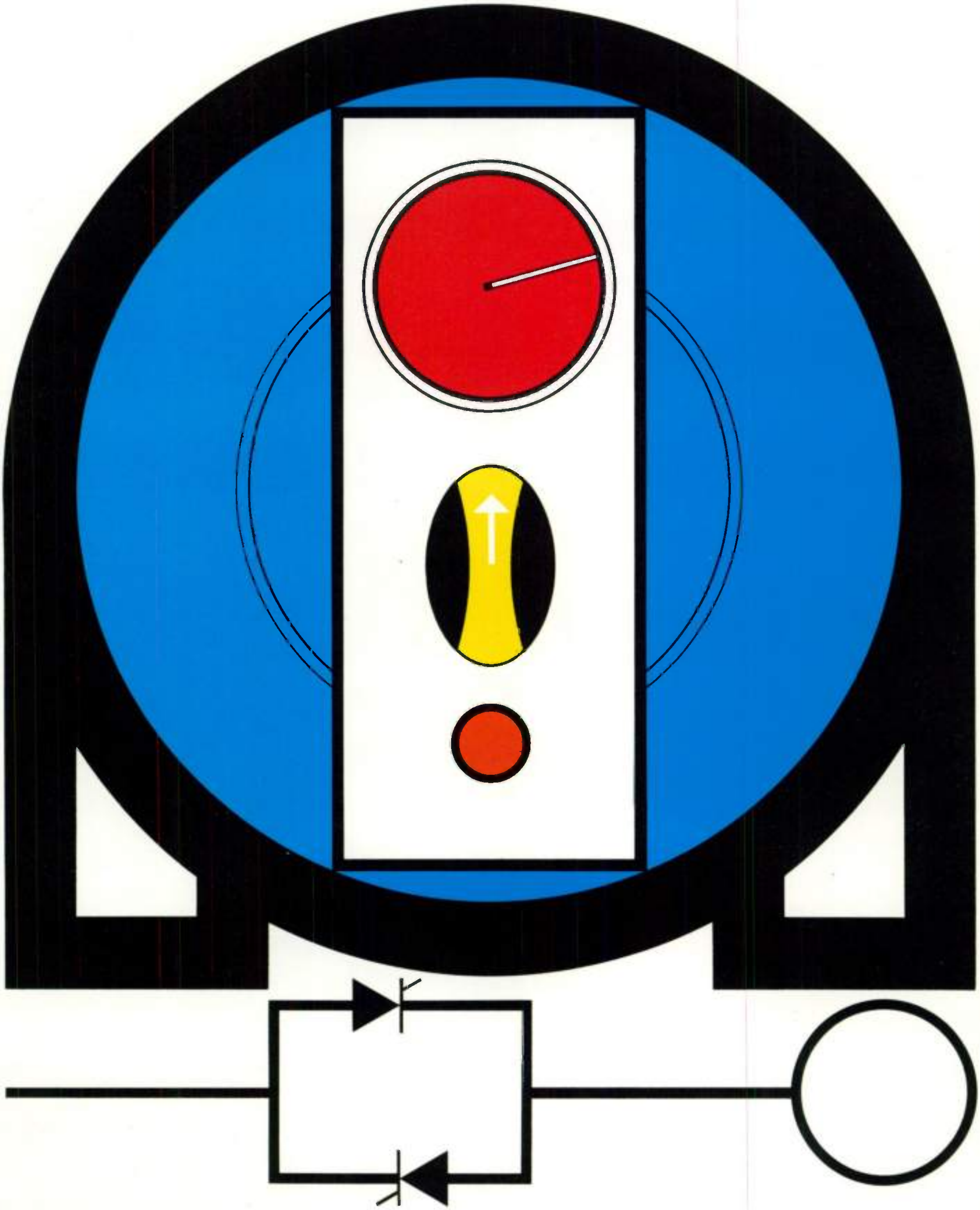
Westinghouse ENGINEER

July 1974



Reactor Vessel Arrives at FFTF Site

The 350-ton stainless-steel reactor vessel has arrived at the Fast Flux Test Facility (FFTF) construction site near Richland, Washington, after a 7100-mile river and ocean voyage via the Panama Canal from the Chattanooga, Tennessee, works of Combustion Engineering, Inc., the vessel's manufacturer. It was fabricated to the specifications of its designer, the Westinghouse Advanced Reactors Division, and is the largest sodium-cooled reactor vessel ever made in the United States. Other components arriving in the same shipment were the vessel's 214-ton closure head and the 129-ton main support structure.

Following arrival at Longview, Washington, the components were placed on transporter rigs aboard two barges and brought up the Columbia River to the Port of Benton just north of Richland. A seven-mile overland trip then brought the reactor vessel to the FFTF construction site on twin transporter crawlers moving at one mile per hour. Special mats were laid in front of the crawler tracks to distribute the weight and prevent highway breakup. The other two components traveled to the site on wheeled heavy-equipment transporters modified to accommodate the size and weight of their load.

The reactor vessel is expected to be installed within its guard vessel in September. The guard vessel is a backup safety feature to insure that the reactor core will always be submerged in the liquid-metal coolant.

The FFTF will have most of the elements of a breeder power reactor plus provisions for testing materials in its core, so it will provide significant research and operational data directed toward introduction of commercial liquid-metal fast breeder reactors. It is being constructed by Westinghouse Hanford Company, a subsidiary of Westinghouse Electric Corporation, under contract to the U.S. Atomic Energy Commission.

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Front Cover: A schematic drive circuit, a control panel, and a motor symbolize solid-state industrial motor drives. An article on the state of the art in such drives and other solid-state power and control equipment begins on the following page. The cover design is by Tom Ruddy.

Solid-State Industrial Power and Control Come of Age

W. R. Harris
R. A. Morgan

Application of solid-state equipment and techniques has produced motor drives that are more capable, more flexible, and more economical than ever before. Other kinds of power supplies and power conditioners have benefited similarly from the same equipment and techniques.

In a previous article on the rapid development of solid-state industrial drives, a number of predictions were ventured about the future of solid-state power-level and signal-level electronics.[1] Briefly, they were that the explosive growth in use of analog and digital techniques would continue, the use and complexity of integrated circuits in controls would increase, new components and new design, construction, and production techniques would proliferate, power-level solid-state devices (diodes and thyristor silicon controlled rectifiers) would replace the motor-generator set, and current and voltage ratings of the power-level devices would increase.

All of the predictions have been fulfilled—some much faster than anticipated, as for example the virtual demise of the motor-generator set and the wide use and great complexity of integrated circuits. System designers have learned to cope effectively with the few disadvantages of solid-state systems—mainly harmonics in the ac supply power and ripple in the dc output current.[2] This article briefly examines the present state of the technology.

Power-Level Electronic Devices

Thyristors can now be obtained with blocking ratings up to 3000 volts and current ratings up to 1000 amperes rms; one bridge can power a 1000-hp dc motor with conventional overload rating. Diodes are available up to 5000 volts blocking and 1500 amperes rms. Fifteen years ago, the maximum ratings for thyristors were about 400 volts and 25 amperes, and for diodes 800 volts and 50 amperes.

The higher ratings have been made possible by commercial availability of single-crystal silicon (the starting material for devices) with more uniform resistivity, less contamination, fewer structural imperfections, and larger diameter. Diameters of diodes and thyristors have increased during their 15-year life span from 15 to 50 mm, with 75- and 100-mm devices on the near horizon. Accompanying the improvement in materials have been improvements in fabrication technology. Development of the gaseous diffusion process has allowed fabrication of a more uniform emitter junction, distribution of filamentary emitter shunts over the cathode area, and easy fabrication of dynamic gate elements. The result is improvement by an order of magnitude in dv/dt and di/dt ratings, turn-on loss, and gate-drive requirements. These increases in voltage and current ratings have also simplified protective and limiting circuitry and devices. The total effect is to lower cost, and the resultant consequence has been an increasingly broad range of practical applications.

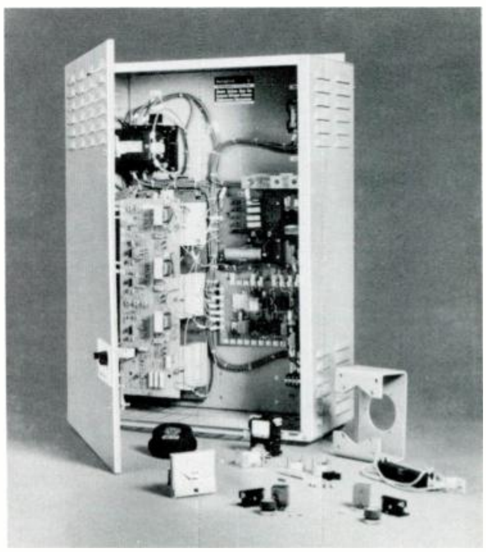
Stud-type thyristor packages threaded into heat sinks continue to be popular in the smaller sizes. However, heat generated in the device must flow through a relatively small annular region at the base of the package, so that type is not well suited for the higher powers. Heat flow was first improved by mounting a compression-bonded fusion directly on an integral heat sink, resulting in low thermal resistance between the fusion and cooling air and consequently in an exceptionally reliable device.

A disc-type package is the only satisfactory method of using devices of 50 mm and larger; heat sinks can be clamped on both sides of the disc, giving low thermal impedance and thus maximum utilization of the inherent capacity of the larger fusions. The package also provides greater flexibility for mounting and interconnection and is less expensive than other packages.

Liquid cooling of the largest sizes is attractive, and a trend in that direction is bound to accelerate as devices larger than 50 mm become available. Liquid-cooled assemblies have the advantages of much smaller volume and, of course, lower thermal impedance and therefore higher continuous capacity. Their disadvantages are a lower ratio of surge-current rating to continuous-current rating (since the continuous rating is increased much more than the surge rating) and the necessity of providing liquid connections and coolant.

DC Adjustable-Speed Drives

The dc solid-state drives were developed and applied more rapidly than ac drives, during the decade of the 1960's, because dc converters are less expensive and less complicated and because the application of high-performance closely regulated single- and multimotor dc drive systems is considerably simpler than that of com-



1—Westinghouse packaged dc drives are small standardized units that serve a wide variety of applications. Some of the functional options available, supplied in kit form, are shown in the foreground. They include provisions for dynamic braking, jogging, threading, acceleration/deceleration, and speed regulation.

2—(Right) *Solid-state dc drives are based on these basic circuits. They range from the relatively simple and inexpensive semiconverters to the more complex, but more capable, dual converters.*

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parable ac systems. (The term "drive" is used in this article to mean a solid-state power supply for energizing a motor; "drive system" means a drive plus the motor and, often, auxiliary control and monitoring equipment.) The advances have been spectacular. Today, the thyristor dc drive is dominant in all sizes.

The publicity given to recent ac inverter drives could lead one to the conclusion that the future of the dc drive is clouded. No doubt, ac drives will continue to proliferate and make substantial inroads in present dc applications because of the simplicity, high speed capability, and low maintenance requirements of ac squirrel-cage motors; because of the adaptability of squirrel-cage motors to adverse environmental factors such as dirty air, explosive atmosphere, and inaccessibility for maintenance; and because inverter drives are well suited for use as common power supplies for groups of motors requiring precise speed synchronization. However, dc drives will continue to be the workhorses of industry because of the advantages mentioned earlier, although ac drives probably will grow to constitute as much as 20 percent of the total drive market.

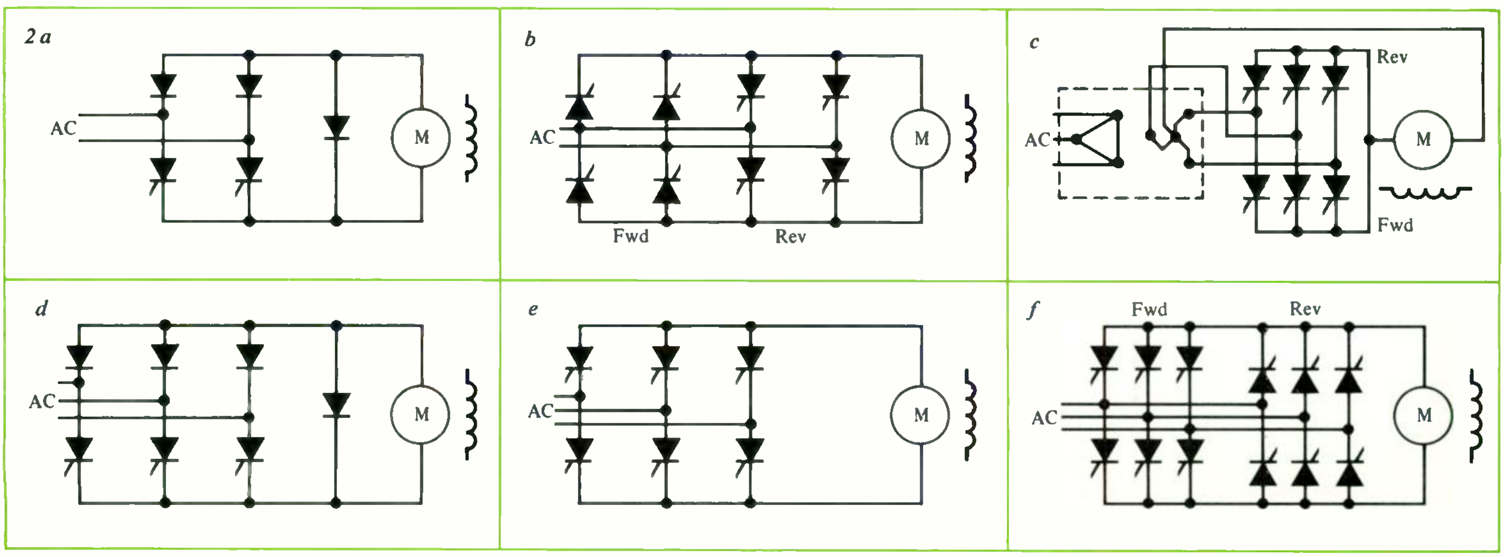
Even in small packaged ("standardized") drive systems, dc types predominate. (An exception is where application of the squirrel-cage ac motor is justified by environmental factors.) Packaged dc drives now have a multiplicity of features and functional options that allow widespread application (Fig. 1). The options enable a user to modify his drive, when his requirements change, with stock components—converting it in a matter of minutes to what formerly was categorized as a custom drive.

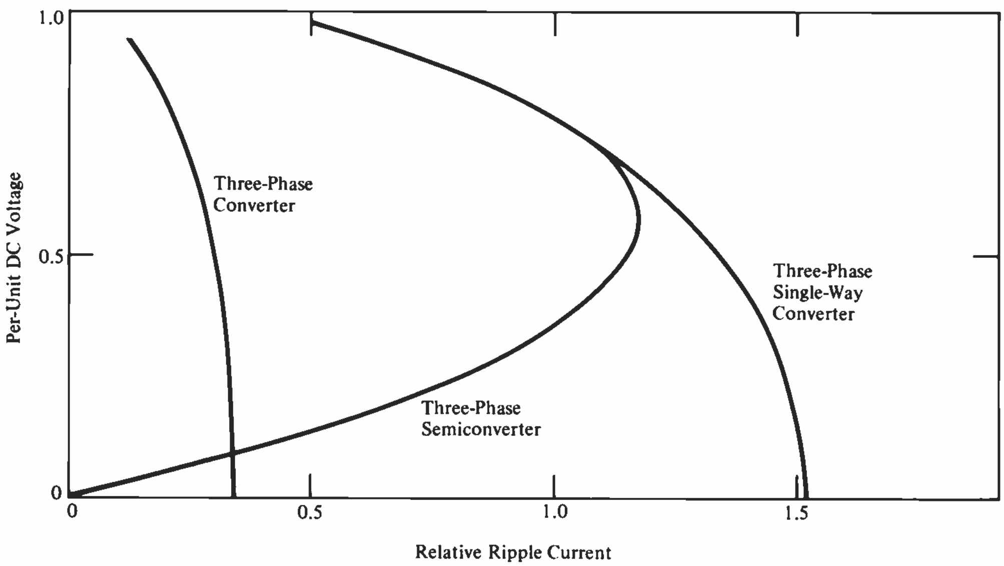
The electronic portions of dc drives are basically semiconverters and converters (Fig. 2 and Table 1). *Semiconverters* have diode rectifiers in one side of the bridge and thyristors in the other side, with a commutating diode across the output (Figs. 2a and 2d). The circuit provides unidirectional dc current and voltage, so it cannot be used for applications that require inherent reversing or regeneration.

Table 1—Solid-State DC Drive Circuits

Circuit (see Fig. 2)	*Reversing or Nonreversing*	*Regenerative*	*Usual Horsepower Range*	*Applications*
a. Single-phase semiconverter	N	No	Fractional to 5	Standardized drives
b. Single-phase dual converter	R	Yes	Fractional to 5	Standardized drives
c. Three-phase single-way dual converter	R	Yes	5 to 100	Standardized drives, small mill and process-line drives
d. Three-phase semiconverter	N	No	5 to 200	Standardized drives, small mill and process-line drives
e. Three-phase single converter	N*	No*	20 to 7500	Mill and process-line drives
f. Three-phase dual converter	R	Yes	20 to 7500	Mill and process-line drives

*Can reverse and regenerate with motor field reversal.





3—The dc drive circuits impose different amounts of ripple current on the motor. The more ripple there is, the more difficult motor commutation becomes and the more motor heating there is; therefore, ripple is one factor making the various circuits most applicable for particular ranges of horsepower rating as indicated in Table 1.

(The motor can be reversed by contactors but not through the inherent capability of the semiconverter.) Automatic dynamic braking can be furnished for slowdown and stopping. Typical applications are conveyors, mixers, paper-pulp washers and deckers, and machine tools.

Converters have thyristors in all legs of the bridge. Because they provide six-pulse ripple current instead of the three-pulse ripple of semiconverters, they are preferred for the larger dc motors.

The single converter (Fig. 2e) supplies current in one direction only but provides voltage in both directions. With current and voltage in the same direction, the circuit acts as a rectifier with power flow from ac to dc. When voltage is reversed, the circuit becomes an inverter with power flow from dc to ac. It is inherently nonreversing and nonregenerative but, by reversing the motor field (with contactors or a dual converter), a reversing-regenerative drive is possible. The control for such a drive is much more complicated than that for a dual converter, and this has limited the number of applications.

Typical applications are rolling-mill loop cars (whose motors have unidirectional torque and current but must reverse their rotation), power supplies for dc motor shunt fields, and paper-machine and other process-line drives that do not have to regenerate.

Dual converters (Figs. 2b and 2f) provide complete control of voltage and current, and thus speed and torque, in both directions of motor rotation. The gating and control circuitry is arranged to provide smooth transition from forward to reverse speeds and to prevent circulating current between the converters. For large drives with light torque requirements in the reverse direction, it is common practice to supply half capacity in the reverse thyristors. Typical applications are machine-tool servos, spindle drives, and rolling-mill drives.

Three-phase single-way dual converters (Fig. 2c) also provide voltage and current in either direction, and they need only six main-circuit thyristors for a full-reversing regenerative drive system. They have found wide use in the machine-tool industry, mainly for spindle drives, and for small mill and process-line drives in ratings from 5 to 100 hp.

Ratings—As Table 1 shows, the various circuits are most applicable for particular ranges of horsepower rating. The reasons are the variations in the way thyristors are used and the different amounts of ripple current imposed on the dc motor (Fig. 3). Those factors practically limit single-way converters to about 100-hp applications and semiconverters to about 200-hp applications. Converters are unlimited as to horsepower, but armature circuit inductance is sometimes added to improve motor commutation.

Table 1 shows 7500 hp as the maximum rating because individual drives seldom if ever exceed that rating. In large multimotor drive applications, multiple power supplies are invariably used; typical examples are paper machines, rolling mills, and process-line drives. Actually, any rating required can be built. For example, the 25-MW frequency changer described in the section titled *Other AC Systems* has single-converter circuitry.

Other DC Systems

Among the first installations of solid-state power electronics were medium to large diode-type rectifiers built to provide dc power for industrial, transportation, electrochemical, and pot-line service. Westinghouse alone has supplied equipment totaling more than 3.5 million kW in rating. The equipment has a variety of single-way and bridge-type rectifier circuits, depending on the dc current and voltage requirements (Table 2).

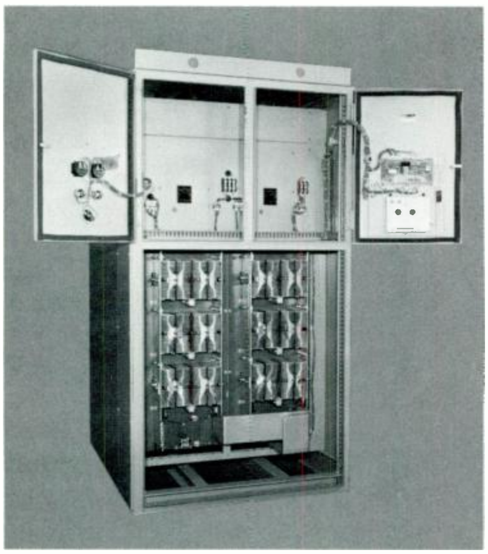
Large diode rectifiers have traditionally had a combination of tap changers, regulating transformers, and saturable reactors for adjustment or control of dc voltage. Those components are expensive to install and maintain, and they are limited in range and speed of response. Thyristor control was too expensive and too complicated until the recent development of large thyristors, which decreased not only the number of thyristors needed in a rectifier but also the amount of gating and protective circuitry. There appears to be a trend toward use of thyristors for voltage adjustment and control, and the trend probably will accelerate.

Large units require careful individual consideration of power factor, efficiency, harmonics, and system layout, but they can be built from a variety of standard building blocks such as phase-tree assemblies. Fig. 4 shows a typical R-1000 industrial rectifier. Optional features include a fault monitor and test panel. An extra bridge is provided when unusual reliability is required; if one bridge goes out, the others carry the load. Each bridge has its own breaker. Standard units are available with up to four bridges and for 125-, 250-, and 125/250-volt three-wire power supply, 800 to 4000 amperes.

Special dc power supplies for large particle accelerators, fusion power research, metal refining, and other applications continue to be built, but they are too varied to describe here.

AC Adjustable-Speed Drives

Solid-state control, and in particular integrated circuits, has given tremendous impetus to development of solid-state ac drives because the control for those drives is very complex. It is now possible to build practical drives capable of operation over a wide speed range and with the control functions necessary to meet drive and process requirements.[3] The main types of ac drives are indicated in Fig. 5 and Table 3.



4—Westinghouse R-1000 industrial rectifiers range in rating from 200 to 1000 kW. They have 50-mm diodes, standardized design, breaker protection without fuses, an integral dry-type transformer rated up to 4160 volts ac, and various optional features. This one has two bridges and is rated 500 kW, 250 volts.

Table 2—Current and Voltage Requirements for Rectifier Applications

Application	*Current (kA)*	*Voltage (V dc)*
Aluminum reduction	75 to 250	30 to 1000
Chlorine production	50 to 300	100 to 900
Caustic soda production	10 to 50	600
Copper refining	8 to 30	50 to 400
Electropainting	5	400
Industrial dc power supplies	2 to 8	250
Transportation dc power supplies	2 to 10	600 to 1000
Fluorine production	Tailored to process requirements	
Titanium production	Tailored to process requirements	
Sodium production	Tailored to process requirements	
Magnesium production	Tailored to process requirements	
Manganese production	Tailored to process requirements	

Adjustable-voltage supplies with squirrel-cage motors are the simplest type (Fig. 5a). The circuit has back-to-back thyristors in each phase. By adjustment of the point on the ac wave at which the thyristors are turned on, ac voltage is controlled to control motor speed. (The torque of a squirrel-cage motor varies as the square of the voltage.)

The main disadvantage of this drive is that rotor losses are proportional to slip. That characteristic limits its use to "soft-start" constant-torque applications where only a limited time is spent at reduced speeds, such as conveyors that require soft start. It is also suitable for pump drives, where torque varies as the square of the speed. There the maximum rotor loss occurs at 2/3 speed and is about 15 percent of rated horsepower; it can be handled by using a motor somewhat larger than standard. The combination of squirrel-cage motor and simple thyristor power supply makes an economical and satisfactory drive for pumps that require controlled speed to give constant water pressure regardless of flow.

Substituting a wound-rotor induction motor with permanent secondary resistance for the squirrel-cage motor provides the arrangement shown in Fig. 5b. It is used in a Westinghouse line of static crane drive systems for hoist, bridge, and travel service. The hoist application has a tachometer generator to sense speed and thereby provide a high-performance speed-regulated drive; the system also has static reversing, stepless speed control, regenerative braking for overhauling loads, very slow first-point speed for easy positioning of critical loads, and counter-torque braking when reducing speed. For bridge and trolley service, the tachometer generator is eliminated and contactor reversing is generally used. Those drives provide stepless torque and speed control, adjustable first-point torque, and fast smooth command of torque under all operating conditions.

Slip-power-reclamation drives (Fig. 5c) also have wound-rotor motors. The ac slip power from the rotor is rectified to dc power, which is inverted and fed back to the ac line. Adjusting the firing angle of the thyristors controls the voltage that the rectifiers can accept, which in turn regulates the rotor's voltage so as to control its speed. The inverter is a line-commutated single converter similar to that shown in Fig. 2e. With the solid-state equipment equal in rating to the motor, this arrangement can be used for constant-torque loads and controlled from zero to near synchronous speed. With tapped or split windings, the converter size can be materially reduced for variable-torque applications; consequently, the drive is attractive for large pumps or fans, where torque varies as the square of speed and where power interruption while switching does not interfere with the process.

Pulse-width-modulated inverters, Fig. 5d, rectify power from the ac lines and then invert it to adjustable-frequency ac power for a squirrel-cage motor. The circuit is diagrammed more fully in Fig. 6. Since the supply voltage to the inverter is dc, the main thyristors must be "force commutated"—forced to zero current so that they will turn off when switching is required. (The circuits for dc drives do not require forced commutation for turnoff because the ac voltage periodically goes through zero, so the devices are "line commutated.") The additional thyristors, capacitors, reactors, and free-wheeling diodes in Fig. 6 are required for forced commutation.

Pulse width is modulated in the inverter in such a manner that each half cycle consists of several pulses arranged by the control so that the effective voltage is such as to maintain essentially constant volts per cycle over the frequency range. Pulse-width modulation also provides a low-harmonic waveform to the motor.

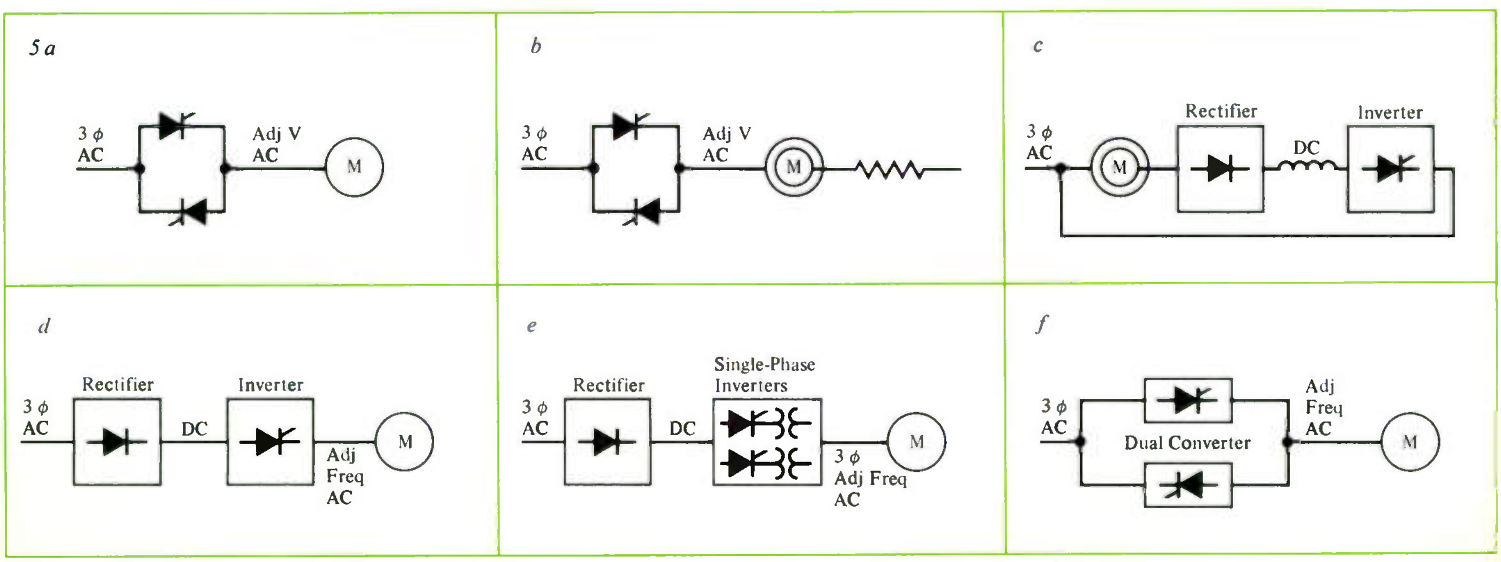
This drive is closely comparable in application with solid-state dc drives, but pulse-width modulation and forced commutation make the power converter and the control inherently more complex and more expensive than a dc drive. On the other hand, integrated circuitry has lowered the cost of the control, and the cost of an ac motor is only 25 to 35 percent of the cost of an equivalent dc motor. Total cost of the system varies with the application; for single-motor applications, it is about 50 to 100 percent more than that of a dc system. Advantages are elimination of the commutator with its maintenance needs and use of a motor that is better suited to hostile environments, inaccessibility, and higher speeds.

AccurCon inverters (Fig. 5e) have also found wide acceptance. The circuit is an arrangement of several single-phase inverter stages (usually 6 to 14) shifted in time phase by a fixed interval and interconnected through transformers to give balanced three-phase output with excellent harmonic cancellation (like that of the

Table 3—Solid-State AC Drive Circuits

Circuit (see Fig. 5)	*Reversing or Nonreversing*	*Regenerative*	*Commutation*	*Usual Horsepower Range*	*Applications*
a. Adjustable-voltage, squirrel-cage motor	N	No	Line	5 to 50	Pump drives, soft-start conveyor drives
b. Adjustable-voltage, wound-rotor motor	R, N	Yes	Line	5 to 200	Crane drives
c. Slip-power reclamation	N	No	Line	300 to 5000	Large pump and fan drives
d. Pulse-width-modulated inverter	R, N	Yes*	Forced	5 to 150	Grinder, small mill, and process-line drives
e. AccurCon inverter	N	No	Forced	150 to 1000	Fiber-spinning drives, uninterruptible power supplies
f. Cycloconverter	R	Yes	Line	500 to 10,000	Large low-speed drives

*With additional equipment.



pulse-width-modulated inverter). Independence and isolation of the stages are such that good three-phase operation is still provided when a phase is lost, though at reduced overload capacity. Thus, the concept is well suited for applications where reliability requirements are high, such as in drives for synthetic fiber spinning and in uninterruptible power supplies.[4]

Cycloconverters (Fig. 5f) have a dual converter similar to that shown in Fig. 2f in each of the three ac phases. By utilizing properly time-spaced sine-wave references to each dual converter, the system changes 60-Hz ac power to adjustable-frequency ac power. The converters are line commutated, since they operate from the ac line. A minimum of 36 thyristors is required, and the frequency range for continuous operation is limited to 0 to 20 Hz. This circuit is, thus, best suited for large low-speed drives such as those for grinding mills and directly driven paper-machine sections, and for special systems such as the peak power compensator described in the next section.

Other AC Systems

Thyristor circuits in the ac line, similar to the crane controls described in the preceding section, have found wide use in ratings of 5 to 500 kW as ac power switches for resistance heating control in various industrial applications. Another use is for control of voltage for ac-to-dc power supplies for low-voltage applications such as battery chargers. Considerably more sophisticated are applications for high-power high-voltage solid-state switching of reactors to prevent arc-furnace flicker and for power-factor control. The theory is the same, but several thyristors in series are required to meet voltage requirements; consequently, gate isolation is more difficult and control is more complex.

A number of special solid-state systems of very high power have been applied recently as a result of the availability of large high-voltage thyristors and in response to special application requirements that solid-state control and power electronics can be easily adapted to meet. The following brief descriptions illustrate the possibilities.

Peak Power Compensator—When large electrically powered excavating machines are used in remote areas where only a small utility power system is available (or a long utility line of small rating), they can cause troublesome voltage and frequency fluctuations because of the large and almost periodic load swings. System load is smoothed somewhat by applying more than one excavator, but line fluctuation still occurs because several excavators' peaks and valleys sometimes coincide. A peak power compensator making use of a cycloconverter solves the problem.[5] It has been applied so far at two remote locations in Australia.

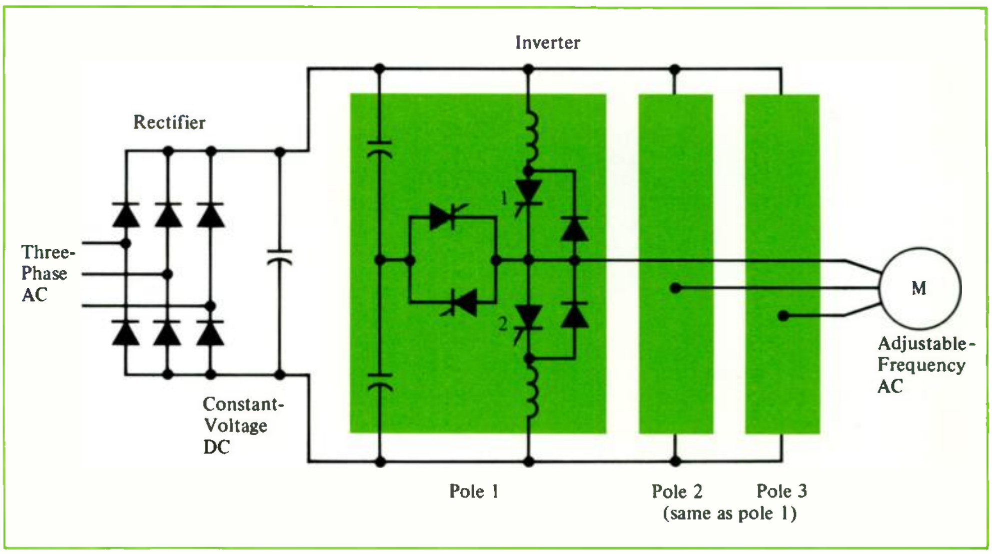
The compensator consists of a cycloconverter, control, switchgear, and 9000-hp wound-rotor motor that is rated at 270 percent peak load and drives a 100-ton flywheel. It is capable of handling a peak of 18,000 kW in either direction.

The cycloconverter and its control regulate the rotor frequency over a range of ±12 percent so that the wound-rotor machine acts either as an induction generator or an induction motor. When operating as a generator, it takes energy from the flywheel to help meet peak power requirements; when operating as a motor, it returns energy to the flywheel during regenerative peaks and off-peak periods. In effect, the compensator smoothes the power flow and limits it within prescribed bounds. Because of the present energy shortage and the remote location of many fossil-fuel beds, such equipment will find wide application.

Frequency Changer—A 25-MVA solid-state frequency changer, 60 Hz to 25 Hz, is being built for a Midwest steel company that is retiring some of its 25-Hz generating equipment. Two parallel links are used because of the large amount of power involved (Fig. 7). The transformers are arranged for 60-degree phase displacement to effect some degree of harmonic cancellation. Single converters (Fig. 2e) are used for all four units. Because of the high dc link voltage, each leg of the converters has several thyristors in series.

5—(Left) Solid-state ac drives are, like the dc drives, available in a wide range of complexity and capacity. They provide adjustable voltage or frequency for adjustable speed control of the ac motor.

6—(Right) *Pulse-width-modulated inverter is diagrammed in somewhat greater detail here. Devices 1 and 2 are the main thyristors. The circuit provides constant volts per cycle in the output power.*

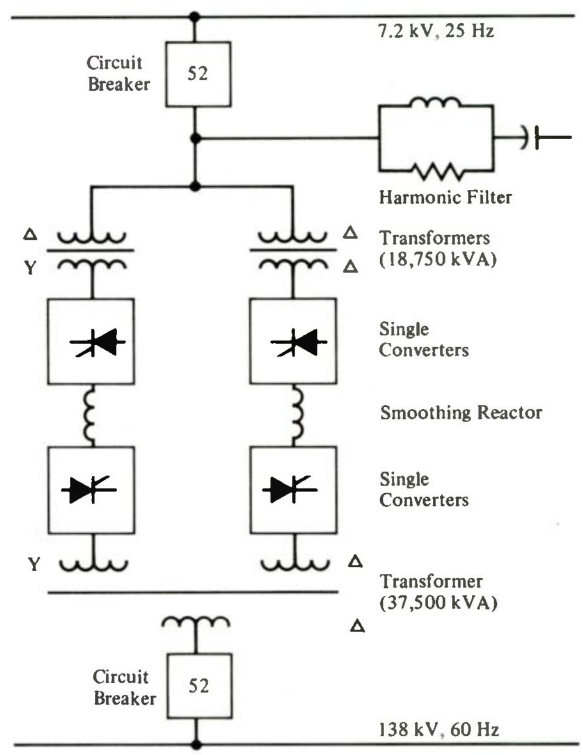


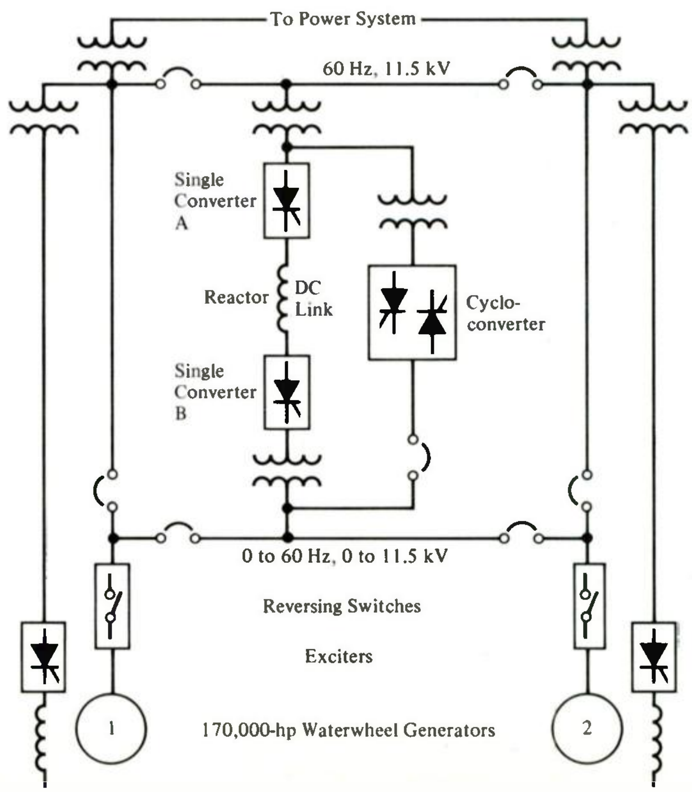
The use of single converters at each end of the dc link enables power to flow in either direction even though the direction of current in the dc link never changes. Reversal of power flow involves only an interchange of gate pulse signals to reverse the rectifier-inverter function at each end. Although the frequency changer is normally intended for power flow from 60 to 25 Hz, the control is arranged to transfer power from 25 to 60 Hz if required as well as to maintain a set level of power flow in either direction.

Both the 60-Hz and the 25-Hz converters are line commutated and consequently require that both 60- and 25-Hz voltages be present before operation of the tie is initiated. This requirement in turn requires that synchronous machinery of adequate impedance rating be connected to the system.

The circuit is similar to that used for high-voltage dc transmission. However, equipment construction for the latter is radically different because of the very high dc voltages used.

Variable-Frequency Starting System—In electric-utility pumped storage installations, the water wheels double as pumps and the generators as motors. During off-peak hours, the generators are reversed and used in the motoring mode to pump water into a storage reservoir. Auxiliary means are necessary to start the huge synchronous machines and bring them up to speed so they can be synchronized with the power line for both pumping and generating. A solid-state variable-frequency starting system has been devised to eliminate the mechanical disadvantages of mounting a large pony motor (controlled by a liquid slip rheostat) on top of the





7—(Top) *Frequency changer is designed to convert 60-Hz supply power to 25-Hz power for use in a steel mill. Power can also flow in the opposite direction when required.*

8—(Bottom) *Starting circuit for a pumped-storage plant in Colorado supplies variable-frequency power to the 170,000-hp synchronous generators, which start as motors in both the generating and motoring modes. When the machines are up to speed, they are synchronized with the line.*

generator. In addition, it provides electrical braking—a major advance not feasible with other schemes.

The main power loop consists of single converters *A* and *B* (Fig. 8). It is similar to the circuit of the frequency changer described above, but the control is different for converter *B* because that converter operates at adjustable frequency.

To start one synchronous machine as a pump motor, its reversing switch is closed and its field is excited at rated current. Since both converters are line commutated and the synchronous machine is at zero speed and voltage, there is no voltage available for commutation. Special means for getting around that problem could have been provided in the converters. However, it is simpler to provide a small (600-kVA) cycloconverter for accelerating the motor from zero to about 5 Hz, where enough synchronous-machine voltage is available to line-commutate converter *B*. At that point, the main circuit takes command with converter *A* acting as a current-controlled rectifier. Converter *B* acts as an inverter with the gating angle fixed by the control. The arrangement applies a fixed torque (proportional to the rating of the rectifier-inverter) to the synchronous machine to accelerate it at gradually increasing frequency and voltage to rated speed, where the machine is synchronized with the power line and can start pumping.

The sequence is similar when starting for generating operation except that the reversing switch is reset.

To brake the system, the sequence just described is reversed. Converter *B* acts as a rectifier and converter *A* as an inverter to feed the regenerative power to the 60-Hz system.

The short-time rating of the main starting converters at rated speed is approximately 16,000 hp. That rating is sufficient to overcome the losses in the generator and dewatered waterwheel, and it provides margin for acceleration and for operation of the generator on overspeed tests.

Solid-State Controls

One of the most significant aspects of the solid-state era has been the explosive trend in development and application of solid-state analog and digital controls. The proliferation of discrete as well as integrated-circuit devices and the trend toward medium- and large-scale integration have made profound changes in design philosophy and techniques, equipment size, and the performance and reliability of systems. Even the small standardized low-cost adjustable-speed drives nearly all have integrated circuits and modern solid-state switching circuitry.

As industry moves from discrete to integrated circuits and on to more complex integrations, the ground rules of design and cost change greatly. For example, in discrete-component design, it is generally desirable to use as few active components (such as transistors and thyristors) as possible. The opposite is true in integrated-circuit design, mainly because passive components (such as capacitors and inductances) are difficult to fabricate whereas active components can be very economically fabricated. Therefore, as designers proceed up the ladder toward large-scale integration, they have to "throw away the handbook" at each step—for system design as well as for hardware.

Another significant trend has been the combining of analog and digital techniques in building complex control systems. Digital switching and logic extend the flexibility and reliability of solid-state control to a marked degree, especially in regard to limiting, protection, and where logic or calculation is required. Many control systems now include programmable controllers and small computers for sequencing, logic, and process control.[6]

Most of the control and gating systems for the new ac drives demonstrate the trend; it would be very difficult and expensive to build them without integrated circuits and the combination of digital and analog techniques. Development of ac systems was hastened more by solid-state control developments than by solid-state power switching devices. It appears certain that application of combined analog and digital techniques will grow at an accelerated pace.

In fact, the overall explosive trends in solid-state control probably will continue and accelerate. New techniques and large-scale integrated circuits will continue to reduce the cost and widen the use of such equipment tremendously.

Conclusion

Fewer and fewer industrial power and control applications today can be satisfied except by the efficiency, flexibility, degree of control, reliability, and response of solid-state equipment. That is equally true for large complex systems and for small standardized drives.

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Ultrasonic System Facilitates In-Line Cleaning of Wire and Strip

M. G. Morris

A new cylindrical ultrasonic transducer, which is a major advance in transducer design, makes in-line ultrasonic cleaning practical even in high-speed production lines. Its high efficiency and high power density enable it to clean better and faster than other methods, and with less power consumption.

In-line cleaning of wire and strip has always presented a difficult problem in the design of continuous multiprocess production lines such as those for plating and various kinds of coating. The speed of most such lines is established by considerations other than cleaning, so the cleaning process must be adapted to the established line speed (and also to the allocated space). At best, the variable parameters available are time, temperature, type of cleaning medium, concentration of the medium, and mechanical energy.

To help solve the problem, a new straight-line ultrasonic cleaning system has been developed to clean wire or narrow strip at high speeds. It is based on a unique cylindrical transducer that generates ultrasonic energy at much higher intensity (amount of useful energy present) than conventional flat transducers can achieve. The result is a great reduction in cleaning time required—generally by a factor of ten or more compared with conventional ultrasonic cleaning systems, and much more compared with other cleaning methods.

Since cleaning time in an in-line process translates into line length, the new system saves a great deal of space. To illustrate, a conventional ultrasonic cleaning system requires an exposure time of 30 seconds for adequate cleaning of a typical product, so at a line speed of 100 feet per minute its transducers would have to be 50 feet in total length just to provide the minimum exposure time needed (no safety factor). The new Westinghouse system, on the other hand, would require only about 3 seconds of exposure time for the same product, so the length of transducer needed would be only about 5 feet. Adding say a foot to that

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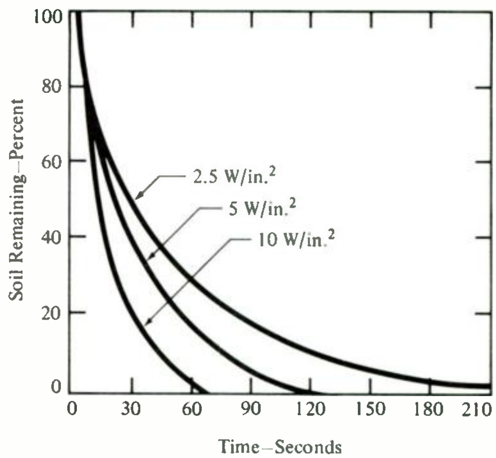
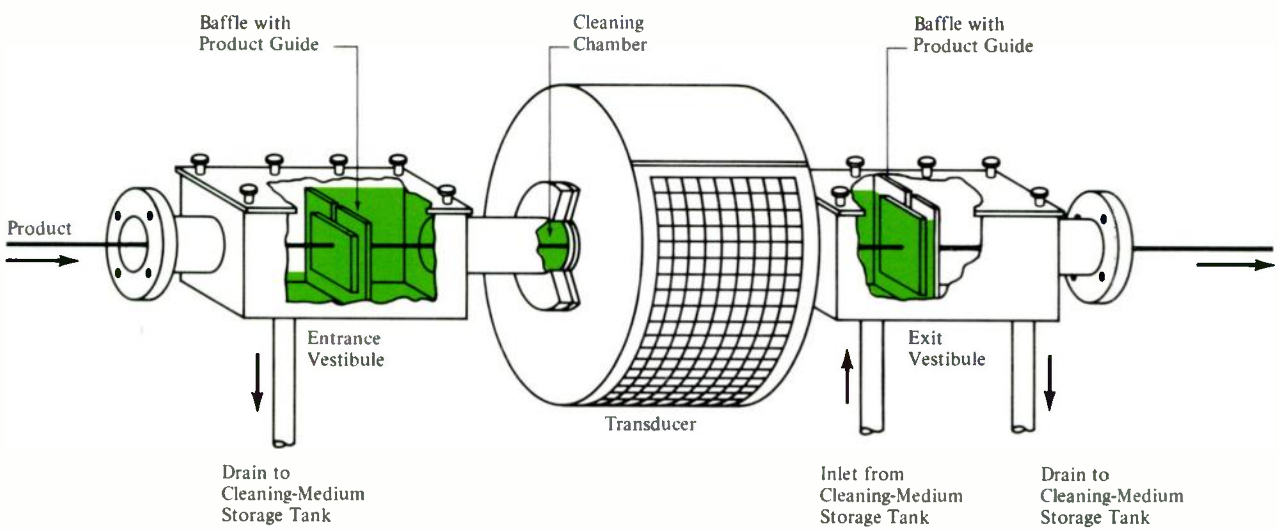


1—(Above) *Tests undertaken to determine the effects of power density on cleaning rates in ultrasonic systems showed that the time required is approximately inversely proportional to power density. Consequently, a new cylindrical type of ultrasonic transducer was developed to maximize power density so as to minimize the cleaning time required and thereby minimize the length of the cleaning section of an in-line process. The tests employed controlled bath temperature, identical cleaning media, and standard samples soiled with standard contamination.*



length would provide a large safety factor to insure that the desired cleanness was achieved under all conditions.

Why Ultrasonics?

Most in-line cleaning cannot be done by chemical means alone; it requires some form of mechanical energy for adequate soil removal. The mechanical energy can be applied by wiping, brushing, or abrasive belt grinding, but all of those have a common problem—wear of the surface in contact with the product. Besides, all suffer from serious buildup of soil at the point of contact, resulting in diminishing rate of soil removal until the device is changed. In addition, the contact devices do not work well on uneven surfaces; pits, scratches, and other surface unevenness usually retain soil.

Applying the mechanical energy in the form of ultrasonic energy eliminates those problems. Its problems in the past, for cleaning wire and strip in an in-line process, have been mainly the limited capability of the available ultrasonic transducers and the consequent cost and length of the great amount of ultrasonic equipment needed to do an acceptable job of cleaning in most in-line processes. Those conventional flat transducers are much more suitable for batch cleaning and conveyor-line cleaning (in which articles are moved through cleaning tanks in baskets or on racks). They just do not generate sufficient energy to be practicable for most in-line cleaning, especially in processes that have high line speed relative to the degree of difficulty of soil removal.

Conventional flat ultrasonic transducers are offered on the market with power density (amount of electrical power put into the transducer per unit of radiating surface area) ranging from 2.5 to 10 watts per square inch. Tests performed by the Westinghouse Process Equipment Department showed that the time required for cleaning diminishes with power density (Fig. 1). On the basis of those tests, the new system's transducer was designed to maximize power density.

2—(Left) *The transducer's cleaning chamber is full of a liquid cleaning medium when the system is operating. Cleaning medium is pumped in through a vestibule on the product-exit side of the transducer so that clean medium contacts the product last. It drains from the entrance vestibule to a tank where it is stored and purified for reuse.*

Cylindrical Transducer

The transducer's core is a stainless-steel tube, approximately 7½ inches long and 3 inches in inside diameter, that also serves as the cleaning chamber (Fig. 2). Magnetostrictive laminations attached radially around the outside of the tube vibrate it at its resonant frequency along its entire length. The tube expands and contracts radially, with expansion causing voids to form in the cleaning medium filling the tube and contraction causing the voids to implode. (See *Ultrasonic Cleaning*, p. 77.)

The transducer is rated at 1 kW, and its power density is 15 watts per square inch of inside surface of the tube—1.5 times the power density of the highest rated conventional flat transducer available. Moreover, its resonant mode of operation makes it more efficient than conventional flat transducers, which are nonresonant.

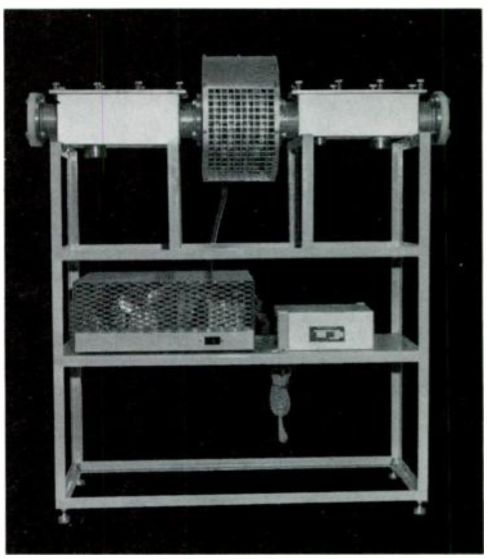
The transducer is, then, an effective electromechanical device vibrating radially and coupled efficiently to a liquid cleaning medium. All of the ultrasonic energy produced is concentrated in the medium and directed, simultaneously and uniformly from all sides, toward the product being cleaned as the product moves through the tube. High power density, the fact that the transducer is an efficient resonating assembly, and high power relative to the volume of liquid in the small cleaning chamber combine to produce cavitation at much higher intensity than is possible with conventional flat transducers.

In-Line Cleaning System

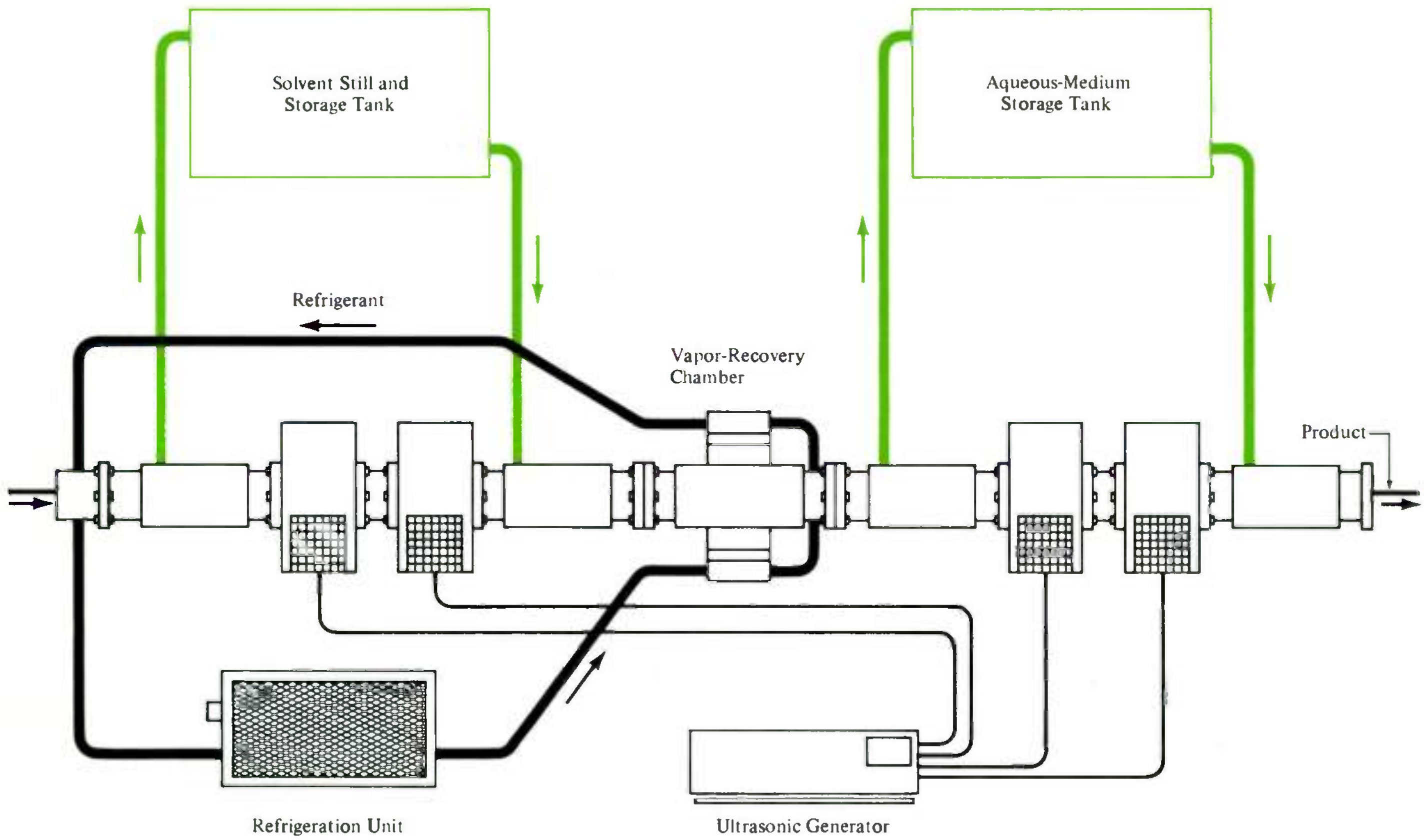
A cleaning system consists of one or more cylindrical transducers with the required piping, power-supply, and accessory equipment. The equipment is modular, so the number and arrangement of transducers and other components can be readily tailored to the cleaning requirements of a particular process line. The system can use aqueous cleaning solutions, any of the commercial degreasing solvents, or combinations of cleaning media.

The basic unit of equipment is a standard cleaning station with one transducer (Fig. 3). It employs the "floodbox" technique, in which cleaning medium is pumped from a storage tank into the cleaning chamber at a rate equal to overflow (Fig. 2). The product moves through the system in a straight line and enters the flooded cleaning chamber through a guide hole sized to accept the product but minimize leakage of medium. The medium flows counter to the direction of product movement so that the product is in contact last with the cleanest medium. Overflowing medium returns to the storage tank and is purified.

To increase the power of a cleaning station and thereby increase line speed, two or more of the 1-kW transducers can be mounted in series for use as a common cleaning chamber. Also, two or more cleaning stations can be used in series to provide



3—*Standard 1-kW cleaning station consists of a support frame, entrance and exit vestibules, transducer, ultrasonic generator, and radio-frequency-interference line filter. The generator and filter are the units seen at left and right, respectively, on the lower level. To provide more ultrasonic power, several transducers can be mounted in series in one cleaning station. Also, stations can be used in series to meet the needs of a particular process line.*



cleaning and rinse stations or to provide separate cleaning stations for different cleaning media; the entrance and exit baffles in the vestibules prevent mixing of the media. Both techniques are illustrated schematically in Fig. 4. Line speed is directly proportional to the number of transducers used in series, so any line speed can be achieved within economic limitations.

The standard 1-kW solid-state ultrasonic generator produces 20-kHz power from 115-volt 60-Hz single-phase power. For cleaning lines with more than one transducer, multi-kW generators operating from higher voltages are supplied. They are free-standing units housed in NEMA 12 enclosures, and their individual 1-kW modules are removable and interchangeable. To save space in the area of the production line, the ultrasonic generators (and also the liquid storage tanks) can be located remotely.

The ultrasonic generators perform the required frequency conversion by thyristor switching. They are automatically tuned, so no operator adjustment is needed. Their efficiency is high—60 to 70 percent from input to output.

The great amount of ultrasonic energy provided by the new system gives process engineers more flexibility than before in adjustment of the other variable parameters (time, temperature, type of cleaning medium, and concentration of the medium). The last three may not be as critical as they are with conventional transducers. However, once standards for them are established, it is imperative for uniformity of results that the system be capable of maintaining them. It is also necessary to control the level of contamination in the medium pumped into the cleaning chamber, because the purity of the make-up determines the irreducible cleanness attainable on the product being cleaned. Temperature and cleanness of the medium are controlled by the storage and purification accessories.

Accessories

Storage and Purification—These facilities are of two general types—one for aqueous

4—(Left) *One of the many possible multitransducer arrangements is illustrated schematically here. Two cleaning stations are provided, each having two standard 1-kW transducers. The first cleaning station employs an organic solvent, and the second employs an aqueous solution to remove soils that are not dissolved by the solvent. Solvent vapor escaping from the first station is condensed by chilled coils in the vapor-recovery chamber.*

5—(Above) *This 6-kW system at Charter Wire Company in Milwaukee removes mill scale from steel wire rod after the rod has passed through a mechanical scale breaker and before it is drawn into wire. It employs an aqueous cleaning medium stored in the tank just below the transducers. The system cleans the rod faster and at less expense than did the sulfuric-acid bath previously used. It also cleans more thoroughly, improving the wire product and prolonging the life of the drawing dies.*

cleaning media and one for nonaqueous organic solvents such as perchloroethylene, trichloroethylene, trichloroethene, methylene chloride, and Freon. Their general features are described in the following paragraphs; design details are varied to meet specific requirements.

The *aqueous-medium storage tank* is made of stainless steel and has two compartments. When the effectiveness of the cleaning medium in one compartment is depleted, or at a predetermined time, the operator switches to the reserve compartment. The used medium in the first compartment is disposed of and fresh solution made up while the line is operating.

The tank has electric immersion heaters, temperature controls, filters, and a pump. Medium is filtered before it enters the cleaning chamber. The rate of flow is generally 2 to 5 gallons per minute, making a rate of turnover of the medium in a 1-kW station of two to ten times a minute. This high rate of turnover minimizes accumulation of soil in the cleaning chamber, reducing the potential for redeposition of soil on the product. Even higher turnover rates are used when required. For example, the rod descaling system (Table 1, Application 10) pumps the medium at 10 to 15 gallons per minute for a turnover of 20 to 30 times a minute. That system is shown in Fig. 5.

Filter types and ratings are selected to meet application requirements. Dual filter housings with valving allow switching from one housing to the other when a cartridge becomes clogged; the clogged cartridge can then be replaced while the line is in operation.

Although purity of the makeup solution determines the cleanness of product leaving a cleaning station, filtering at the cleaning station may not be critical if a subsequent rinse can remove soil carried from the cleaning station. The filters in the cleaning-medium storage tank then can be used to remove gross soil while the final rinse removes the remainder of the soil. That arrangement permits less frequent changing of filter cartridges.

The *solvent still and storage tank* serves the same basic storing and purifying functions as the aqueous-medium tank, but it purifies the cleaning medium in a different way. The aqueous-medium tank filters the medium to remove particulates only and depends on the chemical additive to emulsify oily matter; the organic-solvent tank distills the solvent as well as filtering it. Distillation is generally more important than filtering because organic solvents are ordinarily used to remove soluble soil. Filtering cannot extract such soil from the solvent, but continuous distillation removes it and thereby prevents its recontact with the product being cleaned.

The tank is a stainless-steel two-compartment unit. One compartment is a boiling sump containing heaters that vaporize

Ultrasonic Cleaning

Ultrasonic cleaning is a means of scrubbing a workpiece immersed in a liquid cleaning medium by means of "cavitation" induced in the liquid by ultrasonic energy (sound waves at frequencies well above the audible range—18 kHz and higher). It combines two cleaning methods—the mechanical scrubbing of cavitation and chemical cleaning by the liquid medium, which dissolves soluble soils and wets and disperses insoluble soils. Plain water sometimes suffices as the cleaning medium, but more often the process requires an organic solvent, an aqueous solution, or a combination of both.

Cavitation is the creation of millions of microscopic voids throughout the liquid and the implosion of those voids. The implosions are so violent that they develop enormous pressures and temperatures, calculated at about 10,000 pounds per square inch and 2000 degrees F at each implosion site. While the quantity of energy in any one implosion is extremely small because the void is so small, the cumulative effect of cavitation is highly effective for cleaning because of the vast number of voids formed in each cycle and the high frequency used.

Cavitation is induced in the liquid by a transducer that converts electrical energy to mechanical energy. The simplest kind of transducer is a flat metal plate having magnetostrictive or electrostrictive materials attached to one face. Those materials change dimensions when exposed, respectively, to a varying magnetic or electric field, so reversing the field at high frequency causes high-frequency vibration of the plate. The other face of the plate is in contact with the liquid cleaning medium, and its vibration causes alternate positive and negative pressure in the liquid. In the negative half cycle, pressure in the liquid is reduced to less than the liquid's vapor pressure, causing the voids to form. A half cycle later, pressure becomes positive and the voids implode. That simple flat type of transducer is replaced in the system described in this article by a cylindrical type that produces much greater ultrasonic energy intensity in the cleaning medium.

High-frequency alternating current for driving the transducers is supplied by an electronic circuit called an ultrasonic generator. The Westinghouse cleaning systems employ a solid-state ultrasonic generator that converts line current to high-frequency current by rapid switching of thyristors.

Table 1—Typical Applications of Cylindrical-Transducer Cleaning Systems

Application	*Equipment*	*Media*	*Line Speed*
1. Cleaning aluminum welding wire, 0.125-in. dia.	One 2-kW cleaning station	Trichloroethylene	60 f/min
2. Cleaning alloy welding wire, 0.155-in. dia.	Two 2-kW cleaning stations, one 1-kW rinse station, drying and solvent recovery	Trichloroethene, aqueous alkaline, tapwater rinse	300 f/min
3. Cleaning stainless-steel welding rod, 0.186-in. dia, before coating.	One 1-kW cleaning station	Aqueous alkaline, tapwater spray rinse	200 f/min
4. Cleaning stranded copper wire, 0.032-in. dia, before insulation.*	One 1-kW cleaning station	Trichloroethene	100 f/min
5. Cleaning copper-clad aluminum coaxial cable, 0.250-in. dia, for CATV transmission line before applying insulation and outer shielding.	One 1-kW cleaning station	Aqueous acid, tapwater rinse	100 f/min
6. Cleaning coaxial cable, 1½-in. dia, after application of outer shielding.	One 1-kW cleaning station	Aqueous acid, tapwater rinse	150 f/min
7. Cleaning aluminum magnet wire, 0.125-in. dia, before enameling.	Four 1-kW cleaning stations in parallel, five wires running through each	Heated tapwater	100 f/min
8. Removing drawing lubricants from carbon-steel wire, 0.060 in. dia, for steel-belted tires.	Two 2-kW cleaning stations and 1-kW rinse stations in parallel, four wires running through each	Aqueous acid, tapwater rinse	230 f/min
9. Cleaning copper strip, about 1 in. wide and ⅛ in. thick, after stamping and forming and before plating. End product is electrical connectors.	One 1-kW cleaning station	Perchloroethylene	150 f/min
10. Removing mill scale from carbon-steel wire rod, 9/16-in. dia, before drawing.	One 6-kW cleaning station	Aqueous phosphoric-acid solution, 5 percent concentration by volume	400 f/min

*This is lead wire for instruments that monitor oil wells, so it must be produced in 30,000-foot lengths with no breaks in the insulation and no interruptions in the adhesion of the insulation to the wire.

the solvent, leaving the soluble soils behind. The other is a storage sump containing cooling coils for condensing the solvent and controlling its temperature.

Degassing—An additional function of both storage tanks is degassing of the cleaning medium. (Entrained gas attenuates ultrasonic energy and thereby reduces the efficiency of any ultrasonic cleaning system.) Both tanks degas thermally. The solvent storage tank also inhibits continued entrainment of gas because a vapor blanket forms, eliminating an air/solvent interface.

Rinsing—The importance of the rinsing stage and the complexity of equipment provided for rinsing are proportional to the cleanness required of the product. Rinsing methods used after cleaning with an aqueous medium range from a pass through a bath of flowing tap water to use of ultrasonics with water. The degree of cleanness required also determines the type of rinse water used: tap water, softened water, deionized water, or distilled water.

If ultrasonics is used, the rinsing module can be identical to the cleaning module. If a simple flowing bath is satisfactory, a stainless-steel tube is mounted downstream from the cleaning module.

Rinsing may also be necessary in solvent systems, but there it is accomplished by use of the same solvent used in cleaning. The level of cleanness required determines the rate of distillation necessary for purifying the solvent to a level acceptable for rinsing.

Drying—In aqueous systems, the necessity for drying is determined by the following process stage. Generally, a plating process does not require drying but coating processes do.

Drying is necessary in all solvent systems. The primary purpose is to prevent contamination of the air by minimizing the carrying of solvent on the product out to the atmosphere. The secondary purpose is to reduce operational costs by minimizing solvent consumption. Drying is accomplished by a closed-loop unit consisting of air wipes mounted in a blow-off vestibule, a vapor-recovery chamber containing chilled coils, and a refrigeration unit (Fig. 4). The air is vented to the plant exhaust system after it has passed over all coils.

The total cleaning system including the drying module is a closed system, with the only openings to atmosphere being the product guide holes and any vents from the drying module. When the operator is threading product through the line or has the cleaning system shut down for any other purpose, the system is dry because the medium drains to the storage tanks. That minimizes the operator's contact with the medium and simplifies threading and maintenance.

Determining Cleanness

The degree of product cleanness required is that which gives an acceptable product, whether the purpose of cleaning is cosmetic or to prepare the product for a following process. Once the goal has been set, a means of measuring cleanness is needed. Cleanness is sometimes so critical that scanning electron-beam microscopes and spectroanalysis are used to isolate and identify residues. Usually, however, the simpler methods outlined below suffice.

Smoke Test—Organic residues are detected by resistance-heating a length of the wire to vaporize the soil. The smoke is observed against a dark background and assigned a value on a scale of 1 to 10. It is a subjective test, so observations should be made by more than one person so that the assigned values represent a consensus rather than an individual judgment. The product must be dry because any water or solvent on the surface also vaporizes, and the vapor is indistinguishable from the smoke from soil residues.

The method is good only for checking on organic soil residues. It is useful when adhesion of the coating to be applied is important, or when the product may be entering a controlled-atmosphere heat-treat oven, plating bath, or other process where accumulation of organic residues would affect the oven atmosphere or the bath mixture.

Gravimetric Tests—A sample of the cleaned wire is cleaned again for a prolonged period in an ultrasonic cleaner with a volatile solvent, the solvent is evaporated, and soil left behind is weighed. This test can be used for measuring residual particulates or other nonvolatile soils.

A variation is to filter the solvent, weighing the dried filter paper before and after. The difference in weight represents soil residue.

Wipe Test—A simple wipe test with a paper wipe can give consistent indication of cleanness during the production run. The pressure used in applying the wipe and the time of wiping must be controlled and consistent for dependable results. Wipe tests can be correlated with smoke and gravimetric tests to develop wipes that can be used as standards for comparison with the wipes used during production runs.

Applications

The installations listed in Table 1 are typical successful applications chosen to illustrate the new system's versatility in handling a variety of cleaning problems. The variety includes type of material, type of soil, size of material, line speed, and cleanness requirements.

The 1½-inch-diameter shielded coaxial cable has the largest cross-section area processed to date. The maximum section area that can be processed has not been determined, but there probably is an interrelationship between it and the degree of difficulty in soil removal. That interrelationship did not manifest itself with the 1½-inch material, so it is known at least that a critical size has not yet been reached.

Cleanness requirements vary with the process. The Goodyear Tire & Rubber Company, for example, needed to reduce soils on its wire from 300 to 25 parts of soil to a million parts of wire (Table 1, Application 8). The Westinghouse cleaning system performs the task easily.

Multiple strands can be cleaned simultaneously. For example, in the installation listed in Table 1, Application 7, five wires pass through each transducer about half an inch apart (center to center). Experiments have been run to determine if the positioning of the material in relationship to the axial center of the transducer affects the cleaning results; no measurable difference could be detected. However, care must be taken not to let one wire mask another from ultrasonic energy and not to introduce soil in quantities too great for the system to handle. The latter problem can be solved if use of multiple transducers in series can be justified.

Potential applications should be tested before any attempt is made to choose equipment. The Westinghouse Process Equipment Department has the laboratory facilities for conducting the tests, as well as experienced application engineers.

Costs

Capital cost for the new system is about a third that for a conventional ultrasonic system of equal cleaning capacity. The main reasons for the lower cost are that fewer transducers are needed and, consequently, smaller tanks, filters, stills, etc. suffice. Also, less space is required.

Cost comparisons with other cleaning methods are harder because of the variety of methods and equipment applied. However, the cost of a cleaning station employing the new Westinghouse equipment can be expected to be about half that of a simple brush cleaning station. The latter would not clean as satisfactorily, and it would require frequent and expensive brush replacement.

Operating costs are less than those for a conventional ultrasonic system designed for a comparable cleaning application. One reason is that less electric power is needed because fewer ultrasonic generators are needed. For example, in the typical ultrasonic cleaning systems compared at the start of this article, the power requirement could be as high as 80 kVA for the conventional system as opposed to 10 kVA for the new system.

Great savings also accrue because of the smaller amount of cleaning medium required as a result of the flooded volume being much smaller. The cost of heating also is smaller because it is proportional to the volume of cleaning medium needed. Moreover, there is less loss of medium to the atmosphere because the system is closed. Finally, much less concentrated solutions usually suffice because the intense heating at each implosion point accelerates chemical action there.

Conclusion

The new cleaning system is having a significant impact on a number of industrial processes. It provides a better in-line method for cleaning wire and narrow strip than was previously available.

Ground-Fault Protection and Detection for Industrial and Commercial Distribution Systems

A. A. Regotti
H. W. Wargo

The first article in this series of two dealt with the characteristics of grounded and ungrounded distribution systems when phase-to-ground faults occur.[1] *Since those are the most common faults in distribution systems, they should have a major role (along with economic considerations) in determining the kind and amount of fault protection equipment to include in a system.*

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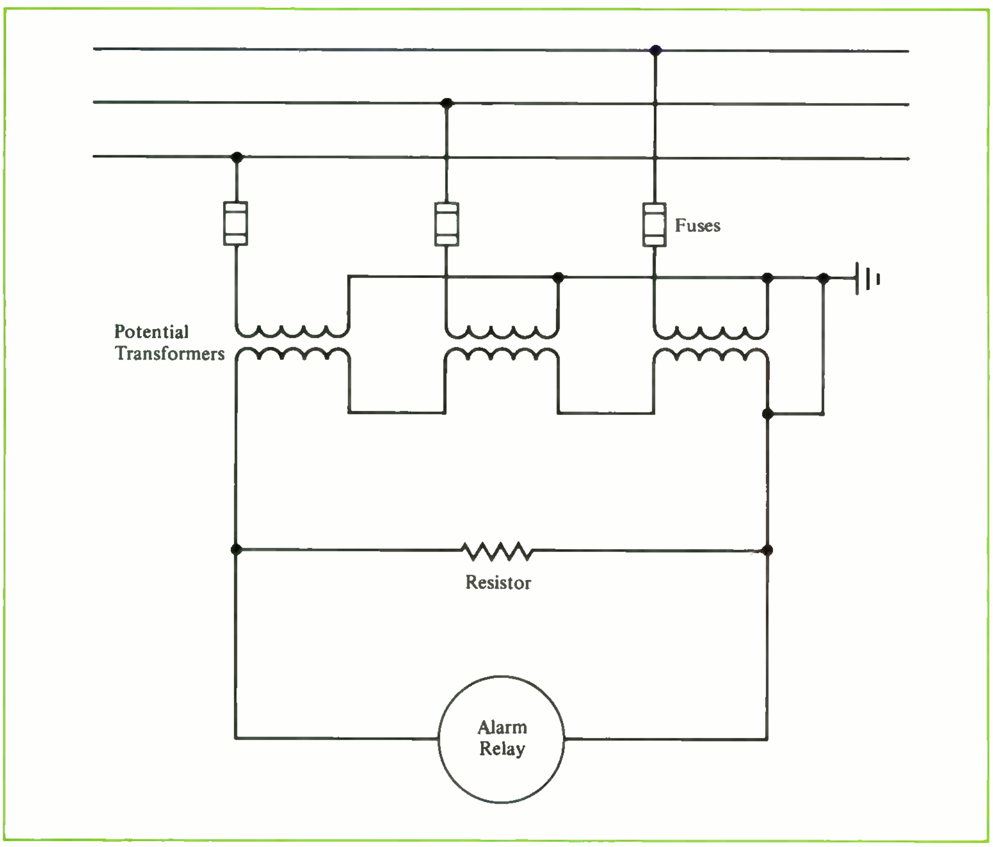
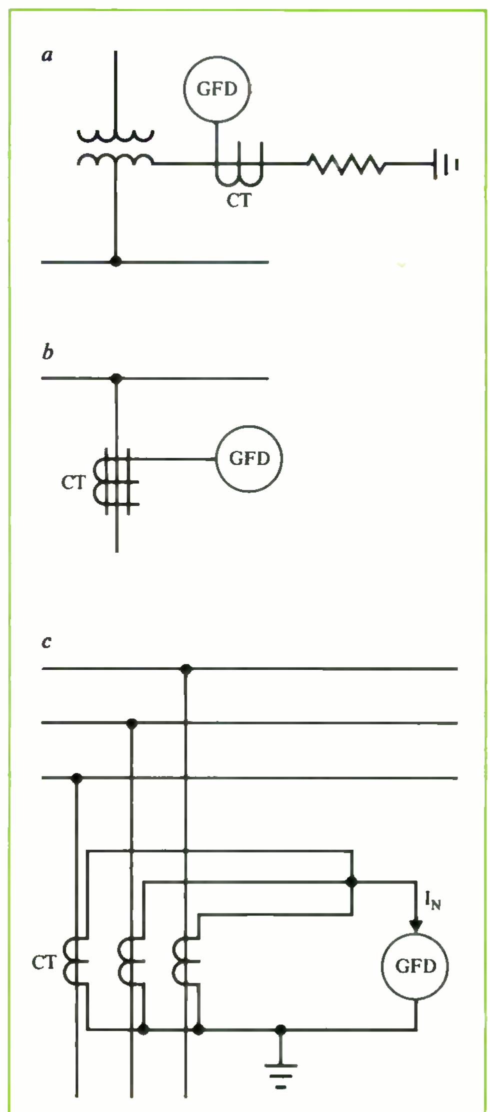
Ground-fault protection is an art as well as a science because of the great variety in distribution systems, plants, processes, and user experience. Moreover, the amount of protection applied is normally a compromise between acceptable equipment damage and continuity of service, with economics determining the type and sensitivity (except in low-voltage systems where NEC dictates that ground-fault protection must be applied on the service entrance[2]).

A well designed distribution system provides both fault protection and continuity of service. For service continuity, selective tripping should be achieved between all protective devices; that is, protective devices should be so coordinated that a fault causes tripping of only the device closest to the fault. Since the majority of faults are ground faults, it seems negligent to provide coordination for phase-to-phase and three-phase faults and accept nuisance tripping of the larger feeder breakers for the more common phase-to-ground faults. Therefore, once the decision to ground has been made, selective ground-fault protection should be considered throughout the system.

In low-voltage systems, equipping all of the smaller branch protective devices with ground-fault protection would be economically infeasible, even though it would be the ultimate in protection and selectivity, so some compromise must be made. The deciding factors for ground-



1—(Above) *Ungrounded distribution systems need an arrangement such as this to detect the first ground fault so it can be corrected before another occurs. The voltages induced in the potential transformers are balanced until a fault occurs; then the unbalance causes the voltage alarm relay to operate and sound an alarm.*



2—(Right) *Methods for detecting ground-fault current in grounded systems include the source neutral scheme* (a), *zero-sequence scheme* (b), *and residual scheme* (c). *All employ a current transformer* (CT) *that senses the current and sends a signal to a ground-fault detector* (GFD), *which is either a sensitive relay* (*to indicate a fault or operate one or more breakers*) *or the static ground-fault detection element of a breaker that has such detection built in.*

fault protection should be the necessity for continuity of service and the size and location of the protective devices. The smaller the ampere rating of a phase-operated device, and the nearer it is to the incoming power, the less need for specific ground-fault protection.

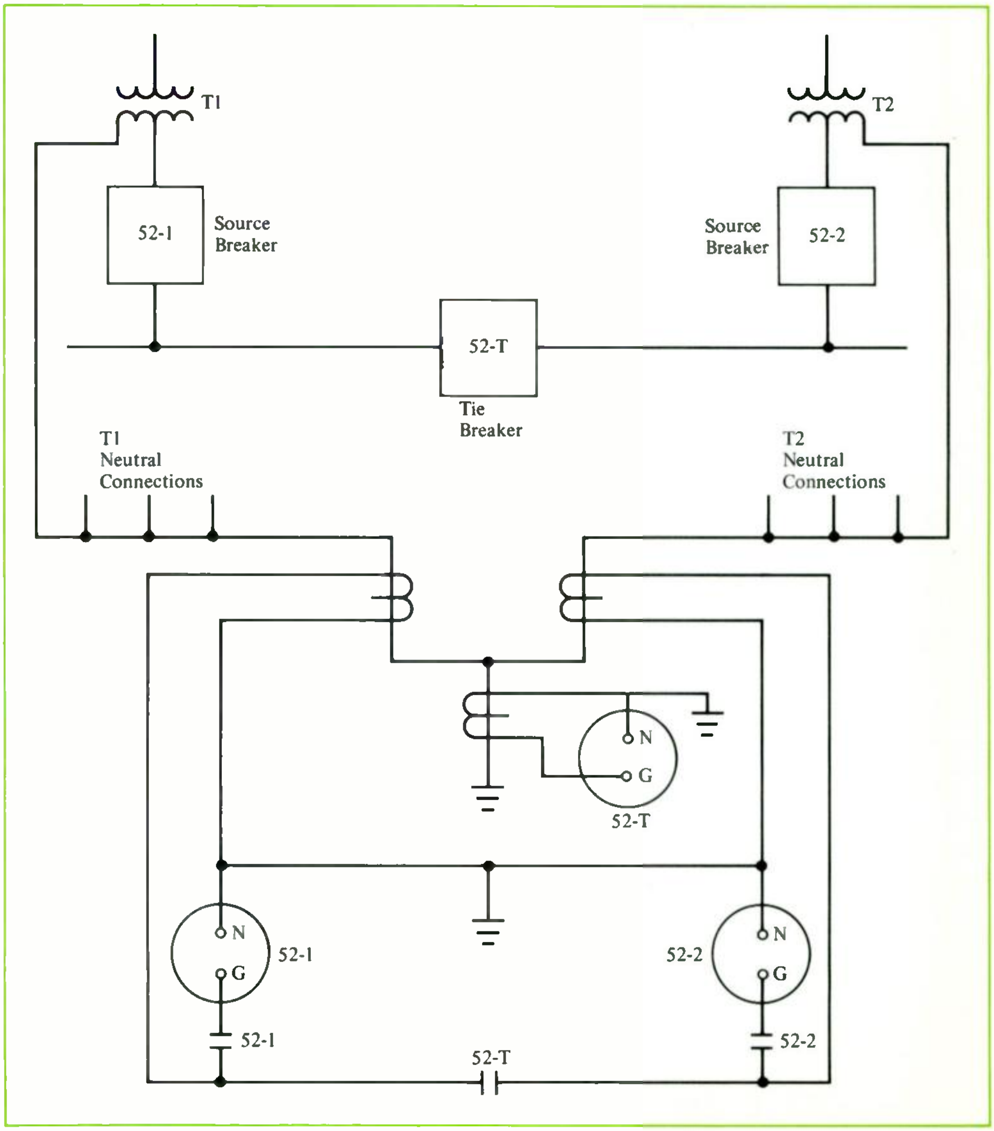
Ground-Fault Detection

A ground-detector scheme must be employed on ungrounded and high-resistance grounded systems. On the basis of industry experience, the authors recommend use of three potential transformers connected in a broken delta scheme (Fig. 1). Since the nonlinear exciting impedance of the grounded potential transformers can oscillate with the system capacitance to ground, a resistor is connected in the circuit to prevent that oscillation (ferroresonance).[3] The resistor is sized to prevent ferroresonance, not sized for system grounding. To achieve system grounding, the resistor current reflected to the primaries of the potential transformers would have to be equal to the system charging current, which would normally warrant use of distribution class transformers instead of potential transformers.

Various overcurrent methods to detect ground faults in grounded systems are illustrated in Fig. 2. The best method is the *source neutral scheme* (Fig. 2a) because it can be made more sensitive than the others by use of low-ratio current transformers. Such transformers can be applied because no currents normally flow through the neutral connection to cause nuisance tripping and also because, during a ground fault, the current transformers are subjected to extremely high currents for only fractions of a second before a protective device opens. Normally, the source neutral scheme is most applicable for the source circuit breakers and tie breaker as applied in a double-ended substation (Fig. 3).

The next best method of ground-fault protection is the *zero-sequence scheme* (Fig. 2b). It consists of a modified bushing-type current transformer with the power leads passing through the opening. The magnetic flux in the core of the current transformer is the sum of the fluxes set up by each phase current passing through the opening. During normal system operation (assuming a three-phase three-wire system), the current through the current transformer to the load through one phase is equal to the return current through the other two phases. Therefore, the net flux that would produce a secondary current is theoretically equal to zero.* During a ground fault, not all of the current feeding the faulted area returns through the remaining conductors; some returns through an external path to the neutral of the power transformer. This external current results in a net flux (proportional to the magnitude of ground-fault current) in the current transformer, producing a current through the ground-fault detector (GFD). This arrangement func-

*Actually, net flux is zero only if all conductors can occupy the same space; that isn't possible for an actual system where the conductors are more or less random. The linkage flux is different for each conductor and may result in some error flux that can cause a false secondary current, which is what makes this method second best. Also, the larger the opening in the current transformer with respect to the phase conductors, and the less circular the resultant flux path, the more chance of producing secondary error current. However, error currents do not present a problem when Westinghouse coordinated Type BYZ current transformers and overcurrent relays are applied.



3—One application of the source neutral scheme is in a double-ended substation. "N" and "G" are the terminals of ground-fault detectors built into the circuit breakers used as the source and tie breakers in this system. The three current transformers have identical ratios. The breakers are coordinated so that the tie breaker opens before the source breakers.

tions only for fault conditions, so the current-transformer ratio can be as small as possible—the ratio has no relation to load current.

An application of the zero-sequence method is illustrated in Fig. 4. It is faster and more convenient than tracing the ground circuit with a zero-sequence clamp-on ammeter.

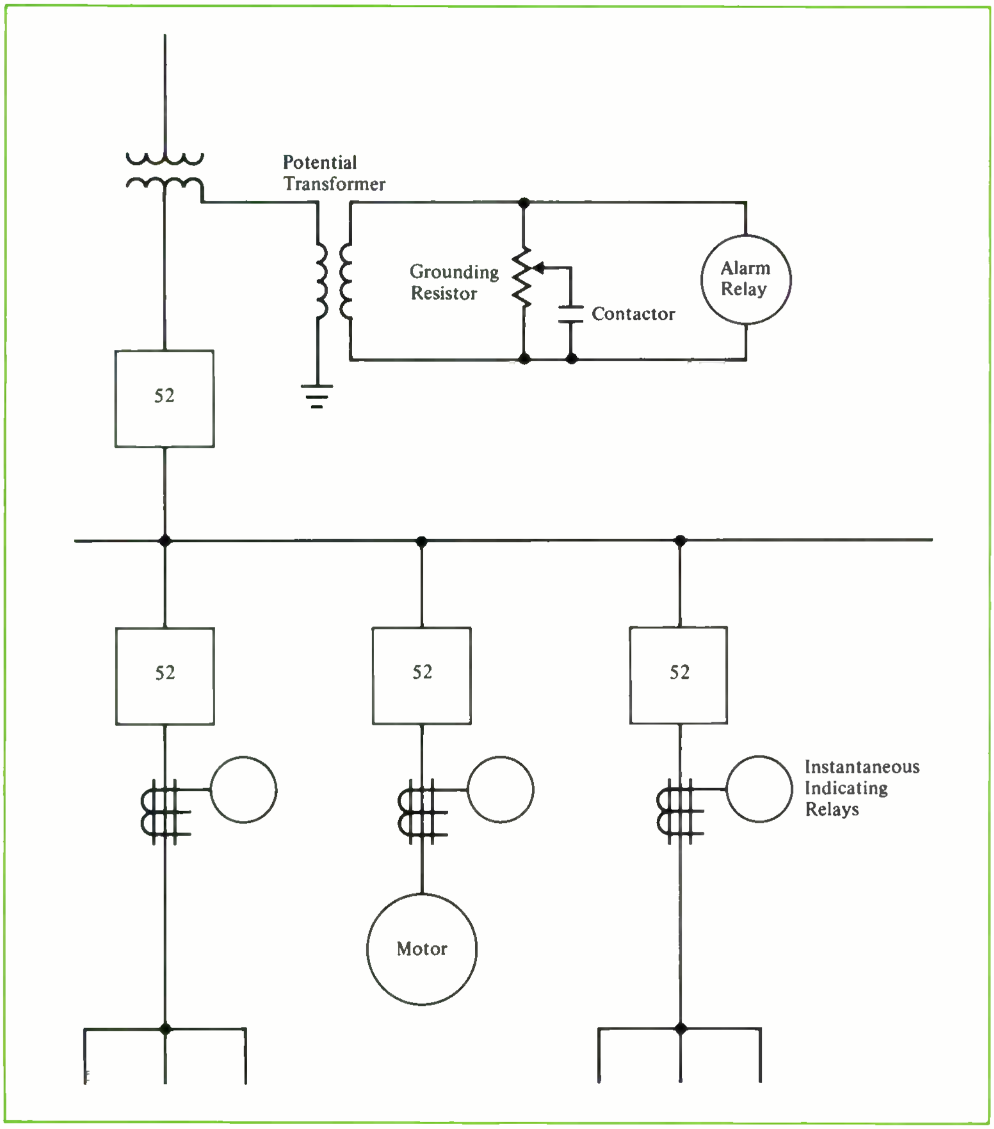
The *residual scheme* consists of a GFD applied to the neutral connection of phase current transformers (Fig. 2c). During normal balanced load or three-phase fault conditions, all currents in the current transformers are equal in magnitude and displaced 120 degrees. Therefore, the vector sum of the secondary current is equal to zero at the neutral (assuming all current transformers saturate equally), and no current flows in the overcurrent relay. However, during a ground fault the currents are not all equal in magnitude and their vector sum does not equal zero at the neutral. The unbalanced current returns to the current transformers via the neutral path and energizes the overcurrent relay.

The amount of neutral current depends on the current-transformer ratio. Therefore, the fault sensitivity, unlike that in the other two schemes, is a function of the normal load conditions that dictate the current-transformer ratio. That is a disadvantage because the current transformers are usually of much higher ratio than they are in the other schemes, and therefore sensitivity is less. However, this scheme may be less costly than the other two.

When a circuit is energized, an offset current (dc component) can cause one of the three current transformers to saturate. The secondary currents then are not faithful reproductions of the balanced primary currents. This saturation effect results in a false current in the current transformer's secondary neutral. If an instantaneous relay is applied, it must be set high to compensate for the false neutral current. Thus, for adequate sensitivity, the relay must incorporate a low-pickup time delay and be delayed sufficiently to allow the false neutral currents to disappear. That requirement sacrifices speed of operation for sensitivity.

The Westinghouse Type DS low-voltage power circuit breaker and SCB molded-case breaker can be applied in any of the three protection schemes because their ground-fault circuits are separate from their phase-fault circuits.

A low-resistance grounded system must be equipped with a protective relay and a primary breaker to isolate the source for a ground fault in the source (breaker *A1*, Fig. 5). When the source is a delta-wye transformer bank (*T2*) with high-side fuses, low-resistance grounding may not be acceptable because the high-side fuses are insensitive to a transformer secondary



4—(Left) *A way of detecting and locating ground faults in a high-resistance grounded system is to provide an alarm across the grounding resistor and equip each circuit with a zero-sequence current transformer and an instantaneous indicating relay. When the alarm sounds, maintenance personnel can determine which circuit is faulted by closing the contactor; it shorts out most of the resistor and thereby allows enough ground-fault current to flow to operate the indicating relay in the faulted circuit and announce which circuit is in trouble.*

5—(Right) *This simplified diagram of a medium-voltage system illustrates complete and coordinated ground-fault protection from the load to the source. Instantaneous protective relays* (50) *are applied nearest the load, and time-delay relays* (51, 151, *etc.*) *are applied at the source. Low-resistance grounding requires application of zero-sequence current transformers for ground-fault protection. Dashed lines indicate breaker trip circuits.*

ground fault. Such a fault is actually phase-to-phase current on the delta side of the bank. If the ground current is restricted by low-resistance grounding, a transfer trip to a high-side feeder breaker should be provided as indicated in Fig. 5.

Conclusions

Low-voltage ungrounded and high-resistance grounded systems require audible alarm provisions that alert the maintenance crew when a ground fault first occurs. If the system is solidly grounded, it should be protected as much as possible with ground-fault sensing devices that automatically isolate the initial ground fault.

High-resistance grounding of *medium-voltage* systems also necessitates alarm provisions for ground faults. Low-resistance grounding permits automatic isolation of ground faults. With zero-sequence ground relaying throughout the system, the maximum ground fault can be limited to approximately 150 amperes. If residually connected current transformers are applied for ground-fault protection, the ground-fault current must not be limited to a value less than the primary current rating of the largest current transformer applied.

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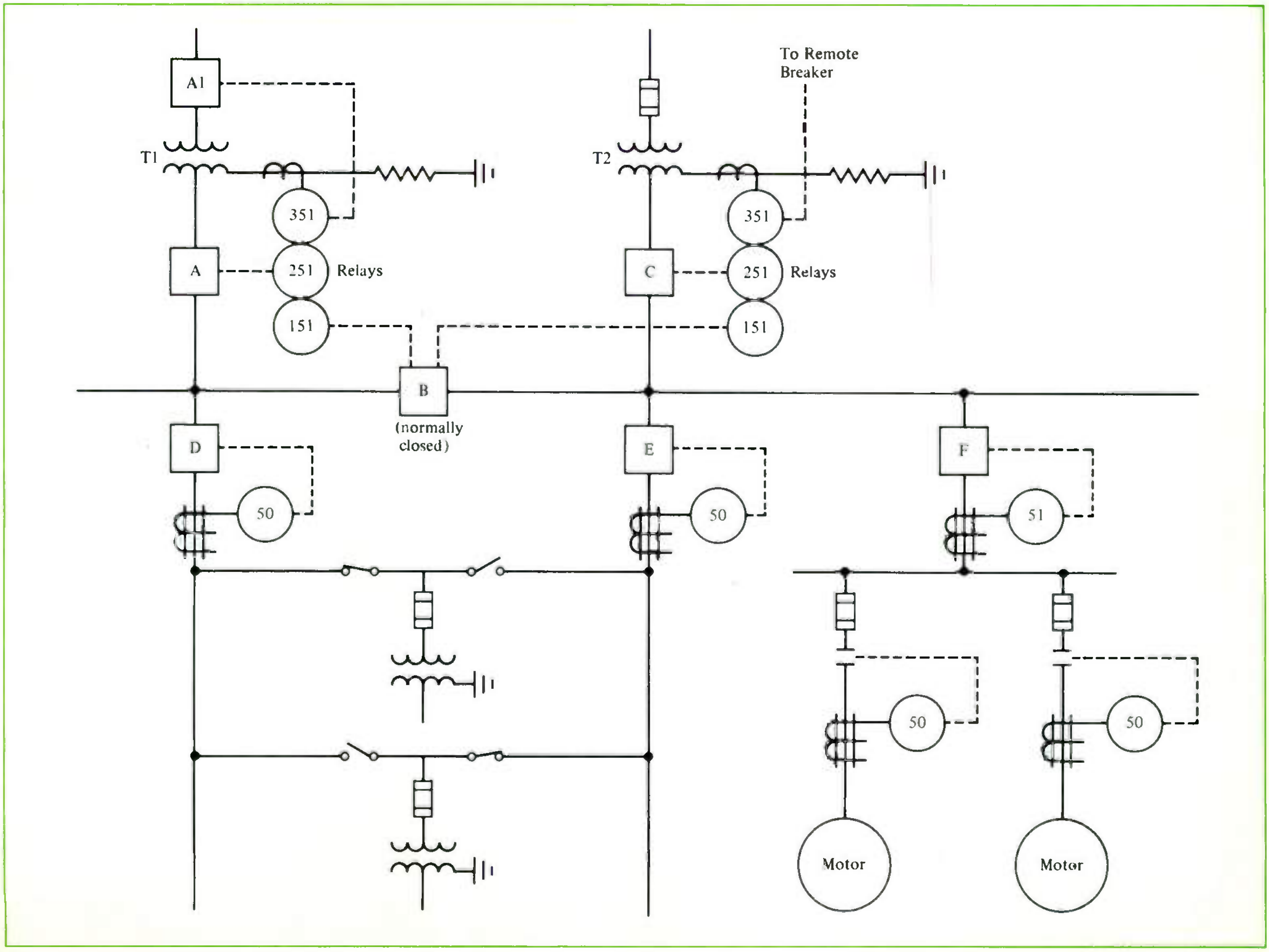

Video Processing Techniques Can Improve Underwater Imaging

W. F. Parrish

The performance of underwater television systems used for biological and geological surveys can be improved with video-processing techniques that increase contrast, increase effective vertical resolution, and eliminate shading patterns.

Recent advancements in low-light-level camera tube technology[1] and micro-miniaturized camera circuitry have resulted in compact high-performance TV cameras for underwater viewing. Those cameras have been used for underwater observation either as the primary sensor or as a "view finder" for high-resolution film cameras.

Signal Processing with the Video Disc

In the underwater application, camera performance is reduced by the spectral filtering effects of water, lowered scene contrast, relative motion of the camera with respect to the scene, optical losses, and other factors. Although low-light-level television (LLLTV) cameras provide adequate capability for many underwater applications, particularly where illumination is restricted, further improvement is desirable. Video signal-processing techniques utilizing the video disc have demonstrated such improvement.[2] The accurate TV line, field, and frame storage and delays at video bandwidths up to 8 MHz that are necessary for those signal processing techniques are made possible by the high time stability of the disc (±75 nanoseconds or better).

In the conventional floodlit underwater TV system, the camera must view the scene through a veiling irradiance produced by the scattering volume formed by the cone of illumination and the camera field of view (Fig. 1). The inherent contrast of the object relative to the background at the scene plane is given by the ratio

$$C_o = (B_o - B_b)/B_b,$$

where B_o is the brightness of the object and B_b is the brightness of the background. However, at the camera, the brightness of the object is $B_o + B_v$ (attenuated by the water) and the background brightness is $B_b + B_v$ (attenuated by the water), where B_v is the veiling irradiance. The reduced or apparent contrast at the camera is given by the ratio

$$C_r = (B_o^r - B_b^r)/(B_b^r + B_v^r),$$

where the superscript r refers to brightness at the plane of the receiving optics. This loss in contrast can be offset by the gains provided by TV signal processing techniques.

Successive Frame Addition—The video signal produced at the camera by light from the scattering volume does not form an image and is random in nature. Thus, picture quality can be improved by storing and adding successive picture frames of a stationary scene with the video disc; signals produced by the image-forming light add directly whereas the random noise-like signals produced by the non-image-forming light add in a root-mean-square fashion. Thus, the theoretical improvement in signal-to-noise ratio is given by:

$$S/N_k = kS/(kN_k^2)^{1/2} = k^{1/2}S/N_k$$

where S is signal amplitude in the picture frame, k is the number of picture frames added, and N_k is the rms noise per frame (in the video bandwidth). The improvement possible with this technique is illustrated in Fig. 2.

Moving Window Display—With the geometry of a typical underwater television

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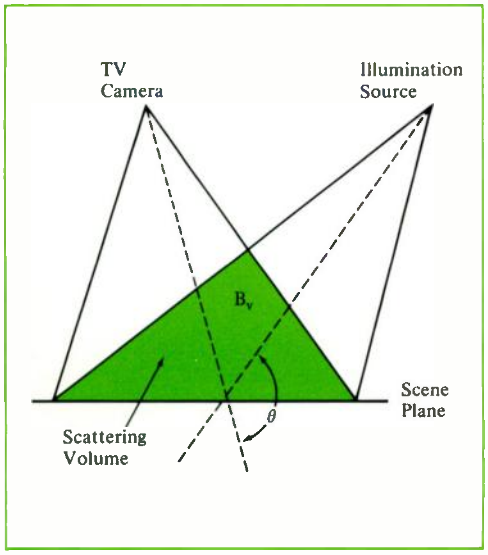
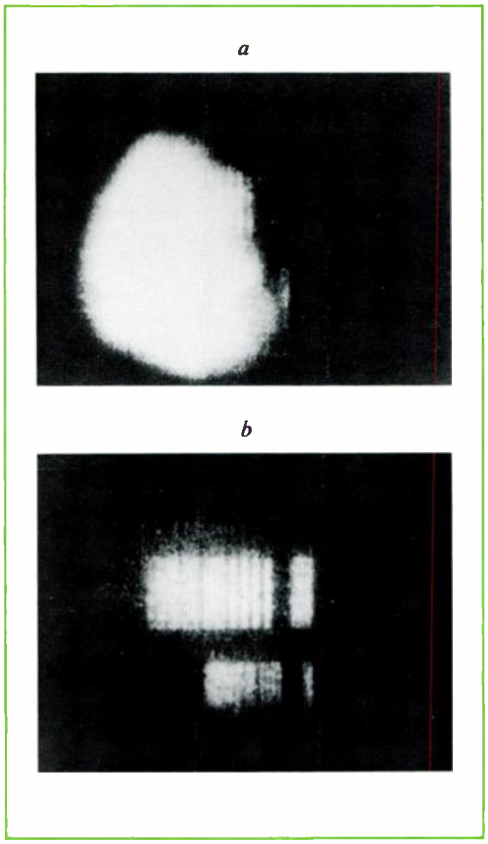
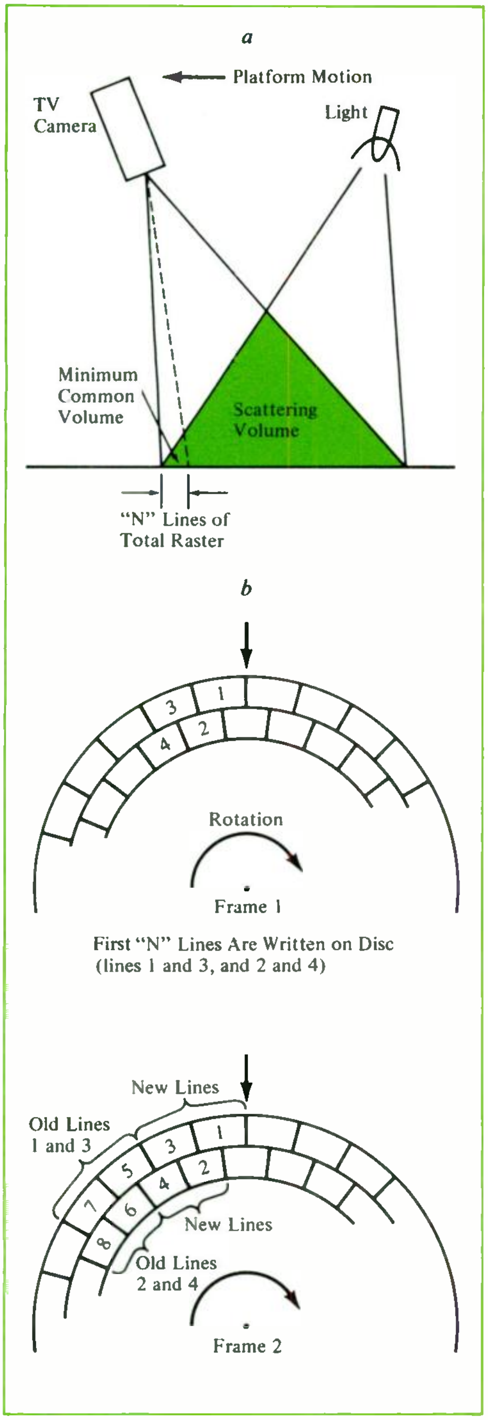


1—In conventional floodlit underwater TV system, contrast at scene plane is reduced by the veiling irradiance of the scattering volume. Brightness of the veiling irradiance (B_v) *is a function of the angle θ.*



2—The improvement in TV picture quality obtained by successive addition with a video disc is illustrated for a target viewed through the scattering volume (a) *and the same target viewed with 10-frame addition* (b).



3—A moving-window display is developed by selecting N *lines from the camera side of the raster* (a) *for recording on the video disc* (b). *The sync generator is reset* N *lines early (4 lines for the application shown), which moves "old" lines* N *lines late or down raster, making room in proper sequence on disc tracks for* N *lines of new information each frame.*

system (Fig. 3a), the common volume formed by the intersection of the cone of illumination and the camera field of view is smallest on the camera side of the scene. Thus, the veiling irradiance and resulting loss of contrast are lowest for that portion of the scene.

The video disc is used to extract a few TV lines from the portion of the illuminated field where the effects of scattering are the least, and those lines are used to form a "moving-window" display (Fig. 3b). A preselected number of active lines (N) are stored on the disc each frame and the remainder of the video information in the frame is discarded. To provide the moving window display, the system sync generator driving the camera and display is reset N lines early during each vertical blanking interval. This causes the video information already stored on the disc to be read off N lines late, providing a continual update of information for each frame and an uninterrupted moving-window display. The number of lines (N) used for early reset per frame must be coordinated with forward velocity of the camera and its height above the bottom. This technique has been demonstrated in scaled laboratory experiments.

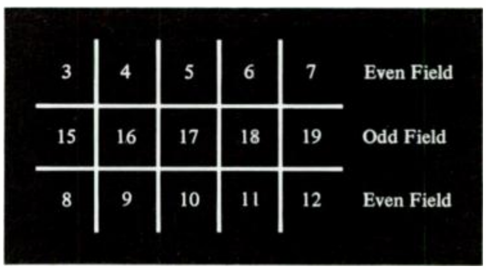
Vertical Aperture Correction—This technique can be used to increase the sharpness of the displayed underwater TV picture. For the small portion of a television raster shown in Fig. 4, the elements numbered 3, 4, 5, 6, 7 represent resolution elements in a scan line of the *even* field, and 8, 9, 10, 11, 12 represent similar elements in the next scan line of the *even* field. The numbers 15, 16, 17, 18, and 19 represent adjacent elements from the interlaced line of the *odd* field. Because of the relatively large size of the scanning electron beam in the camera and lateral leakage on the camera tube's target, the signal obtained by scanning element 17 contains information from elements 5 and 10 from the even field and vice versa. This situation exists for all active elements in the scanned television raster.

Vertical aperture correction is accomplished by simultaneously subtracting information in elements 5 and 10 from element 17—or more generally, subtracting the information contained in the two adjacent scanned elements from the line being scanned throughout the raster-scanning process. The effectiveness of this technique in increasing the Kell factor (or statistical vertical resolution factor) has been dramatically demonstrated by televising an aerial photograph.[3] A similar improvement should be possible for the underwater application.

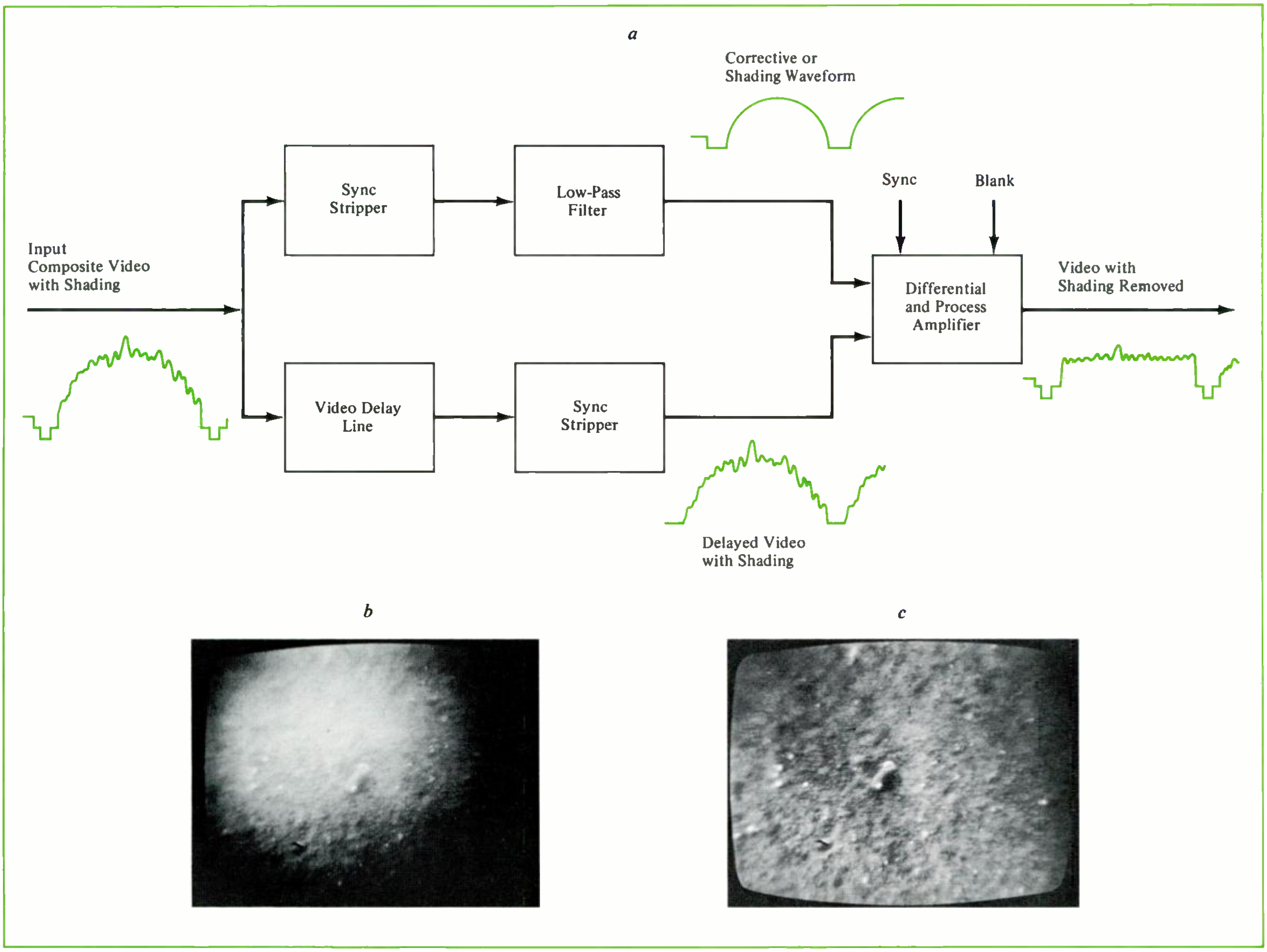
Shading Pattern Correction

Artificially illuminated underwater television pictures frequently have shading patterns, or uneven brightness, caused by the decreased off-axis response of the camera optics and the camera tube and intensifier combined with uneven scene illumination. If the envelope of the shading pattern is suitably derived and subtracted from the original video wave form on a line-by-line basis, shading patterns can be largely corrected.

A block diagram of an adaptive shading corrector is shown in Fig. 5a. The uncor-



4—Diagram of a portion of an interlaced TV raster showing elements from even and odd fields.



5—The block diagram illustrates the signal processing steps for an adaptive shading corrector (a). *The shading pattern typical of artificially illuminated underwater television pictures* (b) *is eliminated with adaptive shading correction* (c).

rected video signal is fed through two paths: in one, the sync signals are stripped and the video signal is fed through a low-pass filter leaving only the shading waveform; the second path delays the video signal for a period equal to the low-pass filter delay, and the sync signals are stripped. The signals are combined in a differential amplifier and processor, where sync signals are reinserted. The result is a system that adapts to uneven illumination, producing a video picture that is corrected for shading on a line-by-line basis, as shown in Figs. 5b and 5c.

A number of these adaptive shading correctors were delivered to the U.S. Navy during 1973.

Conclusion

Sensitive LLLTV cameras are capable of providing good quality imagery for underseas geological, biological, and environmental survey applications. The video-processing techniques that have been demonstrated can improve underwater television picture quality by increasing contrast, by increasing the effective vertical resolution, and by removing shading patterns to restore gray-scale levels in the display.

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Phase-Angle Regulators Optimize Transmission Line Power Flows

L. S. McCormick
R. A. Hedding

The phase-angle regulator is a special application of transformers that can help overcome power flow problems associated with parallel transmission lines or system interties. The use of this unit is well known but only in recent years, with the increase in system interties, has there been economic justification for its use.

Power flow between two systems is accompanied by a voltage drop and a phase-angle shift between the sending and receiving ends of the transmission line. If the systems are connected by parallel lines, a loop exists and therefore any difference in the impedances of the two paths causes a circulating current (Fig. 1).

Assuming unity power factor loading, the reactive voltage drops (jIX) are in quadrature to system line-to-ground voltages and any magnitude difference between reactive drops appears as a voltage in the loop. That voltage causes a circulating current, adding to real power flow in one line and subtracting from real power flow in the other. The insertion of a phase-angle regulator in either line can correct the difference in reactive voltage and thereby control the real power flow over the two ties so that each can be loaded to its maximum capacity.

Any difference in the resistive voltage drops (IR) causes reactive current to flow. Voltage-regulating features can be added to the phase-angle regulator to cancel out the effects of the IR drops. However, in most applications to date, voltage-drop problems have been corrected by the use of voltage-regulating autotransformers.

Benefits of Phase-Angle Correction

The beneficial results that can be obtained through phase-angle correction are best described by example. Consider two parallel transmission lines of equal length (Fig. 2a). One line is an existing 138-kv system to which is being added, in parallel, a 345-kV line to increase total system capacity. The new 345-kV line has 345/138-kV autotransformers at each end.

Assume that 138-kV line capacity is 215 MVA and 345-kV line capacity is 600 MVA. Due to the difference in impedance characteristics of the two lines, which varies with length, there is only one optimum length that will allow both lines to be loaded to capacity simultaneously. The effect of line length on power transfer

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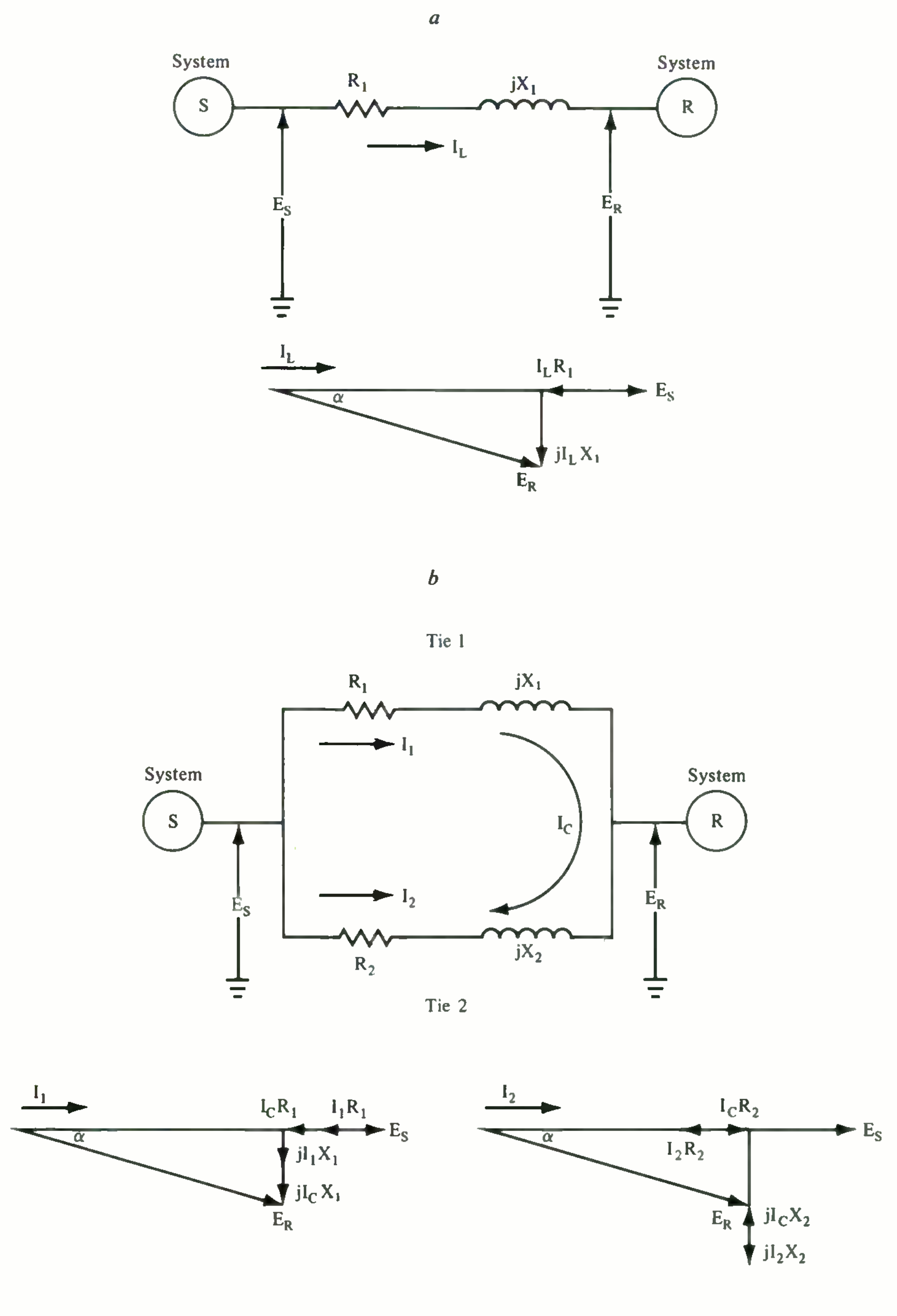

1—Power transfer from sending (S) *to receiving* (R) *systems over a single tie line is accompanied by a voltage decrease and phase shift* (a) *due to transmission line resistance* (R_1) *and reactance* (jX_1)*. When parallel ties are used for transferring power* (b)*, any unbalance in tie-line impedances results in circulating current* (I_C)*.*

capability is shown graphically in Fig. 2b: for short line lengths, total power transfer is limited by the capacity of the 138-kV line; at longer lengths, power transfer is limited by the rating of the 345/138-kV autotransformers.

A phase-angle regulator inserted in the 138-kV line can be used to correct the situation. The phase shift needed to achieve maximum capacity is a function of the line length, as shown in Fig. 2c. Thus, a phase-angle regulator can provide maximum line loading regardless of line length. For example, if the lines were 50 miles long, the regulator setting would be +6 degrees for a unity power factor load. For load power factors other than unity, the required angle of shift changes as indicated in Fig. 2c for 0.8 power factor lagging.

Operation of a Phase-Angle Regulator

A phase-angle regulator compensates for reactive drops by inserting between its input and output terminals a series voltage that is in quadrature with system line-to-ground voltage. This quadrature voltage produces, between the terminals, a phase shift whose magnitude varies with the magnitude of the quadrature voltage.

By definition, load terminals (*L*) are those terminals toward which power is flowing and source terminals (*S*) are those connected to the system supplying power. Either set of terminals could be source or load terminals, depending on the direction of power flow. When load-terminal voltage leads source-terminal voltage, the phase-angle regulator is said to act in the "advance" direction; when load-terminal voltage is lagging, the regulator is acting in the "retard" direction.

The schemes employed to advance or retard load-terminal voltage are many and varied.[1] On the basis of past experience, Westinghouse builds its larger units (100 MVA and above) with a grounded-wye exciting winding (Fig. 3). The windings are located on at least two separate cores, one for the *series unit* and the other for the *exciting unit*. The terminals of the series unit primary windings (*S* and *L*) are con-

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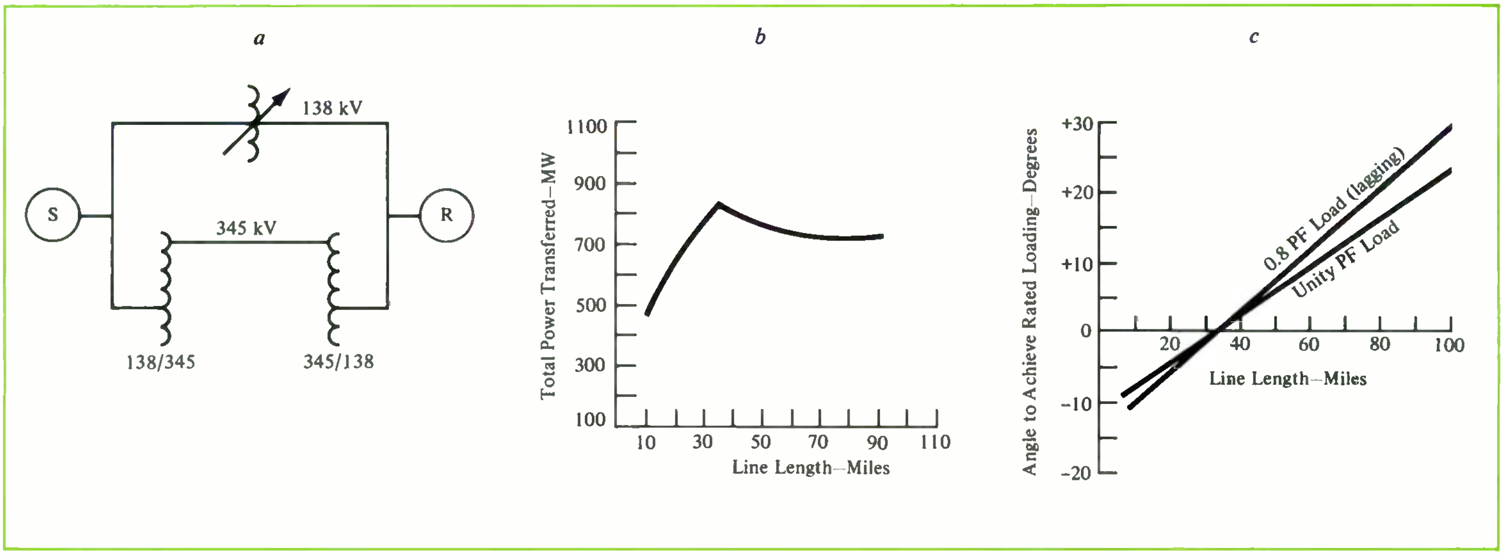

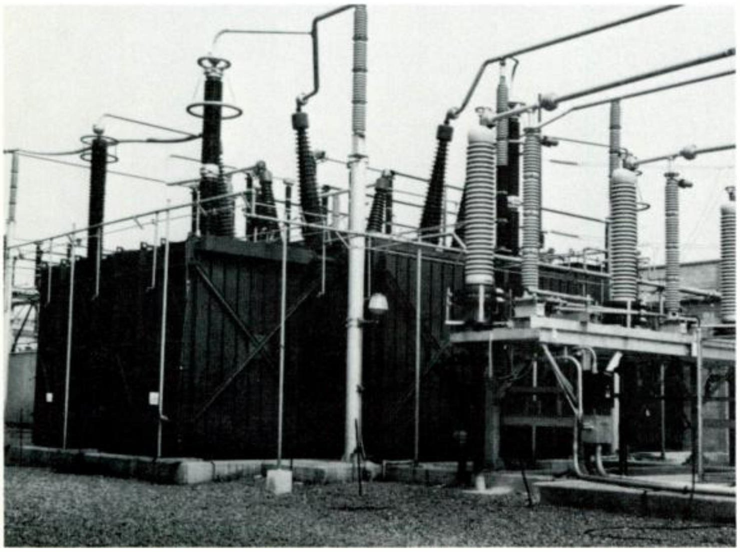

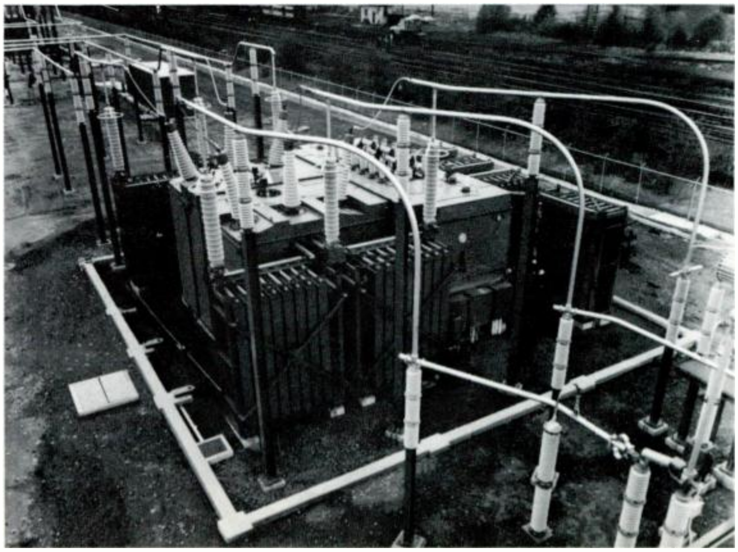

nected to the power system. The midpoints of those primary windings are connected to the primary windings of the exciting unit. The secondaries of the series unit are connected in delta and are excited by the secondaries of the exciting unit. This arrangement has several basic advantages:

1) Since the neutral is grounded, graded insulation and reduced BIL's can be used with the resulting benefits of lower cost and lower through impedance.

2) The grounded neutral reduces the danger of serious overvoltages occurring phase to phase and phase to ground during system disturbances.

3) Relay current transformers can be installed in each phase and in the grounded neutral.

4) Zero-sequence impedance to ground is equal to exciting impedance and is normally very high, while the through zero-sequence impedance is equal to the leakage impedance present with the secondary of the series unit shorted. With this schematic arrangement and the shell-form type of construction, the only path that allows any appreciable zero-sequence currents to flow is the delta formed by the secondaries of the series unit. Since this connection does not change with different load tap changer positions, the zero-sequence impedance remains constant over the regulator's entire phase-angle range.

At zero phase shift, the secondaries of the series unit are shorted and all power flows straight through the primary of the series unit. The exciting unit acts as a bias and carries exciting amperes only. Since the series unit is shorted, it carries load current only. As the tap positions are changed, a quadrature voltage is introduced between S and L, producing the phase shift (α) between the input and output terminals.

The kVA's handled by each component unit (series and exciting) are equal and are minimum at minimum phase shift and maximum at maximum phase shift. The maximum values determine the kVA parts of the regulator. The term "kVA parts" refers to the product of the maximum voltage and maximum current handled by a component such as the series or exciting unit. Since these maximum parameters do not necessarily occur simultaneously (and in some cases cannot), the kVA parts are usually different from the kVA rating. However, the parts are what actually determine the size and weight of a unit.

Thus, the kVA parts and consequently the unit's size and weight depend upon through kVA and maximum angle of shift. If the total shift is to be variable under load, the maximum phase shift that can be

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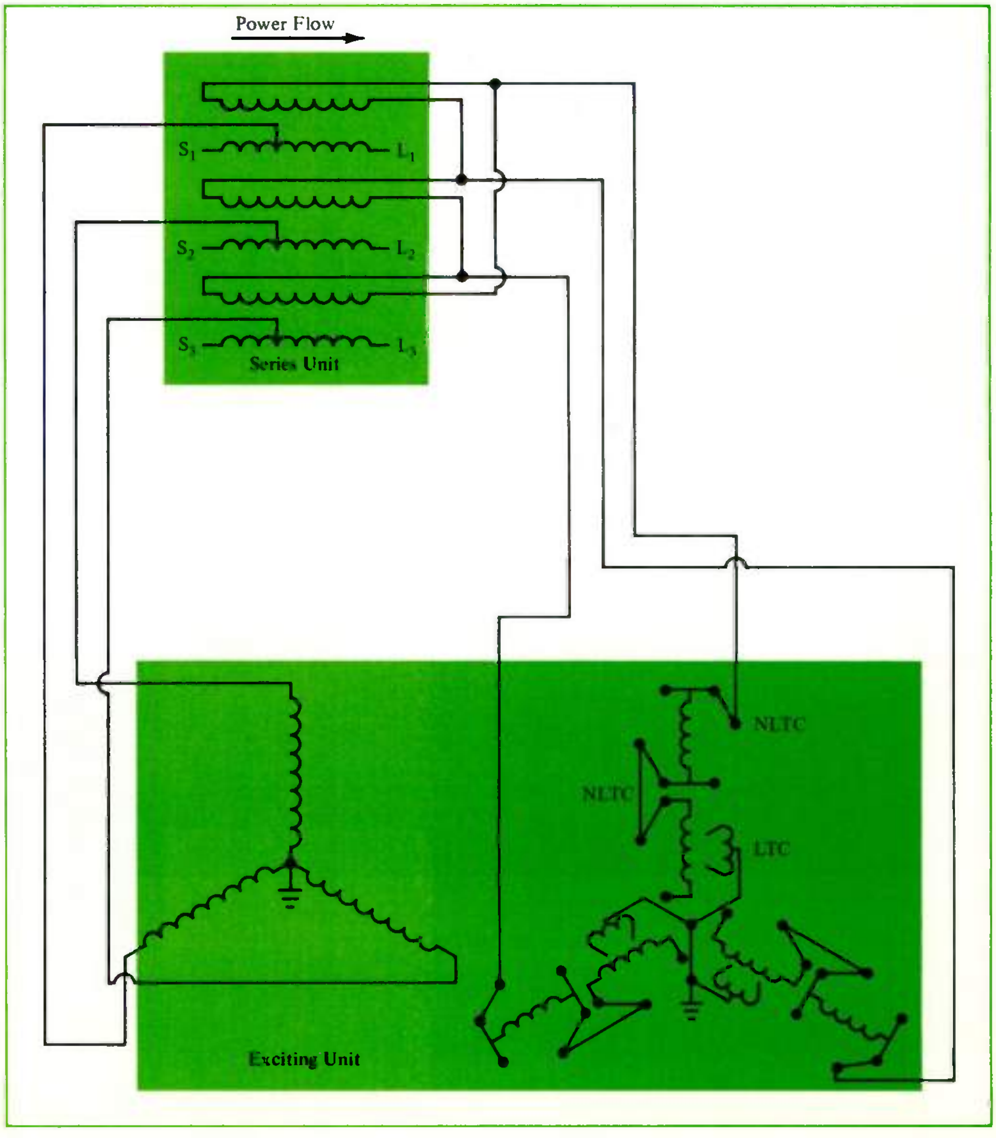

2—A typical application for the phase-angle regulator is in the 138-kV line of this parallel tie (a). *Without the regulator, maximum power transfer is a function of line length* (b). *The phase-angle regulator shift needed to provide maximum power transfer (815 MW) is a function of line length and power factor* (c).

Photo (far left)—*A 345-kV phase-angle regulator installed at the Farragut station of Consolidated Edison Company will provide ±25-degree phase angle shift at no load.*

Photo (left)—*This 230-kV phase-angle regulator at the Waldwick Station of Public Service Electric and Gas Company is rated 216/288/360 MVA.*

3—Transformer connection diagram for a Westinghouse phase-angle regulator is shown. System power flows through primary of series unit from source terminals (S_1, S_2, S_3) *to load terminals* (L_1, L_2, L_3). *Fixed phase shift is adjustable when the unit is de-energized, provided by the no-load tap changer* (NLTC) *on the secondary winding of the exciting unit; variable phase shift under load is provided by the load tap changer* (LTC).

accommodated depends on the maximum kVA that can be handled by the load tap changer. Today's tap changers can handle approximately 475 MVA of through power with a maximum variable angle of ±25 degrees. Thus, neglecting shipping problems, the load tap changer can be the limiting factor in phase-angle regulator size.

One method of circumventing the tap changer limitation is to use two or more load tap changers (LTC's) connected either in parallel or in series. When LTC's are connected in parallel, the problem is to make current divide equally between them and to make them stay in step to prevent circulating currents. When LTC's are connected in series, the problem becomes one of insulation of the LTC to ground. However, the series connection gives the advantage of numerous control schemes that allow the tap changers to be operated together or independently.

Another method of increasing the angle of regulation without increasing the duty of the LTC is to use a combination of fixed and variable phase shift as shown in Fig. 3. If the user's plan of operation allows a fixed shift, then the total capacity of the regulator can be greatly increased because the LTC is no longer the limiting factor. The so-called "fixed" shift can be made adjustable because it can be arranged so that under de-energized conditions the windings can be reconnected to act in either

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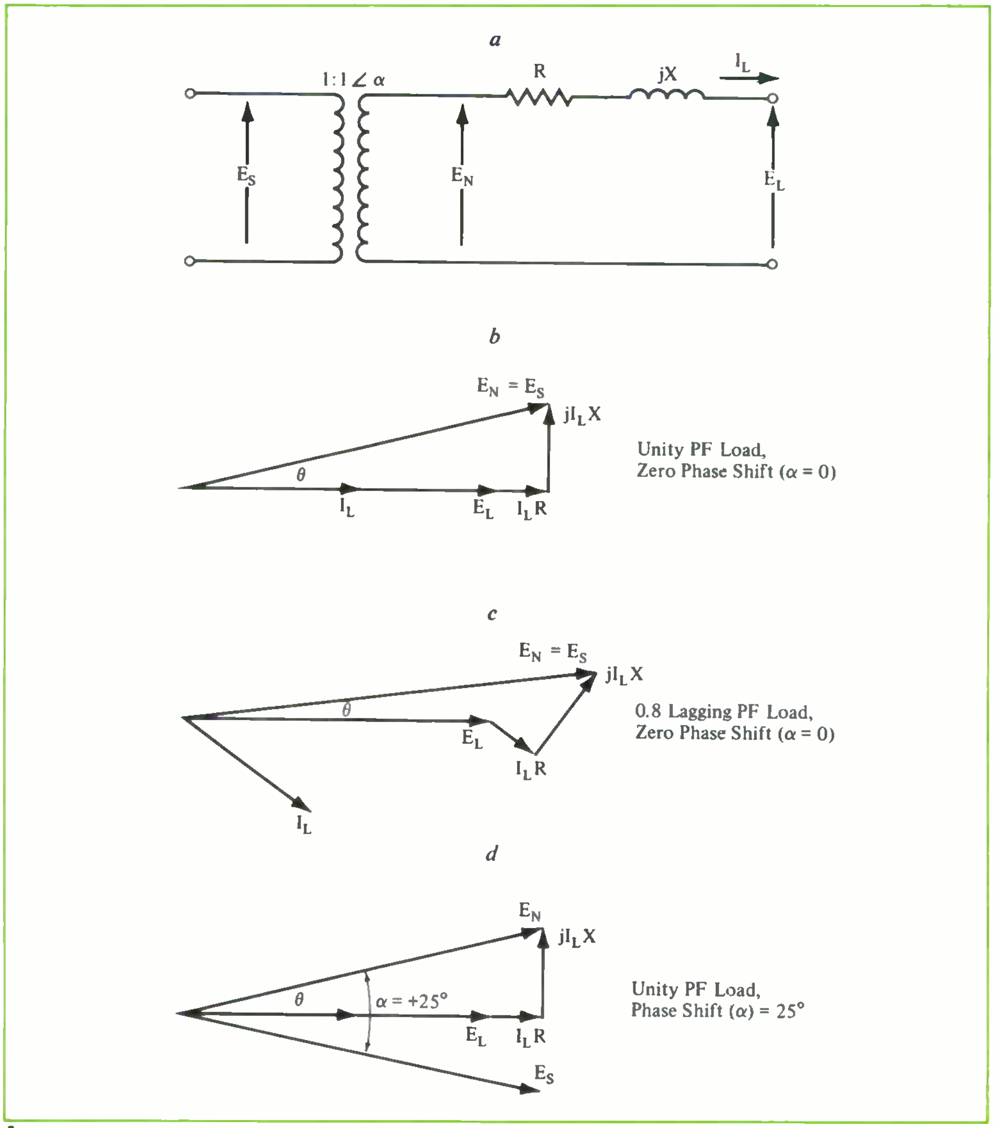

4—Winding resistance and leakage reactance of phase-angle regulators affect both voltage ratio and phase shift under load conditions. To simplify the illustration, the impedance of the regulator is assumed to be lumped on the load side of the equivalent circuit (a) *and the load voltage* (E_L) *is used as the reference phasor. For a unity power factor load with the regulator set for zero phase shift* ($\alpha=0$), *load voltage* (E_L) *will lag source voltage* (E_S) *as indicated on the phasor diagram* (b), *so the regulator is "load retarded"* ($-\theta$) *even though it is set at neutral tap position* ($\alpha=0°$). *The effect of regulator impedance at 0.8 power factor lagging load and at unity power factor with the regulator advanced* ($\alpha=+25°$) *is shown with phasor diagrams* (c, d).

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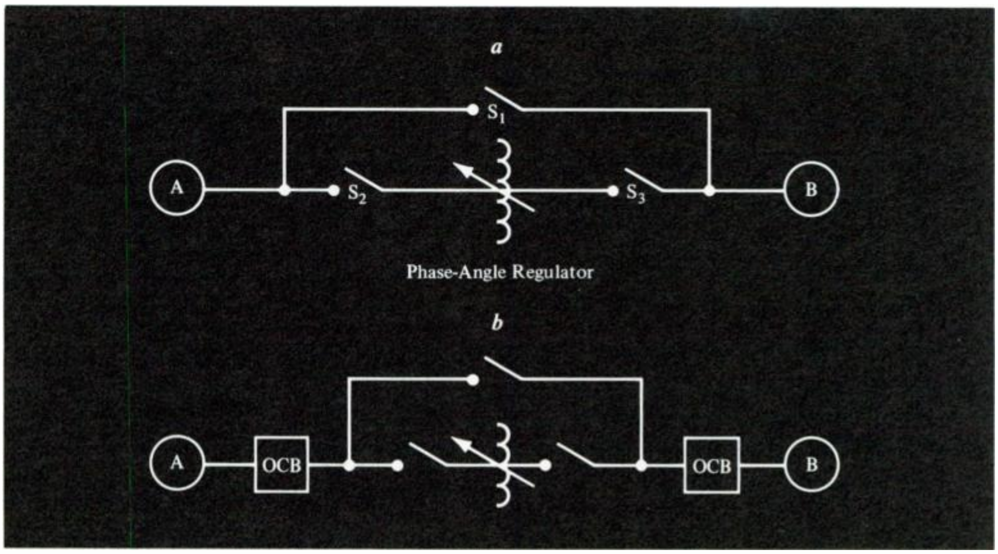

5—(a) *Phase-angle regulators are installed with bypass switch* (S_1) *and isolating switches* (S_2). *All switches can be standard horn-gap switches if the unit can be isolated from both power systems with oil circuit breakers* (b).

the advance or retard direction as needed. This reconnection can be accomplished with a terminal board or with a no-load tap changer while the unit is de-energized.

Application of Phase-Angle Regulators

Regulation—In contrast to voltage regulators, which may have zero through impedance when set on the neutral tap, phase-angle regulators have a minimum impedance of about 6 percent on the neutral tap position. Impedance increases as phase shift increases to approximately double at maximum shift. Thus, the unit windings even at zero phase shift cause voltage drop and phase-angle shift, i.e., regulation. Regulation varies with load magnitude and power factor, and with tap changer position. Consequently, the effective phase shift between input and output terminals is not the same at no load as at full load. The effect of regulation on total phase shift is illustrated in Fig. 4. Although compensation can be built into the phase-angle regulator to offset voltage and phase-angle regulation, this would increase kVA parts and costs significantly.

Switching—Through impedance also affects the selection of bypass and isolating switches for the phase-angle regulator. For the example shown in Fig. 5a, S_1 is the bypass switch and S_2 and S_3 are isolating switches. The switching sequence is: S_1 closes prior to S_2 and S_3 opening, and S_2 and S_3 close prior to S_1 opening. All switching operations must take place on the neutral tap.

All three switches must be insulated for system line-to-ground voltage. Switches S_2 and S_3 interrupt exciting current, which is standard duty for a horn-gap switch. However, the duty for the bypass switch (S_1) is more severe.

For example, consider a phase-angle regulator rated at 600 MVA, 230 kV, with a neutral impedance of 6 percent. If S_1 opens on a current zero, the recovery voltage across S_1 is about 15 kV. That voltage alone is not undesirable, but if the switch were opened under a load current of 1510 amperes rms, the arc reach in air would be greater than the phase separation in the switch, causing disastrous switch operation.

In general, a horn-gap switch cannot be used as a bypass switch for a phase-angle regulator unless the current is reduced to less than one-fourth the full-load current. For full-load operation, some other means of bypassing, such as a circuit switcher, should be explored.

However, if the regulator is used in an interconnection between systems and each system has a circuit breaker available at its end of the tie line (Fig. 5b), a horn-gap switch can be used for bypassing the phase-angle regulator provided the circuit breakers are opened before the horn-gap switch operates.

Internal Fault Protection—Although this article is not intended to cover relay protection of phase-angle regulators, some precautions should be mentioned.

Current transformers can easily be installed on each terminal bushing, in the secondary leads of the series units, and in the neutral end of all windings in the exciting unit. They can be connected to provide information for correct relay operation during most internal faults. However, under certain conditions, an external fault close to the unit may cause a higher than normal voltage to appear across the series windings, causing saturation that in turn causes undesired relay operation. To prevent this, some means of desensitizing the relays during external faults may be desirable.

Other areas of concern are turn-to-turn faults, and faults involving LTC taps or tap sections. Although current in a shorted turn or winding section may be substantial, the current feeding the fault may be insufficient to trip relays. Unfortunately, it is impossible to place current transformers in all the possible locations to provide 100-percent protection. Therefore, the use of sudden-pressure relays is recommended in this instance.

Typical Units

Since 1961, the Westinghouse Power Transformer Division has shipped ten phase-angle regulators rated 100 MVA or more. Three recent shipments illustrate the physical size, weight, and complexity of these devices.

A 138-kV unit is unique in that it is the probable forerunner of a new type regulator that will connect directly to an SF_6 enclosed bus without an oil-to-air interface. The unit has a ±25-degree variable shift at no load. It is rated at 150 MVA, has a gross weight of 225 tons, and occupies 570 square feet. Both the series and exciter units are included in one tank.

A 230-kV unit with a 600-MVA rating is the largest rating shipped to date. It has a total fixed-shift capability of ±15 degrees in addition to a ±15-degree variable shift, all at no load. The series and exciter units are in separate tanks with the winding interconnections made under oil in a common throat. At a gross weight of 770 tons, it has a foundation area of 2910 square feet.

The only 345-kV unit built to date has a ±25-degree variable shift at no load and a rating of 513.3 MVA. The design of this unit required two series transformers. The series units and the exciter unit are each mounted in separate tanks and all enclosed in one acoustical enclosure. The winding interconnections are under oil in throat connections. The gross weight is 785 tons and the floor area is 2500 square feet.

Developments presently under way at the Westinghouse Large Power Transformer Division will lead to the availability of even larger capacity and higher voltage units in the future.

REFERENCES:

[1]*Transmission and Distribution Reference Book*, Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania, Chapter 5, Part XIII.

[2]*Westinghouse Shell Form Phase Angle Regulating Transformers*, Descriptive Literature, Form No. 274 PAR2M.

Subsea Oil Production Systems Permit Deep-Water Operations

Two subsea oil and gas production systems have been developed for safer and cheaper deep-water oil recovery. They are the multiple-well production/manifold center and the single-wellhead completion system. In both, oil production and wellhead control equipment are installed on the ocean floor instead of on a platform, with the installation performed remotely from the surface. The two systems should extend offshore oil production capability to depths approaching 6000 feet from the present limit of about 600 feet, thereby making it feasible to explore almost all continental-shelf areas for economically recoverable oil and gas.

The systems were developed by Subsea Equipment Associates, Ltd. (SEAL), which is jointly owned by Westinghouse Electric Corporation, Mobil Oil Corporation, British Petroleum Company, Ltd., Compagnie Francaise des Pétroles, and Groupe DEEP (a group of British, Dutch, and French engineering companies). Other companies associated with SEAL development programs include Continental Oil Company, Sun Oil Company, and Phillips Petroleum Company (U.S.A.); Petrobras (Brazil); and Elf-Erap and SNPA (France). In addition to development of commercial systems for oil and gas production in deep water, the SEAL consortium offers engineering services, equipment, installation services, and maintenance services for development and operation of subsea oil and gas fields.

Multiple-Well Production/Manifold Center—This system has three major components: a base template, a subsea work enclosure, and wellhead connector assemblies (Fig. 1).

The base template is towed to the production site, submerged, and leveled on the ocean floor (Fig. 2). It then serves as a template to guide drilling of diverging wells. It also serves as a haul-down fixture and foundation for the subsea work enclosure. (See back cover.)

The work enclosure is cylindrical and consists of a control section and a service section. The control section contains the electrical distribution equipment and a remote terminal for a computer control system; the service section contains all of the oil-handling equipment and has an inert nitrogen atmosphere to eliminate any possibility of fire or explosion (Fig. 3). Both sections are kept at atmospheric pressure.

The wellhead connector assemblies are lowered from the ocean surface by guidelines and automatically positioned over the wellheads and vertical penetrations of the subsea enclosure. They can be retrieved should a major tubing workover be required.

The system operates as an automated oil production facility. Each well is monitored and controlled by the computer control system located on a surface support ship, on a nearby oil platform, or at a shore facility. Most well maintenance also is handled routinely under computer control. Oil from each well is manifolded into a single flowline.

Some types of maintenance, however, require manned intervention. Then a maintenance team descends from the surface in a personnel transfer bell (Fig. 4). The bell

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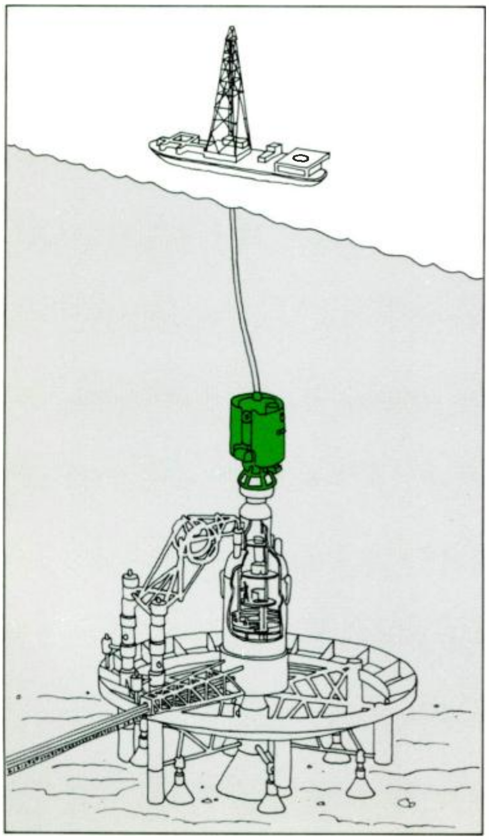

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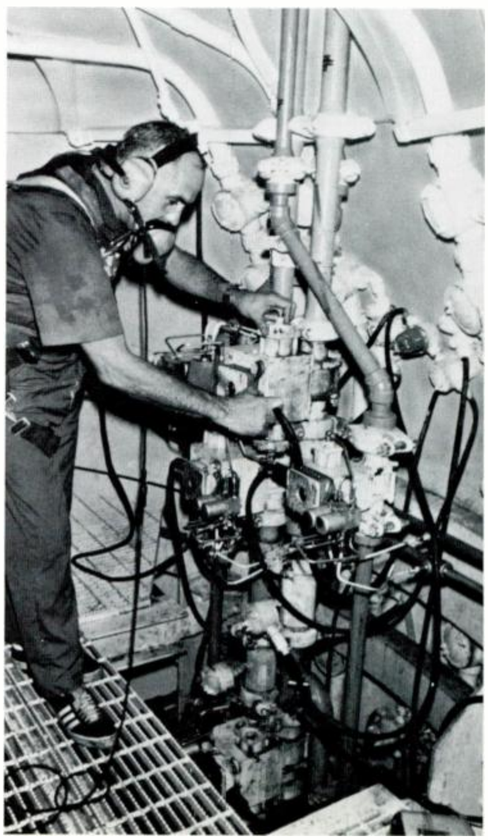
The multiple-well production/manifold center for subsea oil production (1) is permanently installed on the ocean floor. The base template of the production center (2) is towed to the site and lowered to the ocean floor where it serves as a template to guide drilling of diverging wells. The submerged work enclosure (3) contains an inert nitrogen atmosphere to eliminate any possibility of fire or explosion. A personnel transfer bell (4) is used to move personnel from the surface to the subsea work enclosure. A single-wellhead completion system (5) consists of a base/guide structure that remains permanently on the sea floor and upper components (color) that are lowered with a handling tool (5a) and secured to the structure (5b).

3



and the control section of the subsea work enclosure have a breathable atmosphere. Crew members put on breathing apparatus before entering the nitrogen atmosphere of the service section, and one member remains as a safety man in the control section.

Single-Wellhead Completion System—This system is for single high-production wells in moderate to deep ocean depths. It can handle flow rates up to 10,000 barrels per day. The system's basic modules are a base/guide structure, master valve assembly, and production control assembly.

The base/guide structure remains permanently on the sea floor. It supports and aligns the other components of the wellhead and the service equipment (Fig. 5).

The master valve assembly contains reliable components that are seldom operated and rarely require service. It is essentially the lower part of a conventional wellhead operating tree.

The production control assembly contains frequently operated components such as valve actuators. It is remotely controlled and requires no maintenance under operation, and sensitive leak-detection equipment guards against oil pollution of the sea. When servicing is required, usually every two years, the entire production control module is removed and replaced remotely by a surface support ship. If manned intervention is ever necessary, a back-up working enclosure is available. It is a large bell that is installed over the wellhead, drained of sea water, and filled with air at atmospheric pressure. Service personnel are transferred to the enclosure by a personnel transfer chamber.

Advantages—The subsea systems provide capability for economic production of oil and gas in much deeper ocean depths than has been feasible heretofore. Petroleum exploration has been done in depths beyond 5000 feet, wells have been drilled in about 2000 feet of water, but commercial production has so far been limited to less than 400 feet. The multiple-well production system was designed for operation in depths down to 1500 feet, and the single-wellhead system for 1200 feet of water. However, the designs for both systems could be extrapolated for operation in depths approaching 6000 feet. Thus, these systems make it practical to explore much larger areas of the continental shelves for economically recoverable oil and gas.

Another advantage of subsea production systems is the protection they provide against the risk of pollution. Wellhead control equipment is located on the ocean floor, invulnerable to damage by ships and storms. Subsea systems are also less susceptible than platforms to earthquake damage.

Both systems operate automatically, reducing the risk of human error. Should anything go wrong, the wells would shut down until the problem is corrected. Fire hazards are reduced because oxygen atmosphere is eliminated. Hazards to navigation and shipping are also reduced, since fixed surface structures are either eliminated or significantly decreased in size and number.

Subsea systems are also safer for operating personnel because no divers are needed to install, operate, or maintain them. Maintenance crews work in a comfortable

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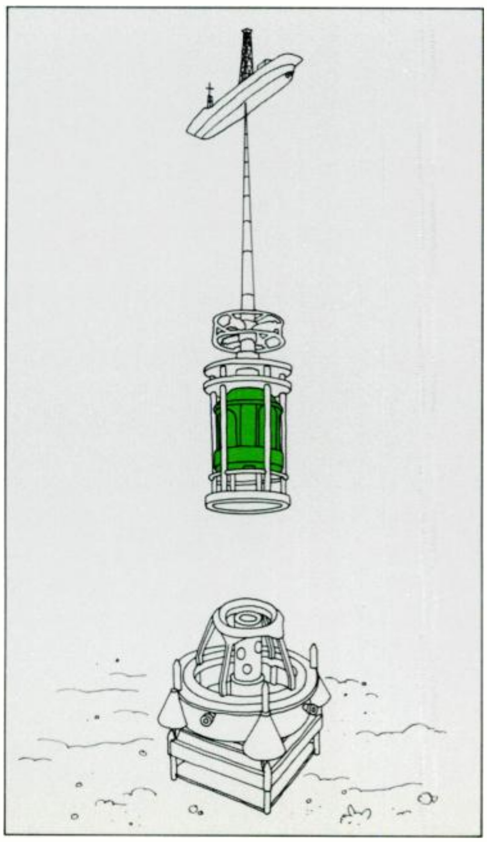
5a



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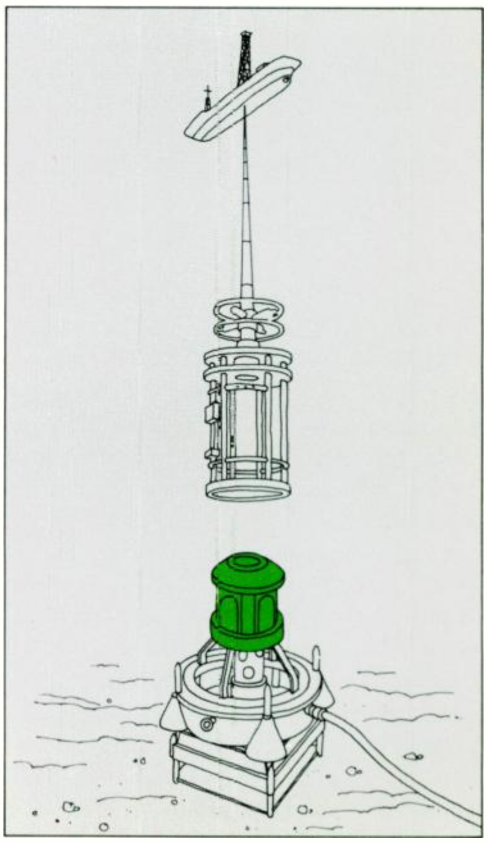


well-lighted environment at atmospheric pressure.

The ocean-floor systems can be designed and fabricated more quickly than platforms, so a newly discovered offshore oil field can begin producing oil about a year earlier with subsea systems than with platforms. Furthermore, they require less than five percent of the steel needed for platforms.

The systems also are competitive in cost with platforms. In general, conventional platforms, which are rigidly erected and rise above the sea surface, are limited economically to depths of about 300 to 600 feet; their cost increases exponentially with water depth. Platforms of new design, which are not rigidly connected to the sea bottom, are generally limited economically to depths of about 400 to 1000 feet; their cost generally increases linearly with depth. The subsea systems are economically attractive in depths of 250 feet and more and are currently the most attractive production method beyond 600 feet; their cost increases at a very low rate with depth.

In the development of many new oil fields, the best approach will be a mix of platforms and subsea systems. For example, a new oil field in the North Sea in 400 feet of water would normally require four platforms for 108 production wells. Equipment costs could total as high as $650 million, or $6 million per well. By using only one platform and completing the remaining wells with subsea production systems, the capital cost could be reduced by $1.5 million to $2.5 million per well—a cost saving of between $150 million and $250 million. Also, the subsea systems could be delivered before the platform, advancing oil production from the field by at least a year.

Finally, because platforms are so expensive, they frequently are spaced at distances that do not permit full recovery of oil from the offshore field, and smaller formations nearby may not be tapped at all. Subsea production systems, however, can produce oil from areas not reached by the platform. They can also produce oil economically from exploration wells, which are normally plugged and abandoned. The base portion of a subsea system can be installed over the exploration well; later, when the field is placed in production, the control portion of the system can be installed.

Wiring Devices Adapted for Wet or Corrosive Conditions

A line of electrical wiring devices originally designed for marine use has been found to be equally suited for use in industrial applications where wet or corrosive conditions pose safety and maintenance problems. They provide safe and trouble-free performance in such locations as chemical plants, dairies, food processing plants, breweries, offshore platforms, paper mills, plating facilities, and petrochemical plants. The devices are supplied by Bryant Electric, a division of Westinghouse.

Devices in the line are high-visibility orange in color, which is the color specified by OSHA to designate hazardous parts of machinery and energized equipment. They include a power inlet, attachment plugs, connectors, neoprene boots, adapters, cord sets, single and duplex receptacles, and outdoor plates for switches and receptacles (see photo).

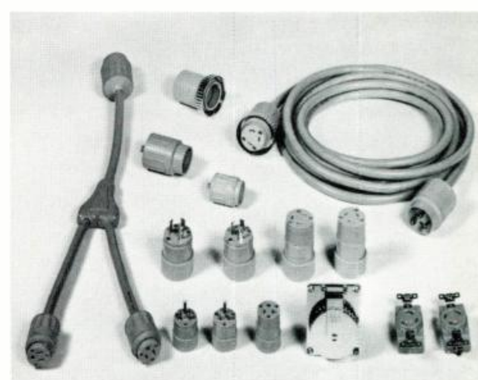
Every device incorporates safety features. For example, the power inlet has a hinged cover that locks in the open position, leaving the hands free for inserting a power-cord connector. The cover and plate are made of heavy chrome-plated brass for corrosion resistance. Cover and plate are threaded so that the cover can be screwed securely to the plate when the inlet is not in use; a neoprene O-ring between them makes a waterproof seal and prevents metal-to-metal contact. Individual wire pockets allow maximum conductor separation, preventing flashover between wires. The inlet is of two-pole three-wire grounding locking design, and it is supplied in ratings of 20 and 30 amperes at 125 volts.

The inlet's corrosion resistance has been tested in compliance with ASTM Standard B117-62. With its cover open, the inlet was drenched continuously with a five-percent salt solution at 95 degrees F for 2000 hours. There was virtually no evidence of corrosion.

The attachment plugs and connectors have dead-front construction and Bryant's exclusive triple gripper, a cord clamp that adapts to all rated cord sizes by automatically gripping the cord as the assembly screws are tightened. That feature saves wiring and disassembly time, protects electrical terminals from damage due to pulls on the power cord, and eliminates the possible shock hazard of metal cord clamps. The plug and connector bodies are made of nylon for strength, resistance to chemical attack, high arc resistance, and insulating ability. The devices are made in two-pole three-wire grounding types and ratings ranging from 15-ampere straight-blade through 30-ampere locking.

Neoprene boots fit over the plugs and connectors to help keep moisture out. They can be had with a chrome-plated brass sealing ring attached; the ring is screwed to the inlet plate to assure a secure and water-tight connection.

The devices are listed by Underwriters'



Wiring devices for use in wet or corrosive conditions exclude water from the conductors and resist corrosion. They include the adapter at left in the photo, the cord set at upper right, and individual attachment plugs, connectors, boots to cover the plugs and connectors, a power inlet, and receptacles.

Laboratories, Inc. They also have the Superior Product Seal of approval from the Marine Testing Institute.

Explosion-Proof Motors Meet Revised Underwriters' Requirements

The line of explosion-proof motors produced by the Westinghouse Medium Motor and Gearing Division, in ratings from 1 through 350 horsepower, has been modified to comply with recently revised requirements of Underwriters' Laboratories, Inc. The new requirements, which are effective December 5, 1974, will enhance the safety of UL-labeled explosion-proof motors.

UL approval in accordance with the new requirements has been obtained for the Division's lines of Class I–Group D and Class II–Groups E, F, and G motors. Briefly, Class I motors are for use in hazardous-vapor atmospheres and Class II for hazardous-dust atmospheres. Such motors are generally of totally enclosed fan-cooled construction, having a shaft-mounted fan that blows cooling air along the external surface to keep surface temperature (and the temperature rise of the windings) within prescribed limits.

The revisions in the UL requirements consist mainly of modification of the maximum allowed surface temperature and the requirement of marking that temperature on the nameplate or label. The change in maximum surface temperature affects both design and construction. Because the effects are greatest in Class II–Group G motors, that type is discussed briefly here.

Class II–Group G motors are intended for use in locations having a hazardous concentration of grain dust. In brief, the prior requirement was that their surface temperature could not exceed 120 degrees C when operated at 100 percent load in a 40-degree-C ambient under the maximum attainable blanket of dry grain dust. The maximum attainable blanket can become quite thick even though the motor's cooling air stream blows off some of the dust that settles on it; dust accumulation may cover part of the upper portion of the frame to the depth of the cooling fins.

The requirement that surface temperature must not exceed 120 degrees C in a 40-degree ambient will continue in effect. The added requirement takes into account the more severe blanketing that can occur when the dusty atmosphere has a high moisture content. Moist dust clings much more, adversely affecting self-cleaning and thus tending to raise surface temperature above that attained with dry-dust blanketing. All Class II–Group G motors labeled in December 1974 and thereafter must have verification that they will not exceed 165 degrees C surface temperature when operating in a 40-degree-C ambient with a maximum moist dust blanket, under all possible load conditions including stalled rotor.

In general, the Westinghouse motors have temperature-limiting devices in their windings, with the operating temperature of the devices such that they are activated well before 165-degree surface temperature is reached.

UL witness testing is required. First, the entire upper half of the motor is plastered with a paste of flour and water to a depth that covers the external frame cooling fins and partially blocks the air-outlet opening of the fan guard. The motor is then run for a sufficient time and at suitable load to "heat soak" it throughout, but to a level that does not quite activate the temperature-limiting device. Surface temperatures are continuously monitored by thermocouples at many points. Then the motor is subjected several times to abusive loading: overload, single phasing, and stalled-rotor. Each is maintained until the temperature-limiting device operates and removes the motor from the power source. The surface thermocouples are monitored during each test and after shutdown until temperatures peak. No surface temperature may at any time exceed 165 degrees C.

Heat Treatment Permits Thinner Walls for Large Steel Pipe

An induction heat-treating process devised for large-diameter steel pipe permits reducing wall thickness without reducing strength. Ability to use thinner-walled pipes in pipelines could result in large savings, both by reducing the amount of steel needed and by reducing material-handling costs through weight reduction.

Testing of one type of low-alloy pipe, for example, showed that thinner-walled pipe treated with the new process had the same pressure capability (100,000 psi) as conventional thicker-walled pipe. Reductions of 10 to 50 percent in wall thickness are possible, depending on pipe diameter. Distortion of the pipe by the heat-treating process is negligible, and the pipe retains its strength at temperatures as low as −60 degrees F.

The new process is the result of full-scale development studies at the Process Equipment Department of the Westinghouse Industrial Equipment Division. It consists essentially of a heat-quench-temper cycle followed by normalizing and aging cycles.

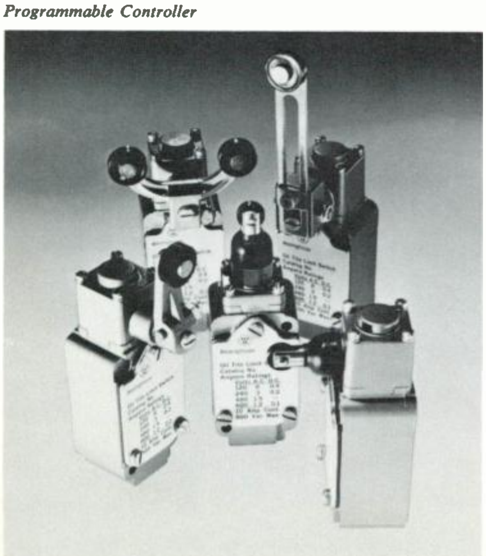
Heating is accomplished at 60 hertz with standard commercially available apparatus (typically, a combination of transformers, reactors, capacitors, switchgear, etc.) in conjunction with induction coils and quench systems sized to suit the pipe size. There are no electrical limitations on production rate. The only limit is the speed with which the handling equipment selected can move the pipe through the coils.

Products and Services

Energy-saving lamps provide a simple means for industrial and commercial users of lighting to substantially reduce the amount of energy consumed by merely changing lamps. The Econ-O-Watt lamps include mercury vapor, fluorescent, and incandescent types. They are designed to reduce power needs by 8 to 25 percent, compared with conventional lamps, with some decrease in light output. The lamps enable users to reduce power consumption without removing lamps and therefore without adversely affecting light distribution and the general appearance of their lighting systems. *Westinghouse Lamp Divisions, 1 Westinghouse Plaza, Bloomfield, New Jersey 07003.*

Programmable controller, the Numa-Logic PC-400 series, communicates in simple direct relay language—the same language that engineers and maintenance personnel have always used for machine control programming. Circuits contain up to ten elements per line and up to eight parallel branch circuits. The controller is entirely solid-state. Auxiliary functions such as timers, retentive memory, counters, and shift registers are directly programmable on both the core read-write memory and the programmable read-only memory. Input and output modules are expandable in increments of eight to a maximum of 512 inputs and 256 outputs. The input module converts 110-volt signals from pushbuttons, limit switches, and proximity switches to controller logic levels. The output modules, in turn, convert commands from the central processor into 110-volt signals that control output devices such as solenoids and motor starters. Both the input and output modules are optically coupled, with LED status indicators for monitoring and troubleshooting. *Westinghouse Control Products Division, Beaver, Pennsylvania 15009.*

Programmable Controller



Solid-State Limit Switch

Solid-state limit switch is for especially demanding industrial environments. It is completely interchangeable with Westinghouse mechanical limit switches, but it is constructed with totally sealed contacts and long (three-foot) leads so that connections can be made away from the wet or otherwise damaging area. Because no electrical parts are exposed, the switch keeps on functioning even if covered with dirt, grease, or coolant. Operating heads are available for rotary and linear travel, and five-direction operation is possible with a "wobble-stick" operator. A wide selection of operating levers includes fixed-roller, adjustable-roller, fork-lever, staggered-fork-lever, rod-lever, and precision-adjustment-roller types. *Westinghouse Control Products Division, Beaver, Pennsylvania 15009.*

Network power filter (NPF) protects solid-state equipment from damage or destruction by transient and surge voltages. It is added directly to the transformer secondary to limit the magnitude of transients in the output. It is available for application on transformers with nameplate ratings from 15 through 1000 kVA. The NPF employs a dual protection system to safeguard against substantially in-phase line-to-neutral transient voltages and unbalanced transient voltages, as well as surge voltages. Voltage clamping would arrest transient spikes, but another solution was necessary to control surge voltages, because they present a different problem: though they may be only a small fraction of the magnitude of the distribution voltage, they are not subject to the step-down ratios of the transformers. Also, they have an extremely fast rise and fall time that exceeds the maximum time-rate-of-change voltage characteristic of solid-state devices. Therefore, the new filter consists not only of voltage clamping devices (to absorb relatively long-time transients having higher magnitudes) but also of capacitors connected line to neutral and line to line across the transformer secondary. The capacitors, chosen to have a good high-frequency characteristic, absorb short-duration surge pulses. *Westinghouse Specialty Transformer Division, Greenville, Pennsylvania 16125.*

Watt-Saver device can be installed in a 400-watt mercury-vapor lamp fixture to reduce the wattage to 250 watts, thus allowing immediate reduction in rating without replacing the lamp or fixture. It is for use in fixtures with high reactance or reactor ballasts. A similar device for 175-watt mercury-vapor lamp fixtures reduces the rating to 100 watts. Watt-saver devices in other types and ratings will be introduced in the near future. *Westinghouse Outdoor Lighting Division, 1216 West 58th Street, P.O. Box 5817, Cleveland, Ohio 44101.*

"Westinghouse Lighting Handbook" is a guide to the various light sources available and their application. Topics covered include light characteristics and measurements, lighting design, wiring, industrial and architectural lighting, floodlighting, roadway lighting, lighting for plant growth, and lighting costs. Price $7.50. *Westinghouse Lamp Divisions, 1 Westinghouse Plaza, Bloomfield, New Jersey 07003.*

About the Authors

V. R. Harris began his career as an application ngineer, and he has stayed close to that first ove in the management positions he has filled ince then. His responsibilities have included oth the development and the application of ower and control equipment for many kinds of ndustrial systems.

Harris attended the University of West Virginia, where he helped pay his expenses by playing axophone in dance bands. He graduated in 1937 vith a BSEE degree and joined Westinghouse on he graduate student training program. A training ssignment in the general mill section of the ormer Industry Engineering Department turned out to be more permanent; he spent the next ight years as an engineer in the section, mostly pplying paper-mill drive and control systems. He also earned an MS degree in Electrical Engineering at the University of Pittsburgh. Harris ransferred to the metal-working section in 1946 o do similar application engineering for metal-olling mills, and he was made manager of the ection in 1948. He became manager of the ormer Industry Engineering Department in 1953, nd in 1964 he moved to Buffalo as Engineering Manager of the Systems Control Division, which ater became the Industrial Systems Division. He is now Manager, Systems Development Engineering, Industry Systems Division.

Harris has served on national and local committees of AISE, ASME, and IEEE. He has been chairman of the IEEE Pittsburgh section and at the moment is Past President of the IEEE ndustry Applications Society. He is also active n the Industrial Control and Systems Section of NEMA and at present is Chairman of two Joint Sections Committees on Controlled Converters and Power Semiconductor Spacings. He has 19 patents to his credit and about 50 technical papers and articles, and he still plays a mean ax in a local dixieland group.

Robert A. Morgan is a prolific writer, having authored technical papers on drives and controls, numerous articles and papers on industrial marketing, and the "Selling Systems" chapter in McGraw-Hill's *Handbook of Modern Marketing*. He also was the editor of a solid-state systems drive course produced by his Division.

Morgan graduated from Bowling Green State University in 1943 with a BS degree (*cum laude*) n business administration. After service in the Army during World War II, he joined the Toledo Blade Publishing Company as State Legislative Correspondent. Morgan came to Westinghouse n 1947 and has made a career in sales, sales promotion, advertising, marketing, and sales development plus various staff assignments. He s presently Manager, Marketing Services, Industrial Equipment Division. Along the way, he earned a Certificate in Graphic Arts at Carnegie-Mellon University.

Off the job, Morgan has been active in political, civic, and community affairs. He served as a Councilman of the Borough of Wilkinsburg, Pennsylvania, from 1961 to 1965; he was vice president of the Council from 1963 to 1965 and also was named Wilkinsburg Man of the Year in 1965. He is now Chairman of the Citizens Advisory Council, Williamsville, New York, School District.

M. G. Morris brings a background of close to 19 years in ultrasonic cleaning to his article in this issue. He has contributed to the design and acceptance of many wire cleaning systems, including the new cylindrical-transducer system.

Morris earned a certificate in mechanical engineering at Bridgeport Engineering Institute in 1941, and he graduated from the University of Bridgeport with a BS in business administration in 1949. He worked first at Harris Transducer Division, General Instruments, where he became Sales Manager. Morris came to Westinghouse in 1964 and served as an ultrasonic cleaning specialist in the Bridgeport sales office. In 1966 he became a sales engineer in the former Industrial Electronics Division. That organization is now part of the Industrial Equipment Division, and Morris is Senior Sales Engineer with responsibility for ultrasonic cleaning systems including wire cleaning systems.

A. A. Regotti graduated from Milwaukee School of Engineering in 1951 with a BS degree in electrical engineering. He joined Westinghouse on the graduate student training program and went to work at the Switchgear Division. There he joined the Switchboard Automatic Control Section, which designed controls for synchronous condensers, carrier relaying for high-voltage transmission lines, and water-wheel generator stations.

Regotti moved in 1959 to the Systems Engineering Section, where he is presently Power System Consultant. He is responsible for all of the Division's fault studies and relay coordination studies and, in addition, he assists industrial and electric-utility district engineers with such studies. He lectures at the Industrial Relay Application School held annually by the Relay-Instrument Division, and he is Chairman of the Westinghouse Relay Protection Committee. He is also a member of the Industrial and Commercial Power Systems Committee of the IEEE Industry Applications Society.

H. W. Wargo earned his BS degree in electrical engineering at Pennsylvania State University, graduating in 1968. He joined Westinghouse and, after the graduate student training program, went to Industrial Projects Marketing as a power systems engineer. That engineering group was integrated into the Industry Services Divisions when the latter were formed in 1971.

Wargo's work involves the study of industrial power distribution systems to insure continuity of service and equipment protection. Those goals are usually achieved by one or more of the following studies: short circuit, device coordination, load flow, motor starting, harmonic analysis, and stability. All of them are computerized and can accommodate the largest industrial distribution systems.

William F. Parrish joined the former Westinghouse Air Arm Division in Baltimore in 1956 to perform advanced development work in infrared and optical imaging systems. He was made a Fellow Engineer in 1959.

Parrish transferred to the Westinghouse Oceanic Division at Annapolis in 1966 to work on television and optical system techniques in the underwater environment. Some of these techniques are described in this issue.

Parrish holds a BEEE degree from Johns Hopkins University (1942). He served overseas with the U.S. Army during World War II as a Captain, Corps of Engineers. Previous experience includes design of instrumentation systems, servo systems, and microwave circuitry. He is the author of more than a dozen technical articles, has several patents, and is a Registered Professional Engineer (Maryland).

L. S. McCormick is a Design Engineer in the special projects development section at the Westinghouse Large Power Transformer Division, Muncie, Indiana. He started on this assignment in early 1972 after 20 years of experience in the design of all types of power transformers, including EHV units and phase-angle and voltage regulators.

McCormick received his BSEE degree from Clemson University in 1952. He is a member of IEEE and is presently active on several subcommittees and working groups associated with the Transformers Committee.

Roger A. Hedding earned his BSEE at Marquette University, graduating in 1971. He came with Westinghouse on the graduate student course, and after an assignment at the Large Power Transformer Division, Hedding joined the transmission and distribution systems group as a Transmission Engineer. There he is responsible for assisting electric utility customers and Westinghouse transmission divisions in the planning and application of transmission equipment.

Westinghouse Electric Corporation
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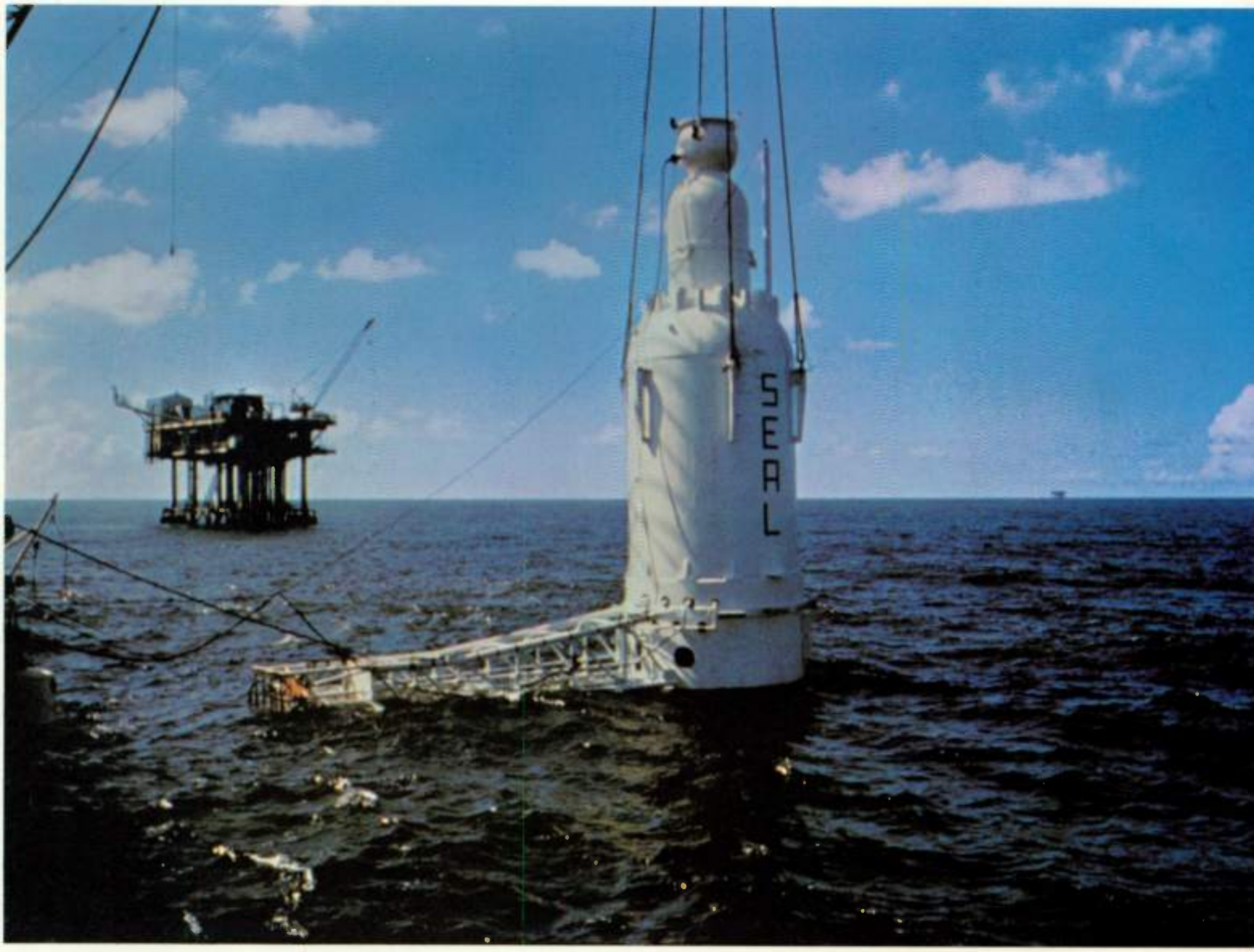
Gateway Center
Pittsburgh, Pennsylvania 15222



Part of a multiple-well production/manifold center for ocean-bottom oil and gas production is being lowered into the sea in this photograph. It is the center's work enclosure, and maintenance crews will be transferred to it when needed. For more information, see page 92.