. In parallel control, the voltage and current controllers are functionally in a parallel arrangement. Both controller outputs feed into a power amplifier, which energizes the field of the generator that supplies power for the dc motor armature. However, only one of these controllers is operating at any given time, a feature that makes voltage control and current control independent of each other. This feature suits parallel control especially to equipment that requires fast acceleration within current limits and without overshooting. Such equipment includes excavators (shovels, draglines, dredges), screwdown drives in steel mills, and log-carriage drives in lumber mills.



1—Drive-motor voltage and current can be controlled in three different ways. Spill-over control *(a)* has been used until now for the types of equipment treated in this article, but it is hard to adjust and the designer has to compromise between the desired steady-state and dynamic performances *(b)*. Multiloop control *(c)* has the advantage of a separate controller for each controlled variable but is unsuitable in other respects. The newly applied parallel control *(d)* has separate controllers arranged in parallel for better use of power and better protection of the equipment.

Advantages of Parallel Control

Drive and control systems for the equipment just mentioned need both voltage and current control to meet three essential requirements:

1) Because of the large investment in such equipment, the control must use the built-in power capacity completely during each duty cycle to achieve the highest possible productivity. This means that the drive should always work either at maximum available torque or at maximum speed. The limits of torque and speed (or of their analog variables, current and voltage) are determined by the electrical and mechanical design of the machine.

2) The control must limit drive torque quickly and securely, when the machine is overloaded, to protect the expensive mechanical and electrical equipment.

3) The control must provide smooth and efficient drive operation to allow the operator to control speed and torque easily. For that, the speed of the drive must follow a reference signal without overshooting, and the torque must have a closely limited buildup rate.

Voltage and current for such drives have been controlled in three different ways: spill-over control, multiloop control, and the newly applied parallel control discussed in this article.

The main advantage of *spill-over control*, which has been used until now for excavators, is that it requires the least equipment and thus is the least expensive solution so far as initial cost is concerned. Only one controller, usually a magnetic amplifier, is needed. In a voltage control with current-limit override, for example, the voltage signal is always fed to the controller (Fig. 1a). Current feedback is blocked by a dead band until the current-limit value is reached. Since there is only one controller for the two variables, voltage and current, it is necessary to compromise in the controller adjustment to come as close as possible to the required steady-state characteristic and desired

---

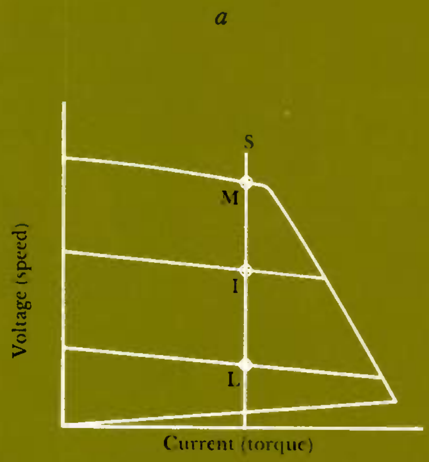
H. Eisele and A. M. Vance are in the Industrial Systems Division, Westinghouse Electric Corporation, Buffalo, New York.

dynamic response. In particular, the slope of the required current-limit characteristic influences the achievable response of the control. A vertical current limit, desired in some applications, cannot be obtained: the maximum value of armature current depends on the reference voltage (Fig. 1b).

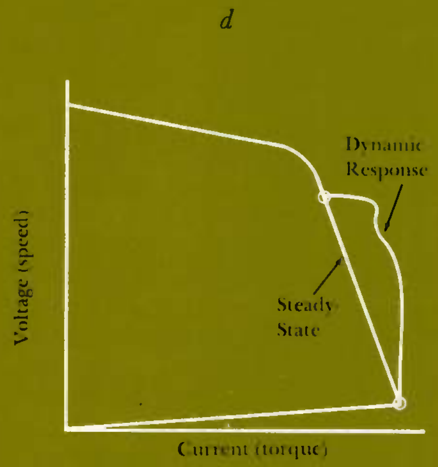
Multiloop control has a separate controller, usually an operational amplifier, for each controlled variable (Fig. 1c). The primary variable is controlled in the outer loop, and the output of the outer controller is the reference for the inner control loop. By limiting the output of the outer controller, almost every desired current-limit characteristic is easily obtained. The outer loop is adjusted to be only half as fast as the inner loop to provide dynamic separation of the two control loops. Startup is relatively simple, since the adjustments of the steady-state and dynamic characteristics are independent of each other. This type of control is often used for main drives in steel mills and paper mills, but it is not suited for the types of equipment mentioned earlier, for reasons that will be stated shortly.

In *parallel control*, a separate controller for each controlled variable is used, as in the multiloop type. However, the controllers are in a parallel arrangement, and their outputs are connected through a switching circuit to a common terminal (Fig. 1d). Only one controller is in operation at a time. In the example illustrated, the voltage controller is in operation as long as the current limit is not reached; the current controller is off during this time. When current reaches the limit, the current controller takes over the control of the drive and the voltage controller is automatically switched off. In essence, the current controller is working as a limit controller, and the voltage controller is in operation as long as no limit is reached. Steady-state and dynamic characteristics are adjustable independently of each other, just as in a

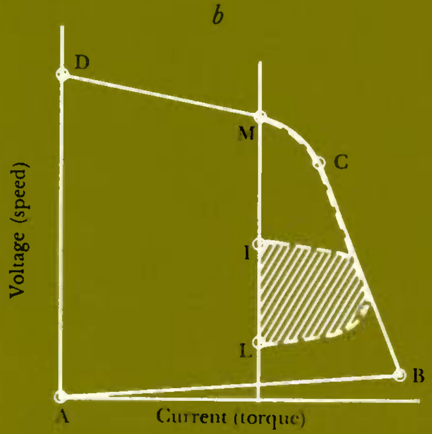
2—Ideal control performance for shovels and draglines, two main applications of parallel control. The curves closely represent actual performance of a parallel control system.



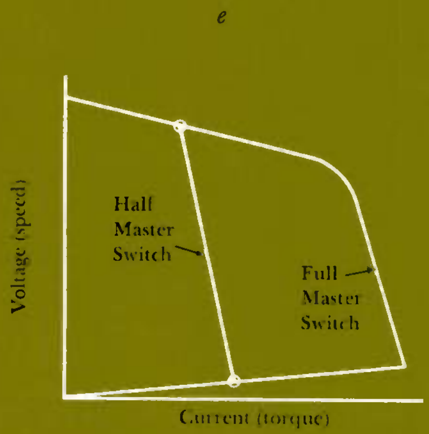
Steady-State Performance



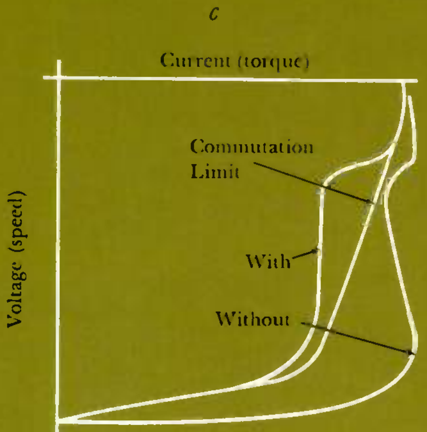
Dynamic Performance During Sudden Stalling



Dynamic Performance



Swing Motion Torque Characteristics



Dynamic Performance With and Without Plugging Rate Control multiloop control. The two control loops can be optimized independently, since only one controller is working at any one time.

Multiloop control and parallel control are clearly superior to spill-over control in performance and in simplicity of start-up. Parallel control has a number of advantages over multiloop control for the types of equipment that were mentioned earlier:

1) Shaping the required volt-ampere curves is simpler.

2) Voltage control is independent of the mechanical time constant of the drive. This is important because the mechanical time constant is changed at times during a duty cycle by weakening of the motor field. Also, inertias and corresponding mechanical time constants can change in certain applications, such as log carriers in sawmills.

3) Voltage overshooting can be avoided more easily.

4) Rate of current rise can easily be restricted within safe limits to extend the life of the commutators, brushes, and armatures.

These advantages led to the design of the new control system employing the parallel control concept. The system has been applied successfully and has proved itself in service. Before it is described, the drive requirements of excavators will be discussed as examples of the types of service for which the system was designed.

Excavator Requirements

Power shovels—machines of up to six cubic-yard capacity—were first used extensively to load rail cars and trucks in mining metal ores. Now, however, most loading shovels have grown to 10- and 15-yard machines. In strip coal mining, shovels and draglines of 100-, 150-, and 200-yard capacity are being used to remove overburden (see photograph). Machines of up to 50-yard size are used in phosphate mining.

With the machines growing larger, naturally an increasingly large investment is involved in each one. It is, therefore, increasingly important to the user to be able to place the machines into service quicker, obtain more production from the electrical equipment, and still provide better protection to this electrical equipment under operating conditions.

Shovel of 150 cubic-yard capacity is used for stripping overburden from coal deposits. It, like other large excavators, is powered by a number of dc motors energized by m-g sets. Motor speed and torque control must be precise and fast acting for maximum productivity and safe operation of the massive machinery. This control, effected by regulating the generator fields, has been greatly improved by application of the parallel control technique. (The shovel illustrated was built by Bucyrus-Erie Company for Peabody Coal Company.)

Individual dc motors were first used for each motion of a shovel or dragline. But as the machines grew larger, individual motor drives became impractical because of inertia and mechanical problems. The largest dragline today has 12 motors to power the hoist motion alone; 30 motors, energized by six 3000-horsepower synchronous m-g sets, are required to power all three motions. (In dragline operation, the *hoist* motion raises and lowers the bucket, which is suspended by cables; the *drag* motion fills the bucket by pulling it toward the cab; and the *swing* motion rotates the cab and boom to position the bucket as desired for digging and dumping. In shovel operation, the *hoist* motion pivots the "dipper stick" on which the bucket is mounted; the *crowd* motion pushes the dipper stick away from the cab, forcing the bucket into the bank to regulate the rate at which it is filled; and the *swing* motion rotates the cab and boom.)

The increase in machine size has created an urgent need for improvement in dynamic performance and protection of the equipment during sudden stalls. The following paragraphs describe ideal performance characteristics. Such characteristics are more closely attained by parallel control than by any other type of control available.

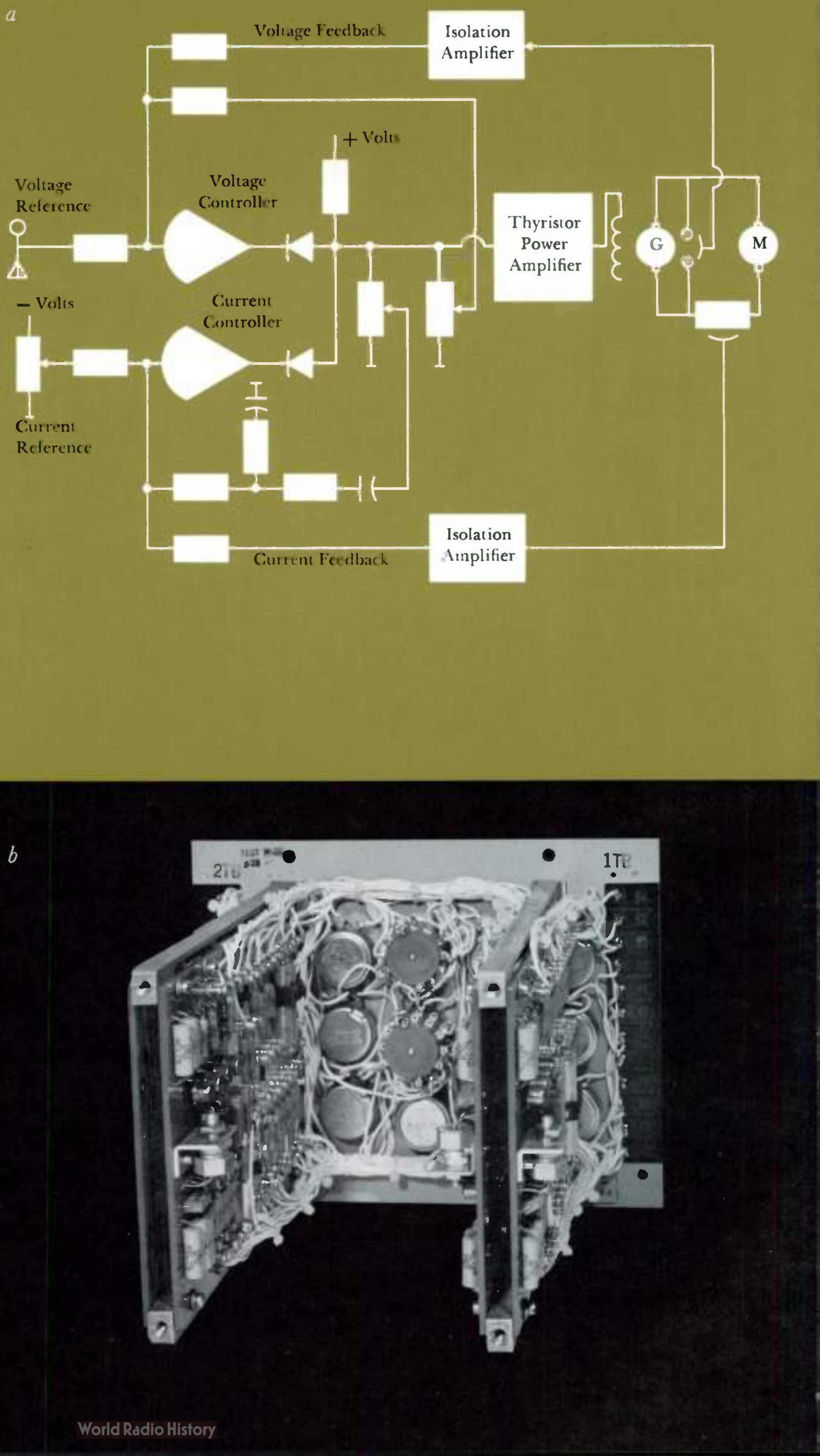
Hoist Motion–Several possible hoist-motion steady-state conditions are illustrated in Fig. 2a. If full-bucket motor torque is a value at "*S*", steady-state speed would be a point *L* for a low master-switch setting, *I* for intermediate, and *M* for maximum position. In excavator service, however, steady-state conditions are seldom maintained because circumstances are continually changing, requiring changes in speed from one steady-state condition to another.

The dynamic changes in speed in going from one steady-state condition to another are illustrated in Fig. 2b. While pulling in a dragline bucket, for example, the hoist is used to control the rate of loading the bucket. Each point in the path going from low (*L*) to intermediate (*I*) speed represents the speed and torque required at a specific instant to perform this operation. The greater the power available (shaded area) to perform the speed change, the more responsive the hoist motion is to the operator's signals.

When hoisting a loaded bucket to the dump area, dynamic performance must be such as to operate the electrical equipment as close to its commutation ability as possible to maximize production. That is, the hoist motion must approach the steady-state volt-ampere characteristics (*ABCD* in Fig. 2b) as closely as possible in going from point *L* to *M*.

To decrease the time needed to lower the empty bucket back into the pit, the hoist motor field is weakened. As the bucket nears the bottom, the operator rapidly changes the master switch from full-speed lowering to full-speed hoisting. This action, which includes automatic strengthening of the hoist motor field, produces a high-current high-power plugging peak at maximum motor voltage and speed. Plugging control must be provided to insure that the high current and power are held to the commutating limits of the motor and generator (Fig. 2c). When the drive is stopped without plugging rate control, the dynamic characteristics exceed the motor and generator design commutation limits and cause deterioration of commutation. The parallel control system provides the characteristics required to prevent excessive sparking at motors and generators at maximum speed.

Drag and Crowd Motions—The bucket, ropes, rack, and machinery are subjected to severe shock loading in these motions, the severity depending on the type of overburden, quality of blasting, and ability of the operator to avoid striking "hard spots" at high speeds. The control must have fast response to master switch



3—Parallel control system *(a)* for hoist, drag, or crowd motion of a shovel or dragline, diagrammed in simplified form. The voltage and current controllers are operational amplifiers for fast response and accurate control. These operational amplifiers are housed in an enclosed module *(b)*. The standardized module serves all excavator sizes because control parameters are adjustable through a wide range.

World Radio History

movement so the motion will speed up and slow down as required. However, it also must provide good torque protection by limiting current overshooting and mechanical stresses during the sudden stalls when hard spots are struck (Fig. 2d). The smaller the overshoot, the better the commutation of the motors and generators.

Swing Motion–This motion is the key to a more profitable cycle because it takes approximately two-thirds of the total cycle time. Swing duty is basically acceleration and deceleration, with little constant-speed running. Two factors influence the type of control needed. First, the drive's external inertia is much greater than that of the motors. Second, abrupt reversals must be prevented to protect the boom structure; therefore, drift should be available when the master switch is moved to the "off" position. For these reasons, the swing control should be a current or torque regulator and not a voltage or speed regulator as provided for the other motions.

The control must be so designed that the amount of torque available is proportional to the amount of master switch signal. The no-load (or maximum) speed will not be proportional to the master switch signal, so any speed is obtained by accelerating to the desired speed and bringing the master switch back to neutral. If the master switch is at 50 percent, the stall torque is 50 percent of maximum torque available (Fig. 2e). With the master switch in the neutral position and with the cab moving at some speed, the cab coasts because the regulator is controlling the drive for zero torque.

Operation of the Controllers

Operational amplifiers with solid-state components are used as voltage and current controllers in the new system (Fig. 3). They are almost ideal controllers because of their fast response and high gain.

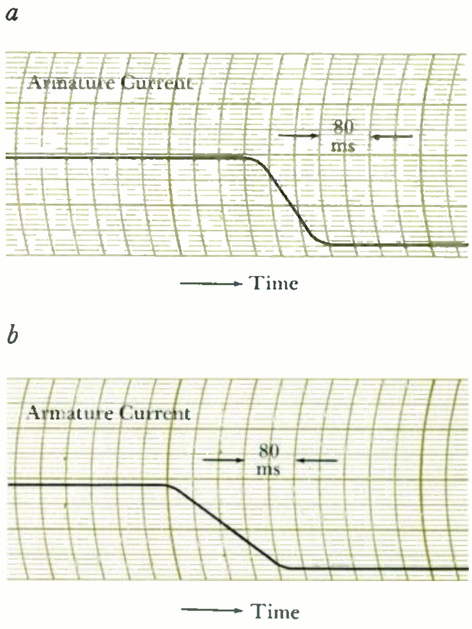
The master switch signal goes to the voltage controller, which has a proportional response and a gain adjusted so that 90 percent of the final voltage is reached 0.4 second after a step change in the reference. The current controller is an amplifier with PID (proportional plus integral plus differential) response, which permits compensating for generator and armature time delays. This makes a very fast current loop possible. The current, in fact, reaches current limit with a stalled motor about 0.04 second after a step reference change. Fast response of the current loop is essential to keep the current overshoot small when, for example, a bucket is stalled and the motor comes to a sudden stop. On the other hand, fast current response results in a high rate of rise of armature current, which could deteriorate the commutation of the drive during normal operation. Therefore, rate of current rise is limited to an adjustable value as long as the drive is operating inside the steady-state volt-ampere curve (Fig. 4).

Connection of only one controller at a time to the power amplifier, a thyristor module that energizes the generator field, is accomplished by the diode network shown in Fig. 3. The input voltage to the gating module is determined by the amplifier with the lower output voltage. Connection of the feedbacks of both amplifiers to a common terminal provides the correct initial conditions when an amplifier is switched in, and it produces a smooth take-over without steps.

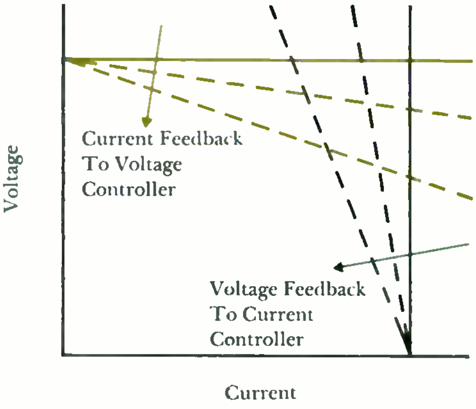
For the swing motion of a shovel or dragline, the current controller is the primary controller, with the current reference signal coming from the master switch. Otherwise, the controller arrangement is the same as that shown in Fig. 3. The integral portion of the current controller makes control of zero armature current at zero reference input possible for any armature voltage. This feature is important for the control of the swing motion since it avoids the provision, otherwise necessary, of a generator self-field.

Shaping the Volt-Ampere Curves

The curve shapes required for the specific application are achieved by applying additional feedbacks to the amplifiers (Fig. 5). Actual volt-ampere curves obtained during a laboratory test with different adjustments of the steady-state characteristics are shown in Fig. 6.



4—Rate of current rise is restricted to extend the life of commutators, brushes, and armatures. The response of armature current is illustrated *(a)* as it would be without limitation on rate of rise and *(b)* as it is with the limitation.



5—Steady-state characteristics required for excavator service are achieved by adding additional feedbacks to the voltage and current controllers seen in Fig. 3. Solid lines show what the characteristics would be *without* these feedbacks (color for voltage control loop, black for current loop). Dashed lines show the characteristics *with* the feedbacks; combined, these lines form the desired volt-ampere curves.

World Radio History

Component Arrangement

The entire parallel control system consists of two enclosed modules. One houses the operational amplifiers, with the required feedback networks, and the potentiometers for adjusting dynamic and steady-state control characteristics (Fig. 3b). The unit can be applied either as a current controller with voltage limit or as a voltage controller with current limit. Switching from one mode to the other requires only reconnection of jumpers.

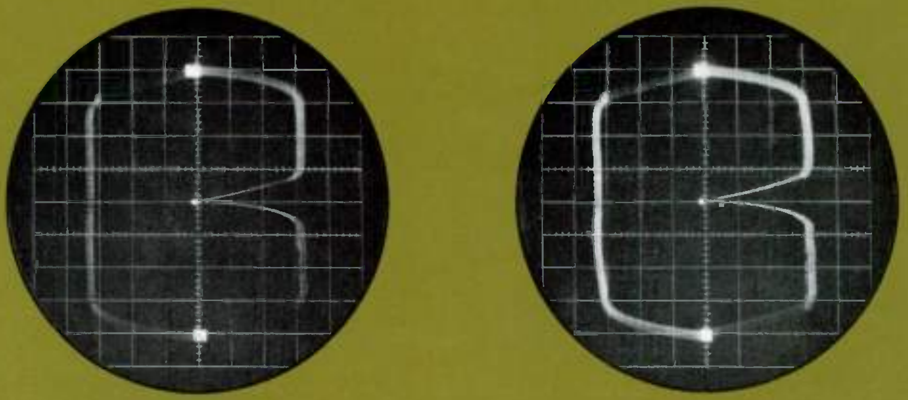
The second module contains the reference-shaping network and two magnetic amplifiers that isolate the feedback signals of voltage and armature current. These isolation amplifiers allow use of standard voltages for the feedback signals, independent of the power rating of the drive. The high gain of the isolation amplifiers also makes it possible to take the actual current signal from the shunt in the armature loop instead of using the voltage drop across the commutating winding. This frees the current signal from the voltage ripple across the commutating winding and makes it independent of operating temperature.

Summary

The parallel control concept has many advantages over the presently used spillover control for such applications as excavator drives. The main advantages are better use of the built-in power capacity, better protection of the mechanical and electrical equipment under impact overloads, and simpler startup. The basic controller can be used as either a speed or a torque controller, and its range of parameter adjustments covers all equipment sizes.

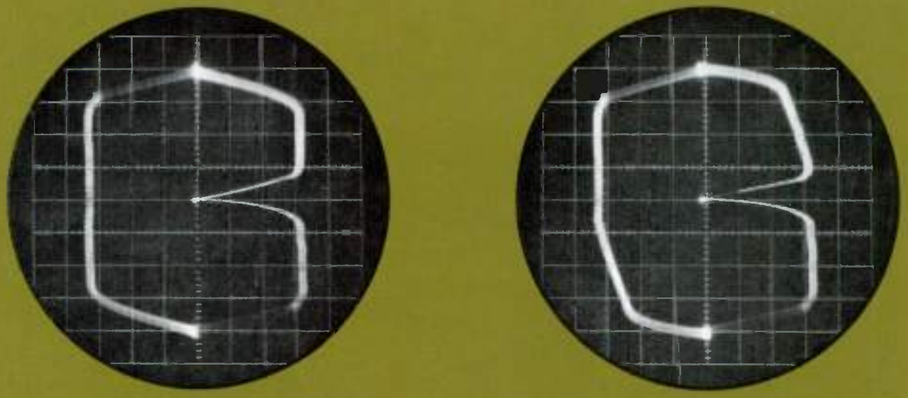
Westinghouse ENGINEER July 1966

Reference:
Stahl, K., "Limiting Control of Electrical Drives," *Proceedings of the First International Congress of the International Federation of Automatic Control*, Moscow. Published by Butterworth, London.



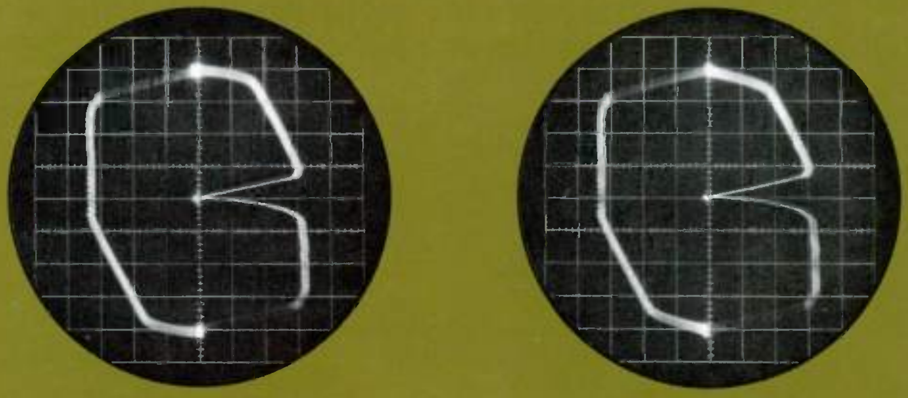
Vertical Current Limit, No IR Droop

Vertical Current Limit, One-Half IR Droop



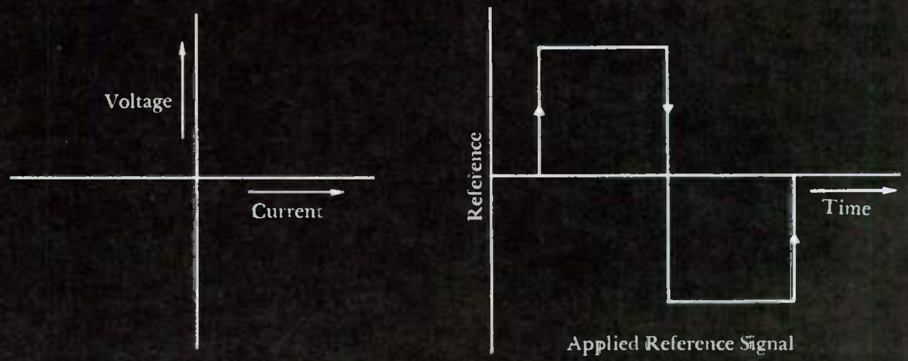
Vertical Current Limit, Full IR Droop

One-Half Current Limit Slope, One-Half IR Droop



Full Current Limit Slope, One-Half IR Droop

Full Current Limit Slope, Full IR Droop



6—Actual dynamic volt-ampere curves recorded with various adjustments of the controller parameters, resulting in different steady-state characteristics. The reference voltage was applied directly without plugging control and was switched from zero to full on, then to full reverse, and back to zero.

World Radio History

Automated Research Ship Outfitted

The *Oceanographer*, probably the world's most advanced deep-sea research ship, has been outfitted with the electronic equipment that makes her a floating laboratory capable of carrying out worldwide deep-water surveys. The main tasks of the equipment are to process huge amounts of oceanographic data and to monitor the ship's automated central engine-room control systems.

The data-processing system relieves scientific personnel of the tedious task of correlating and analyzing information collected from long expeditions at sea. In the past, many weeks or months were needed to process such data. The system will enable *Oceanographer* to carry out a wide range of oceanographic, geophysical, and hydrographic surveys.

The 303-foot 3800-ton vessel was constructed at Jacksonville Shipyards, Inc., Jacksonville, Florida, for the Coast and Geodetic Survey, now an agency of the U.S. Department of Commerce's new Environmental Science Services Administration. It is the forerunner of a sister ship, *Discoverer*, scheduled for outfitting later this year.

EHV Current Transformers Shipped Completely Assembled

Shipment and installation of large EHV current transformers are being facilitated by newly developed equipment consisting of rigid steel cradles, which support and protect the transformers, and specially modified tractor-trailer units. The equipment and techniques were worked out to ensure fast and safe delivery of the 25-foot 7½-ton current transformers that provide the signals to operate SF_6 power circuit breakers. The new shipping method also has the advantage of transporting the transformers completely assembled for easy erection: they can be installed in a matter of hours after their arrival.

Each tractor-trailer unit can deliver three transformers. On arrival, each shipping cradle with its current transformer is unloaded from the trailer by a crane and set vertically next to a prebuilt steel pedestal (see photos). The transformer is then separated from the cradle and hoisted onto its pedestal adjoining the SF_6 circuit breaker. Cradles are returned to the factory. The unit in the photos was one of three 2000-ampere transformers of 1800-kv BIL rating shipped 1033 miles in two days—from the factory at Sharon, Pennsylvania, to the Oklahoma Gas & Electric Company's Ft. Smith substation in Arkansas.

EHV current transformer is lifted from special truck in its protective cradle, set upright, separated from the cradle, and lifted into place on its foundation.

Electron-Beam Welder Operates Out of Vacuum

An electron-beam welder has been developed to make high-quality joints without enclosing the workpiece in a vacuum. The welder ejects its powerful beam of electrons through an orifice system that shields the beam from air with a cloak of lightweight helium molecules so it can do its work at atmospheric pressure. In addition, the new device is so designed that the welding head can be brought to the work rather than having to move the work under the welder. This unique portability qualifies the unit for consideration as a fabrication tool for large rocket boosters and space vehicles.

Electron-beam welding uses a minimum of heat to produce a joint, so the joint closely matches the strength of the highly efficient materials used in today's welded products. Efficient welds mean lighter structures and thus greater payloads. The problem has been that electron-beam welding has had to be done in a chamber evacuated below one-millionth of an atmosphere, and this restriction has severely limited the process by restricting its use to portions of a structure that could fit into the vacuum chamber.

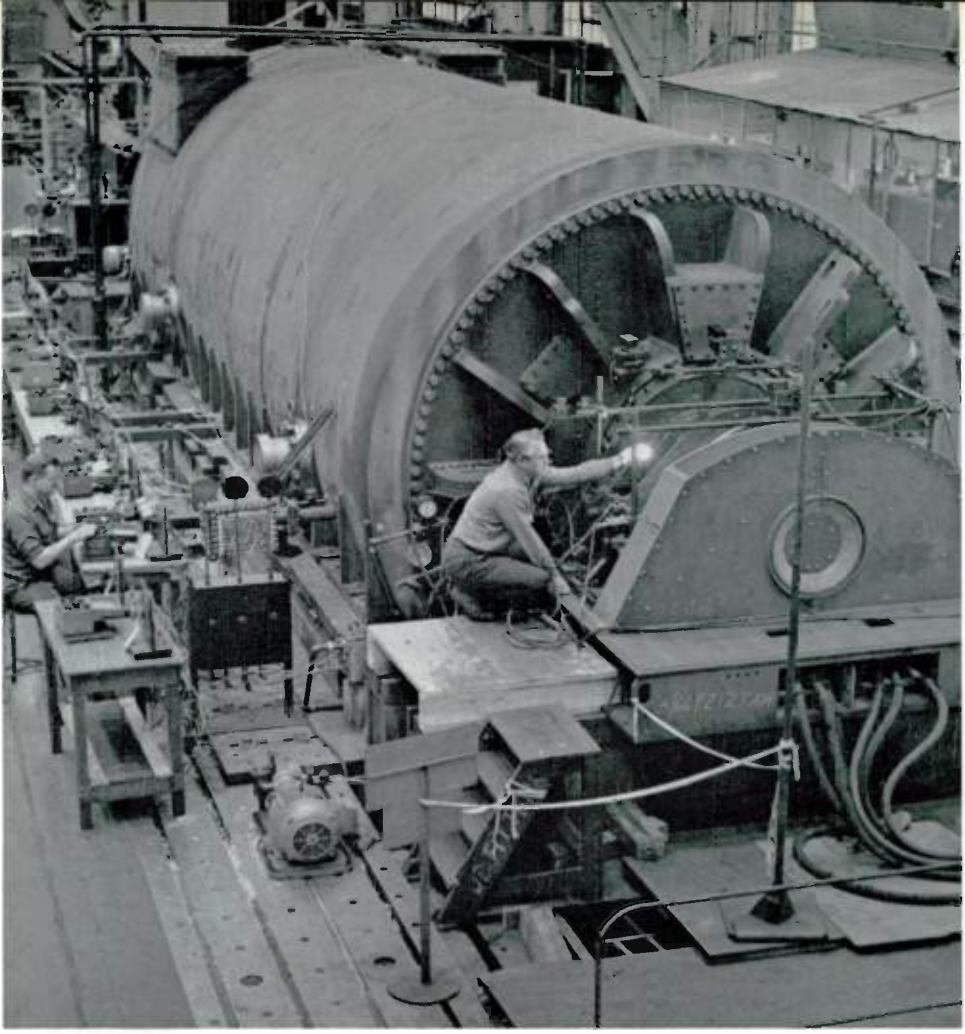
Under contract with NASA's Marshall Space Flight Center, Huntsville, Alabama, Westinghouse engineers are optimizing the new welding technique and have built a production model of a portable welder. The production model employs 13,000 watts of power at 150,000 volts. The electrons that make up its beam are emitted from a tungsten rod; under partial vacuum at their source,

World Radio History

they are accelerated and focused by a combination of electric and magnetic lenses. As the beam passes into the open atmosphere, helium gas flows around it to prevent heavier air molecules from dissipating the beam's energy. The helium also prevents oxidation of the workpiece. The welder can join metals up to one-half inch thick. It operates under a wide range of power levels and is designed for flexibility of operation.

Connecticut Yankee Generator Completed

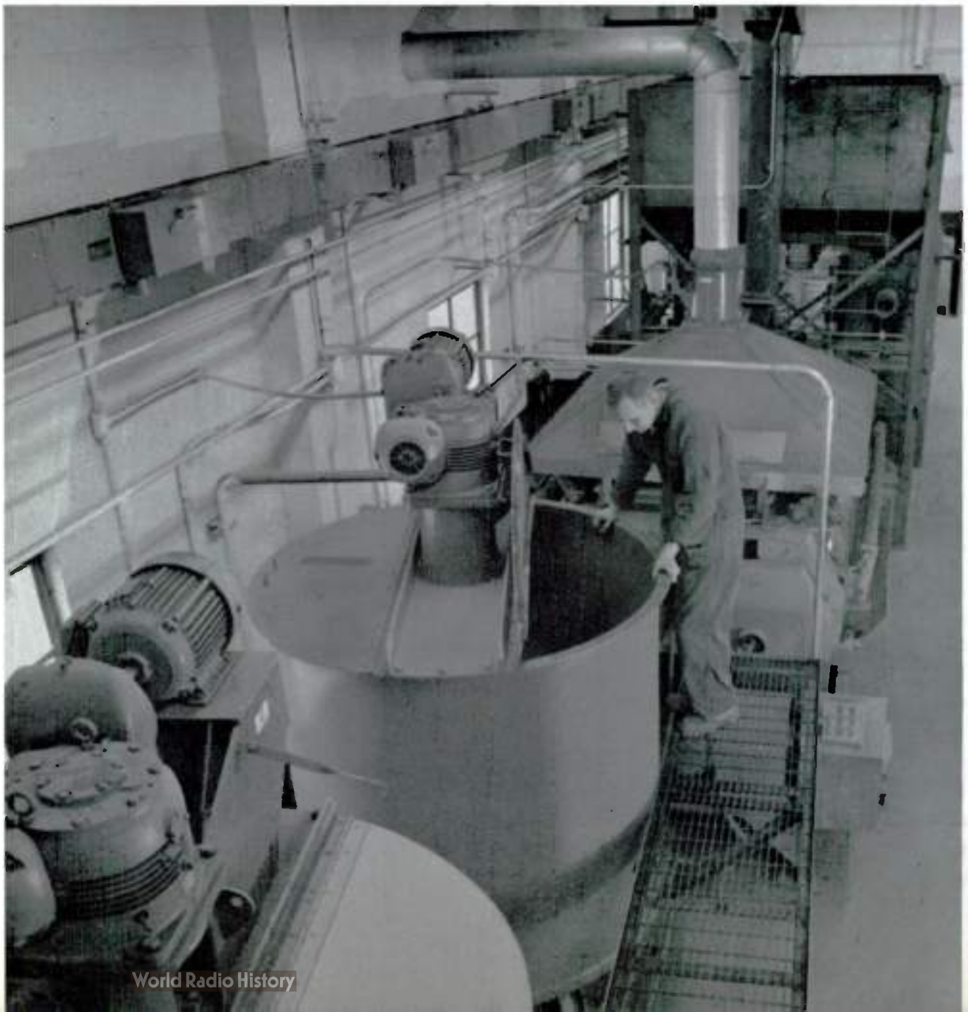
The generator for the nuclear plant of the Connecticut Yankee Atomic Power Company recently underwent rigid preshipment tests at the plant where it was built (see photograph, top right). The generator has hydrogen inner cooling and is rated 667,000 kva, 0.90-percent power factor at 60 psig. It weighs approximately 520 tons and is about 50 feet long. Excitation is provided by a 2600-kw brushless system employing rotating rectifiers, rather than by a conventional commutator-type dc excitation machine requiring brushes and slip rings.



Production Line Makes Superior Magnet Materials

An automated production line, the first in the industry, has been put into service at the Westinghouse Materials Manufacturing Division to produce ferrite powders for powerful ceramic permanent magnets. The line mixes the raw ingredients, dries them, and calcines the mixture, with an operator initiating and monitoring the various stages of the process (see photograph, right). The results are better and more uniform products and faster production.

After leaving the line, the ferrite pow-



Materials for ceramic permanent magnets are mixed and processed in this automated facility. Uniform processing improves quality and uniformity of the ferrite powder and also increases production of the end product—powerful permanent magnets.

World Radio History

der is compacted in special magnetic-orientation molds to form the desired shapes and the desired magnetic characteristics. The pieces are then sintered in a furnace to convert them to a hard material, ready for magnetization.

The powder line is part of an expanded facility for making sulfate-modified strontium-ferrite permanent magnets, which have about 30 percent higher coercive force (resistance to demagnetization) than other commercial ceramic magnets. This property makes them widely used in such applications as iron-ore separators, vacuum ion pumps, and refrigerator door latches; the new magnet facility is intended to broaden the range of uses still further by expanding production capability.

More Electric Helpers for the Home

Much of the continually increasing growth in residential electric loads can be attributed to the ever-increasing number of new jobs being found for electricity around the home. Two of the most recent homemaker's helpers are built into new Westinghouse electric ranges—an automatic stirrer and an oven cleaner.

The automatic stirrer uses the simple principle of "locking" one magnet to another (see photograph). A stirring arm and magnet assembly is placed in the cooking utensil, and a motor-driven rotating magnet in the center of the heating element then makes the stirrer rotate in synchronism. Thus, continuous automatic stirring is obtained without effort, making possible smoother sauces, cereals, puddings, and gravies without scorching. The automatic stirrer will operate in almost any kind of cooking utensil. This includes aluminum, glass, ceramic, and nonmagnetic stainless steel—about everything but the old iron skillet, which isn't used much in modern kitchens anyhow.

The second development takes care of the mess made when the cherry pie bubbles over—an oven that cleans itself electrically. Again, a simple principle is involved—merely apply enough heat to completely oxidize spilled food so that only a slightly adhering ash remains, which can easily be wiped away.

An automatic stirrer placed in a cooking utensil *(top)* is driven by a rotating magnet beneath the heating element. Self-cleaning oven *(bottom)* employs high temperature to oxidize charred food residues.

The homemaker just sets a switch and latches the oven door—the rest is automatic. (The latch mechanism locks to keep the door from being opened until the heating cycle is completed.) The oven heats to 1050 degrees F and then cools. The complete cycle requires about two hours, less than other "self-cleaning" ovens, which use lower temperatures. This higher temperature is made possible by the development of a new oven-lining enamel that can withstand the higher temperature.

Smoke is eliminated by forcing it into contact with the heating element, which operates at 1400 to 1550 degrees F (see sketch). This completes the oxidation process, so only clean gases can escape. To force the smoke particles into physical contact with the heater surface, numerous small ports are located directly above (and near) the heating element; all smoke must pass over the heating element to reach the exhaust plenum. Thus, a single Corox heating element in the top of the oven compartment provides both the heat for cleaning the oven and the heated surface to eliminate smoke.

At an electric rate of two cents per kilowatthour, the cost of cleaning an oven electrically is only about six cents.

Fresh-Water Factories to Provide Large-Scale Water Conversion

As water desalting plants increase in size and efficiency, they are being resorted to increasingly as sources of water for drinking, industrial uses, and boiler feed where natural fresh water is not available or where special purity is required. Two installations now being engineered illustrate the trend. One, to be built at Key West for the Florida Keys Aqueduct Commission, is the largest single-unit desalting plant in the world. The other, for the government of Kuwait, represents the largest contract ever placed for desalting equipment. Both are being built under turnkey contracts for design, engineering, construction, and initial operation of the plants.

World Radio History

The Key West plant, which will produce 2,620,000 gallons a day, is the first commercial application in the United States of a seawater desalting plant to provide a community's water needs. (Most other plants in this country are experimental units built under the Federal demonstration program.)

Residents and commercial establishments on Key West and the lower Keys now get their water supply from the U.S. Navy. A Navy-owned 18-inch pipeline transports 6,000,000 gallons of water daily 135 miles—from the Florida mainland to the lower Keys. The Navy now uses approximately 2,500,000 gallons of this water daily and sells the remainder to the Commission. However, the Navy has announced that it must increase its own use. The new desalting plant, plus a duplicate plant contemplated for construction by 1972, will give the Commission its own supply of 5,240,000 gallons a day.

The new plant will be the most efficient water desalting facility ever constructed, on the basis of the amount of steam required to produce a gallon of water. It will employ the multistage flash evaporation process, in which salt water is heated by steam from a boiler and sprayed into a series of chambers maintained at successively lower pressures and temperatures. A portion of the heated salt water flashes into vapor in each stage; the vapor is then condensed into pure water suitable for drinking or for industry.

The Kuwait installation will consist of three multistage flash evaporator units, each producing 2,400,000 gallons of drinking water a day from Persian-Gulf seawater. One unit will be built at Shuaiba, the other two at Shuwaikh. The units will operate with existing power stations at both sites and may replace obsolete desalting equipment there.

Products for Industry

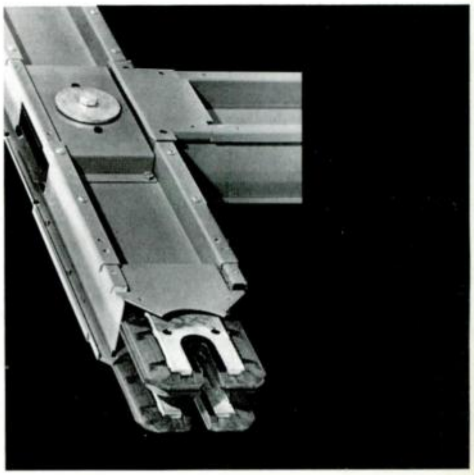
Field checking circuit assures motor field continuity before starting a synchronous motor. It prevents starting the motor if it detects an open circuit during its automatic prestart check of field winding, slip rings, brushes, and field discharge resistor circuit. Checking circuit is activated by pressing *start* button on controller. It is available as an option on new starters or can be added to existing starters. *Westinghouse General Control Division, 4454 Genesee Street, P.O. Box 225, Buffalo, New York 14240.*

Combustible limit relay (CLR) gives efficient, accurate, and rapid indication of unsafe accumulation of combustible gases in power transformers. The CLR is permanently mounted on a transformer to monitor it for signs of trouble so that action can be taken to prevent a more serious fault. It automatically samples the gas once a day and also can be operated manually anytime. Percentage of combustible gases is shown on a meter, and a relay operates an alarm if the amount of gas is excessive. A recorder can be connected to make a permanent record of gas percentage. *Westinghouse Power Transformer Division, Sharpsville Avenue, Sharon, Pennsylvania 16146.*

Raised flooring has die-cast aluminum girder understructure and Micarta surfaces. Applications include computer rooms, telephone installations, laboratories—anywhere easy access to underfloor wiring, plumbing, and other services is required. *Westinghouse Architectural Systems Division, 4300 36th Street, Grand Rapids, Michigan 49508.*

Six-Pak magnetostrictive immersible transducer system for ultrasonic cleaning has one six-kw ultrasonic generator driving six one-kw transducers instead of the conventional arrangement of one generator for each transducer. This arrangement makes for lower first cost. The immersible transducers are enclosed in leakproof stainless-steel cases and can be mounted in existing tanks, transferred from one tank to another, and used with several different cleaning fluids. The unit operates on 220/440-volt three-phase power instead of 110-volt single-phase, improving phase balance. Constructed of nickel rather than ceramic, the transducers are shock- and vibration-resistant. *Westinghouse Industrial Equipment Division, 2519 Wilkens Avenue, P.O. Box 416, Baltimore, Maryland 21203.*

Totally enclosed low-impedance bus duct can be installed in confined areas or where ventilated bus is prohibited. Voltage drop is less than three percent per 100 feet. Basically a feeder bus duct, the H-5000 line is intended for service at 600 volts ac or dc. Current ratings range from 600 to 5000 amperes with one, two, or three bars of aluminum or copper. Fault capacity is 100,000 amperes. The bus duct is available in three-phase three-wire or three-phase four-wire, half or full neutral. Installation is simplified by the use of a single-bolt splice. *Westinghouse Standard Control Division, Beaver, Pennsylvania 15009.*



World Radio History

About the Authors

K. M. Watkins earned his higher national certificate in electrical engineering in 1955 at Coventry Technical College, Coventry, England, while working as a student engineer with General Electric Company. Two weeks after taking his final examinations, Watkins was "called upon to serve the Queen," as he puts it. He was assigned to a technical training battalion and then saw active service with an armored regiment in the Middle East during the Suez crisis. He returned to General Electric after discharge to develop computer power supplies and readout devices. There he became interested in static power devices, an interest that has shaped his subsequent career.

Watkins moved to the (English) Westinghouse Brake and Signal Company, Rectifier Division, in 1958, where he worked on the design of control circuits for transistor and thyristor equipment and on new thyristor circuits. In 1961, he joined A. P. T. Electronic Industries to guide the design and production of transistor and thyristor power supply units. He then went to Winston Electronics in 1963, where he became chief engineer with responsibility for original circuit designs. Watkins came to the United States the following year to join the Westinghouse General Control Division, where he designs static power equipment—mainly inverters.

C. G. Helmick's name is familiar to *Westinghouse ENGINEER* readers, for he has been a frequent contributor of articles on industrial drive and control systems. He has helped develop such systems since his first Westinghouse assignment, which was with the Industrial Engineering Department in 1951.

Helmick earned his BSE in electrical engineering at the University of Michigan in 1950 and his MSE there the following year. He joined Westinghouse on the graduate student course and has since taken graduate work in business administration at the University of Pittsburgh and Carnegie Institute of Technology. Helmick transferred to the General Control Division in 1964 as product line administrator for adjustable-frequency inverters, a responsibility that includes systems engineering and coordination. He has been closely associated with the development of the adjustable-frequency inverters described in this issue.

Walter Sinton came to Westinghouse in 1941 after graduation from the University of Nebraska with a BSc in Mechanical Engineering. After completing the graduate student course, he was assigned to the pump and blower section of the Steam Division to design turbine-driven forced-draft blowers for naval application. In 1944, Sinton moved to the Large Turbine Department where he was responsible for the design of an integrated line of AIEE-ASME preferred standard Westinghouse steam turbines, in ratings ranging from 12.5 to 100 megawatts. Approximately 200 of these units are now in service.

Sinton was made manager of the Medium Turbine Apparatus Section in 1956, responsible for the design of all units to 100 megawatts maximum. He assumed his present position in 1961 when he was appointed manager of the Large Turbine Apparatus Section, responsible for customer order engineering design of large turbines.

Charles H. Carothers graduated from the University of Texas with a BSEE in 1959, and came with Westinghouse on the graduate student course. After six months on student assignments, he joined the lightning arrester engineering section of the Distribution Apparatus Department. His primary responsibility is the design and development of distribution- and secondary-voltage lightning arresters. In addition to the solder-sealed Type LV distribution arrester described in this issue, Carothers has also been instrumental in the design of the Westinghouse handwheel Type LV distribution arresters and the Type AP appliance protector.

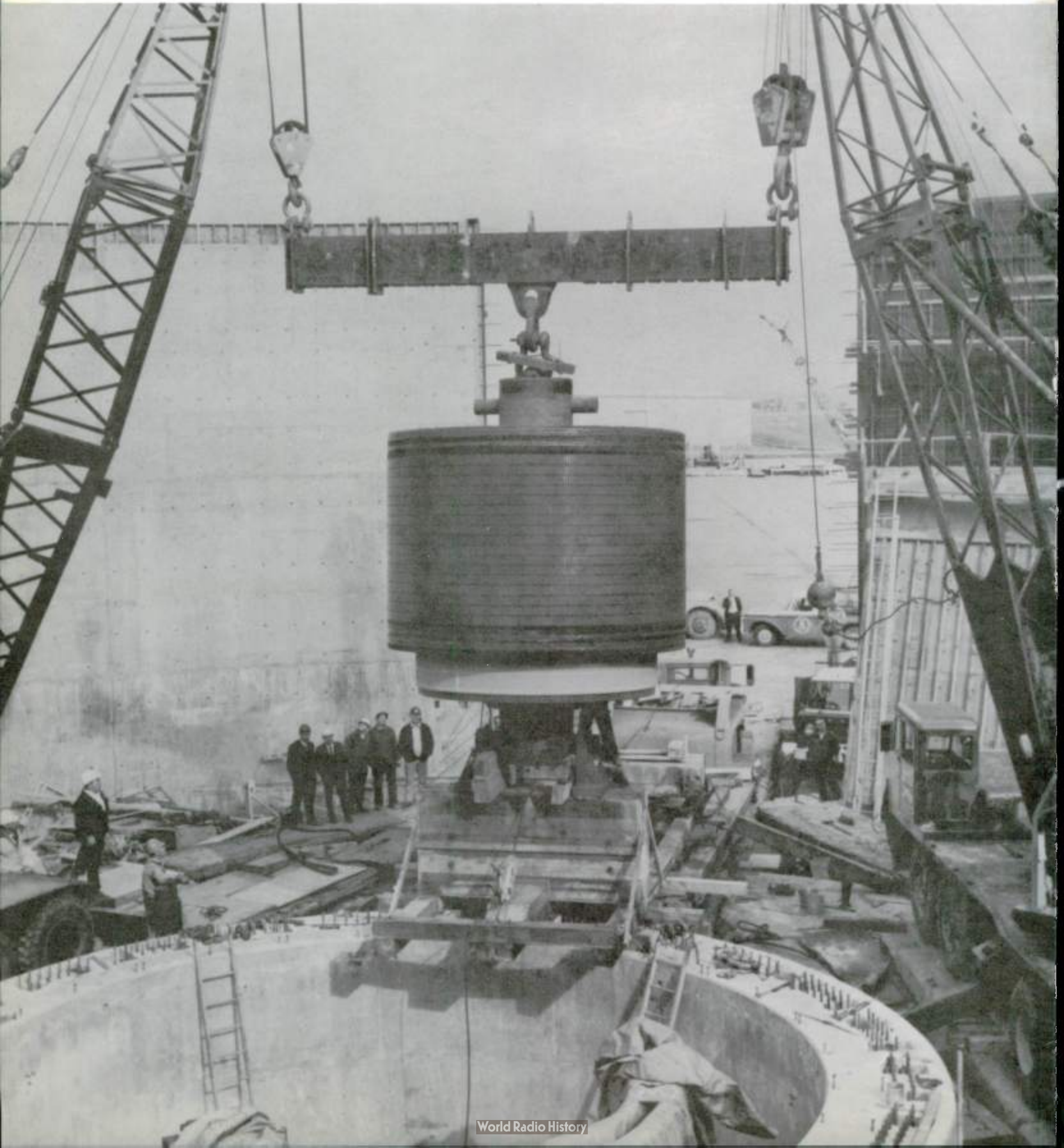
Dr. Hermann Eisele attended the Technical University, Stuttgart, Germany, and earned his doctorate in electrical engineering there in 1963. He also worked as a technical assistant at the university. Dr. Eisele joined the Westinghouse Industrial Systems Division in 1964 to work on the design and standardization of feedback control systems for industrial applications. Among those systems is the parallel control described in this issue.

A. M. Vance graduated from Colorado State University with a BSEE in 1943. He joined Westinghouse on the graduate student course and was assigned to the Motor Division to design rotating equipment for the Navy. He served next in the Welding Department, designing rotating welder power supplies, and then returned to the Motor Division to design Rototrol rotating regulators for steel mills. In 1956, Vance transferred to Industry Engineering, where he worked with equipment for excavators. That has been his main field since, and he is now responsible for open-pit mining equipment in General Industries Systems, Industrial Systems Division.

World Radio History

Round-Trip to Mars

Ground simulation of the dynamic behavior of a three-man spacecraft entering the earth's atmosphere at speeds of 42,000 miles an hour (the speed of return from Mars) will be possible with this centrifuge now being built at NASA's Ames Research Center. The cranes are lowering the rotor of the world's most powerful dc motor, which will produce 5.58 million pounds of torque and 18,800 peak horsepower. The motor will generate forces of up to 20G while whirling a 2000-pound Apollo-type capsule and gimbal arrangement at the end of a 50-foot arm at 52 rpm. Except for weightlessness, the capsule environment system will simulate the entire range of pilot experiences for flight to the moon or Mars and return. The manned centrifuge will be used for research, not astronaut training.



World Radio History